EARTH SCIENCE SYMPOSIUM ON HUDSON BAY

Ottawa, February, 1968

Edited by
PETER J. HOOD

NATIONAL ADVISORY COMMITTEE ON RESEARCH

Published by the Geological Survey of Canada as GSC Paper 68-53

GEOLOGICAL SURVEY
OF CANADA

PAPER 68-53

EARTH SCIENCE SYMPOSIUM ON HUDSON BAY

Proceedings of a symposium held in Ottawa February 19-20th, 1968 under the sponsorship of the National Advisory Committee on Research in the Geological Sciences and the Associate Committee on Geodesy and Geophysics of the National Research Council.

Edited by Peter J. Hood
Associate Editors: G.D. Hobson
A.W. Norris
B.R. Pelletier

DEPARTMENT OF ENERGY, MINES AND RESOURCES

Indexed 69/70
WH

Available by mail from the Queen's Printer, Ottawa,

from Geological Survey of Canada,
601 Booth St., Ottawa,

and at the following Canadian Government bookshops:

HALIFAX
1735 Barrington Street

MONTREAL
Æterna-Vie Building, 1182 St. Catherine St. West

OTTAWA
Daly Building, Corner Mackenzie and Rideau

TORONTO
221 Yonge Street

WINNIPEG
Mall Center Bldg., 499 Portage Avenue

VANCOUVER
657 Granville Street

or through your bookseller

Price $5.00 Catalogue No. M44-68-53

Price subject to change without notice

Queen's Printer

Ottawa, Canada
1969

CONTENTS

CONTENTS (cont'd)

FOREWORD

The Earth Science Symposium on Hudson Bay was held in Camsell Hall at the Department of Energy, Mines and Resources in Ottawa on February 19th and 20th, 1968. The main objective of the meeting was to summarize our present knowledge of the underlying geology of Hudson Bay and more specifically to present the principal results of the 1965 Hudson Bay Oceanographic Project. Papers describing the geology of the Hudson Bay Lowlands resulting from the 1967 Operation Winisk of the Geological Survey of Canada were also presented. Because of its multi-disciplinary nature, the symposium was sponsored both by the National Advisory Committee on Research in the Geological Sciences and the Associate Committee on Geodesy and Geophysics of the National Research Council. The Organizing Committee for the symposium consisted of G.D. Hobson, P.J. Hood (Chairman), A.W. Norris, and B.R. Pelletier, and these persons also undertook the task of editing this volume. The meeting, which was attended by approximately 150 geologists and geophysicists from the oil companies, research foundations, and Federal and Provincial agencies, was opened by Dr. W.M. Cameron, Director, Marine Sciences Branch (DEMR) who gave the address of welcome. It is our hope that this endeavour might serve as a model for other multi-disciplinary assaults on areas of the continental crust in Canada and elsewhere.

Peter J. Hood,
Editor and Chairman,
Organizing Committee.

Ottawa,
December 1968.

HISTORY OF EXPLORATION IN HUDSON BAY

Leslie H. Neatby
Department of Classics, University of Saskatchewan

The early history of exploration in Hudson Bay more resembles an epic myth than a passage from modern history. The history of discovery in Latin America is well known and well documented as to dates, circumstances and incident; but from Nova Scotia north the record is far less precise. No one knows exactly where John Cabot made his American landfall and the original sighting of Hudson Strait is an even deeper mystery. Until recently the date could be placed anywhere within three quarters of a century, from a voyage by Corte Real in 1501 to the third voyage of Martin Frobisher in 1578; and recently Icelandic scholars have pushed it back into the period of the Vinland saga.

It has always been known that Norsemen from Greenland visited and attempted to found settlements somewhere on the North American shore about 1,000 A.D.; and that thereafter voyages, were occasionally made to Labrador to procure the timber which Greenland lacked. This fact has recently been confirmed by the discovery by Helge Ingstad of remains, probably Norse, at L'Anse aux Meadows in northern Newfoundland. But recently the late Professor Tryggvi Oleson in his "Early Voyages and Northern Approaches", the first volume in the McLelland and Stewart Centenary Series, advanced in English and theory, derived from a work in Icelandic by Jon Duason, that the Norsemen also passed through Hudson Strait and ascended to Melville Peninsula (Figure 1). There they hunted the polar bear, and lost their racial identify by merging with the Dorset Eskimo to form the Thule culture. As evidence Professor Oleson cites the discovery of stone structures on Melville Peninsula which he identifies as bear traps, a device employed by Norsemen, but unknown to the Eskimo. But Melville Peninsula seems a remote place for Greenlanders to hunt bears for transportation alive to the courts of European potentates, and the impressive evidence of the supposed traps is not in itself conclusive. The Welsh Icelandic authority, Professor Gwyn Jones in a friendly scholarly critique points out that two hundred years is too short a period for the complete and harmonious blending of Norsemen and Eskimo, and that it is hard to believe that no tradition would survive of this large-scale biological merger. Tradition has great vitality among the Eskimos. "In the present state of knowledge", concludes Professor Jones, "the mildest verdict possible upon the Duason-Oleson thesis is 'Not Proven'". I mention it, however, because it has been advanced by a distinguished Canadian scholar, and because future research may strengthen his thesis. In my own field of ancient literature and history we have learnt to be cautious in our scepticism, because the archaeologist is always barging in to disturb the security of our beliefs.

The first unambiguous written reference to Hudson Strait which we have dates from the third voyage of Martin Frobisher to Baffin Island in 1578.

Figure 1. Map of Hudson Bay and its environs.

But Europeans had evidently learned of its existence at some earlier date. A State Paper of Elizabeth I dated supposedly 1575, speaks of a passage from the North Sea to the South (that is, to the Pacific), north of Labrador and above latitude 60°N. It is called "The Narrow Sea or Streite of the Three Brethren". The record states that this channel is ice-free the year round owing to "the swifte ronnynge of sea into sea". This description, though inexact, must apply to Hudson Strait. From what source or sources was it derived? The British historian J. A. Williamson puts forward a strongly argued claim on behalf of Sebastian Cabot as the discoverer in 1508-09.

Sebastian Cabot, born in Italy a little after 1480, came with his father to England, where he spent his early manhood. In 1512 he entered the service of the King of Spain and there remained for thirty years. In old age he came back to England and helped to found the Muscovy Company and forwarded the search for a Northeast Passage through the Russian Arctic.

During his stay on the Continent Cabot at various times made references to a voyage under his command in the years 1508-09. He sailed from Bristol to American waters and ascended as high as latitude 67 $\frac{1}{2}$°N. Putting all these facts together Professor Williamson believes that he sailed through the Strait to Hudson Bay, where he was turned back by his mutinous crews. He quotes two pieces of supporting evidence: first the Globe of Gemma Frisius, dated not later than 1537, which shows a broad channel, which must be Hudson Strait, opening out into a great ocean beyond. Secondly he cites the "History of Travayle in the West and East Indies", published by Ralph Willes in 1577. This author, who had the use of charts of Cabot, since lost, gives the Strait as lying between latitudes 61° and 64°N., continuing west 10 degrees, then opening southward, extending down to the Tropic of Cancer and debouching into the South Sea where it is 18 degrees wider than at its Atlantic end. As far as what we know of Hudson Strait is concerned, it will be seen that Willes was remarkably near to the facts.

Professor Williamson offers a plausible explanation of Cabot's reluctance to make a full disclosure while he remained in the employ of Spain. That country, controlling two routes to the Pacific, one by Magellan's Strait, the other by the Isthmus of Panama, had no interest in using the far northern channel of Sebastian Cabot. On the other it had a strong interest in hindering its English and French competitors from exploiting such a channel, should it be proven to exist. Williamson records a conversation in which Cabot told the Venetian ambassador that it would be more than his life was worth, should it come to the ears of his Spanish masters that he had found such a passage and had been treating with English merchants for its development. But on his return to England why did he promote a trade route to China by way of the Russian Arctic, when on his own showing he had discovered a promising passage to the west?

G. M. Asher in his "Henry Hudson, the Navigator" takes little notice of Cabot. No doubt the sources used by Williamson were not available to him.

But he argues at some length to prove that Hudson Strait was explored by the Portugese. "They seem to have advanced slowly," he writes, "step by step, first along the shore of Newfoundland, then up Hudson's Strait, then through that strait, and at last into Hudson Bay. With a certain number of maps, ranging from 1529 to 1570 before us, we can trace this progress step by step. In 1544 the Portugese seem not to have reached the mouth of Hudson Strait; in 1558 their geographical knowledge extends beyond the mouth of the Strait; and in 1570 they have reached the Bay. Our authorities for all this are ancient geographical delineations. Ancient geographical delineations are not infallible guides. Why has no written record survived? We know that the Portugese government exerted itself to conceal discoveries made under its auspices from competitors; but if their discoveries were accurately recorded on maps how were they withheld from the printer? Mapmakers were prone to use imagination when knowledge failed them: the west coast of North America was fantastically distorted before the voyages of Cook and Vancouver. But the correct latitude is too often assigned to the east end of Hudson Strait for it to be accident. Beyond that nothing is clearly established.

Martin Frobisher is the first man whose claim to have entered the Strait is unquestioned. In 1578 he sailed for America with a squadron of fifteen ships to exploit the goldmine which he was supposed to have discovered on South Baffin Island. Near Resolution Island the ships were scattered in storm and fog: Frobisher's vessel with some other stragglers were carried into Hudson Strait. Despite the protests of his chief pilot that he was not in the waters he sought but in a "false strait", Frobisher sailed into it a distance of sixty leagues and privately boasted that but for his responsibility for the other ships under his command, he would have sailed through to the South Sea. As he had disregarded orders by this excursion he made no public claim of discovery, and but for the industry of Hakluyt, all record of it might have perished. This is a consideration which should make one cautious in rejecting claims on behalf of Cabot and the Portugese. In any case Frobisher did not receive due credit for centuries, as owing to his defective navigation many supposed that he had not been in America but on the east coast of Greenland.

Nine years later, in 1587, a more skilful seaman, John Davis, returning from Baffin Bay was caught in the tide race on Hudson Strait. "To our great admiration we saw the sea falling down into the gulf with a mighty overfal, and roring, and with divers circular motions like whirlpooles, in such sort as forcible streams pass through the arches of bridges". On the next day, August 1, Davis sighted and fixed Cape Chidley in "61 degrees and 10. minutes of latitude".

The outbreak of war between England and Spain and commercial enterprise elsewhere diverted attention from America for two decades. In 1601, George Weymouth sailed deep into the Strait before his crew mutinied and forced him to turn back. Then in 1610-11 came Hudson's great voyage. He carried his discovery clean through the Strait and, aiming for the South

Seas--James Bay is on the same longitude as the Isthmus of Panama- he headed south and wintered in James Bay. In the spring he was turned adrift by his mutinous crew and the ship was brought home by Robert Bylot. A serving man of Sir Dudley Digges, one of Hudson's sponsors Abacuck Prickett, has left us a graphic account of the tragedy, which deserves to be better known. He and the other survivors would doubtless have been hanged as mutineers but for the importance of the discoveries they reported. In 1612 Sir Thomas Button with Bylot and Prickett aboard, took two ships into the Bay. He reached the west shore at Churchill, coasted southwards to Port Nelson, and there wintered. He names the port after an officer who died there. In the next summer he went up the coast as far as Southampton Island and thence home.

Button had covered a great deal of coast and much dampened hopes of a western passage, but in 1615 Robert Bylot was sent in the Discovery with William Baffin as pilot to test the Bay farther north. They coasted up the northeast shore of Southampton Island, passed Cape Comfort, but were stopped by ice in Frozen Strait. Baffin, a very skilful pilot, judged from tidal observations that no western outlet existed.

In 1631, despite Baffin's discouraging report, two English seaports renewed the search for a passage west from the Bay. From Hull came Luke Foxe, and from Bristol Thomas James. Foxe, a rough seaman of great ability, first entered the channel between the mainland and Southampton Island, and named it Sir Thomas Roes Welcome. He then turned south past Port Nelson and finding James in those waters, again turned north, ascended Foxe Basin as far as the Arctic Circle, and from there went home, making observations on the inner shore of Baffin Island on his way out, a brilliant achievement for one season. James, "no seaman", according to Foxe, explored the southwest angle of the Bay, named Cape Henrietta Maria after his ship and wintered on Charlton Island in James Bay. James was not a hard-boiled master mariner, but a gentleman who muddled through by luck and good humour. At Charlton Island he scuttled his ship in shallow water lest she be swept away by the ice, and when his crew exclaimed that she could never be floated, and they must perish the lingering death of starvation James replied that "they were much indebted to God Almighty for granting them so long a time for repentance". Both he and Foxe left excellent accounts of their travels.

The fur traders came into the Bay in 1668; their struggles with the French from the St. Lawrence and preoccupation with business put an end to discovery by sea until well into the 18th century, if we except the disastrous voyage of James Knight, who perished with his crews at Marble Island in 1719-20.

Baffin had concluded that there was no salt water passage to the west, because he had found the tide relatively slight on the west shore of the Bay and no evidence of flood tide from the Pacific. But Luke Foxe had noted a stronger tide inside Southampton Island. We know that this was caused by the meeting of the Atlantic flood tides coming up Roes Welcome Sound and Frozen Strait, but Southampton Island was then thought to be a peninsula, and so doubt was cast on Baffin's conclusion, and in 1740, Arthur Dobbs, and Irish M.P. prevailed on the British Government to send Captain Christopher Middleton to renew the search. In 1742 Middleton sailed north from Churchill, noted Chesterfield Inlet, examined Wager Bay without success, searched another inlet to the north and finding it closed also, in bitterness named it Repulse Bay. He had done an excellent summer's work by discovering Frozen Strait and so proving the insularity of Southampton Island. But he had disappointed the expectations of Dobbs, who, on his return, accused him of bad faith, supported by Moor and Rankin, officers of the expedition, who had supported Middleton's conclusions on the spot, but now joined Dobbs in accusing him. Middleton's findings have been proved correct, but they had been hastily made. The captain had been in a dilemma to which the Arctic explorer is particularly liable: if he was quick in judging a lead to be false, he might be accused of giving up too soon; if he tested it to the limit, the sub-Arctic summer might be gone before he could test a more promising opening elsewhere. Further search up to 1751 was made by Moor, Bean and Moses Norton: Chesterfield Inlet was explored and Baker Lake discovered, but still no passage to the west. It is a pity that the names of Dobbs and Moor should be on the map today and Middleton's omitted.

Perhaps in consequence of Dobbs' agiation the western Quebec side of the Bay was examined also. The mouth of the Eastmain (Slude) River had been visited by 1679, and a post set up at its mouth in 1724. In 1744 the Company officers, Mitchell and Longland made a northward excursion from the Bottom of the Bay adding to the map Fort George, Great and Little Whale Rivers, and Richmond Gulf. This survey was extended to Digges Island in 1749.

In 1821-23 a British naval expedition under Captains Parry and Lyon, seeking the western passage as a matter of science more than of commerce, carried Middleton's survey to the north, traced the east shore of Melville Peninsula, and discovered but failed to penetrate the Strait of Fury and Hecla. Parry named Foxe Basin in honour of its discoverer, and from Eskimo reports made a relatively accurate tracing of the west side of Melville Peninsula. Captain Lyon, like Prickett, Foxe and James, an entertaining writer, has left an interesting and valuable study of Eskimo ways.

At the beginning of this century the east side of Foxe Basin, roughly from the Arctic Circle to Fury and Hecla Strait remained unexplored. In 1911 Bernard Hantzsch, a German ornithologist, explored this coast as far as Piling Bay. His observations were confirmed and extended in 1928-29 by the Canadian zoologist, J. D. Soper, and by Matheasen and Freuchen of the Fifth Thule expedition. In 1936 a British scientific team, led by T. H. Manning, and consisting of Messrs. Bray, Rowley, Keeling and Baird, spent the summer on Southampton Island. They set up winter-quarters on the mainland at Repulse Bay; and from there in the winter months Rowley and Bray journeyed to Igloolik, spent the weeks of deep winter there and with returning light went down the Baffin Island to Piling Bay. So they put the final touch on the work of geographical discovery begun three and half centuries before by Frobisher and Davis.

FAUNAL STUDY, HUDSON BAY AND TYRRELL SEA

Frances J. E. Wagner
Atlantic Oceanographic Laboratory, Bedford Institute
Dartmouth, Nova Scotia

Abstract

Published records of fossil and living species of Hudson and James Bays, and their fore-runner, the Tyrrell Sea, date back to 1862. Two hundred and sixty-three species have been recorded, of which 26 are known only as fossils, and 120 have been found only in recent deposits. The species collected from Hudson Bay in 1965 showed distributional variation to be related primarily to bottom sediment texture and dissolved oxygen content of the water, with depth being apparently of secondary importance. Bottom temperature, salinity, and hydrogen-ion concentration were relatively uniform at the depths sampled (between 35 and 286 metres) and were not significant with regard to distribution of species. Faunal changes shown by fossil assemblages from Tyrrell Sea suggest that water temperatures were probably not dissimilar to those of Hudson Bay, but that the waters were probably less saline than at present. Radiocarbon dates on marine shells indicate Tyrrell Sea may have reached its maximum extent between 5,000 and 6,000 B.C.

A study of the literature indicates that apparently the earliest organized investigation of the fauna of Hudson and James Bays, or their forerunner, the post-glacial Tyrrell Sea, was carried out by a Mr. Drexler who was travelling under the auspices of the Smithsonian Institution. He visited the southeastern coast of Hudson Bay during the summer of 1860, and proceeded south from there along the shores of James Bay as far as Hannah River where he obtained a collection of fossil marine shells that had washed out of the river bank. At Cape Hope, on the east coast of James Bay about latitude 52°10'N, he collected living molluscs from the upper tidal zone, as well as empty shells believed to be of Pleistocene age. These shells were identified by William Stimpson who published his findings in 1862. Numerous collections have been made by officers of the Geological Survey of Canada, starting with Robert Bell in the 1870's and continuing to the present. Members of other organizations (see Bibliography) have also collected in the area.

The early collections consisted primarily of fossil marine molluscs, plus a few barnacles and brachiopods. Some living molluscs were also obtained. Sponges, echinoderms, foraminifers, bryozoans and annelid worms have been added to the list by more recent collectors. Most of the living forms of the earlier collections were picked up from shallow water. Exceptions were the molluscs and sponges dredged from Clearwater Lake, Quebec in 1902 by A.P. Low. The first major study of the living fauna was conducted

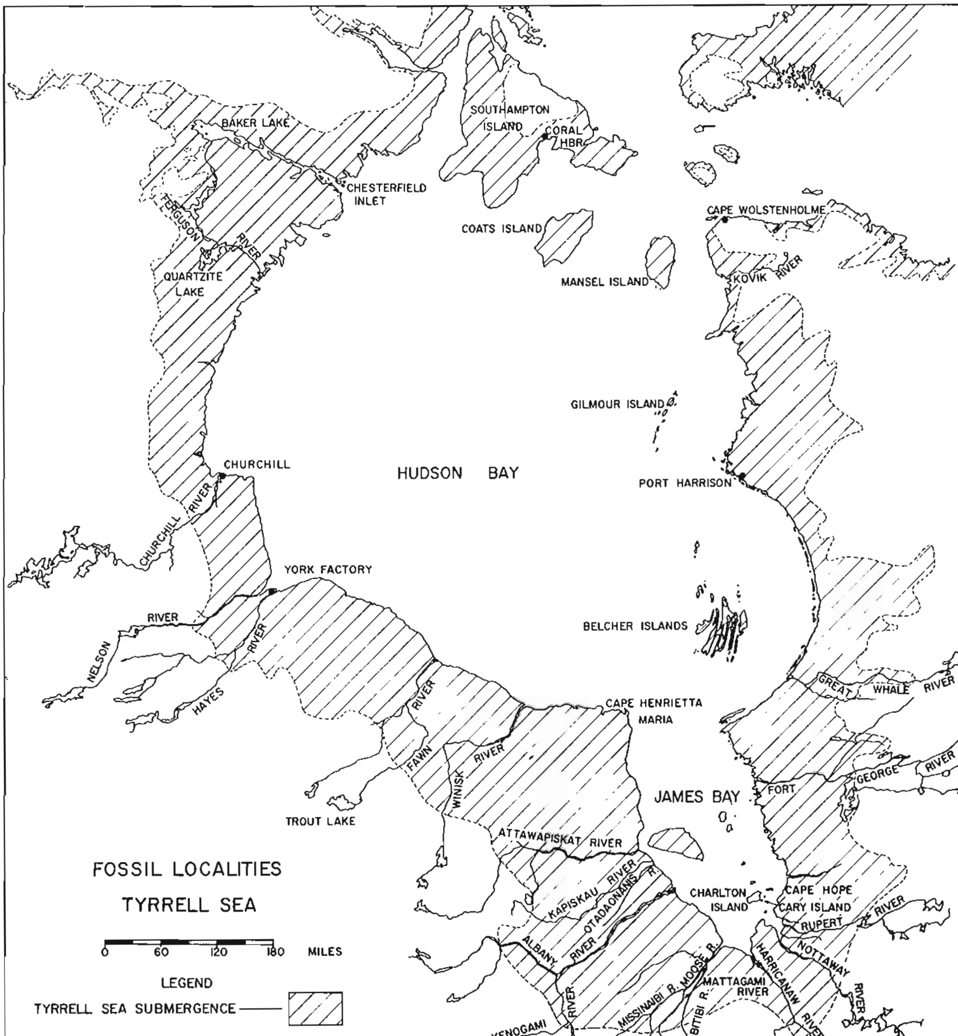


Figure 1. The general limits of Ancient Tyrrell Sea as indicated by the dashed lines. Fossils were recovered from raised beaches occurring in the area of former submergence.

by members of the Hudson Bay Expedition in 1920. All of the references to collections of fossil and recent organisms that I have been able to find are summarized in Table I. Figure 1 shows areas where collections have been made. Although a variety of faunal groups are recorded in Table I, only those with which I am most familiar, namely the Foraminiferida and Mollusca, will be discussed at length in this paper.

TABLE I

Summary of faunal records, Tyrrell Sea area

Author or Collector	Area	Organisms collected
Drexler, 1860	James Bay (eastern and southern) " " " "	Fossil molluscs and brachiopods Recent molluscs
Bell, 1872	Kenogami and Albany Rivers, Ontario	Fossil molluscs
Bell, 1877	Mattagami and Missinaibi Rivers, Ontario Rupert's House area, Quebec	Fossil molluscs, brachiopods and cirripeds Recent molluscs
Bell, 1879a	Missinaibi, Moose and Opasatika Rivers, Ontario; also east side of Hudson and James Bays	Fossil molluscs
Bell, 1879b	Steel River (?=Hayes River), York Factory area, and lower Nelson River, Manitoba	Fossil molluscs
Bell, 1880	Lower Churchill River, Manitoba " " "	Fossil molluscs and brachiopods Recent molluscs
Bell, 1881	East coast of Hudson Bay; also York Factory, Manitoba	Fossil molluscs
Bell, 1887	Albany and Attawapiskat Rivers, Ontario	Fossil molluscs
Low, 1887	Fawn River, Ontario	Fossil molluscs and brachiopods
Low, 1889	Fort George and Great Whale Rivers, Quebec	Fossil molluscs

Bell, 1896	Cape Wolstenholme and Nottaway River, Quebec	Fossil molluscs
Tyrrell, 1896	Baker and Quartzite Lakes, District of Keewatin	Fossil molluscs
Parks, 1899	Abitibi River, Ontario	Fossil molluscs
Low, 1903	Kovik River, Quebec Clearwater Lake, Quebec	Fossil molluscs Recent molluscs and sponges
Wilson, 1903	Kapiskau, Otadaonanis and Stooping Rivers, Ontario	Fossil molluscs and cirripeds
Bell, 1904	Moose River, Ontario	Fossil molluscs
McInnes, 1904	Winisk River, Ontario	Fossil molluscs
Baker, 1911	Moose River, Ontario	Fossil molluscs
Tyrrell, 1913	Trout Lake area, Ontario	Fossil molluscs
Williams, 1921	Albany and Kenogami Rivers, Ontario	Fossil molluscs
Clark, 1922	Hudson Bay	Recent echinoderms
Cushman, 1922	Eastern Hudson and James Bays	Recent foraminifers
Mossop, 1922	Hudson Bay	Recent molluscs
Dall, 1924	Fullerton, and Southampton Island, Hudson Bay	Recent molluscs
Kindle, 1924	Moose River, Ontario	Fossil molluscs
McLearn, 1927	Mattagami, Missinaibi, Opasatika, Soweska and Wabishagami Rivers, Ontario	Fossil molluscs
Dyer, 1929	Direct quotations from Kindle, 1924 and McLearn, 1927	
Dyer & Crozier, 1933	Abitibi River, Ontario	Fossil molluscs
Brooks, 1935	Southampton Island, Hudson Bay	Recent molluscs

Nichols, 1936	Churchill, Manitoba; Coral Harbour, Southampton Island, Hudson Bay; Port Harrison and Wolstenholme, Quebec	Fossil foraminifers, brachiopods and molluscs
Richards, 1936	Moose and Rupert Rivers, Ontario; Cary and Charlton Islands, James Bay	Fossil molluscs and brachiopods; also recent molluscs
Clark, 1937	Hudson Bay	Recent echinoderms
Richards, 1940	Belcher Islands, Hudson Bay	Fossil molluscs, brachiopods and cirripeds
Richards, 1941	West coast of Hudson Bay	Fossil molluscs, brachiopods and cirripeds
Cushman, 1948	Hudson Bay	Recent foraminifers
Chamberlin, 1950	Moose River, Ontario	Fossil molluscs
Wagner, 1950	Moose River, Ontario	Fossil molluscs and brachiopods
Lee, 1952	West side of Hudson Bay	Fossil molluscs, brachiopods and cirripeds
McGill, 1952	Ferguson River, District of Keewatin	Fossil molluscs and cirripeds
Fyles, 1954	Beverly Lake, District of Keewatin	Fossil molluscs
Hughes, 1954	Missinaibi, Opasatika and Soweska Rivers, Ontario	Fossil foraminifers, molluscs and cirripeds
Harrison, 1956	Belcher Islands, Hudson Bay	Fossil foraminifers, molluscs, cirripeds and echinoids
Porsild, 1957	Attawapiskat River and Cape Henrietta Maria areas, Ontario	Fossil molluscs and cirripeds
Lee, 1958-59	Fort George and Great Whale Rivers, Quebec	Fossil foraminifers and molluscs
Jackson, 1958	Belcher Islands, Hudson Bay	Fossil molluscs and cirripeds

Lubinsky, 1958	Northern and western Hudson Bay	Recent molluscs
C.G.S. Labrador, 1959	Northern Hudson Bay	Recent foraminifers, molluscs and brachiopods
Fisheries Research Board, 1960	Chesterfield Inlet area, District of Keewatin	Fossil molluscs and cirripeds
Clarke, 1963	Eastern Hudson Bay	Recent molluscs
Hughes, 1963	Mattagami River, Ontario	Fossil foraminifers and molluscs
Leslie, 1963	Hudson Bay	Recent foraminifers
C.S.S. Hudson, 1965	Churchill area, Manitoba; Coats, Gilmour, Mansel and Southampton Islands, Hudson Bay	Fossil molluscs and cirripeds
	Hudson Bay	Recent foraminifers, bryozoans, molluscs, annelid worms and echinoids
Leslie, 1965	Hudson Bay	Fossil and recent foraminifers
Prest, 1965	Little Abitibi River, Ontario	Fossil foraminifers and molluscs
Grainger, 1966	Hudson Bay	Recent asteroids

At least 263 species, fossil and recent, have been recorded from the area. Included are all species noted in the literature, plus those I have identified from collections made by officers of the Geological Survey of Canada since 1952, and the C.S.S. Hudson collections of 1965 (Pelletier et al, 1968, in press). Foraminiferida comprise the bulk of these with Mollusca being next in number of species. A comparison of the number of fossil and recent species of the various groups may be outlined as follows:

Faunal group		Fossil only	Fossil and recent	Recent only	Total
		Number of species			
Foraminiferida		9	77	56	142
Porifera		0	0	3	3
Bryozoa		0	0	4	4
Brachiopoda		0	1	0	1
Annelida		0	0	1	1
Mollusca	(Gastropoda	11	15	13	39
	(Pelecypoda	6	21	12	39
	(Scaphopoda	0	0	1	1
	(Amphineura	0	0	1	1
Cirripedia		0	2	0	2
Echinodermata	(Crinoidea	0	0	1	1
	(Echinoidea	0	1	0	1
	(Holothuroidea	0	0	7	7
	(Ophiuroidea	0	0	7	7
	(Asteroidea	0	0	14	14
	TOTAL	26	117	120	263

The species of Foraminiferida identified, both recent and fossil, are listed in Table II, the Mollusca in Table III, and the other types of organisms, i.e., Porifera, Bryozoa, Brachiopoda, Annelida, Cirripedia and Echinodermata (Crinoidea, Echinoidea, Holothuroidea, Ophiuroidea and Asteroidea) in Table IV. Names in the tables are given in accordance with current usage; out-of-date names recorded in the earlier literature are listed in Appendix I.

As a preliminary step in the discussion of the distribution of the recent faunas, it will be well to look briefly at some of the important physical characteristics of the bottom environment of Hudson Bay. Depth of water and type of bottom sediment were noted at each sampling station. Samples of the bottom

Table II. Foraminiferida from Tyrrell Sea and Hudson Bay.

Species	Collector or Author												
	Nichols 1936	Hughes 1954	Harrison 1956	Lee 1958-59	Hughes 1963	Leslie 1965	Prest 1965	Cushman 1922	Cushman 1948	"Labrador" 1959	Leslie 1963	Leslie 1965	"Hudson" 1965
Cassidulina laevigata d'Orbigny	x												
Lagena sp.	x												
Virgulina sp.	x												
Astrononion stellatum Cushman & Edwards	x					x		o		o	o	o	
Buliminella elegantissma (d'Orbigny)	x					x						o	
Cassidulina crassa d'Orbigny	x						x			o			
Cibicides lobatulus (Walker & Jacob)	x		x	x		x		o	o	o	o	o	o
Elphidiella arctica (Parker & Jones)	x		x	x		x		o	o	o	o	o	o
Elphidium bartletti Cushman	x		x	x		x				o	o	o	o
Elphidium incertum (Williamson)	x					x		o	o		o	o	o
Globigerina pachyderma (Ehrenberg)	x									o	o	o	o
Guttulina dawsoni Cushman & Ozawa	x											o	o
Lenticulina sp.	x									o			
Nonionellina labradorica (Dawson)	x		x	x		x		o	o	o	o	o	o
Protelphidium orbiculare (Brady)	x	x	x	x	x	x	x	o	o	o	o	o	o
Lamarckina haliotidea (Heron-Allen & Earland)		x											
Buccella frigida (Cushman)		x	x	x		x		o	o	o		o	o
Elphidium frigidum Cushman		x	x				x						o
Melonis zaandami (van Voorthuysen)		x				x				o	o	c	o
Islandiella islandica (Nørvang)			x	x		x				o	o	o	o
Islandiella norcrossi (Cushman)			x	x		x				o	o	o	o
Islandiella teretis (Tappan)			x	x		x				o		o	o
Buccella inusitata Andersen				x	x					o			
Cassidella complanata (Egger)				x		x				o	o	o	o
Dentalina baggi Galloway & Wissler				x		x				o	o	o	o
Dentalina ittai Loeblich & Tappan				x		x				o	o	o	
Elphidium incertum clavatum Cushman				x	x		x			o			o
Fissurina marginata (Montagu)				x		x				o	o	o	o
Glandulina glacialis Cushman & Ozawa				x		x	x			o	o	o	
Lagena gracillima (Seguenza)				x	x	x				o	o	o	
Lagena laevis (Montagu)				x		x				o	o	o	o
Lagena parri Loeblich & Tappan				x						o	o	o	
Lagena semilineata Wright				x						o	o	o	
Laryngosigma hyalascidia Loeblich & Tappan				x	x					o			
Nonionella auricula Heron-Allen & Earland				x		x				o		o	
Oolina caudigera (Weisner)				x		x				o		o	
Oolina hexagona (Williamson)				x						o		o	
Oolina melo d'Orbigny				x		x				o	o	o	
Pateoria hauerinoides (Rhumbler)				x				o	o		o	o	
Pseudopolymorphina novangliae (Cushman)				x	x				o				
Pyrgo williamsoni (Silvestri)				x			x				o		
Pyrulina cylindroides (Roemer)				x			x			o			
Quinqueloculina stalkeri Loeblich & Tappan				x		x					o	o	o
Silicosigmoilina groenlandica (Cushman)				x		x				o		o	o
Orbulina universa d'Orbigny					x								
Triloculina trihedra Loeblich & Tappan					x								
Elphidium subarcticum Cushman					x	x	x			o		o	
Quinqueloculina seminulum (Linné)					x		x	o	o	o		o	o
Parafissurina fusuliformis Loeblich & Tappan						x							
Pullenia bulloides d'Orbigny						x							
Adercotryma glomeratum (Brady)						x				o	o	o	o
Ammodiscus planus Höglund						x						o	
Angulogerina angulosa (Williamson)						x					o	o	o
Astacolus hyalacrulus Loeblich & Tappan						x						o	o
Asterellina pulchella (Parker)						x						o	
Bigenerina arctica (Brady)						x						o	
Bolivina pacifica Cushman & McCulloch						x	x				o	o	
Buccella tenerrima (Bandy)						x					o	o	o
Cassidella tessellata (Phleger & Parker)						x						o	
Cribrostomoides jeffreysi (Williamson)						x		o	o	o		o	o
Dentalina frobisherensis Loeblich & Tappan						x				o	o	o	o
Eggerella advena (Cushman)						x		o	o	o	o	o	o
Elphidium articulatum (d'Orbigny)						x						o	
Epistominella takayanagii Iwasa						x						o	o
Fissurina cucurbitasema Loeblich & Tappan						x						o	o
Fissurina serrata (Schlumberger)						x				o	o	o	
Glabratella wrightii (Brady)						x		o	o				
Globobulimina auriculata arctica Höglund						x				o		o	
Lagena flatulenta Loeblich & Tappan						x				o		o	
Lagena mollis Cushman						x				o	o	o	
Oolina borealis Loeblich & Tappan						x				o	o	o	o
Patellina corrugata Williamson						x		o	o	o	o	o	
Pyrgo subsphaerica (d'Orbigny)						x						o	o

Table II Concluded:-

	Nichols 1936	Hughes 1954	Harrison 1956	Loe 1956-59	Hughes 1963	Leslie 1965	Prest 1965	Cushman 1922	Cushman 1948	"Labrador" 1959	Leslie 1963	Leslie 1965	"Hudson" 1965
Recurvoides turbinatus (Brady)						x				o		o	o
Reophax scorpiurus Montfort						x						o	o
Reophax scottii Chaster						x						o	
Reophax subfusiformis Earland						x	x					o	
Robertinoides charlottensis (Cushman)						x						o	o
Saccammina atlantica (Cushman)						x						o	o
Scutuloris terminis Loeblich & Tappan						x	x			o		o	
Sigmomorphina undulosa (Terquem)						x						o	
Spiroplectammina biformis (Parker & Jones)						x					o	o	
Textularia contorta Hoglund						x						o	
Triloculina trigonula (Lamarck)						x					o	o	o
Trochammina squamata Jones & Parker						x					o	o	
Sigmomorphina sp.							x						
Ammotium cassis (Parker)								o	o	o		o	
Cyclogyra foliacea (Philippi)								o	o				
Dentalina calomorpha (Reuss)								o	o				
Guttulina lactea (Walker & Jacob)								o					
Oolina globosa (Montagu)								o	o				
Pelosina cylindrica Brady								o	o				
Pelosina rotundata Brady								o	o				
Pelosina variabilis Brady								o	o				
Polymorphina lanceolata Reuss								o					
Polymorphina oblonga d'Orbigny								o					
Polymorphina ovata d'Orbigny								o					
Psammatodendron arborescens Norman								o	o				
Psammosphaera fusca Schulze								o	o				
Reophax curtus Cushman								o	o	o	o		
Sorosphaera confusa Brady								o	o				
Tholosina bulla (Brady)								o	o				
Triloculina oblonga Montagu								o	o				
Trochammina rotaliformis Wright								o	o		o	o	
Webbinella arctica Cushman								o	o				
Esosyrinx curtus (Cushman & Ozawa)									o				
Angulogerina fluens Todd										o			
Astrorhiza cf. A. limicola Sandahl										o			o
Bolivina pseudopunctata Höglund										o			
Cribrostomoides crassimargo (Norman)										o	o	o	o
Dentalina pauperata d'Orbigny										o	o	o	
Fissurina laevigata Reuss										o			
Fissurina semimarginata (Reuss)										o			
Globorotalia sp.										o			
Hyperammina subnodosa Brady										o		o	
Lagena apiopleura Loeblich & Tappan										o	o	o	o
Lagena setigera Millett										o			
Oolina lineata (Williamson)										o	o	o	o
Pseudopolymorphina suboblonga Cushman & Ozawa										o			
Quinqueloculina agglutinata Cushman										o	o	o	o
Spirillina vivipara Ehrenberg										o	o		
Trichohyalis bartletti (Cushman)										o			
Trochamminella atlantica Parker										o	o	o	o
Cassidulina laticamerata Voloshinova											o		
Glandulina laevigata d'Orbigny											o	o	
Hippocrepina indivisa Parker											o	o	
Hyperammina elongata Brady											o	o	o
Lagena meridionalis Weisnor											o	o	
Nonionella atlantica Cushman											o		
Oolina lineatopunctata (Heron-Allen & Earland)											o	o	o
Oolina striatopunctata (Parker & Jones)											o	o	o
Quinqueloculina arctica Cushman											o	o	o
Reophax arctica d'Orbigny											o		
Saccammina difflugiformis (Brady)											o		
Textularia torquata Parker											o		
Trochammina quadriloba Höglund											o		
Oolina squamosa (Montagu)												o	
Parafissurina himatiostoma Loeblich & Tappan												o	
Robertina arctica d'Orbigny												o	
Sigmoidella pacifica Cushman & Ozawa												o	
Trochammina nana (Brady)												o	o
Trochamminella bullata Höglund												o	o

x Fossil occurrence
o Recent occurrence

Note
Species names in the table are given in accordance with present-day usage, and differ in some cases from those appearing in the older literature. The older names are recorded in Appendix I. The same remarks apply to Tables III and IV.

Table III. Mollusca from Tyrrell Sea and Hudson bay.

Species	Stimpson 1862	Bell 1872	Bell 1877	Bell 1879a	Bell 1879b	Bell 1880	Bell 1881	Bell 1887	Low 1887	Low 1889	Bell 1896	Tyrrell 1896	Parks 1899	Wilson 1903	Bell 1904	McInnes 1904	Baker 1911	Tyrrell 1913	Williams 1921	Kindle 1924	McLearn 1927	Dyer 1929	Dyer & Crozier 1933	Nichols 1936	Richards 1936	Richards 1940	Richards 1941
Gastropoda																											
Admete viridula (Fabricius)	x																										
Buccinum undatum Linné		x	x		x																						
Buccinum tenue (Gray)					x		x		x	x						x			x						x		x
Natica clausa Broderip & Sowerby					x																						
Littorina littoralis (Linné)							x																				
Natica (Acrybia) flava Gould							x																				
Boreotrophon clathratus (Linné)									x																		
Neptunea despecta Linné															x										x		
Colus ventricosus (Gray)																	x										
Cylichna alba (Brown)																			x						x		
Lunatia pallida (Broderip & Sowerby)																			x						x		
Lepeta caeca (Müller)																								x			
Trichotropis borealis Broderip & Sowerby																								x			x
Acmaea testudinalis Linné																									x	x	x
Lora incisula (Verrill)																									x		
Hydrobia minuta (Totten)																									x		
Littorina saxatilis (Olivi)																									x		x
Lora americana Packard																									x		
Puncturella noachina (Linné)																										x	x
Lora scalaris (Montagu)																											x
Margarites umbilicalis Broderip & Sowerby																											x
Tachyrhynchus erosum (Couthouy)																											x
Acirsa costulata Mighels & Adams																											
Buccinum ciliatum Fabricius																											
Lora turricula (Montagu)																											
? Molleria sp.																											
Littorina groenlandica Menke																											
Acmaea emydia Dall																											
Admete laevior Jeffreys																											
Buccinum cyaneum Hancock																											
Buccinum hydrophanum Hancock																											
Margarites cinereus Couthouy																											
Margarites helicinus Phipps																											
Plicifusus kroyeri (Möller)																											
Lora spp.																											
Capulus ungaricus (Linné)																											
Colus islandicus (Gmelin)																											
Haminoea solitaria (Say)																											
Margarites costalis (Gould)																											

Species	Chamberlin 1950	Wagner 1950	Leo 1952	McGill 1952	Fyles 1954	Hughes 1954	Harrison 1956	Porsild 1957	Lee 1956-59	Jackson 1958	Fish. Res. Bd. 1960	Hughes 1963	"Hudson" 1965	Prest 1965	Stimpson 1862	Bell 1877	Bell 1880	Low 1903	Mossop 1922	Dall 1924	Kindle 1924	Brooks 1935	Richards 1936	Lubinsky 1958	"Labrador" 1959	Clarke 1963	"Hudson" 1965
Gastropoda																											
Admete viridula (Fabricius)																											
Buccinum undatum Linné																				o							
Buccinum tenue (Gray)		x	x																	o						o	
Natica clausa Broderip & Sowerby																											o
Littorina littoralis (Linné)																o	o										
Natica (Acrybia) flava Gould																											
Boreotrophon clathratus (Linné)																				o							o
Neptunea despecta Linné						x																					o
Colus ventricosus (Gray)																											
Cylichna alba (Brown)																											
Lunatia pallida (Broderip & Sowerby)		x							x																		o
Lepeta caeca (Müller)													x												o		o
Trichotropis borealis Broderip & Sowerby																											o
Acmaea testudinalis Linné		x		x			x													o		o	o				
Lora incisula (Verrill)																											
Hydrobia minuta (Totten)																							o				
Littorina saxatilis (Olivi)		x														o		o		o		o	o			o	
Lora americana Packard		x																									
Puncturella noachina (Linné)																											
Lora scalaris (Montagu)																											
Margarites umbilicalis Broderip & Sowerby																						o					
Tachyrhynchus erosum (Couthouy)				x																							o
Acirsa costulata Mighels & Adams	x																										
Buccinum ciliatum Fabricius				x																o		o					o
Lora turricula (Montagu)						x																					
? Molleria sp.							x																				
Littorina groenlandica Menke															o												
Acmaea emydia Dall																				o							
Admete laevior Jeffreys																				o							
Buccinum cyaneum Hancock																				o		o					
Buccinum hydrophanum Hancock																				o							
Margarites cinereus Couthouy																				o							
Margarites helicinus Phipps																				o							
Plicifusus kroyeri (Möller)																						o					o
Lora spp.																										o	
Capulus ungaricus (Linné)																											o
Colus islandicus (Gmelin)																											o
Haminoea solitaria (Say)																											o
Margarites costalis (Gould)																											o

Polecypoda																																																						
Astarte arctica (Gray)	x		x	x	x	x	x																							x																								
Astarte montagui striata (Leach)	x			x				x																x	x	x	x		x					x			x			x					o									o
Chlamys islandicus (Müller)	x			x		x	x								x	x								x	x	x	x			x								x		x							o		o			o	o	o
Clinocardium ciliatum (Fabricius)	x		x	x	x	x	x	x	x					x	x	x	x		x	x	x	x		x	x		x		x	x			x		x	x			x											o			o	o
Macoma calcarea (Gmelin)	x	x	x	x	x	x	x	x	x				x	x	x	x	x		x	x	x	x		x	x		x		x				x		x	x			x						o									o
Mya truncata Linné	x	x	x	x		x	x	x	x	x			x	x	x	x	x		x		x	x			x	x	x			x			x		x		x	x	x	x			o						o					o
Mytilus edulis Linné	x	x	x	x	x		x			x			x	x		x				x		x		x	x	x	x		x				x	x	x					x		o	o	o		o	o	o	o	o	o		o	
Nucula tenuis (Montagu)	x																			x		x																																
Nuculana pernula (Müller)	x		x		x															x		x		x	x	x			x							x																o	o	o
Portlandia arctica (Gray)	x	x	x									x								x		x													x				x	x	x				o									o
Hiatella arctica (Linné)		x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x		x	x	x	x	x				o		o		o	o		o		o
Macoma balthica (Linné)		x	x	x	x		x	x		x	x		x	x	x	x	x			x		x	x	x	x		x		x			x			x			x		x		o	o							o			o	o
Serripes groenlandicus (Bruguière)		x						x						x		x								x	x					x			x						x														o	
Mya pseudoarenaria Schlesch			x	x	x	x	x			x				x	x	x	x							x			x		x				x	x					x															
Nucula bellotii Adams					x																																								o									o
Nuculana buccata (Steenstrup)														x													x																											o
Pandora trilineata Say																				x		x																																
Astarte borealis Schumacher																								x	x	x	x		x																		o		o					
Astarte elliptica (Brown)																								x																														
Mya truncata uddevallensis Forbes																								x																														o
Pandora glacialis (Leach)																									x																													o
Portlandia lenticula (Möller)																									x				x							x																		o
Pseudamussium binominatus Hanna																													x												x				o									o
Astarte crenata Gray																														x															o									
Macoma brota Dall																																	x			x																		
Crenella faba Fabricius																																							x								o							
Musculus discors Linné																																							x						o				o					
Thracia myopsis Möller																																													o									o
Macoma intermedia Broderip & Sowerby																																															o							
Thyasira flexuosa sarsi Philippi																																																				o	o	o
Yoldia limatula (Say)																																																				o		o
Bathyarca glacialis (Gray)																																																						o
Cuspidaria obesa Lovén																																																						o
Lyonsia arenosa (Möller)																																																						o
Musculus discors laevigatus Gray																																																						o
Musculus niger (Gray)																																																						o
Nuculana minuta (Fabricius)																																																						o
Nuculana tenuisulcata (Couthouy)																																																						o
Periploma fragilis Totten																																																						o
Scaphopoda																																																						
Siphonodentalium lobatum (Sowerby)																																																						o
Amphineura																																																						
Tonicella marmorea (Fabricius)																																													o									

x Fossil occurrence

o Recent occurrence

Table IV. Porifera, Bryozoa, Annelida, Cirripedia, Brachiopoda and Echinodermata, Tyrrell Sea and Hudson Bay.

Species	Collector or Author																						
	Stimpson 1862	Bell 1877	Bell 1880	Low 1887	Wilson 1903	Nichols 1936	Richards 1936	Richards 1940	Richards 1941	Wagner 1950	Lee 1952	McGill 1952	Hughes 1954	Harrison 1956	Porsild 1957	Jackson 1956	"Hudson" 1965	Low 1903	Clark 1922	Clark 1937	"Labrador" 1959	"Hudson" 1965	Grainger 1966
Porifera																							
Craniella cranium (Müller)																		o					
Suberites montalbidus																		o					
? Echinoclathria sp.																					o		
Bryozoa																							
Cystisella saccata (Busk)																						o	
Escharella ventricosa (Hassall)																						o	
Hippothoa divaricata (Lamouroux)																						o	
Myriozoum subgracile d'Orbigny																						o	
Brachiopoda																							
Hemithiris psittacea (Gmelin)	x	x	x	x		x	x	x	x	x	x										o	o	
Annelida																							
Cistenides sp.																						o	
Cirripedia																							
Balanus balanus (Linné)																	x					o	
Balanus crenatus Bruguière		x			x			x	x		x	x	x	x	x	x						o	
Echinodermata -- Crinoidea																							
Heliometra glacialis (Leach)																			o	o			
Echinodermata -- Echinoidea																							
Strongylocentrotus drobachiensis (Müller)														x								o	
Echinodermata -- Holothuroidea																							
Cucumaria frondosa (Gunnerus)																			o	o			
Cucumaria calcigera (Stimpson) Selenko																			o				
Psolus fabricii (Düben & Koren)																				o			
Psolus peronii Bell																				o			
Psolus phantapus (Strussenfelt)																				o			
Myriotrochus rinkii Steenstrup																				o			
Chiridota sp.																				o			
Echinodermata -- Ophiuroidea																							
Gorgonocephalus eucnemis (Müller & Troschel)																			o				
Ophiacantha bidentata (Retzius)																			o	o			
Ophiopholis aculeata (Linné)																			o	o			
Ophiocten sericeum (Forbes)																			o	o			
Ophioglypha robusta (Ayres)																			o	o			
Gorgonocephalus arcticus (Leach)																				o			
Ophiura sarsii (Lütken)																				o			
Echinodermata -- Asteroidea																							
Solaster papposus (Linné)																			o	o			o
Urasterias lincki (Müller & Troschel)																			o	o			o
Leptasterias groenlandica (Lütken)																			o				o
Leptasterias polaris (Müller & Troschel)																			o	o			o
Ctenodiscus crispatus (Retzius)																				o			o
Henricia perforata (Müller)																				o			o
Leptasterias sp.																				o			
Lophaster furcifer (Düben & Koren)																				o			o
Poraniomorpha tumida (Stuxberg)																				o			o
Pteraster militaris (Müller)																				o			o
Pteraster obscurus (Perrier)																				o			o
Solaster endeca (Linné)																				o			o
Pteraster pulvillus Sars																							o
Stephenasterias albula (Stimpson)																							o

x Fossil occurrence
o Recent occurrence

waters were taken in Nansen bottles equipped with thermometers. Temperature, dissolved oxygen content, and hydrogen-ion concentration were determined on board ship; salinity analyses were carried out at the Bedford Institute. Sediment samples and benthonic organisms were obtained mostly by grab sampler. A few samples were taken by dredge.

Figure 5 of Pelletier (this volume) presents the current ideas concerning the bathymetry of Hudson Bay. The major part of the bay is shallower than 160 metres. Recent soundings indicate that the small central shoal area shown on the older charts is actually the northern part of a ridge that extends from the southern rim of the bay between the mouths of the Severn and Winisk Rivers, and that divides the central part of the bay into two basins. This ridge rises to within 40 metres of the surface. Several depressions deeper than 240 metres lie within the western basin, and the outer part of the eastern basin. These depressions form part of a submerged valley system extending from the present-day river estuaries along the western and southern shores of the bay to Hudson Strait. Greater depths were encountered in the outlet into Hudson Strait and in the strait.

Bottom water temperatures in the area of the bay covered by the project, i.e. where depths were greater than about 35 metres, were -1.0°C or colder (see Pelletier, Fig. 8, this volume). Temperatures in the western basin were lower than those in the eastern basin. As depths are not dissimilar in the two basins, this difference presumably is a reflection of the bottom circulation, with colder waters flowing in from Foxe Basin, circulating in a counter-clockwise direction, and apparently being deflected north at depth by the central ridge. Summer bottom water temperatures in shallow coastal areas may rise above 0° C. Such values have been noted by F.G. Barber (1967) along the northwestern rim of the bay.

Salinity of the bottom water is presented by Pelletier (this volume, Fig. 10). Except for a narrow peripheral band along the major part of the coastline, but broader in the vicinity of James Bay, bottom water salinities are generally about 33 °/oo or slightly higher. Along the east coast of the bay, values may be as low as 28 °/oo. The highest value recorded was in the central part of the western basin where the salinity was slightly higher than 34 °/oo. Over the shoal area near the northern end of the central ridge the salinity was between 32 °/oo and 33 °/oo, only slightly less than the value prevailing over most of the bottom of the bay. Salinities at the surface are lower than those at the bottom, and vary from 20 °/oo or less in James Bay to 32 °/oo in northern Hudson Bay (Barber, 1967). Inflow of fresh water from rivers around the bay and melting of the ice cover have a definite effect on surface salinity and temperature, and on bottom salinity and temperature in shallow waters.

The shallow central ridge appears to be an important factor with regard to distribution of dissolved oxygen in the bottom waters. In general, highest values are found near shore and lowest values in the deeper waters of the bay (see Pelletier, Figure 9). However, areas with depths of 240 metres or more in the western basin have a higher dissolved oxygen content (6.0 - 7.0 ml/l) than do areas less than 200 metres deep east of the central ridge, where values of less than 5.0 ml/l are widespread.

Hydrogen-ion concentration values were quite uniform throughout the bay, and ranged between 6.5 and 6.7. A very few readings reached 6.8.

Distribution of sediments on a textural basis lacks the general concentric pattern observed for the various water properties (see Pelletier, Figure 14). Sand and sandy gravel are found predominantly in a band along the western and southern rim of the bay. This band is narrow in the north, but broadens in the south and projects northward to include the ridge. Coarse gravel and blocks were found locally on the ridge. Currents in this part of Hudson Bay are stronger than along the east coast, and the tidal range is also greater. Furthermore, the large streams entering the bay from the west and south bring in coarse material. Sand and sandy gravel are also found in a limited area offshore from Port Harrison. Silty sand covers a major part of the bottom of the bay including most of the shallower areas along the east coast. Very fine material, silty sand and clay, is found almost exclusively in the deepest part of the western basin.

During the 1965 project, samples were collected by both C.S.S. Hudson and M.V. Theron. This faunal study is based on the bottom samples from C.S.S. Hudson that were studied on board the ship. I found 50 species of Foraminiferida in samples from 24 stations and 40 species of Mollusca from 63 stations. Proper facilities for processing the foraminiferal samples were lacking, so undoubtedly many specimens were lost. Leslie (1965) recorded 90 species of Foraminiferida from the bay, 47 species of which are common to my list. He stained his samples with rose Bengal and so was able to differentiate between those individuals that were alive at the time of collection and those that were dead. His depth ranges are, therefore, based exclusively on live individuals. Samples taken by C.S.S. Hudson and preserved for future examination were stained, but those that were examined on the spot were not. Thus, the depth ranges as shown in Table V are based on an undifferentiated mixture of dead and living specimens. Figure 2 shows the areas of greatest foraminiferal variety and is based on my own and Leslie's findings. Areas of greatest variety occur where depths are less than 160 metres with peaks at depths less than 120 metres. An exception was noted at the outlet of the bay into Hudson Strait where assemblages of considerable variety were found at depths greater than 160 metres. The areas that support the most diverse assemblages are those that also support the most abundant living populations (Leslie, 1965). Species found to be predominant in some of the sediment samples from the shallow areas were *Buccella frigida*, *Islandiella teretis* and *Protelphidium orbiculare*. The latter two species were found throughout the depth range that was sampled, i.e. from 43 to 276 metres, but they occurred in greatest abundance in samples from depths of less than 125 metres. *Buccella frigida* was found in greatest numbers in the 117- to 126-metre range, but it was also found as shallow as 43 metres and as deep as

Table V. Recent Foraminiferida, C.S.S. "Hudson" collections.

Station Number	70	8	155	12	240	266	93	96	81	175	18	140	244	79	102	257	42	32	170	83	28	110	54	206
Longitude (west)	85 44.2'	93 05.0'	90 24.0'	91 20.2'	84 51.0'	86 00.0'	81 43.0'	84 09.2'	83 59.5'	85 43.0'	89 11.0'	90 26.0'	83 52.0'	85 15.0'	85 33.0'	81 05.0'	87 50.5'	88 11.5'	85 49.0'	83 10.0'	87 14.1'	87 03.8'	86 35.0'	80 59.8'
Latitude (north)	59 07.4'	59 05.3'	58 02.0'	59 07.8'	58 29.4'	57 37.2'	60 41.0'	59 43.5'	59 36.4'	62 25.0'	59 19.5'	58 29.5'	59 30.0'	59 32.5'	59 30.8'	58 31.0'	62 29.5'	61 09.2'	60 52.4'	59 33.0'	60 05.6'	59 11.5'	59 34.0'	63 00.2'
Depth (metres)	43	48	66	101	101	104	111	117	126	126	137	139	145	146	148	152	165	181	190	192	199	203	210	276
Dissolved Oxygen (ml/l)	6.82	8.51	7.94	7.25	5.14	6.56			5.40	6.86	6.10	6.40	4.81	5.71		4.58	7.08	5.99	6.35	5.40	7.08			7.21
Temp. (C)	-1.7	-0.9	-1.5	-1.6	-1.3	-1.6	-1.3	-1.3	-1.3	-1.2	-1.6	-1.6	-1.3	-1.6	-1.5	-1.3	-1.5	-1.5	-1.6	-1.4	-1.6	-1.6		-1.2
Species																								
Astacolus hyalacrulus	x																							
Dentalina pauperata	x																							
Fissurina cucurbitasema	x																							
Oolina borealis	x																							
Oólina lineata	x																							
Quinqueloculina seminulum	x																							
Fissurina marginata	x	x	x	x																				
Elphidiella arctica	x	x	x	x																				
Oolina lineatopunctata	x			x																				
Lagena apiopleura	x									x														
Dentalina frobisherensis	x		x		x	x		x	x	x		x					x							
Epistominella takayanagii	x					x	x		x	x							x							
Buccella frigida	x	x	x		x	x		x	x	x					x			x						
Buccella tenerrima	x						x											x						
Cibicides lobatulus	x	x	x					x	x	x			x						x					
Silicosigmoilina groenlandica	x							x											x					
Melonis zaandami	x		x		x	x		x			x							x			x			
Angulogerina angulosa	x				x		x	x		x											x			
Cribrostomoides crassimargo	x				x			x	x		x		x		x	x			x	x		x	x	
Quinqueloculina stalkeri	x					x					x			x	x	x		x		x		x	x	
Reophax scorpiurus	x							x	x		x		x	x					x	x	x	x	x	
Elphidium bartletti	x	x	x			x				x														x
Islandiella islandica	x	x	x	x		x	x	x		x							x	x				x		x
Islandiella teretis	x	x	x		x	x	x	x	x	x	x	x				x	x	x						x
Protelphidium orbiculare	x	x	x	x	x	x	x	x		x		x				x	x							x
Elphidium clavatum	x		x		x	x		x								x	x	x						x
Hyperammina elongata	x		x	x	x	x		x	x				x						x					x
Islandiella norcrossi	x		x		x	x		x		x		x	x		x			x	x		x			x
Adercotryma glomeratum	x			x	x	x	x	x	x	x	x	x		x	x	x			x			x	x	x
Cassidella complanata	x					x				x							x							x
Nonionellina labradorica	x					x				x		x						x						x
Pyrgo subsphaerica	x					x																		x
Lagena laevis	x																							x
Guttulina dawsoni			x																					
Elphidium incertum			x					x																
Triloculina trigonula					x											x								
Cribrostomoides jeffreysi					x		x						x		x	x					x	x	x	
Astrorhiza cf. A. limicola							x																	
Globigerina pachyderma							x											x						x
Dentalina baggi								x																
Saccammina atlantica								x	x					x	x				x					
Elphidium frigidum										x														
Quinqueloculina agglutinata										x														
Robertinoides charlottensis										x														
Recurvoides turbinatus												x											x	
Trochamminella bullata														x										
Trochamminella atlantica																	x	x						
Trochammina nana																					x			
Eggerella advena																							x	
Quinqueloculina arctica																								x

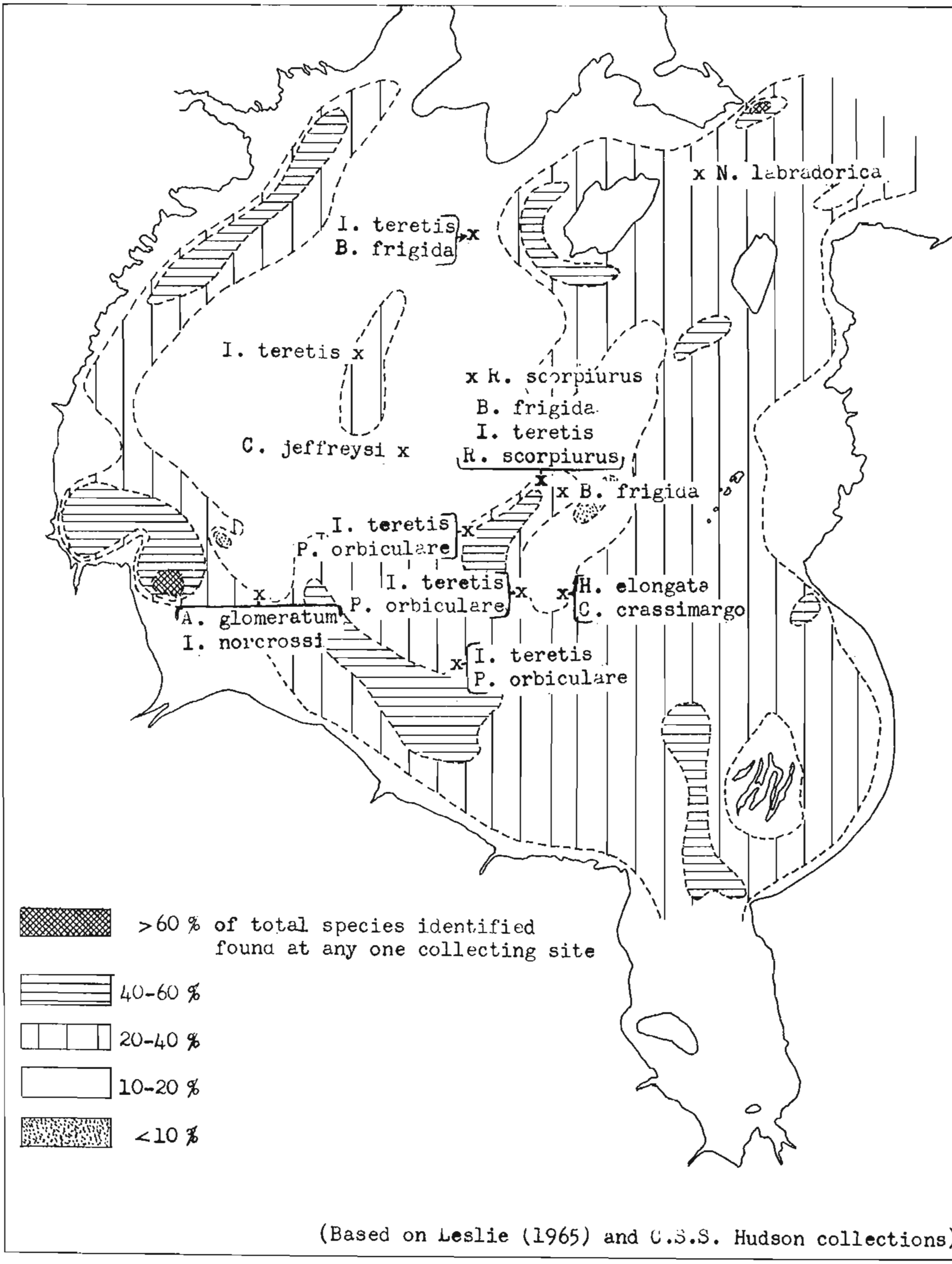


Figure 2. Faunal variety and dominant species of Foraminiferida.

Nonionellina labradorica was the predominant species at the deepest station (276 metres), although it, too, was also found at the shallowest station. All of the foregoing are calcareous forms. A half-dozen species were common in certain of the samples from areas of the bay characterized by a lack of variety of species. Of these species, all but one, Islandiella norcrossi, were arenaceous. Adercotryma glomeratum, Hyperammina elongata and Islandiella norcrossi were obtained from the shallowest and deepest stations sampled, and they were predominant species in samples from between about 140 and 150 metres. Cribrostomoides crassimargo and Reophax scorpiurus were found as shallow as 43 metres, but not deeper than 210 metres. They were noted to be the predominant species in samples from 145 metres and 117 metres respectively. Cribrostomoides jeffreysi was the dominant species in a sample from a depth of 199 metres. Its total range noted was from 100 to 210 metres. These dominant species and depth ranges differ somewhat from those given by Leslie, whose results were based on a greater number of samples.

Most of the 10 species discussed above were found throughout the entire depth range that was sampled. Therefore, some factor other than depth must be responsible for the marked differences in areas of predominance. The chief controlling factor would appear to be the texture of the bottom sediment. Calcareous species were found to be characteristic of bottoms composed of silty sand or coarser material, whereas the arenaceous foraminifers were found to be indigenous on silt or clay bottoms.

Of the various properties of the water that were investigated, only the dissolved oxygen seemed to have any effect on the distribution of the foraminifers. Areas characterized by waters having the highest oxygen content generally supported the greatest number and variety of foraminifers. Where the oxygen content was less than about 6 ml/l, the foraminiferal faunas were much less varied and prolific. Bottom temperature, salinity and hydrogen-ion concentration all showed only slight range in variation, and they appeared to have no particular influence on the faunal distribution.

Table VI lists all of the molluscs identified to date from collections of the Hudson Bay Oceanographic Project of 1965. As with the foraminifers, a mixture of living and dead specimens was collected. However, with the molluscs it was possible to distinguish the live from the dead without staining. Living representatives of 9 of the 40 species identified were found. Those found alive included the pelecypods Chlamys islandicus, Clinocardium ciliatum, Hiatella arctica, Mya truncata, Nuculana minuta and Macoma balthica, the gastropods Lepeta caeca and Natica clausa, and the scaphopod Siphonodentalium lobatum. Of these, the first five species were common to abundant at one or more localities, although Clinocardium ciliatum and Nuculana minuta were found in greater abundance as dead shells at shallower depths than where they were found alive. Several other species that were not collected alive occurred as predominant species at some of the stations. These were the pelycypods Astarte montagui striata, Nuculana buccata,

Table VI. Recent Mollusca, C.S.S. "Hudson" collections.

x Dead specimens
o Living specimens
Living and dead specimens

Station Number	118	70	8	146	149	155	142	268	153	196	136	194	259	186	188	192	12	240	92	266	134	225	93	190
Longitude (west)	85 22.0'	85 42.2'	93 05.0'	91 57.0'	91 45.0'	90 24.0'	90 57.0'	85 28.0'	90 51.5'	83 19.7'	89 28.0'	83 43.0'	80 34.0'	85 38.0'	85 02.0'	87 10.0'	91 20.2'	84 51.0'	81 40.0'	86 00.0'	88 58.0'	81 01.0'	81 43.0'	84 36.0'
Latitude (north)	58 45.0'	59 07.4'	59 05.3'	58 30.0'	58 22.5'	58 02.0'	58 31.0'	57 37.5'	58 08.8'	63 35.1'	58 30.0'	63 25.0'	58 30.0'	62 48.0'	62 54.0'	63 12.5'	59 07.8'	58 29.4'	60 32.5'	57 37.2'	58 29.5'	60 41.5'	60 41.0'	62 56.0'
Depth (metres)	35	43	48	62	64	66	76	79	80	88	90	90	90	92	97	99	101	101	103	104	106	106	111	113
Dissolved Oxygen (ml/l)	8.57	6.82	8.51		8.25	7.94	7.20	5.85	7.50	7.69	7.56	7.93	5.46	7.52	7.81	7.82	7.25	5.14	6.00	6.56	6.59	5.80		7.54
Temp. (C)	-1.0	-1.7	-1.0	-1.5	-1.4	-1.5	-1.6	-1.4	-1.6	-1.8	-1.6	-1.1	-1.4	-0.7	-1.2	-1.1	-1.6	-1.3	-1.3	-1.6	-1.6	-1.3	-1.3	-1.3
Species																								
Gastropoda																								
Boreotrophon clathratus			x																					
Margarites costalis			x	x	x				x															
Lunatia pallida				x																				
Plicifusus kroyeri				x																				
Buccinum ciliatum				x										x										
Natica clausa							o																	
Lepeta caeca							x					x				x								x
Trichotropis borealis									x															
Tachyrhynchus erosum									x	x		x				x								
Capulus ungaricus												x												
Haminoea solitaria																								
Colus islandicus																								
Neptunea despecta																								
Pelecypoda																								
Mya truncata uddevallensis	x																							
Mya truncata	#		#	x		x						x		x	o									
Hiatella arctica	#		#	#	x		x		x	x	#	x			x					x				x
Musculus discors laevigatus	o			o																				
Astarte montagui striata		x		x				o			#							o		x	#		#	
Nuculana pernula		#			x			o			#										x	x	x	
Thracia myopsis		x							x												x			
Pseudamussium binominatus		x																					x	
Chlamys islandicus			#	#	x		x		x					x	x	x								x
Nuculana minuta			x	x	x				x	x	#	x			o	x			x	x	x			
Macoma balthica			#						x															
Clinocardium ciliatum			x	x	x	#	x		x	#	#	x				x	x							
Nuculana buccata				x	x	o	#		x					x										
Musculus niger				#	x							x												
Macoma calcarea				x			o				#	x	x								#			x
Thyasira flexuosa sarsi						o																		
Pandora glacialis						o			x															
Nucula bellotii											o													
Nuculana tenuisulcata																	#							
Portlandia lenticula																		o						
Periploma fragilis																				o				
Lyonsia arenosa																					x			
Portlandia arctica																							#	
Bathyarca glacialis																								
Cuspidaria obesa																								
Yoldia limatula																								
Scaphopoda																								
Siphonodentalium lobatum																								

x x x	-1.3		117	59 43.5'	84 09.2'	96
o x o	-1.6		119	58 29.5'	85 52.2'	122
o # o x x o o x	-1.7	7.39	119	58 30.0'	89 55.6'	138
x x x	-1.3	7.00	119	62 10.5'	84 41.8'	179
#	-1.3	7.10	119	62 02.2'	84 13.0'	181
x	-1.5	6.71	125	59 01.5'	85 53.5'	75
# x	-1.3	5.40	126	59 36.4'	83 59.5'	81
x x x	-1.2	6.86	126	62 25.0'	85 43.0'	175
x	-1.3	5.76	126	60 58.0'	81 08.5'	223
o o # o x x	-1.2	6.86	128	62 18.5'	85 10.5'	177
o	-1.3	5.51	134	59 45.5'	81 20.0'	84
o #	-1.6	6.10	137	59 19.5'	89 11.0'	18
# x o	-1.6	6.40	139	59 29.5'	90 26.0'	140
o o	-1.3	4.81	145	59 30.0'	83 52.0'	244
# x	-1.6	5.71	146	59 32.5'	85 15.0'	79
o x	-1.5		148	59 30.8'	85 33.0'	102
x o x	-1.3	4.58	152	58 31.0'	81 05.0'	257
x	-1.6	6.04	155	58 29.5'	88 27.7'	132
x x	-1.3	5.18	156	59 49.5'	80 27.5'	86
x	-1.3	7.33	156	63 17.0'	81 46.2'	202
x # o	-1.5		159	60 15.5'	84 10.0'	100
# x # # # # o # x x #	-1.5	7.08	165	62 29.5'	87 50.5'	42
o	-1.6	6.40	170	59 17.2'	86 05.0'	47
x	-1.5		170	60 23.5'	84 10.0'	101
o	-1.5	5.99	181	61 09.2'	88 11.5'	32
#	-1.5		189	59 09.2'	87 26.0'	107
x	-1.6	6.35	190	60 52.4'	85 49.0'	170
x	-1.4	5.40	192	59 33.0'	83 10.0'	83
x x	-1.2	7.06	196	61 44.2'	81 30.5'	218
o	-1.6	7.08	199	60 05.6'	87 14.1'	28
x	-1.1		199	59 18.0'	86 59.0'	105
o o x x			210	59 34.0'	86 35.0'	54
x x x x	-1.4	7.49	214	63 07.0'	80 30.0'	207
x #			225	63 06.5'	81 26.0'	204
# x # o	-1.3	7.21	235	63 12.0'	80 07.0'	208
# x	-1.5	7.40	254	63 07.5'	79 36.0'	210
o o o o o o	-1.2	7.21	276	63 00.2'	80 59.8'	206
x	-1.2	7.20	276	62 40.0'	80 20.0'	214
x x x	-1.3	7.30	285	62 59.0'	79 49.0'	212

Nuculana pernula, Macoma calcarea, Nucula bellotii and Portlandia lenticula. Areas of greatest molluscan variety are shown in Figure 3.

The molluscs are apparently controlled more by depth than are the foraminifers, although the texture of the bottom sediments and the dissolved oxygen content of the bottom waters appear to be important factors also. Mya truncata was not collected from depths greater than 100 metres, and the species was most common at the shallow end of its range, i.e. between about 35 and 50 metres. Other species of apparently restricted depth range included Hiatella arctica, collected only between 35 and 165 metres, Nuculana buccata 62 to 92 metres, and Chlamys islandicus 48 to 113 metres, all at the shallow end of the scale. Optimum depths noted were between 35 and 60 metres for H. arctica, 50 and 60 metres for C. islandicus, and 60 and 80 metres for N. buccata. Four species collected over a broader range in depth were Astarte montagui striata and Nuculana minuta between 43 and 214 metres, Nucula bellotii between 90 and 276 metres, and Portlandia lenticula between 100 and 276 metres. The first two species named were found in greatest numbers at the shallow end of their range, between 43 and 106 metres for A.m. striata, and 80 and 90 metres for N. minuta. The other two species were more common at greater depth, with N. bellotii occurring most abundantly in a sample from a depth of 165 metres and P. lenticula being most common between 117 and 196 metres. Finally, Clinocardium ciliatum, Nuculana pernula and Macoma calcarea were found throughout most of the depth range sampled. C. ciliatum was dominant in samples from about 60 to 65 metres, whereas the optimum depth for N. pernula was between about 90 and 105 metres, and for M. calcarea between 165 and 235 metres.

Mollusc distribution was apparently less affected by bottom texture than was distribution of the foraminifers. Many of the small, delicate, thin-shelled species were found mainly in areas where the bottom was silt, silty clay or clay, but they were also found where the bottom was of coarser sediment. The larger, more robust-shelled species occurred more commonly where the bottom was silty sand or coarser sediment. However, they were also found where the bottom was of finer material. It therefore appears that depth, rather than bottom texture, was the dominant factor affecting distribution of the molluscan species. There is a close parallel between the molluscs and foraminifers regarding the effect, or lack of it, of the various water properties on their distribution. Mollusc faunas were most abundant and varied where oxygen content of the water was high.

On the basis of M.J. Dunbars' (1951, 1953) definition, and as shown by E.H. Grainger (1966, Figure 63), Hudson Bay falls within the arctic rather than the subarctic faunal region, being characterized by waters having negative temperatures, i.e. below 0 °C, and salinity of about 33 ‰ or lower. Waters with these properties form the upper 200 to 300 metres of the water mass throughout most of the arctic, and extend southward by way of the Gulf of Boothia and Fury and Hecla Strait to Foxe Basin and thence to Hudson Bay. Subarctic water from the Atlantic flows into Hudson Strait and may penetrate

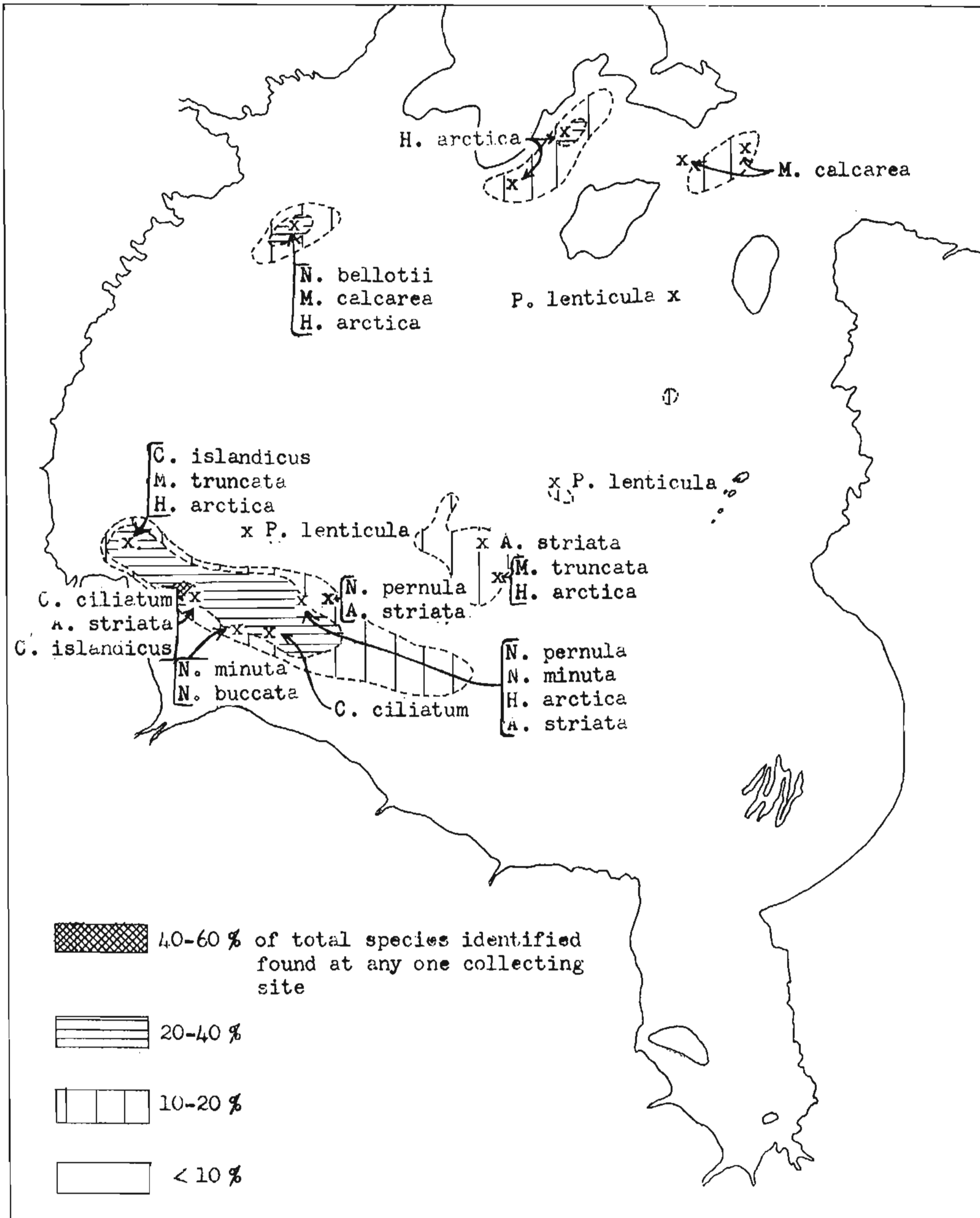


Figure 3. Faunal variety and dominant species of Mollusca.

into the bay at depth. However, as D.V. Ellis (1960) points out, differences in faunal composition in arctic and subarctic regions appear to be slight. Species generally restricted to either the arctic or subarctic faunal associations are found in the bay, but most species present show affinities with both.

The majority of fossils that have been collected were from the uplifted marine deposits rimming Hudson and James Bays. The main exception was the fossil foraminifers that Leslie (1965) recovered from cores taken from the bottom sediments of Hudson Bay. Foraminifers and molluscs were the predominant organisms found in the pre-Hudson Bay deposits. Brachiopods, barnacles and echinoids were present as minor constituents of the fauna. All but 26 of the 143 species identified from the Tyrrell Sea deposits have been found also in Hudson Bay. Most of these 26 species were of very limited occurrence. Only two species, Astarte arctica and Mya pseudoarenaria, were common.

Many of the records of fossil collections leave much to be desired in that the elevations of the localities were not given. Any changes in the fauna with relation to elevation above present sea-level must, therefore, be determined on the basis of the few collections for which elevations were given. The highest definite elevation was 142 metres, although Robert Bell (1887) reported marine shells from an estimated 152 metres above sea-level east of James Bay.

Above 122 metres elevation, Hiatella arctica, Mya truncata, Macoma balthica and Clinocardium cilliatum were the only species recorded. H. arctica and M. truncata were more common than the other two species. They occur presently in both arctic and subarctic waters. M. balthica and C. ciliatum are characteristic of subarctic or more temperate waters. These four species are euryhaline. As all four species were found from the highest raised deposits down to present sea-level, and also living in Hudson Bay, it would appear that conditions during the early stages of the Tyrrell Sea may not have differed greatly from those prevailing now. Any differences may have been in salinity, with the waters being less saline than at present. Some of the later species to arrive, primarily those found below about 60 metres above present sea-level, were species characteristic of more truly marine conditions. This observation agrees with what Leslie (1965) has noted regarding the foraminifers, i.e. that the first species to enter the Tyrrell Sea were those tolerant of brackish conditions. As the salinity increased following the decrease of freshwater runoff from the land, a more diverse and abundant fauna became established.

Possibly some or all of the 26 species reported only as fossils are still living in the area and will be found by further exploration. However, they may have been intolerant of change, and only a slight shift in the environment was sufficient to eliminate them from the area.

Radiocarbon dates have been reported by H. A. Lee (1960) and

B. Matthews (1966), and both authors have calculated the rate of uplift of the land around Hudson and James Bays since the withdrawal of the glaciers. Both have concluded that the initial rate of uplift, before 6,000 - 7,000 years B.P., was on the order of about 6 metres per century. This rate subsequently decreased to a value of from one-third of a metre to about one metre per century. A date of 7270 ± 120 years B.P. for shells collected about 142 metres above sea-level from a ridge 55 miles southwest of Churchill, Manitoba that is believed to mark the limits of the Tyrrell Sea in this area, would suggest that maximum inundation occurred between 5,000 and 6,000 B.C.

Eleven samples that I collected in 1965 were dated. These dates ranged from 7115 ± 100 years B.P. for marine shells collected at an elevation of 91 metres, to 385 ± 80 years B.P. for shells from about 3½ metres above present sea-level. These dates, with those from intervening elevations, are in good agreement with the uplift curves presented by Lee and Matthews (Wagner, 1967).

In summary, collection of fossil and living organisms in and around Hudson and James Bay has been carried out from at least as early as 1860. Prior to the Hudson Bay Expedition in 1920, most of the specimens were obtained incidentally to geological investigations in the area. At least 263 species have been identified, of which 142 were foraminifers and 80 were molluscs. The remainder comprised sponge, bryozoan, brachiopod, annelid worm, and barnacle species, plus representatives of various groups of echinoderms. Of the different properties of the water that were determined, i.e. temperature, salinity, dissolved oxygen content, and hydrogen-ion concentration, only the dissolved oxygen in the bottom water appeared to have any major influence on faunal distribution. Temperature, salinity and hydrogen-ion concentration were relatively constant, or varied within narrow limits. Texture of the bottom sediment, and depth of water were the other important factors affecting the distribution of the various species. The species found, both living and fossil, were characteristic of the arctic and subarctic faunal regions. Most of the 143 species found as fossils have also been collected from Hudson Bay. Species from the Tyrrell Sea deposits higher than about 122 metres above present sea-level hint at more brackish conditions, but with water temperature probably not too different from the present. Species found below about 61 metres above present sea-level point to salinities comparable to those now prevailing in Hudson Bay. On the basis of radiocarbon-dated shells, the period of maximum extent of Tyrrell Sea is believed to have been reached between 5,000 and 6,000 B.C. Initial uplift of the land following withdrawal of the glacier ice was rapid, about 6 metres per century, but since about 6,000 - 7,000 years B.P. it has slowed to a rate of between one-third of a metre and one metre per century.

APPENDIX I

Names in current usage are listed alphabetically for each table separately. These are followed by the name or names used in earlier listings. Where an organism has not been identified to species it has been assigned in the table to a common species of the genus for simplification of listings. For example, Balanus sp. will be found under Balanus crenatus Bruguiere

Synonymies for Table II

Ammotium cassis (Parker)

Ammobaculites cassis (Parker) -- Cushman, 1922; Cushman, 1948.

Astrononion stellatum Cushman & Edwards

Nonion stelligera (d'Orbigny) -- Nichols, 1936

Nonionina stelligera d'Orbigny -- Cushman, 1922

Astrononion gallowayi Loeblich & Tappan -- Leslie, 1963

Buccella frigida (Cushman)

Eponides frigidus var. calidus Cushman & Cole -- Hughes, 1954.

Pulvinulina frigida Cushman -- Cushman, 1922

Eponides frigidus (Cushman) -- Cushman, 1948

Cassidella complanata (Egger)

Bulimina exilis Brady -- Lee, 1958-59; Leslie, 1963

Cibicides lobatulus (Walker & Jacob)

Truncatulina lobatulus (Walker & Jacob) -- Cushman, 1922

Cribrostomoides crassimargo (Norman)

Alveolophragmium crassimargo (Norman); also Haplophragmoides major Cushman -- Leslie, 1963

Cribrostomoides jeffreysi (Williamson)

Haplophragmoides canariensis (d'Orbigny) -- Cushman, 1922; Cushman, 1948.

Cyclogyra foliacea (Philippi)

Cornuspira foliacea (Philippi) -- Cushman, 1922; Cushman, 1948.

Dentalina calomorpha (Reuss)

Nodosaria calomorpha Reuss - Cushman, 1922; Cushman, 1948.

Eggerella advena (Cushman)

Verneuilina advena d'Orbigny -- Cushman, 1922; Cushman, 1948.

Elphidiella arctica (Parker & Jones)

Elphidium arcticum (Parker & Jones) -- Nichols, 1936.

Polystomella arctica Parker & Jones -- Cushman, 1922.

Elphidium incertum (Williamson)

Polystomella striato-punctata (Fichtel & Moll) var. incerta (Williamson) -- Cushman, 1922.

Esosyrinx curtus (Cushman & Ozawa)

Pseudopolymorphina curta Cushman & Ozawa -- Cushman, 1948.

Glabratella wrightii (Brady)

Discorbis wrightii (Brady) -- Cushman, 1922.

Eponides wrightii (Brady) -- Cushman, 1948.

Globigerina pachyderma (Ehrenberg)

Globigerina sp. -- Nichols, 1936.

Globulina glacialis Cushman & Ozawa

Guttulina glacialis (Cushman & Ozawa) -- Leslie, 1965

Guttulina lactea (Walker & Jacob)

Polymorphina lactea (Walker & Jacob) -- Cushman, 1922.

Islandiella islandica (Nørvang)

Cassidulina islandica Nørvang -- Harrison, 1956; Lee, 1958-59;

Leslie, 1963; Leslie, 1965.

Islandiella norcrossi (Cushman)

Cassidulina norcrossi Cushman -- Harrison, 1956; Lee, 1958-59;

Leslie, 1963; Leslie, 1965.

Islandiella teretis (Tappan)

Cassidulina teretis Tappan -- Harrison, 1956; Lee, 1958-59;

Leslie, 1965.

Melonis zaandami (van Voorthuysen)

Nonion barleeanum (Williamson) -- Hughes, 1954

Melonis zaandamae (van Voortuysen) -- Leslie, 1965;

'C.G.S. Labrador', 1959.

Nonion zaandamae van Voorthuysen -- Leslie, 1963.

Nonionellina labradorica (Dawson)

Nonion labradoricum (Dawson) -- Nichols, 1936; Harrison, 1956; Lee, 1958-59; Cushman, 1948.

Nonionina scapha (Fichtel & Moll) -- Cushman, 1922

Nonionella labradorica (Dawson) -- Leslie, 1963; Leslie, 1965.

Oolina borealis Loeblich & Tappan

Oolina costata (Williamson) -- Leslie, 1963.

Oolina striatopunctata (Parker & Jones)

Lagena striatopunctata Parker & Jones -- Leslie, 1963.

Pateoris hauerinoides (Rhumbler)

Quinqueloculina subrotunda (Montagu) -- Cushman, 1922; Cushman, 1948; Leslie, 1963.

Protelphidium orbiculare (Brady)

Nonion orbicularis (Brady); also Nonion depressula (Walker & Jacob) -- Nichols, 1936.

Nonion orbiculare (Brady) -- Hughes, 1954; Cushman, 1948.

Elphidium orbiculare (Brady) -- Harrison, 1956; Lee, 1958-59; Leslie, 1963.

Nonionina orbicularis (Brady) -- Cushman, 1922.

Pseudopolymorphina novangliae (Cushman)

Pseudopolymorphina sp. -- Lee, 1958-59; Hughes, 1963.

Pyrulina cylindroides (Roemer)

Pyrulina sp. -- Prest, 1965

Webbinella arctica Cushman

Webbinella hemisphaerica (Jones, Parker & Brady) -- Cushman, 1922.

Synonymies for Table III

Gastropoda

Acmaea testudinalis Linné

Acmaea patina Eschscholtz -- McGill, 1952

Acmaea sp. -- Harrison, 1956

Boreotrophon clathratus (Linné)

Trophon clathratus Linné -- Low, 1887

Boreotrophon clathratus Gould -- Dall, 1924

Colus ventricosus (Gray)

Fusus ventricosus Gray -- Baker, 1911

Hydrobia minuta (Totten)

Paludestrina minuta (Totten) -- Richards, 1936

Littorina groenlandica Menke

Littorina groenlandica Chemnitz (? = *L. tenebrosa*) -- Stimpson, 1862.

Littorina littoralis (Linné)

Littorina palliata Say -- Bell, 1881

Littorina sp. -- Bell, 1880

Littorina saxatilis (Olivi)

Litorina rudis (Maton) -- Low, 1903

Littorina rudis Donovan -- Dall, 1924

Littorina rudis tenebrosa Montagu -- Brooks, 1935

Littorina rudis (Maton) -- Richards, 1936

Lora americana Packard

Bela americana Packard -- Richards, 1936

Lora incisula (Verrill)

Bela incisula Verrill -- Richards, 1936

Lunatia pallida (Broderip & Sowerby)

Natica groenlandica Muller -- Williams, 1921; Richards, 1936.

Polinices pallidus (Broderip & Sowerby) -- Lee, 1958-59.

Natica clausa Broderip & Sowerby

Natica affinis (Gmelin) -- Bell, 1879b

Neptunea despecta Linné

Fusus toxnatus -- Bell, 1904

Neptunea sp. -- Hughes, 1954

Plicifusus kroyeri (Möller)

Colus kroyeri Möller -- Brooks, 1935

Puncturella noachina (Linné)

Puncturella princeps Mighels & Adams -- Richards, 1940; Richards, 1941.

Tachyrhynchus erosum (Couthouy)

Turritella erosa Couthouy -- Richards, 1941

Tachyrhynchus sp. -- McGill, 1952

Pelecypoda

Astarte arctica (Gray)

Astarte sp. -- Bell, 1877

Astarte lactea (Broderip & Sowerby) -- Bell, 1879a; Bell, 1881.

Astarte lactea -- Bell, 1879b.

Astarte montagui striata (Leach)

Astarte striata (Leach) -- Stimpson, 1862; Richards, 1936; Richards, 1940.

Astarte laurentiana (Lyell) -- Bell, 1879a; Harrison, 1956; Jackson, 1958.

Astarte laurentiana -- Bell, 1887.

Astarte banksii (Leach) -- Nichols, 1936; Richards, 1941.

Astarte banksii var. striata (Leach) -- Low, 1903.

Chlamys islandicus (Müller)

Pecten islandicus Müller -- Stimpson, 1862; Bell, 1879a; McInnes, 1904; Richards, 1936; Richards, 1940; Richards, 1941; Dall, 1924; Brooks, 1935.

Pecten islandicus -- Bell, 1880.

Pecten islandicus Chemnitz -- Bell, 1881.

Pecten islandicum -- Bell, 1904.

Pecten islandicus var.; also *Pecten islandicus* and *Pecten islandicus insculptus* Verrill -- Nichols, 1936.

Clinocardium ciliatum (Fabricius)

Cardium islandicum Chemnitz -- Stimpson, 1862; Bell, 1881.

Cardium islandicum Linné -- Bell, 1877; Bell, 1879a; Bell, 1879b; Baker, 1911; Kindle, 1924.

Cardium islandicum -- Bell, 1880; Bell, 1904; McLearn, 1927; Dyer, 1929.

Cardium islandicum Chemnitz (= *C. ciliatum* Fabricius) -- Low, 1887.

Cardium ciliatum -- Wilson, 1903.

Cardium ciliatum (Fabricius) -- McInnes, 1904.

Crenella faba Frabricius

Crenella sp. -- Hughes, 1963.

Hiatella arctica (Linné)

Saxicava rugosa -- Bell, 1872; Bell, 1879a; Bell, 1880; Bell, 1887; Bell, 1896; Parks, 1899; Wilson, 1903; Bell, 1904; Tyrrell, 1913; McLearn, 1927.

Saxicava arctica Linné -- Bell, 1877; Nichols, 1936; Richards, 1936; Richards, 1940; Richards, 1941; Low, 1903; Dall, 1924; Brooks, 1935.

Saxicava rugosa (Lamarck) -- Bell, 1879b.

Saxicava pholadis Linné (= *Saxicava rugosa* Lamarck) -- Low, 1887.

Saxicava rugosa Linné -- Low, 1889; McInnes, 1904; Williams, 1921; Kindle, 1924; Dyer, 1929.

Saxicava arctica -- Tyrrell, 1896.

Saxicava rugosa Linné; also *Saxicava arctica* Linné -- Baker, 1911.

Macoma balthica (Linné)

Tellina groelandica -- Bell, 1872; Bell, 1877 (Recent); Bell, 1879b; Bell, 1887; Bell, 1896.

Macoma fragilis Fabricius (*Tellina grönlandica*) -- Bell, 1877; Bell, 1879a; Stimpson, 1862.

Macoma fragilis Fabricius -- Bell, 1881

Tellina groenlandica Beck -- Low, 1889

Tellina groenlandica; also *Macoma fragilis* -- Parks, 1899.

Tellina groenlandica; also *Maconea fragilis* -- Bell, 1904.

Macoma fusus Say -- Baker, 1911.

Macoma calcarea (Gmelin)

Macoma sabulosa (Spengler) (*Tellina proxima*) -- Stimpson, 1862.

Tellina proxima -- Bell, 1872; Bell, 1880; Bell, 1887.

Macoma sabulosa Spengler -- Bell, 1877.

Macoma calcarea (Tellina proxima) -- Bell, 1879a; Bell, 1904.

Macoma calcarea Chemnitz; also *Tellina proxima* -- Bell, 1879b.

Macoma calcarea Chemnitz -- Bell, 1881; Low, 1887.

Macoma calcarea -- Parks, 1899

Macomus proxima Gray -- Baker, 1911

Musculus discors Linné

Musculus sp. -- Hughes, 1963

Modiolaria discors (Linné) -- Low, 1903.

Mya pseudoarenaria Schlesch

Mya arenaria Linné -- Bell, 1877; Bell, 1879a; Bell, 1881; Low, 1889; McInnes, 1904; Baker, 1911; Nichols, 1936; Richards, 1941; Hughes, 1954; Harrison, 1956.

Mya arenaria -- Bell, 1879b; Bell, 1880; Wilson, 1903; Bell, 1904.

Mya truncata Linné

Mya sp. -- Parks, 1899

Nucula bellotii Adams

Nucula tenuis var. inflata (Hancock) -- Bell, 1879b

Nucula expansa (Reeve) -- Low, 1903

Nucula tenuis (Montagu)

Nucula expansa Reeve (Nucula tenuis) -- Stimpson, 1862

Nucula sp. -- Kindle, 1924; Dyer, 1929

Nuculana buccata (Steenstrup)

Leda buccata -- Wilson, 1903

Leda buccata (Steenstrup) -- Richards, 1941

Nuculana pernula (Müller)

Leda pernula (Müller) -- Stimpson, 1862; Kindle, 1924; Dyer, 1929; Richards, 1936; Richards, 1940.

Leda pernula (Möller) -- Bell, 1877; Bell, 1879b.

Nuculana sp. -- Clarke, 1963.

Pandora glacialis (Leach)

Kennerlia glacialis (Leach) -- Richards, 1936.

Portlandia arctica (Gray)

Yoldia portlandica (Hitchcock) -- Stimpson, 1862

Leda truncata -- Bell, 1872

Portlandia glacialis Gray (or Leda truncata Wood) -- Bell, 1877

Leda arctica -- Tyrrell, 1896

Portlandia glacialis Gray -- Kindle, 1924; Dyer, 1929

Yoldia arctica (Gray) -- Hughes, 1963

Portlandia sp. -- Prest, 1965

Portlandia glacialis (Wood) -- Low, 1903

Portlandia lenticula (Möller)

Yoldia abyssicola (Torrell) -- Richards, 1936; Lee, 1958-59

Pseudamussium binominatus Hanna

Pecten (Camptonectes) groenlandicus (Towerby) -- Low, 1903

Serripes groenlandicus (Bruguière)

Cardium groenlandicum -- Bell, 1872; Bell, 1887.

Seripes groenlandicus -- Wilson, 1903

Seripes groenlandicus (Gmelin) -- McInnes, 1904

Thracia myopsis Möller

Thracia myopsis (Beck) Moller -- Low, 1903

Thyasira flexuosa sarsi Philippi

Thyasira sp. -- Clarke, 1963

Synonymies for Table IV

Brachiopoda

Hemithiris psittacea (Gmelin)

Rhynchonella psittacea Chemnitz -- Stimpson, 1862; Low, 1887.

Rhynchonella psittacea Gmelin -- Bell, 1877; Richards, 1940.

Rhynchonella psittacea -- Bell, 1880.

Hemithyris psittacea (Gmelin) -- Nichols, 1936; Richards, 1936, Richards, 1941; Lee, 1952.

Cirripedia

Balanus crenatus Brugière

Balanus sp. -- Richards, 1941.

Balanus sp. (probably *Balanus crenatus*) -- Porsild, 1957.

Echinodermata - Asteroidea

Solaster papposus (Linné)

Crossaster papposus -- Clark, 1922; Clark, 1937.

Leptasterias polaris (Müller & Troschel)

Asterias acervata borealis -- Clark, 1922

Henricia perforata (Müller)

Henricia sanguinolenta -- Clark, 1937

REFERENCES

Abbott, A.T.
1954: American seashells; D. van Nostrand Co. Inc., New York.

Baker, M. B.
1911: Iron and lignite in the Mattagami Basin; Rept. Ontario Bur. Mines, vol. 20, pt. 1, No. 4, pp. 214-246.

Barber, F. G.
1967: A contribution to the oceanography of Hudson Bay; Marine Sci. Branch, Can. Dept. Energy, Mines Resources, MS. Rept. Ser. No. 4.

Barker, R. W.
1960: Taxonomic notes on the species figured by H. B. Brady in his report on the Foraminifera dredged by H.M.S. Challenger during the years 1873-1876; Soc. Econ. Paleontologists Mineralogists, Spec. Publ. No. 9.

Bell, J. M.
1904: Economic resources of Moose River Basin; Rept. Ontario, Bur. Mines, vol. 13, pt. 1, No. 5, pp. 135-179.

Bell, Robert
1872: Report on the country between Lake Superior and the Albany River; Geol. Surv. Can., Rept. Prog. 1871-72, pt. 4, pp. 101-114.

1877: Report on an exploration in 1875 between James Bay and Lakes Superior and Huron; Geol. Surv. Can., Rept. Prog. 1875-76, pt. 14, pp. 294-342.

1879a: Report on an exploration of the east coast of Hudson's Bay, 1877; Geol. Surv. Can., Rept. Prog. 1877-78, pt. C, pp. 1-37.

1879b: Report on the country between Lake Winnipeg and Hudson's Bay, 1878; Geol. Surv. Can., Rept. Prog. 1877-78, pt. CC, pp. 1-31.

Bell, Robert (con't)

1880: Report on exploration on the Churchill and Nelson Rivers and around God's and Island Lakes, 1879; Geol. Surv. Can., Rept. Prog. 1878-79, pt. C, pp. 1-72.

1881: Report on Hudson Bay and some of the lakes and rivers lying to the west of it; Geol. Surv. Can., Rept. Prog. 1879-80, pt. C, pp. 1-113.

1885: Observations on the geology, mineralogy, zoology and botany of the Labrador coast, Hudson's Strait and Bay; Geol. Surv. Can., Rept. Prog. 1882-84, pt. DD, pp. 5-62.

1886: Observations on the geology, zoology and botany of Hudson's Strait and Bay, made in 1885; Geol. Surv. Can., Ann. Rept., n. s., vol. 1 (1885), pt. DD, pp. 5-27.

1887: Report on an exploration of portions of the Attawapiskat and Albany Rivers, Lonely Lake to James Bay; Geol. Surv. Can., Ann. Rept. vol. 2 (1886), pt. G, pp. 5-39.

1896: Proofs of the rising of the land around Hudson Bay; Am. J. Sci., Ser. 4, vol. 1, pp. 219-228.

1897: Evidences of northeasterly differential rising of the land along Bell River; Bull. Geol. Soc. Am., vol. 8, pp. 241-250.

1901: Report on an exploration on the northern side of Hudson Strait; Geol. Surv. Can., Ann. Rept., vol. 6 (1898), pt. M, pp. 5-38.

Bousfield, E. L.

1960: Canadian Atlantic sea shells; Queen's Printer, Ottawa.

Clark, A. H.

1922: Results of the Hudson Bay Expedition, 1920. III. The Echinoderms; Contrib. Can. Biol., n.s., vol. 1, No. 2, pp. 21-25.

1937: Biological and oceanographic conditions in Hudson Bay. II. Echinoderms of Hudson Bay; J. Fisheries Res. Board Can., vol. 3, No. 4, pp. 350-357.

Clarke, A. H., Jr.,

1963: Canada - land of untouched shelling areas; Shells and their neighbours, No. 20, pp. 1-2.

Clench, W. J. (editor)

1950: Note; Johnsonia, vol. 2, No. 29, p. 246.

Craig, B. G., and Fyles, J. G.
1960: Pleistocene geology of Arctic Canada; Geol. Surv. Can., Paper 60-10.

Cushman, J. A.
1922: Results of the Hudson Bay Expedition, 1920. I. The Foraminifera; Contrib. Can. Biol., (1921), No. 9, pp. 135-147.

1948: Arctic Foraminifera; Cushman Lab. Foram. Res., Spec. Publ. No. 23.

Dall, W. H.
1924: Mollusks, Recent and Pleistocene; Rept. Can. Arctic Exped., 1913-18, vol. 8, pt. A, pp. 31-35.

Dunbar, M. J.
1951: Eastern Arctic waters; Fisheries Res. Board Can., Bull. 88.

1953: Arctic and subarctic marine ecology: immediate problems; Arctic, vol. 6, No. 2, pp. 75-90.

Dyer, W. S.
1929: Geology and economic deposits of the Moose River Basin; Rept. Ontario Dept. Mines, vol. 37 (1928), pt. 6, pp. 1-69.

Dyer, W. S., and Crozier, A. R.
1933: Lignite and refractory clay deposits of the Onakawana lignite field; Rept. Ontario Dept. Mines, vol. 42, pt. 3, pp. 46-78.

Ellis, D. V.
1960: Marine infaunal benthos in Arctic North America; Arctic Inst. North Amer., Tech. Paper 5.

Feyling-Hanssen, R. W.
1964: Foraminifera in late Quaternary deposits from the Oslofjord area; Norg. Geol. Undersokelse, No. 225.

Foster, R. W.
1946: The genus Mya in the western Atlantic; Johnsonia, vol. 2, No. 20, pp. 29-35.

Grainger, E. H.
1966: Sea stars (Echinodermata: Asteroidea) of Arctic North America; Fisheries Res. Board Can., Bull. 152.

Harrison, J. M.
1956: see Wagner, 1956.

Hughes, O. L.
1963: see Wagner, 1963.

Jackson, G. D.
1958: see Wagner, 1959a.

1960: Belcher Islands, Northwest Territories (33M, 34D, E); Geol. Surv. Can., Paper 60-20.

Kindle, E. M.
1924: Geology of a portion of the northern part of Moose River Basin, Ontario; Geol. Surv. Can., Summ. Rept., 1923, pt. Cl, pp. 21-41.

La Rocque, Aurèle
1953: Catalogue of the recent Mollusca of Canada; Natl. Museum Can., Bull. 129.

Lee, H. A.
1958: see Wagner, 1958.

1959a: Surficial geology of southern District of Keewatin and the Keewatin ice divide, Northwest Territories; Geol. Surv. Can., Bull. 51 (see Wagner, 1952).

1959b: see Wagner, 1959b.

1960: Late glacial and post-glacial Hudson Bay sea episode; Science, vol. 131, pp. 1609-1611.

Leslie, R. J.
1963: Foraminiferal study of a cross-section of Hudson Bay, Canada; Geol. Surv. Can., Paper 63-16.

1965: Ecology and palaeoecology of Hudson Bay Foraminifera; Bedford Inst. Oceanogr., Rept. 65-6.

Loeblich, A. R., Jr., and Tappan, Helen
1953: Studies of Arctic Foraminifera; Smithsonian Inst. Misc. Collections, vol. 121, No. 7.

Low, A. P.
1887: Preliminary report on an exploration of country between Lake Winnipeg and Hudson Bay; Geol. Surv. Can., Ann. Rept., vol. 2 (1886), pt. F, pp. 5-24.

1889: Report on an exploration in James Bay and country east of Hudson Bay drained by the Big, Great Whale and Clearwater Rivers; Geol. Surv. Can., Ann. Rept., vol. 3 (1887-88), pt. J, pp. 5-94.

Low, A. P. (con't)
1903: Report on an exploration of the east coast of Hudson Bay; Geol. Surv. Can., Ann. Rept., n.s., vol. 13 (1900), pt. D, pp. 5-84.

1906: The cruise of the Neptune, 1903-04. Report on the Dominion Government expedition to Hudson Bay and the Arctic Islands on board D.G.S. Neptune, 1903-04; Geol. Surv. Can., Pub. No. 905.

Lubinsky, Irene
1958: Studies on Mytilus edulis L. of the "Calanus" expeditions to Hudson Bay and Ungava Bay; Can. J. Zool., vol. 36, pp. 869-881.

MacGinitie, Nettie
1959: Marine Mollusca of Point Barrow, Alaska; Proc. U.S. Natl. Museum, vol. 109, pp. 59-208.

MacNeil, F. S.
1965: Evolution and distribution of the genus Mya, and Tertiary migrations of Mollusca; U.S. Geol. Surv., Prof. Paper 483-G.

McGill, W. P.
1952: see Wagner, 1952b.

McInnes, W.
1904: The Winisk River, Keewatin District; Geol. Surv. Can., Summ. Rept., 1903, pt. A, pp. 100-108.

McLearn, F. H.
1927: The Mesozoic and Pleistocene deposits of the lower Missinaibi, Opazatika and Mattagami Rivers, Ontario; Geol. Surv. Can., Summ. Rept., 1926, pt. C, pp. 16-47.

Matthews, Barry
1966: Radiocarbon dated postglacial land uplift in northern Ungava, Canada; Nature, vol. 211, No. 5054, pp. 1164-1166.

1967: Late Quaternary marine fossils from Frobisher Bay (Baffin Island, N.W.T., Canada); Palaeogeogr., Palaeoclimatol., Palaeoecol., vol. 3, pp. 243-263.

Mossop, B. K.
1922: The rate of growth of the sea-mussel (Mytilus edulis L.) at St. Andrews, New Brunswick; Digby, Nova Scotia; and Hudson Bay; Trans. Roy. Soc. Can., vol. 14, No. 31, pt. 1, pp. 3-21.

Nichols, D. A.
1936: Post-Pleistocene fossils of the uplifted beaches of the eastern Arctic regions of Canada; Can. Field-Natur., vol. 50, No. 8, pp. 127-129.

Parks, W. A.
1899: The Nipissing-Algoma boundary; Rept. Ontario Bur. Mines, vol. 8, pt. 2, pp. 175-196.

Pelletier, B. R., Wagner, F. J. E., and Grant, A. C.
1968: Marine geological investigations in Hudson Bay; in Science, History and Hudson Bay, vol. II, chapt. 9, pt. III, Can. Dept. Energy, Mines Resources.

Prest, V. K.
1966: see Wagner, 1966.

Richards, H. G.
1936: Recent and Pleistocene marine shells of James Bay; Am. Midland Naturalist, vol. 17, pp. 528-545.

1940: Pleistocene fossils from the Belcher Islands in Hudson Bay; Ann. Carnegie Mus., vol. 28, pp. 47-52.

1941: Post-Wisconsin fossils from the west coast of Hudson Bay; Notulae Naturae, No. 84, 10 pp.

1962: Studies on the marine Pleistocene, Part II. The marine Pleistocene mollusks of eastern North America; Trans. Am. Phil. Soc., n.s., vol. 52, pt. 3, pp. 42-141.

Schenck, H. G.
1939: Revised nomenclature for some nuculid pelecypods; Jour. Paleontol., vol. 13, pp. 21-41.

Stimpson, William
1862: On the marine shells brought by Mr. Drexler from Hudson Bay, and on the occurrence of a Pleistocene deposit on the southern shore of James Bay; Proc. Acad. Nat. Sci. Phila., vol. 13 (1861), p. 97.

Terasmae, J., and Hughes, O. L.
1960: A palynological and geological study of Pleistocene deposits in the James Bay Lowlands, Ontario (42 N $\frac{1}{2}$); Geol. Surv. Can., Bull. 62. (see Wagner, 1954).

Tyrrell, J. B.
1896: Report on the Doobaunt, Kazan and Ferguson Rivers and the north-west coast of Hudson Bay; Geol. Surv. Can., Ann. Rept., n.s., vol. 9, pt. F, pp. 5-218.

1913: Hudson Bay exploring expedition, 1921; Rept. Ontario Bur. Mines, vol. 22, pt. 1, No. 4, pp. 161-209.

Wagner, F. J. E.
1952a: Report on fossil shells submitted by H. A. Lee from the District of Keewatin; Geol. Surv. Can., Foss. Rept. P1-2-52/53.[1]

1952b: Report on fossil shells submitted by W. P. McGill from the District of Keewatin; Geol. Surv. Can., Foss. Rept. P1-3-52/53.

1954: Report on fossils from Missinaibi River, Northern Ontario, submitted by O. L. Hughes, December 1954; Geol. Surv. Can., Foss. Rept. P1-6-54/55.

1956: Report on shells from Innetalling Lake, Belcher Islands, submitted by J. Harrison, 1956; Geol. Surv. Can., Foss. Rept. P1-4-56/57.

1958: Report on shells from northwestern Quebec, submitted by H. A. Lee, April 1958; Geol. Surv. Can., Foss. Rept. P1-1-58/59.

1959a: Report on fossil shells from Belcher Islands, collected by G. D. Jackson, 1958; Geol. Surv. Can., Foss. Rept. P1-8-58/59.

1959b: Report on shells from Fort George and vicinity, submitted by H. A. Lee, 1959; Geol. Surv. Can., Foss. Rept. P1-9-59/60.

1963: Report on fossils from northern Ontario, submitted by O. L. Hughes, 1963; Geol. Surv. Can., Foss Rept. P1-8-63.

1966: Report on fossils from Little Abitibi River, Ontario, collected by V. K. Prest, 1965; Geol. Surv. Can., Foss. Rept. P1-1-66.

1967: Additional radiocarbon dates, Tyrrell Sea areas; Mar. Sediments, vol. 3, No. 4, pp. 100-104.

Williams, M. Y.
1921: Palaeozoic stratigraphy of Pagwachuan, lower Kenogami and lower Albany Rivers; Geol. Surv. Can., Summ. Rept., 1920, pt. D, pp. 18-25.

Wilson, W. J.
1903: Reconnaissance surveys of four rivers southwest of James Bay; Geol. Surv. Can., Summ. Rept., 1902, pt. A, pp. 222-243.

Zenkevitch, L.
1963: Biology of the seas of the U.S.S.R.; George Allen and Unwin Ltd., London.

---

[1]The faunal lists contained in these internal office reports are incorporated in tables accompanying this paper and the reports are listed for cross reference with the collector's name.

THE PATTERN AND INTERPRETATION OF RESTRAINED, POST-GLACIAL AND RESIDUAL REBOUND IN THE AREA OF HUDSON BAY

J. T. Andrews
Institute of Arctic and Alpine Research
University of Colorado

Abstract

The recovery of the earth's crust from glacial loading is divided into three periods: the first is termed restrained rebound and occurs prior to deglaciation of a site; the second is post-glacial rebound; and the third is residual or the amount of rebound still remaining. The relationship of Hudson Bay to former glacial centres is discussed by an appraisal of a map illustrating isolines on the marine limit and on post-glacial uplift. A true isobase map showing relative land movement in the last 6,000 years is presented and compared with the isoline maps above. Calculations on the amount of residual rebound are attempted and a map is drawn. Restrained rebound is difficult to map at this time, but a cross-profile running NW-SE illustrates possible values and trends of this parameter. The centre of Hudson Bay appears as an area of convergence rather than an uplift centre. The isobase map indicates two uplift centres, one located over the area of Baker Lake and the other over east Hudson Bay. The map of residual rebound is presented in the hope that it will be tested by geophysicists.

INTRODUCTION

The dimensions of the load applied to the earth's crust during the last glaciation over North America are impressive; the ice cap had a radius of approximately 1,700 km, an area of $1.1817 \times 10^{13} m^2$, and a volume of $2.6 \times 10^{16} m^3$. The last estimate is based on the assumption that the shear stress averaged 1.0 bar at the base of the ice sheet. It is generally conceded that this mass was sufficient to result in isostatic compensation of the crust to amounts proportional to the varying thickness of the ice sheet. Estimates for total compensation range from 1/2 to 1/4 the overlying thickness of the ice load. This paper is not particularly concerned with the 'how' of the isostatic recovery process, but it should be noted that part of the recovery is elastic in nature and, therefore, 'instantaneous'. The geomorphologist is more concerned with the plastic and long continued part of the process; it is here that isostatic rebound has to be considered in his evaluation of late and post-glacial events and, moreover, it is here that he can contribute information of direct interest to the geophysicist.

From a time and also a functional break-down, the recovery process can be considered to operate in three periods.

$$S = Ur + Up + Urr \qquad (1)$$

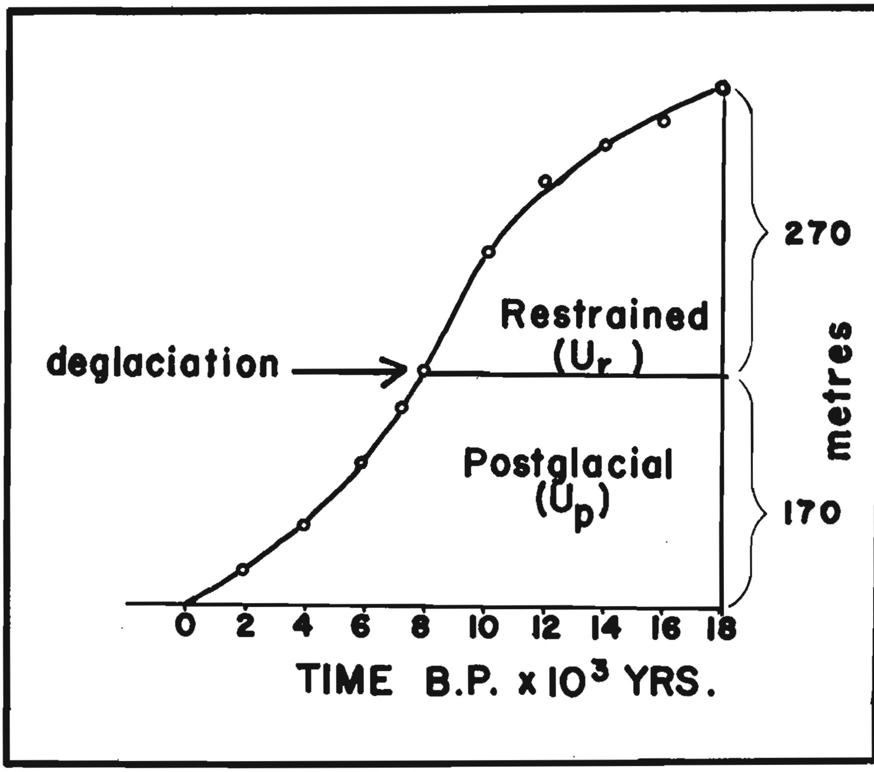


Figure 1. A suggested continuous curve for the Ottawa Islands showing the changing rate of restrained and post-glacial rebound.

The quantity S represents that part of the isostatic process attributable to plastic deformation. At a moment in time the ice cap begins to thin and retreat. Isostatic rebound begins at this time and is called restrained rebound (Ur). As the load decreases, glacial unloading and the rate of restrained rebound increases toward the moment of deglaciation and passes smoothly into the period of post-glacial rebound. Tanner (1965) has suggested that this initial period of rebound functions as a positive exponential process. Between the moment of site deglaciation and the present day is the period of post-glacial uplift (Up), the quantity that is most easily measured in equation (1). The amount of rebound that remains before isostatic equilibrium is achieved is here called the residual rebound (Urr). Figure 1 portrays the possible relation of restrained and post-glacial rebound - note that the latter is a function such that the rate of uplift decreases with time after deglaciation.

To understand the early glacial, late glacial and post-glacial rebound history of Hudson Bay, it is necessary to consider Hudson Bay in relationship to the surrounding areas. Only in this way may a suitable perspective be achieved. Detailed local field studies complement this approach. Presently available radiocarbon dates suggest that deglaciation of Hudson Bay commenced 7, 800 to 8, 200 years ago (see Craig, this volume).

ELEVATION OF THE POST-GLACIAL MARINE LIMIT AND POST-GLACIAL UPLIFT

Ideally, I would like to present a series of maps, beginning with one for the amount of restrained rebound and concluding with a map of residual rebound. However, the amount of restrained rebound is the most difficult quantity of the three to measure - it is consequently dealt with last.

Before proceeding further, I would make one statement: prior to the Quaternary period there is considerable evidence (Kupsch, 1967) for relative movements of land and sea in Canada. There is a problem of differentiating between the effects of glacio-isostatic recovery and the effect of local or regional tectonic histories.

Within the last six years, three maps showing isolines on the elevation of the marine limit within Canada have been published. Despite internal differences, all emphasize the complexity of the marine limit surface and contrast, therefore, with the maps published in the early part of this century, which showed a simple pattern related to an uplift centre near James Bay. The most recent maps are by Farrand and Gadja (1962), King (1965) and Bird (1967). The map of Farrand and Gadja and that of King are inaccurate along their eastern/northeastern margins and overemphasize the elevation of the marine limits in these areas (see Ives, 1963). The map of Bird does not perpetuate this error. All three maps show a zone of high marine limits asymmetric to Hudson Bay with a centre located over Richmond Gulf.

I have recently prepared a map for the National Atlas of Canada that will be published shortly[1]. It was obvious from the start of the project that no map at a compilation scale of 1:7.5 M could record all the variations of the marine limit that are now known. Detailed studies indicate that in adjacent fiords the elevation of the marine limit may: 1) rise steadily inland, 2) decline steadily inland, or 3) any combination of 1 and 2. Elsewhere I have shown how the marine limit reflects the interaction of date of ice retreat and former ice thicknesses (Andrews, 1968b). To simplify the map and yet provide a surface with some meaning, the following methodology was adopted: the map was crossed by a grid; at 125 grid intersections a 4 cm^2 template

---

[1] Single copies of the map will be available from the Surveys and Mapping Branch, Department of Energy, Mines, and Resources, Ottawa and will form part of the National Atlas of Canada.

was laid over the intersection and the highest marine limit was noted and placed on the grid intersection. The resulting network was then contoured. The map represents the maximum potential marine limit – thus sites may lie below an isoline but not above. Where the local marine limit is, say, one contour interval beneath the regional isoline, this may be explained by the effect of 'late ice'. Detailed discussion of the map is not necessary here. However, the result of field work on the Ottawa Islands (59°50'N and 80°00'W) (where the marine limit is at 155 m asl) led to a 'pinching-in' of the 200 m contour and it steepens the gradient from the high over Richmond Gulf (near 56°N and 76°W). In terms of Hudson Bay, the map indicates that the major portion of Hudson Bay occupies a saddle between two major highs – one located over Bathurst Inlet, the other centred over east Hudson Bay.

Post-glacial uplift is defined as the sum of the elevation of the marine limit and the appropriate eustatic sea-level using the date of glaciation to enter one of the eustatic sea-level curves. There is no one accepted sea-level curve; in this paper the smoothed curve of Shepard (1963) is used. The map in the National Atlas of Canada also shows maximum potential post-glacial uplift. Because the eustatic sea-level correction decreases toward the present day from a maximum of ca. 110 m, the margins of the former ice cap(s) have a greater additive correction than the central areas. Thus, the result of adding the eustatic sea-level is to decrease surface gradients and to increase the elevation of the surface.

ISOBASE MAP FOR 6,000 YEARS BP

An isobase is defined as a line joining points that have rebounded equal amounts in the same interval of time. Maps in Farrand and Gadja (1962), King (1965), and Bird (1967) and in the National Atlas of Canada are not isobase maps and do not necessarily portray low and high cells of post-glacial rebound. It is generally considered that an isobase map reflects the true synchronous deformation of the earth's crust, something that isolines on the marine limit need not.

Figure 2 is an isobase map for eastern North America, showing the amount of relative sea-level change in the last 6,000 years.[1] The map may be converted to one of post-glacial uplift in the last 6,000 years by the addition of the eustatic sea-level 6,000 years ago; that is, by an addition of 8 m (Shepard, 1963). The map was constructed on the following basis: in a recent paper (Andrews, 1968a), I examined post-glacial uplift curves from Arctic Canada and suggested that they are approximated by:

$$Up'_t = A\% \frac{(1-i^t)}{1-i} \qquad t \geqslant 1.0 \times 10^3 \text{ yr} \quad i = 0.6777 \qquad (2)$$

---

[1] This map supersedes a map based on fewer points and for a more restricted area published in Andrews (1968b).

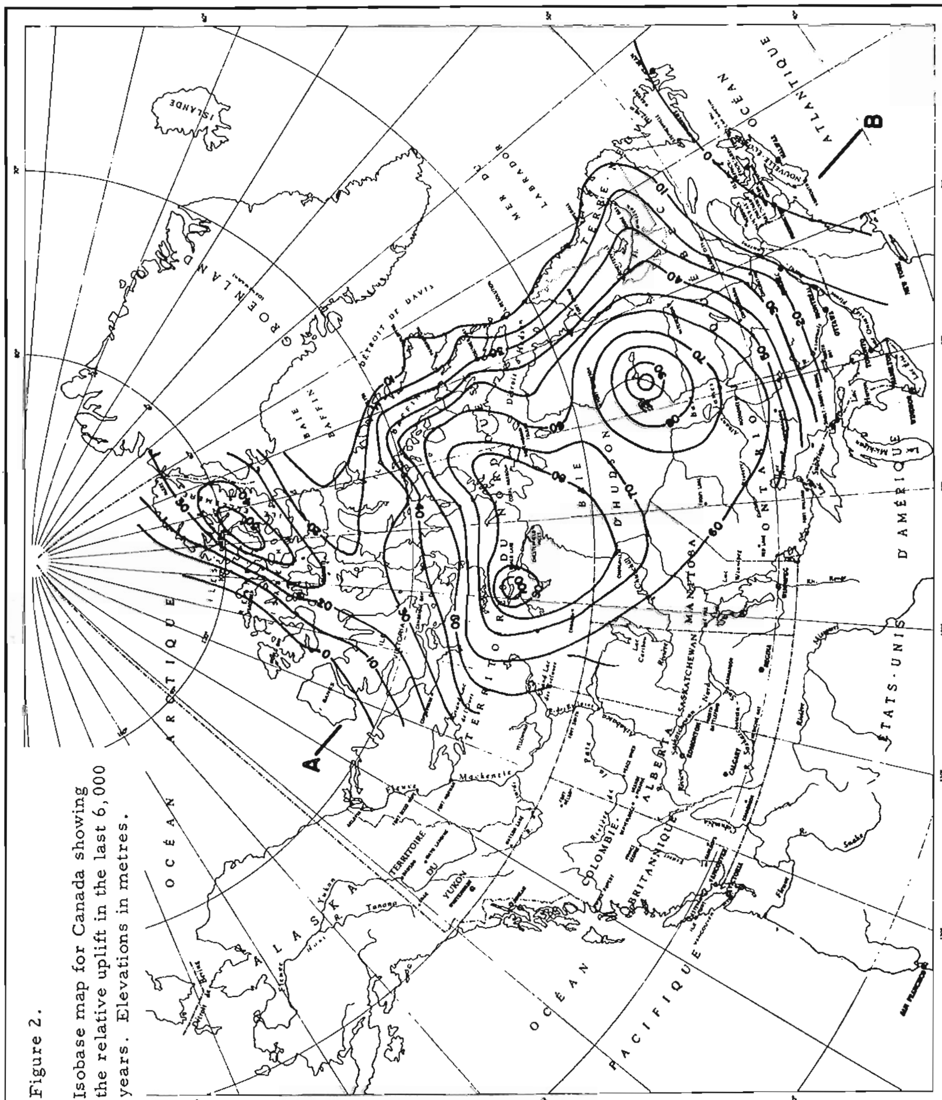


Figure 2.

Isobase map for Canada showing the relative uplift in the last 6,000 years. Elevations in metres.

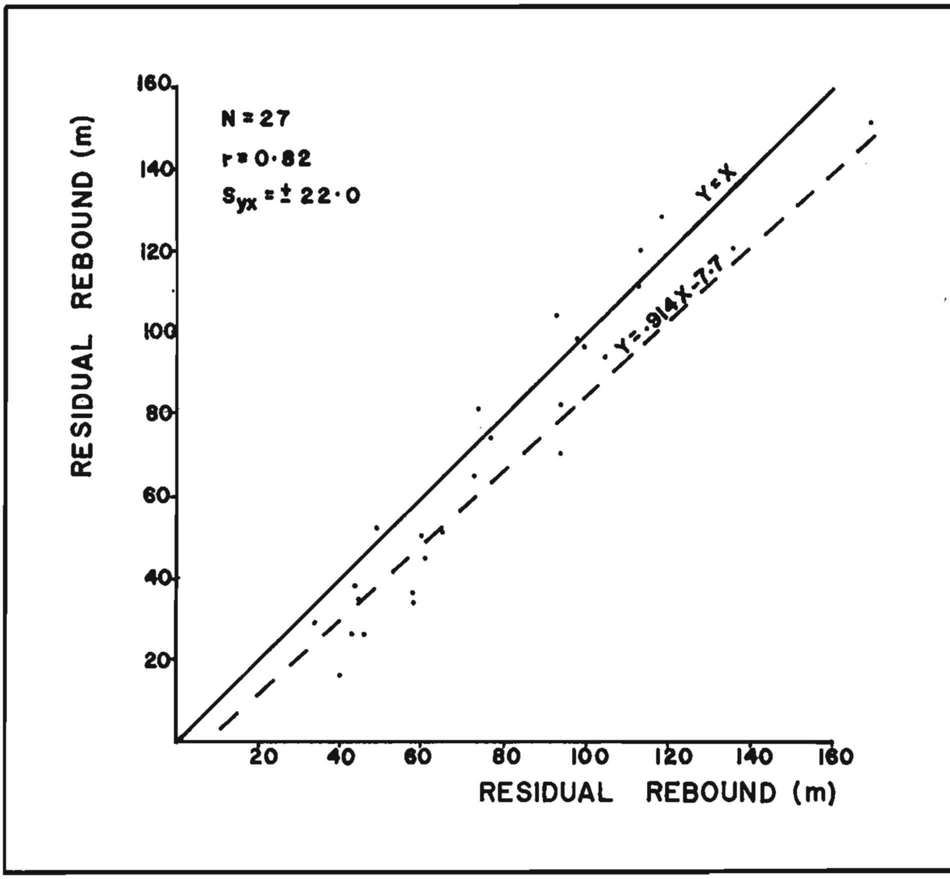


Figure 3. The relationship between the amount of residual rebound calculated from equation (3) (Gutenberg's, 1941 method) on the y axis and from equation (5) (Einarsson's, 1966 method) on the x axis. The theoretical relationship y = x is shown and the computed-least squares solution.

where uplift in time t is Up'_t and A% is the per cent of uplift in the first 1.0×10^3 yr, and is dependent on the length of the post-glacial interval at the site. The form of the post-glacial uplift curve for a 10.0×10^3 yr period of rebound is shown as Figure 3 (Andrews, 1968a). Tables and graphs are also presented to enable post-glacial uplift curves to be predicted ~~if~~ the age and elevation of a marine limit are known. Fifty-eight sites throughout northern North America were selected where the two above conditions were met. Equation (2) was solved to give the amount of land uplift between the date of glaciation and the year 6,000 BP. Subtraction of the 8-m eustatic sea-level correction constituted the final part of the calculations. The sites were then contoured.

Figure 2 may be compared with the map in the National Atlas of Canada. There is a centre of uplift still located over east Hudson Bay, but the small high and low cells of the last map are not present. There is no high centre over Bathurst Inlet; instead the centre of uplift has shifted southeast and occurs over Baker Lake. Another high occurs between Ellesmere and Axel Heiberg Islands. The main basin of Hudson Bay still represents a saddle in the constructed surface. It is now appropriate to question the general belief that Hudson Bay was a glacial dispersal centre; Figure 2 rather indicates that central Hudson Bay was a zone of convergence of ice flow. On the Ottawa Islands the unpublished results of Falconer and myself indicate an early ice movement toward the northeast, followed by an anti-clockwise sequence, moving from north to south of west. This series is explicable in terms of the marine invasion of the bay and a division of the ice sheet into two, possibly through the saddle shown on Figure 2. The map does not contradict a northeast movement of the ice across the islands.

Note that evidence for post-glacial uplift is not available for the central land tracts and it is pertinent to remember that Barnett and Peterson (1964) have proposed a centre of post-glacial uplift in central Labrador-Ungava.

In summary, Figure 2 represents the first isobase map to be drawn on a continental scale for North America. The map departs significantly from a map of isolines on post-glacial uplift.

RESIDUAL REBOUND

Of particular interest to the geophysicist is the amount of residual glacio-isostatic rebound. Innes and Weston (1966) have examined the problem through the use of corrected gravity values. However, this approach poses some difficulties. A complementary analysis is presented in this paper and relies for its solution on the form of the post-glacial uplift curves. Theory suggests that the rate of recovery is a function of the horizontal dimensions of the ice load and mantle viscosity. Examination of post-glacial uplift curves for Arctic Canada indicated that they are proportionally similar and thus in agreement with this principle. Gutenberg (1941) proposed that residual uplift could be estimated from:

$$d_1 = \frac{a v_1^{1/3}}{v_2^{1/3} - v_1^{1/3}} \qquad (3)$$

where d_1 is the future uplift, a is the amount of uplift between t_1 and t_2, and v_1 and v_2 are the respective velocities. Post-glacial uplift curves enable rates of uplift to be obtained either by differentiation or by graphical solution.

For twenty-seven sites where uplift curves were available, equation (3) was solved. Equation (3) provided reasonable results, but its use is limited by the small number of post-glacial uplift curves. A method proposed by Einarsson (1966) was therefore considered and adopted. The initial statement is:

$$V = (Up\text{-}Urr) \quad R/(Up/A) \tag{4}$$

where V is mantle viscosity in arbitrary units, R is radius of the ice cap (km), and A is the length of the post-glacial period (x 10^3 yr). Rearranging to solve for residual rebound (Urr) leads to:

$$Urr = Up - [V/(R/(Up/A))] \tag{5}$$

or that residual rebound is a function of post-glacial uplift (m), and mantle viscosity and inversely proportional to the dimensions of the load and rate of uplift. All variables are obtainable apart from V. To obtain an estimate of the viscosity (in arbitrary units) the following steps were taken: 1) Gutenberg's (1941) equation was used to estimate d_1 i. e., Urr from the Ottawa Islands data (Andrews, 1968a); a figure of 100 m was obtained. 2) With this estimate of Urr and a value for Up of 170 m, equation (4) was solved for various values of A. Equation (4) indicates that the viscosity units increase linearly with an increase in post-glacial time.

At the fifty-eight sites used to determine relative sea-level 6,000 years ago, variables Up and A are known. R is set equal to 1,700 km and V is computed as mentioned above. A simple computer program was written to compute equation (5). It should be clear that the determinations of Urr are directly dependent upon the initial estimate of Urr from the Ottawa Islands. However, there is good agreement between estimates of Urr derived from Gutenberg's method (1941), and those from Einarsson's method (Fig. 3). The least-squares solution is:

$$Y = .914X - 7.7 \tag{6}$$

with a standard error of ±22.0 m. The correlation coefficient, r, equals 0.82, indicating a highly significant correlation between the two methods. The scatter is attributed to errors in constructing and approximating the post-glacial uplift curves.

The fifty-eight values were plotted and contours drawn. Figure 4 is, therefore, a map of the estimated residual rebound (Urr) for northern North America. The surface represents a broad mirror-image of the post-glacial uplift surface. This is notably shown by the location of a low centred over

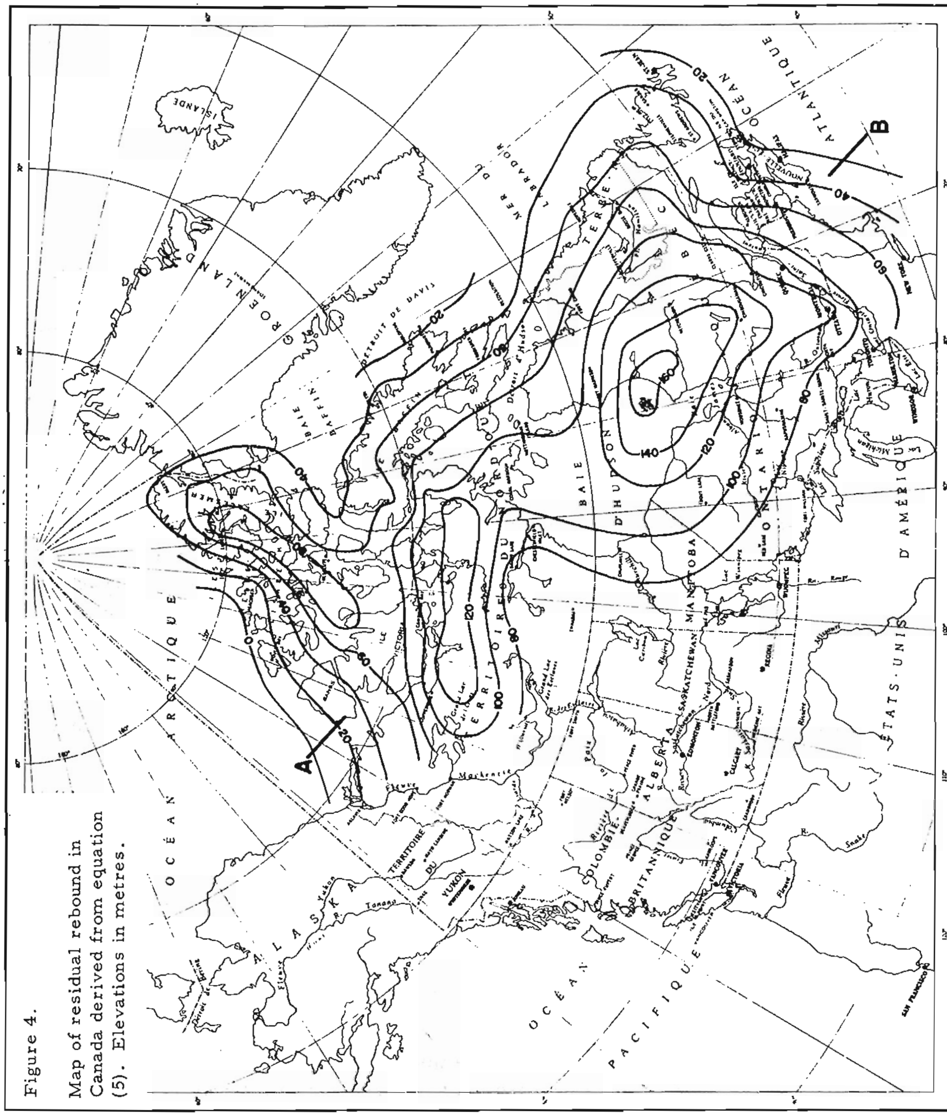


Figure 4.

Map of residual rebound in Canada derived from equation (5). Elevations in metres.

Bathurst Inlet. The map illustrates that the -100 m contour virtually surrounds Hudson Bay. A maximum depression of -160 m is suggested for the eastern shore of the bay.

It is hoped that geophysicists will use Figure 4 as a model on which they may test known gravity data.

RESTRAINED REBOUND

The most difficult variable to estimate in equation (1) is the amount of restrained rebound (Ur), and yet in many ways it is the most important to the glacio-geomorphologist. There is no doubt that a glacio-isostatic rebound proceeds while a site is still ice-covered. The best evidence for this conclusion is the repeated sharp reduction in the elevation of the marine limit between distal and proximal slopes of major late-glacial moraines; differences of a few metres to 100 m are known. The importance of restrained rebound is also well known in the literature where there are frequent references to the effect that 'late ice has led to a low (relatively) marine limit'. It might be argued that areas of low post-glacial uplift might become relatively 'high' through the contribution of residual rebound. However, Figure 4 indicates that is not the case, and the rapid decay of post-glacial uplift curves is added confirmation.

In a recent analysis of the effect of date of deglaciation on the amount of post-glacial rebound (Andrews, 1968b), I examined post-glacial uplift as a function of distance (D) from the former ice margin and date of deglaciation (A) or:

$$Up = f(D, A) \qquad (7)$$

A second degree polynomial with two independent variables was solved for sixty-four sites and was in the form:

$$Up = A_o + A_1D + A_2A + A_3D^2 + A_4DA + A_5A^2 \qquad (8)$$

The multiple coefficient of determination equaled 0.8; thus 80 per cent of the variation in Up is explained by the sums and cross-products of D and A. It was notable that the east Hudson Bay sites had residuals 100 m higher than the expected value. Equation (8) indicated the importance of date of deglaciation (i.e., length of the post-glacial rebound, which is inversely proportional to the length of the restrained rebound) and distance from the former ice edge, a measure of former ice thickness. Sixty-four per cent of the variation of Up is associated with fourth regression coefficient A_4DA.

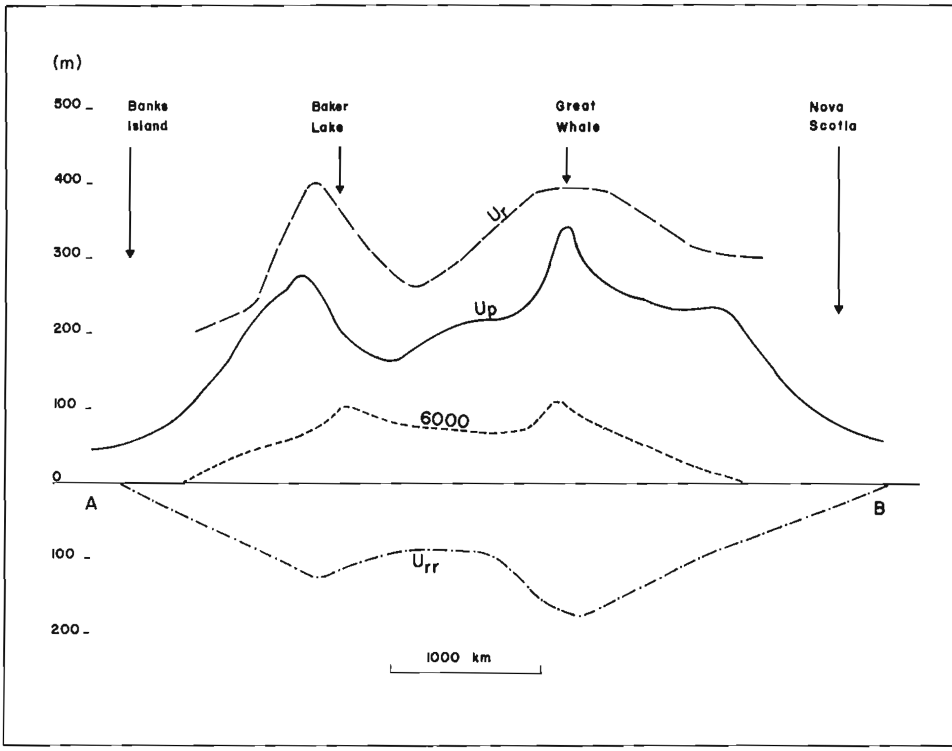


Figure 5. A cross-section from A-B (Fig. 2) showing cross-section through surfaces showing:
a) amount of post-glacial rebound (Up);
b) amount of relative uplift in the last 6,000 years;
c) amount of residual depression (Urr); and
d) the suggested form of restrained rebound (Ur).

No map of restrained rebound can yet be drawn, and indeed all that I can envisage is a map that shows 'trends'. As a temporary measure, I would like to consider the cross-section A-B on Figures 2 and 4. Figure 5 shows cross-sections of Up, Urr and uplift in the last 6,000 years. The figure also includes a possible plot of the amount of restrained rebound. This line was computed from:

$$Ur = S - (Up + Urr) \tag{9}$$

S was calculated on the assumption that ice behaves as a perfect plastic substance and that the elevation of the ice surface is given by:

$$h = CD^{0.5} \tag{10}$$

where C is dependent upon the average shear stress at the base of the ice and D is distance from the ice edge. An average shear stress of 0.8[1] bar was used, and it was further assumed that $S = h/3$. The profile shows the major amount of restrained rebound occurring, as expected, over the Keewatin Ice Divide.

SUMMARY

In this paper, I have presented new data on post-glacial rebound in Arctic Canada, and I have tried to examine the total picture of glacio-isostatic recovery. Nothing in this paper supports the concept of an ice mass centred over Hudson Bay. However, it is well to remember that no islands occur in the centre of the bay, and the isarithmns are drawn on the basis of known information. Hudson Bay apparently represents a zone of convergence between two ice centres located over the Baker Lake area and east Hudson Bay. Maps or profiles of four surfaces have been discussed; these group themselves into:

1) The map of post-glacial uplift (Up) is a mirror image of the map showing the amount of residual uplift (Urr).
2) A true isobase surface for northern North America showing uplift in the last 6,000 years is similar in gross character (i.e. location of peaks, etc.) to the surface of restrained rebound.

Sets 1) and 2) possess some overall similarities but differ in some important respects, notably the shift of the 'high' cell between Bathurst Inlet and the Keewatin Ice Divide. In this volume on Hudson Bay it is appropriate to mention that analysis of amounts of post-glacial uplift indicates that the 300 m figure for east Hudson Bay is approximately 100 m too high (Andrews, 1968b). The reason for this anomaly is not known.

ACKNOWLEDGMENTS

Most of this paper was conceived while I was on the staff of the Geographical Branch, Department of Energy, Mines and Resources. The Geographical Branch provided support to work on the Ottawa Islands, N.W.T. The final compilation and writing was undertaken at the University of Colorado in the Institute of Arctic and Alpine Research. Attendance at the Earth Sciences Symposium on Hudson Bay was made possible by a travel grant from the National Research Council of Canada. Mrs. Lyn Arsenault provided the writer with invaluable research assistance. Dr. V.K. Prest kindly provided information on elevations on the marine limit from the 'Glacial Map of Canada'. (Map 1253A, Geological Survey of Canada.)

---

[1] The decision to use a shear stress of 0.8 bar rather than 1.0 bar or other value is arbitrary. Use of other values will not alter the trend of Ur but will alter the magnitude.

REFERENCES

Andrews, J. T.
1968a: Post-glacial rebound in Arctic Canada: similarity and prediction of uplift curves; Can. J. Earth Sci., vol. 5, pp. 39-47.

1968b: Pattern and cause of variability of post-glacial uplift and rate of uplift in Arctic Canada; J. Geol., vol. 76, pp. 404-425.

Barnett, D. M., and Peterson, J. A.
1964: The significance of Glacial Lake Naskaupi 2 in the deglaciation of Labrador-Ungava; Can. Geograph., vol. 8, pp. 173-181.

Bird, J. B.
1967: The physiography of Arctic Canada; The Johns Hopkins Press, Baltimore.

Einarsson, T.
1966: Late- and post-glacial rise in Iceland and subcrustal viscosity; Jőkull, vol. 111, pp. 157-166.

Farrand, W. G., and Gadja, R. T.
1962: Isobases on the Wisconsin marine limit in Canada; Geograph. Bull. Can., No. 17, pp. 5-22.

Gutenberg, B.
1941: Changes in sea-level, post-glacial uplift and mobility of the earth's interior; Bull. Geol. Soc. Am., vol. 52, pp. 721-772.

Innes, M. J. S., and Weston, A. A.
1966: Crustal uplift of the Canadian Shield and its relation to the gravity field; Ann. Acad. Sci. Fennicae, ser. A, vol. 111, pp. 169-176.

Ives, J. D.
1963: Determination of the marine limit in eastern Arctic Canada; Geograph. Bull. Can., No. 19, pp. 117-122.

King, P. B.
1965: Tectonics of Quaternary Time in middle North America; in The Quaternary of the United States, edited by H. E. Wright, Jr. and D. G. Frey, Princeton, pp. 831-870.

Kupsch, W. O.
1967: Post-glacial uplift: a review; in Life, land and water, edited by W. J. Mayer-Oakes, University of Manitoba Press, pp. 155-186.

Shepard, F. P.
1963: Thirty-five thousand years of sea level; in Essays in Marine Geology, in honour of K. O. Emery, University of Southern California, Los Angeles, pp. 1-10.

Tanner, W. F.
1965: Cause and development of an ice age; J. Geol., vol. 73, pp. 413-440.

LATE-GLACIAL AND POSTGLACIAL HISTORY OF THE HUDSON BAY REGION

B. G. Craig
Geological Survey of Canada, Ottawa

Abstract

Retreat of the main Wisconsin ice sheet began in northern Canada some 13,000 or more years ago, although ice probably remained in the Hudson Bay area until about 7,000 years ago. The stratigraphic succession of deposits, variations in the pattern of ice-flow features and their relation to the maximum elevation and extent of the marine invasion, and radiocarbon age of organic remains allow a rough chronology of the sequence of events to be established.

Around the south and southwest periphery of Hudson Bay and James Bay the ice margin retreated into an area presently covered by the sea; on the east and west sides it retreated away from the area of the bay. Following deglaciation the region was invaded by the Tyrrell Sea, although in the James Bay area and the Hayes River-Nelson River-Churchill River area a lacustrine episode preceded the marine invasion. The elevation of the upper limit of marine features varies throughout the area and can be related to the pattern of ice retreat.

The oldest recorded radiocarbon dates on marine shells give an approximation of the time of deglaciation of various parts of the area. It appears that the Hudson Bay region first became invaded by the sea through Hudson Strait a little over 8,000 years ago. At about the same time, or slightly later, the area south of James Bay became ice free and inundated by marine water. Few significant dates are available from the east side of Hudson Bay, but along the west side of the bay, dates approximating the time of the invasion become progressively younger to the northwest, i.e. 7,600 years ago in the Hayes River area, 7,300 years ago in the Churchill area and 7,000 years ago in the east central part of Keewatin.

Radiocarbon dates on marine shells from shoreline deposits in the Churchill area indicate that for the period 3,000 to 1,000 years ago the land was rising at a rate of about 5 feet per century.

This report is based largely on information collected by the author and B.C. McDonald in 1967 on the Geological Survey of Canada helicopter supported "Operation Winisk", which involved a geological study of the bedrock and Quaternary geology of the Hudson Bay Lowland. Earlier published and unpublished data collected by the author and by other workers have been incorporated to provide a framework for an interpretation of the late Quaternary history of the whole of the Hudson Bay region.

This interpretation is based on several lines of evidence. (1) Throughout most of the area glacial landforms indicate the direction of ice-flow. For the most part such features were formed in the marginal zone of the ice sheet during retreat and hence record the trends of successive ice movements near the margin during deglaciation. (2) The processes active during the period resulted in a stratigraphic succession of deposits that indicate various environments of deposition. (3) The maximum elevation of the marine inundation and variations in it may give an insight into the relative time of deglaciation in some areas. (4) In areas inundated by the sea following deglaciation, remains of marine organisms and their associations give further evidence of environment and by means of Carbon 14 age determination allow a chronology of certain events to be established.

The last Wisconsin Laurentide ice sheet began to retreat in northern Canada some 13,000 or more years ago; final disappearance of the ice in the Hudson Bay region took place about 7,000 years ago. The last vestiges of the continental ice mass appear to have persisted slightly longer in Foxe Basin, north of the area being discussed here.

Figure 1 shows the generalized direction of marginal flow as recorded by various glacial landforms around the periphery of Hudson Bay. The arrows, identified by letters, depict zones or parts of the ice sheet that behaved as entities that had a continuing regularity in their retreat, and that in a gross way are chronologically distinct.

The last well-documented readvance of the retreating ice sheet that is significant for this discussion, the Cochrane advance, is best recorded south of the area shown in Figure 1. Within this region there is no geomorphic evidence of stillstands or readvances.

The James Bay Lowland was the first part of this area to become ice free (Zone A). There, a lacustrine episode succeeded the ice retreat and was subsequently followed by a marine episode. A section exposed in the Adams Creek diversion channel, near Smoky Falls, 100 miles southwest of Moosonee, shows a sequence of till, diamicton, varves, and marine clay. Elsewhere in the James Bay area similar sequences have been observed.

In order for the marine waters to have invaded this area the sea must have spread southward from Hudson Strait. Earlier workers have suggested a marine connection between James Bay and the St. Lawrence either through Lake Timiskaming or through Lake St. John (La Rocque, 1949; Potter, 1932). Both of these routes must be rejected as impossible because of the elevation of the divides, in the order of 1,000 and 1,500 feet respectively, between the St. Lawrence and James Bay drainage. The location of the initial waterway south from Hudson Strait is uncertain. Lee (1968) has suggested that for the southern part of Hudson Bay and James Bay the waterway was along the east side and that the first part of the present land area to be covered with marine waters was east of James Bay.

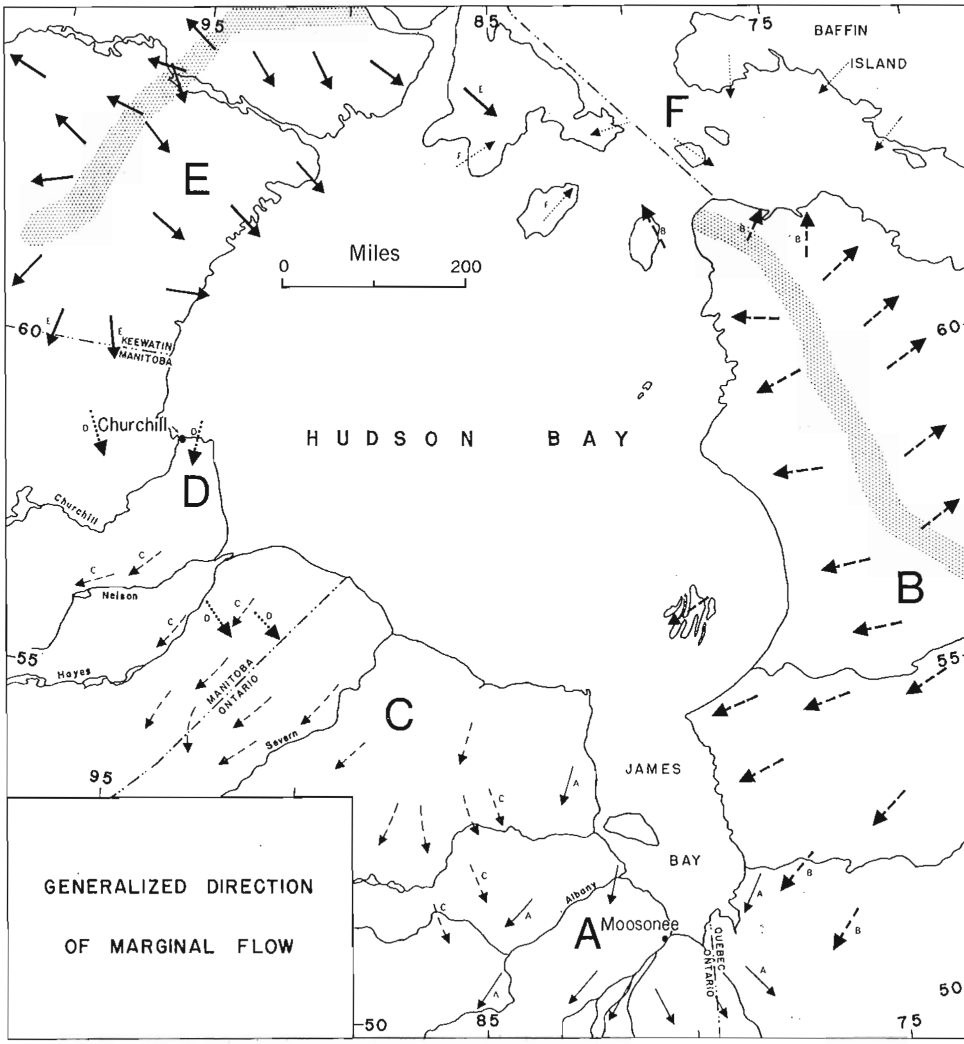


Figure 1. Generalized direction of marginal flow. Letters depict zones of the ice sheet that had a continuing regularity in their retreat; dotted pattern outlines areas of last remnant ice west (Keewatin ice divide) and east of Hudson Bay.

In Quebec the pattern of retreat as shown by various ice-flow features appears straightforward, as shown by the arrows in zone B; a regular shrinking back, more or less at right angles to the present shore, culminated in a zone of remnant ice, shown as a dotted pattern, from which flow was both to the east and west before final disappearance of the ice.

A far more complicated pattern developed in the western part of the region. West of the James Bay Lowland in a zone extending northwest as far as Nelson River ice retreat was toward an area presently covered by the sea (Zone C). At that time western Hudson Bay was still ice-covered although C14 dates suggest that then James Bay was open to the sea. Marine water was prevented from inundating the area of southeasterly flow by the presence of glacial ice, although the land elevation is lower than the marine limit to the east.

Although ice retreat in northern Ontario and Manitoba south of the area shown in Figure 1 was exceedingly complex, the pattern developed across the Hudson Bay Lowland appears to indicate a regular northward and northwestward retreat towards the ice mass in western Hudson Bay. There is no stratigraphic evidence of a lacustrine or subaerial episode following deglaciation in this area, hence the sea probably was in contact with the retreating ice margin.

At the northwest end of zone C a re-entrant developed in the margin in the Nelson-Hayes River area, probably in part by formation of a calving bay by water of Lake Agassiz. The presence of a lake is indicated by the occurrence of post-till – pre-marine clay, lacustrine sediments extending as far northwest as South Knife River.

As northward retreat proceeded (Zone D) the re-entrant was enlarged and eventually marine inundation occurred, probably from the southeast.

Finally, only a remnant of the continental ice sheet remained along the west side of Hudson Bay. Ice-flow features show a radial pattern around this mass marking successive marginal positions, as shown by the arrows in Zone E. The last ice lay along a narrow zone parallel to the present coast of Hudson Bay and some 150 miles inland, the Keewatin ice divide, shown as a dotted pattern on Figure 1.

On Baffin and Southampton islands, and on some of the smaller islands in northeastern Hudson Bay and the west end of Hudson Strait, the directional arrows are designated F. In that area the relationships of various directions are obscure, and are not pertinent to this discussion.

The maximum elevations attained by the Tyrrell Sea (Fig. 2) appear to be quite variable but can be related to the pattern of deglaciation already described. Discussion of the east side of the bay in this regard is omitted, partly because of the lack of field data from that area, and partly because interpretation of the features seen there is still questionable.

In the James Bay Lowland there is an increase in the elevation of the marine limit from just over 400 feet to 625 feet in a northeastward

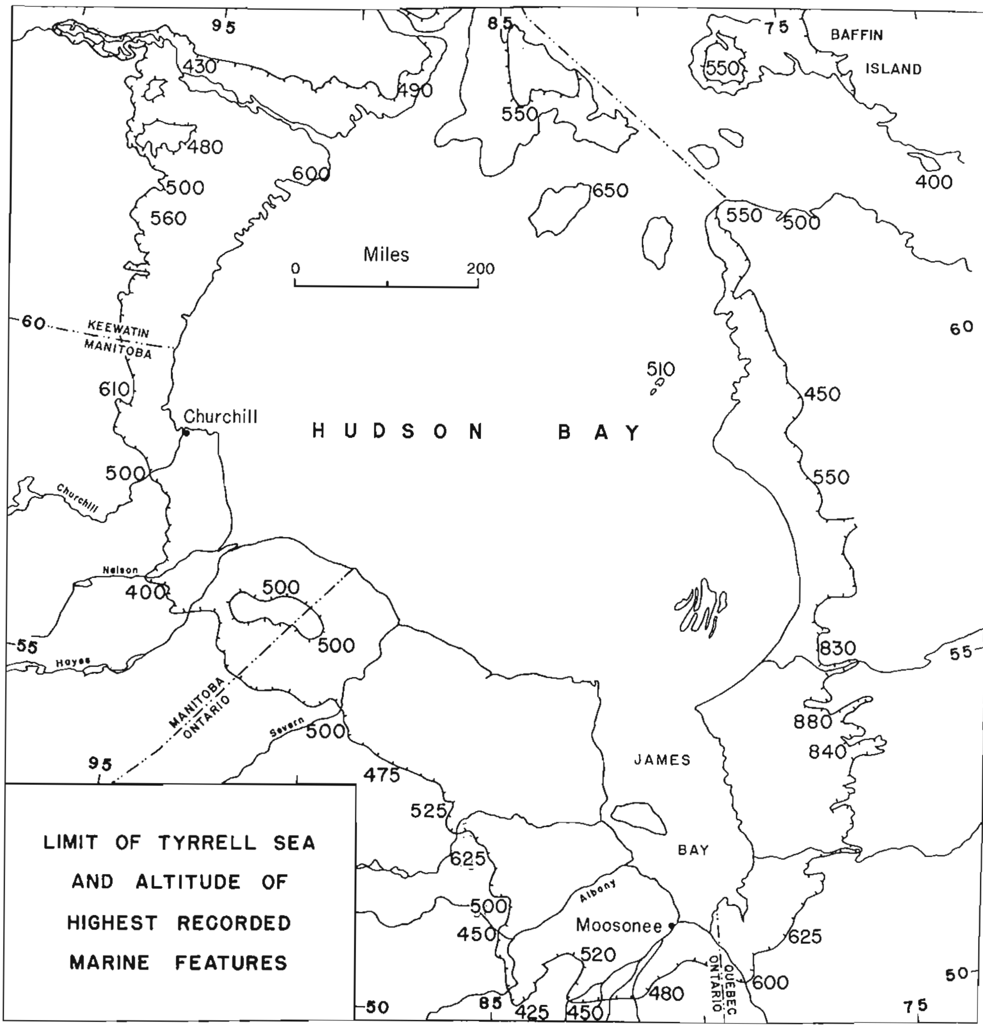


Figure 2. Limit of Tyrrell Sea (hachured line) and altitude (in feet) of highest recorded marine features.

direction in the region designated A (Fig. 1). In most of this area, as already pointed out, a lacustrine episode followed deglaciation so that the area was virtually ice-free by the time the marine connection to the north was established. Therefore, rather than a gradual inundation such as took place in areas where marine water was in contact with the retreating ice margin, the sea covered the whole of the James Bay Lowland in a very short interval. The high marine features whose elevations these figures represent were formed more or less contemporaneously. The northeastward increase in elevation indicates that the amount of isostatic rebound following the marine invasion was greater towards the northeast. It is a matter of conjecture as to whether the high marine limits along the east side of James Bay bear any relation to this model.

Northwest from the James Bay Lowland the marine limit drops from a maximum of 625 feet in zone A to about 500 feet in zone C and is more or less at this elevation across the zone as far as Hayes River. Ice remained in that area long enough after the James Bay Lowland was inundated for about 100 feet of uplift to take place. Then, after the margin had retreated beyond what is now the 500-foot level the area became inundated from the southeast.

In the Nelson River area the marine limit elevation is about 100 feet lower than to the southeast, suggesting that the sea was prevented from inundating this area for the interval required for that amount of uplift to take place. Northwest from Nelson River to just north of Churchill River a pre-marine lacustrine episode indicates that much of the zone was deglaciated before the marine invasion took place. These elevations were determined on a series of marine limit shoreline features that appear to be contemporaneous and increase in elevation from 400 feet to about 500 feet. Inundation was rapid and the differences in elevation of the marine limit are due to differential isostatic readjustment, not to differences in the time of deglaciation.

In the northwest part of the Hudson Bay region, in the area extending outward from the Keewatin ice divide, the marine transgression followed the retreating ice margin. The westward and northwestward decrease in elevation of the marine limit from 600 feet to slightly more than 400 feet is a reflection of the time of ice retreat.

Because the sea followed immediately or relatively soon after deglaciation in much of the region, radiocarbon dates (Table I) on marine shells deposited close to the limit of the marine invasion permit a rough chronology to be established for the time of deglaciation of the various areas outlined. The first problem to be considered is the time of entry of the sea into Hudson Bay.

At Sugluk near the northwest tip of Quebec, Matthews (1967) collected shells that are 7,970 $\pm$ 250 C14 years old (Fig. 3, loc. 1) and, although collected at an elevation of 324 feet, represent a sea level elevation of 460 feet. At the same locality he determined the marine limit to be 500 feet above sea level. Therefore, the time of deglaciation and submersion by the sea is the age determined for the shells plus the time required for isostatic readjustment in the order of 40 feet to take place. Estimates for the rate of isostatic readjustment about 7,000 years ago by Matthews for this area, by Lee (1964) for southern Hudson Bay and from data presented by Andrews (in Andrews and Drapier, 1967, pp. 156-157) from the Ottawa Islands average about 22.5 feet per century. Assuming a figure of 20 feet per century, a drop in sea level of 40 feet at that time would have required

Table I

Early Postglacial Radiocarbon Dates on Marine Shells

Locality No. (see Fig. 3)	Approx. alt. of sample ft. a.s.l.	Collector and/or reference	Laboratory Dating No.[1]	Age (radiocarbon years B.P.)
1	324	Matthews, 1967	GSC-672	7,970 ± 250
2	245	Blake, 1966	GSC-425	7,980 ± 220
3	190	Wagner, 1967	GX1068	7,170 ± 90
4	300	Wagner, 1967	GX1070	7,115 ± 100
5	400	Terasmae and Hughes, 1960; Hughes, 1965	I(GSC)-14	7,875 ± 200
6	345	Craig (unpubl.)	GSC-897	7,760 ± 160
7	400	Craig (unpubl.)	GSC-880	7,720 ± 140
8	178	Archer (Lowdon, Fyles, and Blake, 1967)	GSC-595	6,420 ± 240
9	460	Andrews and Drapier, 1967	GSC-706	7,430 ± 180
10	450	Craig (unpubl.)	GSC-877	7,400 ± 140
11	375	Craig (unpubl.)	GSC-878	7,570 ± 140
12	465	Dyck and Fyles, 1964	GSC- 92	7,270 ± 120
13	210	Lee, 1959	I(GSC)-8	6,975 ± 250
14	415	Craig, 1965	GSC-289	6,830 ± 170
15	360	Dyck, et al., 1966	I-1224	6,015 ± 150

[1] In addition to the Geological Survey of Canada (GSC), the abbreviations used here refer to the following laboratories: GX - Geochron Laboratories, Inc.; I and I(GSC) - Isotopes, Inc.

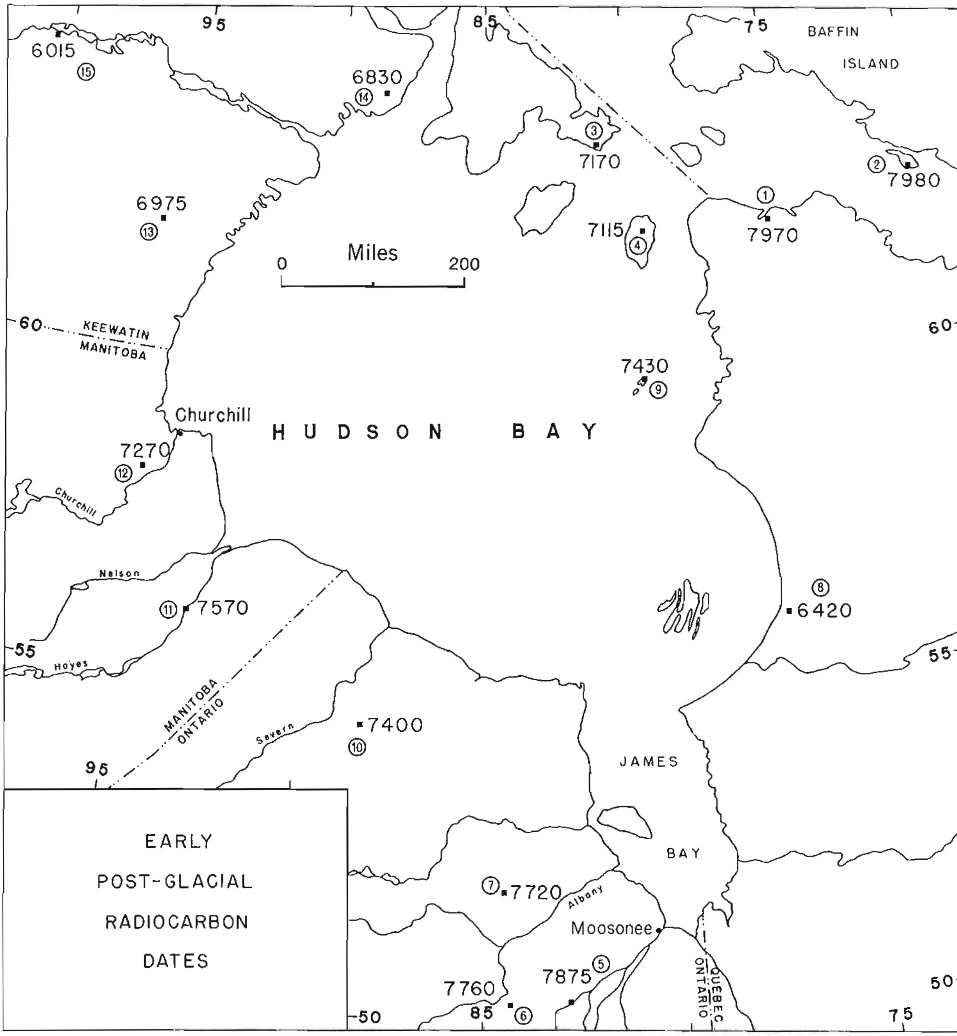


Figure 3. Early postglacial radiocarbon dates (C14 years B.P.) on marine shells. Numbers refer to localities in Table I.

200 years, fixing the time of entry of the sea at Sugluk at about 8,000 C14 years B.P. If the eustatic sea level rise at this time is accepted at about 3 feet per century (see Washburn, 1956, p. 32) it would have no significant effect on these figures.

Slightly to the east on Big Island (loc. 2), Blake (1966) collected shells 120 feet below the marine limit that are dated at 7,980 ± 220 years.

About these he states (p. 13) "There is a good possibility that shells nearer the marine limit could be more than 8, 000 years old".

Similarly, dates of 7, 170 ± 90 from Southamptin Island (loc. 3) and 7, 115 ± 100 from Mansel Island (loc. 4) have been determined from samples collected by Wagner (1967) which are below the local marine limit. There, also, shells from nearer the marine limit could well date over 8, 000 years.

On the basis of these figures it appears that Hudson Strait and at least the northeast part of Hudson Bay was ice free and open to the sea over 8, 000 years ago.

In the James Bay Lowland radiocarbon ages of three marine shell samples (locs. 5-7) range from 7, 700 to nearly 7, 900 years. Again, probably a few years should be added to these figures to allow for the time that elapsed between the initial incursion of the sea and deposition of the shells, and for sea level to drop from the marine limit which is about 50 feet higher than the elevation at which the oldest shells were collected. Hughes (1965, p. 563) estimated at least 8, 275 years ago as a minimum time for the end of the Cochrane advance so it is not unreasonable to assume that the sea penetrated south of James Bay about 7, 900 years ago.

There are no radiocarbon dates available on the mainland east of Hudson Bay to indicate when that area became ice-free. A date of 6, 420 ± 240 years from a low-level collection (loc. 8) by Archer (in Lowdon, et al., 1967, p. 179) near Richmond Gulf provides a minimum data but deglaciation probably took place much earlier. Andrews (in Andrews and Drapier, 1967, p. 157) suggests the date of 7, 430 ± 180 years ago as the time of deglaciation of Gilmour Island (loc. 9). This date suggests that a seaway existed between Hudson Strait and James Bay while ice still extended westward beyond the present shore of the bay.

There are two significant problems related to radiocarbon dating of events between the south end of James Bay and the northwest corner of Hudson Bay. First, the margin of statistical error in the dates themselves, in the order of plus or minus 150 to 200 years, is in the same order of magnitude as the apparent differences in age of samples from one zone to the next. Nevertheless, there is a real difference in the ages of samples collected from the north and south ends of the area along the west side of the bay.

Secondly, in the Hudson Bay Lowland marine shells have been found that were deposited before the last marine episode. They have been found at the localities shown in Figure 4 and are probably more widespread. They occur in sub-till marine deposits and stream gravels, and in the tills. As they are the same species as the Tyrrell Sea fauna they present a problem of contamination. Two dates from the lowland may be derived from contaminated collections.

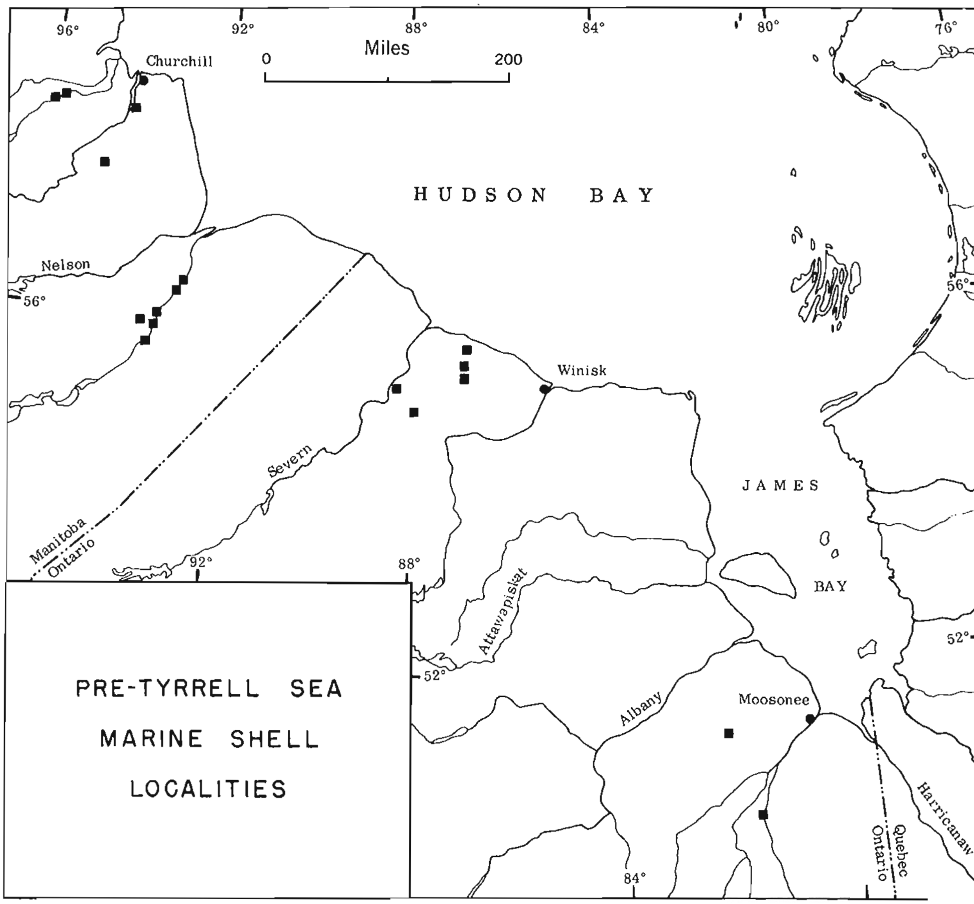


Figure 4. Pre-Tyrrell Sea marine shell localities.

Along the south side of Hudson Bay two dates of 7,400 ± 140 and 7,570 ± 140 years (locs. 10 and 11) indicate that that area was ice covered probably 200 or 300 years longer than the James Bay Lowland. Between these two localities a small collection composed almost entirely of shell fragments gave an age of 8,530 ± 220 years. On the basis of the dates from the other nearby localities and the postglacial history of the whole Hudson Bay region it seems likely that this sample is contaminated.

In the Churchill area, it appears that marine invasion took place about 7,300 years ago and that the main part of Hudson Bay except for a zone along the present coast was ice free by that time. In that area also a date was obtained on a sample which the author believes to be contaminated by older shells. Not far from the locality where shells were dated 7,270 ± 120

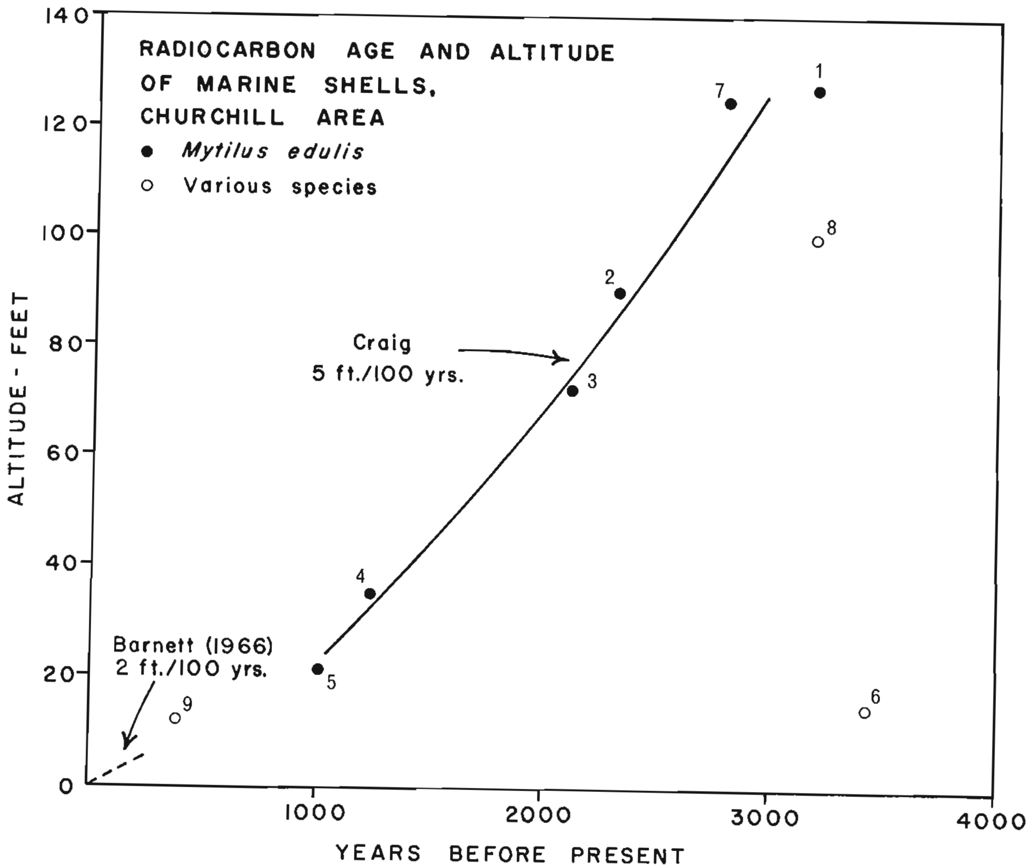


Figure 5. Radiocarbon age and altitude of marine shells, Churchill area. Numbers refer to localities in Table II.

years (loc. 12) another collection was dated at 8,010 ± 95 years (Wagner, 1967). Such an age for postglacial marine shells is not compatible with the history being presented here.

In the District of Keewatin (loc. 13) a date of 6,975 ± 250 years (Lee, 1959, p. 25) indicates the approximate time that the last remnant ice lay along the Keewatin ice divide.

The date of 6,830 ± 170 years (Craig, 1965, p. 6) west of Southampton Island (loc. 14) appears to be correlative with a series of dates around Foxe Basin and indicates the time of marine invasion of that area, slightly later than that of the Hudson Bay region.

The date of 6,015 ± 150 years (Dyck, et al., 1966, pp. 118-119) from Beverly Lake (loc. 15), although derived from a sample collected well below the marine limit, gives a minimum time for the sea to have breached

Table II

Radiocarbon Dates on Marine Shells, Churchill Area

Locality No. (see Fig. 5)	Approx. alt. of sample ft. a.s.l.	Species	Collector and/or reference	Laboratory Dating No.[1]	Age (radiocarbon years B.P.)
1	124	Mytilus edulis	Craig (unpubl.)	GSC-685	3,180 ± 140
2	90	Mytilus edulis	Craig (unpubl.)	GSC-683	2,370 ± 130
3	72	Mytilus edulis	Craig (unpubl.)	GSC-723	2,120 ± 130
4	35	Mytilus edulis	Craig (unpubl.)	GSC-682	1,240 ± 130
5	21	Mytilus edulis	Craig (unpubl.)	GSC-684	1,020 ± 140
6	15	various[2]	Craig (unpubl.)	GSC-735	3,430 ± 140
7	125	Mytilus edulis	Wagner, 1967	GX1065	2,800 ± 110
8	100	various[3]	Wagner, 1967	GX1072	3,190 ± 80
9	12	various[4]	Wagner, 1967	GX1073	385 ± 80

[1] In addition to the Geological Survey of Canada (GSC), the abbreviations used here refer to the following laboratory: GX-Geochron Laboratories, Inc.

[2] Mytilus edulis, Chlamys islandicus, Astarte banksii, Clinocardium ciliatum, Hiatella arctica, Mya sp., Hemithyris psittacea, Balanus sp.

[3] Mytilus edulis, Macoma balthica, Hiatella arctica.

[4] Mytilus edulis, Macoma balthica, Hiatella arctica, Astarte sp.

the Keewatin ice divide and for virtual disappearance of ice from the mainland west of Hudson Bay.

Uplift curves relating postglacial sea level elevation to time in this area all show a rapid drop in relative sea level for about 6, 000 years and a slow drop from 6, 000 years ago until the present, although they vary slightly depending on the area studied.

In the Churchill area data have been obtained (Table II) that relate to the lower part of such a curve, from 3, 000 years ago until the present (Fig. 5). The six solid circles represent collections of Mytilus edulis, the common blue mussel. This animal is most common in the intertidal zone and probably gives a more accurate estimate of sea level elevation at the time of its death than other species which live in a wide range of water depths. Furthermore, collections from localities 1 to 5 were made from beach deposits. The open circle in the lower right corner demonstrates the uncertainty of determining contemporary sea level from a mixed assemblage The collection which provided this date was composed of shells of several of the common species of pelecypods found in the Tyrrell Sea deposits, and the enclosing material was representative of a sea bottom, not a strandline environment. The other two circles (locs. 8 and 9) are dates from samples containing various species and are not considered as reliable as dates derived from samples composed entirely of mussel shells.

The solid circles fall closely along a line with a slope that indicates that for the period 3, 000 to 1, 000 years ago relative sea level was falling at the rate of approximately 5 feet per century.

Barnett (1966) has determined from tide gauge records at Churchill for the period 1940-1964 that uplift is still taking place at a rate in the order of 2 feet per century. An extension of this line is shown in the lower left corner of the figure.

REFERENCES

Andrews, J.T., and Drapier, L.
1967: Radiocarbon dates obtained through Geographical Branch field observations; Geog. Bull. vol. 9, no. 2, pp. 115-162.

Barnett, D.M.
1966: A re-examination and re-interpretation of tide gauge data for Churchill, Manitoba; Can. J. Earth Sci., vol. 3, no. 1, pp.77-88.

Blake, W., Jr.
1966: End moraines and deglaciation chronology in northern Canada with special reference to southern Baffin Island; Geol. Surv. Can., Paper 66-26.

Craig, B.G.
1965: Notes on moraines and radiocarbon dates in northwest Baffin Island, Melville Peninsula, and northeast District of Keewatin; Geol. Surv. Can., Paper 65-20.

Dyck, W., Lowdon, J.A., Fyles, J.G., and Blake, W., Jr.
1966: Geological Survey of Canada radiocarbon dates V; Radiocarbon, vol. 8, pp. 96-127.

Hughes, O.L.
1965: Surficial geology of part of the Cochrane District, Ontario, Canada; Geol. Soc. Am., Sp. Paper 84, pp. 535-565.

LaRocque, A.
1949: Post-Pleistocene connection between James Bay and the Gulf of St. Lawrence; Bull. Geol. Soc. Am., vol. 60, no. 2, pp. 363-380.

Lee, H.A.
1959: Surficial geology of southern District of Keewatin and the Keewatin ice divide, Northwest Territories; Geol. Surv. Can., Bull. 51.

1964: Method of deglaciation, age of submergence, and rate of uplift west of Hudson Bay, Canada; Biul. Peryglacjalnv, no. 11, pp. 239-245.

1968: Quaternary geology, in Science, History and Hudson Bay, vol. 2, Chap. 9, pt. 1; C.S. Beals, (ed.), Queen's Printer, Ottawa. pp. 503-543.

Lowdon, J.A., Fyles, J.G., and Blake, W., Jr.
1967: Geological Survey of Canada radiocarbon dates VI; Radiocarbon, vol. 9, pp. 156-197.

Matthews, Barry
1967: Late Quaternary land emergence in northern Ungava; Arctic, vol. 20, no. 3, pp. 176-202.

Potter, David
1932: Botanical evidence for a post-Pleistocene marine connection between Hudson Bay and the St. Lawrence Basin; Rhodora, vol. 34, pp. 68-69, 101-112.

Terasmae, J., and Hughes, O.L.
1960: Glacial retreat in the North Bay area, Ontario; Science, vol. 131, no. 3411, pp. 1444-1446.

Wagner, F.J.E.
1967: Additional radiocarbon dates, Tyrrell Sea area; Maritime Sediments, vol. 3, no. 4, pp. 100-104.

Washburn, A.L.
1965: Geomorphic and vegetational studies in the Mesters Vig district, northeast Greenland; Medd. om Grønland, bd. 166, nr. 1.

GLACIAL AND INTERGLACIAL STRATIGRAPHY, HUDSON BAY LOWLAND

Barrie C. McDonald
Geological Survey of Canada
Ottawa, Ontario

Abstract

Sub-till non-glacial sediments include marine strata, peat, and stream deposits and are widespread in the Hudson Bay Lowland. They are considered to be interglacial partly because (a) they are underlain and overlain by till; (b) they include marine strata, thereby requiring that Hudson Bay and Hudson Strait be at least partly glacier-free; and (c) subaerial environments at low altitudes and streams which flowed northward at low altitudes both require that Hudson Bay and Hudson Strait be glacier-free. The presence of interglacial marine strata in the Lowland, and of marine-shell fragments in tills west of 86° W longitude, indicate that Hudson Bay was a depression occupied by the sea at least as early as Sangamon time. Associated peats from six different localities are all beyond the range of radiocarbon dating.

Glacial events post-dating the interglacial are recorded throughout the Hudson Bay Lowland by two tills that are locally separated by proglacial-lake sand and silt. In the southeastern and northwestern parts of the Lowland sand and silt, apparently of fresh-water origin, overlie the upper till but underlie sediments of the Tyrrell Sea. These may represent the northern extensions of glacial lakes Barlow-Ojibway and Agassiz, respectively. The northwestern lake may have drained eastward to the sea near the present Fawn River shortly after 7,400 C^{14} – years B.P. In the central part of the Lowland evidence of a post-glacial lake phase is absent, and locally it appears that the Tyrrell Sea was in contact with the receding glacier.

INTRODUCTION

A study of Quaternary stratigraphy exposed in river sections in the Hudson Bay Lowland[1] was made in 1967 and has provided many new data pertinent to the glacial and interglacial history of the region. This 3 1/2-month field reconnaissance study was a part of the helicopter-supported Operation Winisk under the direction of Dr. A. W. Norris. Glacial sediments were sampled locally and buried organic zones were sampled in detail for future palynologic examination.

[1] Hudson Bay Lowland is used here as defined by Bostock (1964).

The Lowland, approximately 800 miles long and 150 miles wide, is an area of very low relief with an average seaward gradient of 3 feet per mile. Tyrrell (1916, p. 8) called this area the 'Archudsonian Swamp' and described it thus:

> "... a vast level plain extends to the limit of vision. This plain, which reaches to the shore of Hudson Bay, and has an area of something like 100,000 square miles, is one continuous swamp covered with a thick water-soaked blanket of bog mosses with their usual association of northern swamp-loving plants."

The general blanket of peat and marine clay, in addition to very poor surface drainage, has restricted exposure of glacial sediments to river valleys. River-bank sections, however, are abundant and are commonly as high as 100 feet; they expose a fairly consistent Quaternary stratigraphy throughout the Lowland.

Few generalizations can be made regarding average drift thicknesses in the region. In a detailed study at Onakawana, Dyer and Crozier (1933, p. 68) shows drift thickness varying as much as 75 feet in 1/4 mile. The average thickness of unconsolidated sediment in the Lowland may be in excess of 40 feet; a probably abnormal thickness of 700 feet has been reported from between the Mattagami and Missinaibi Rivers (Hogg, Satterly, and Wilson, 1953).

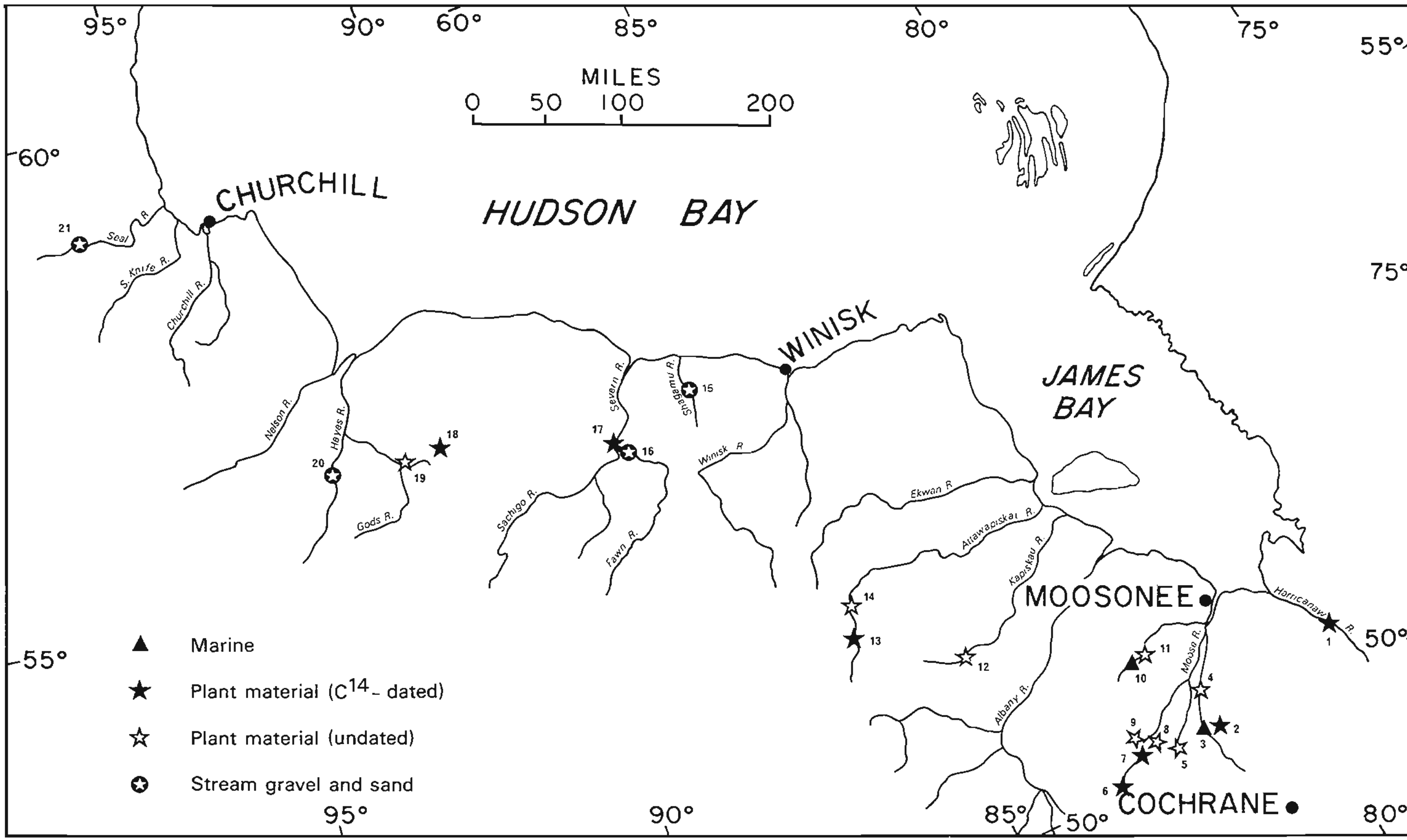
In addition to the writer's observations, Quaternary sections were described by Dr. B.G. Craig and by H. Gwyn, to both of whom the writer is also grateful for much stimulating discussion.

INTERGLACIAL GEOLOGY

Existence of non-glacial plant-bearing sediments beneath till in the Lowland has long been known, especially in the Moose River Basin[1] south of James Bay, but controversy has surrounded interpretations of the age and significance of these sediments. The existence in this area of Cretaceous lignites made suspect earlier assignments of this peat to the Pleistocene. Terasmae (1958) and Terasmae and Hughes (1960) reviewed the problem, established the Quaternary age of many of these sediments, and indicated the existence of the Missinaibi interval - a Pleistocene non-glacial phase accompanied by peat deposition along the Missinaibi and Opasatika Rivers.

---

[1] Throughout this discussion 'Moose River Basin' refers to the present drainage basin rather than to the Paleozoic sedimentary basin.



GSC

Figure 1. Hudson Bay Lowland, showing general areas where interglacial sediments are exposed.

Locality Key to Figure 1

Site No.	Location	Reference (s)
1	Harricanaw R.	Stuiver, M., et al., 1963
2	Little Abitibi R.	Lowdon et al., 1967
3	Abitibi R.	Prest, 1966
4	Onakawana	Dyer and Crozier, 1933
5	Mattagami R.	Montgomery and Watson, 1929; this report
6	Missinaibi R.	Terasmae and Hughes, 1960 (see their report for other sources)
7	Missinaibi R.	Terasmae and Hughes, 1960
8	Opasatika R.	Terasmae and Hughes, 1960
9	Soweska R.	Bell, 1904; McLearn, 1927; this report
10	Kwataboahegan R.	Bell, 1904; Wilson, 1906; this report
11	Kwataboahegan R.	this report
12	Kapiskau R.	this report
13	Attawapiskat R.	Prest, 1963; this report
14	Attawapiskat R.	this report
15	Shagamu R.	this report
16	Fawn R.	this report
17	Severn R.	Tyrrell, 1913; this report
18	unnamed tributaries	this report
19	to Echoing R.	this report
20	Hayes R.	Tyrrell, 1913; this report
21	Seal R.	Taylor, 1961

Distribution

Several new areas in which sub-till non-glacial sediments occur were discovered in 1967. Figure 1 shows twenty-one general areas where these materials are exposed in the Lowland (see key to numbered sites, below). Not all of these localities were visited during 1967. A single symbol on Figure 1 may represent as many as half a dozen separate good exposures. In several localities, these sediments were seen to rest on till, thus indicating their Pleistocene age. Locations shown on this map reflect in part the rivers which have been traversed. Many more localities remain undiscovered. The concentration of sites in the Moose River Basin is considered to be more apparent than real; because of the economic interest in the area, much more work has been done here than elsewhere in the Lowland. Omitted from Figure 1 are several sites which have been reported in the literature but for which either the exact location was not given or the details reported permit only uncertain stratigraphic assignment. Most of these omitted localities are in the Moose River Basin where the Cretaceous-lignite problem exists, but where there are a sufficient number of well documented Quaternary sites to indicate the widespread evidence in this basin for a major non-glacial Quaternary event. Detailed presentation of these sites is given by Terasmae and Hughes (1960, p. 2).

The sub-till marine strata (sites 3 and 10) are at an altitude of 250 feet above present sea-level; the plant-bearing beds vary between altitudes of 250 feet (sites 10, 11) and 510 feet (site 13); and sub-till stream gravels vary between 200 feet (sites 15 and 16) and over 500 feet (site 21).

Sediments

Three principal sediment facies occur in the sub-till non-glacial interval: (a) marine strata, (b) peat and associated sediments, and (c) stream gravel and sand.

Sub-till marine strata are exposed in two sections 2 1/2 miles apart on the Kwataboahegan River. J.M. Bell (1904, p. 168) described these marine beds and correctly interpreted their significance. The downstream section (MR-12/67; site 10 on Fig. 1), at 82°03'W longitude, shows the following stratigraphy from the top down (the top of the exposure is several feet below the general level of the surrounding plain):

Thickness (ft.)	Unit description
6.0	TILL; grey-green; stony; strongly calcareous; very compact; coarse, blocky structure; 0.5 ft. lens of buff, medium-grained, calcareous sand at 5 ft. depth.

Thickness (ft.)	Unit description
5.5	CLAY; 'blue-grey' (7.5 YR 3/0, very dark grey, by Munsell colour notation); sticky and plastic; no stones; no lamination visible; massive; strongly calcareous; rounded peat nodules up to 2 inches diameter present throughout; persistent 1-inch bands of light brown marl.
2.5	PEAT; dark brown; extremely compact and coarsely fissile; woody layer mid-way through unit has individual pieces 6 inches long by 1/2 inch wide; some 2-inch-thick marl strata in the peat.
>1.0	MARINE SAND; light green; medium-grained sand with some pebbles; strongly calcareous; numerous *Hiatella arctica* with individual valves as long as 1 inch, shells tend to be cracked; foraminifera present in 0.25-0.50 mm size range.
1.0	Covered to river level.

At the upstream section, the same stratigraphy is also well exposed and the marine sand unit is 2 feet thick. The peat bed there is exposed along the river edge continuously for 100 yards; 50 yards away from the principal exposure the peat rests directly on compact till.

The only other site in the Hudson Bay Lowland where *in situ* sub-till marine beds have been described is near 50°19'N latitude on the Abitibi River where Prest (1966) has examined fossiliferous marine beds beneath till.

Sub-till peat beds and silts that are rich in plant detritus are widespread in the Lowland (Fig. 1). As shown in the above section, they are stratigraphically above the marine strata, suggesting a facies relationship very like that of the post-glacial with widespread peat development over marine strata of the Tyrrell Sea. The nature of the sub-till peat on the Kwataboahegan River is characteristic of peats in this stratigraphic position throughout the Lowland. But not all sub-till plant detritus occurs in peat beds. On the Kapiskau River (Plate IA), a 24-foot sequence of sub-till laminated silt is grey, non-calcareous, and contains finely divided and dispersed plant material, with only local thin peat beds. Of a similar nature are the non-glacial sites on the Mattagami and Attawapiskat Rivers. The depositional environment may have been a shallow peat-surrounded lake into which plant material was washed.

Sub-till stratified sediments associated with peaty beds also have a remarkably uniform stratigraphy throughout the region. For comparison, two non-glacial sequences are described from farther west in the Lowland:

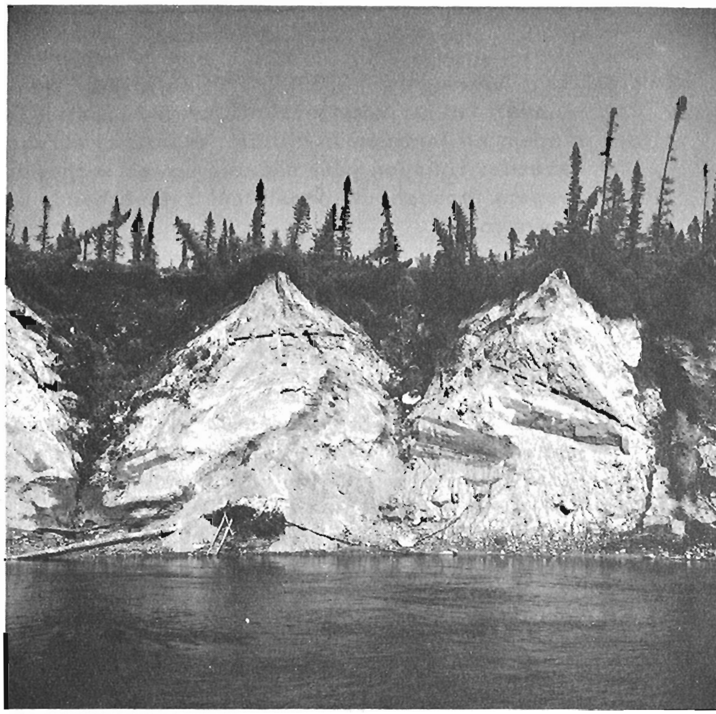


Plate IA. A section on the Kapiskau River exposing 24 feet of organic-rich silt and peat overlain in turn by 7 feet or more of till and by 2 feet of post-glacial peat. (GSC 138318; site 12 on Fig. 1)

(a) Severn River, section MR-147/67; site 17 on Figure 1; (described from top down).

Thickness (ft.)	Unit description
20.0	TILL; brown; sandy silty (with numerous pebbles); strongly calcareous; compact.
3.0	CLAY; 'blue-grey'; sticky and plastic; no stones; finely laminated; thoroughly leached except for secondary calcite precipitation in zones bordering joints which extend downward for 1 foot from overlying till; reddish stain on joint surfaces.
1.5	CLAY; same as above but strongly calcareous.
1.5	CLAYEY SAND; grey; poorly sorted; sand admixed with 'blue' clay of overlying unit; no obvious lamination; calcareous; compact.

Thickness (ft.)	Unit description
2.25	CLAYEY SAND; brownish-grey; similar to overlying unit except for peaty lenses 6 inches long by 1/4 inch thick; individual plant fragments to 3/8 inch long.
0.75	SAND; buff-orange in coarse-grained strata and buff-grey in fine-grained laminae; well stratified; non-calcareous.
>1.0	GRAVEL; buff-orange; pebbly; well stratified; non-calcareous.
10.0	Covered to river level.

(b) Hayes River, section MR-176/67; site 20 on Figure 1; Plate IB; (described from top down):

Plate IB. Sub-till non-glacial sediments in section MR-176/67 (see text for description) on the Hayes River. Top of shovel marks base of the till. (Shovel 20 inches long.) (GSC 138346; site 20 on Fig. 1)

Thickness (ft.)	Unit description
15.0	TILL; grey (2.5 YR 5/0); silt-rich, pebbles present but not abundant; strongly calcareous; compact; blocky structure with joint surfaces stained reddish; rare calcareous shell fragments.
0.5	CLAY; 'blue-grey' (7.5 YR 3/0 - very dark grey); sticky and plastic; rare small pebbles; very finely laminated; calcareous; reddish stain on joint surfaces.
0.5	SILT; alternating buff and light grey laminae; well sorted; very evenly laminated in couplets 3/8 to 1/2 inch thick - many couplets show grading from coarse silty base to fine silty clayey top; proportion of coarse: fine changes considerably from one couplet to the next; calcareous.
1.5	DIAMICTON; buff-brown; silty sand, poorly sorted; contorted thin sand lenses; rare shell fragments; calcareous.
>1.5	PEBBLY SAND; buff-orange; coarse to very coarse grained with pebbles to 1/2-inch diameter; well cross-stratified with current parallel to and in same direction as present Hayes River; shell fragments to 1/4-inch diameter are common; calcareous.

(river level)

Sticky 'blue-grey' clay caps most of the non-glacial sequences and has been noted by earlier workers as well. X-ray analyses of samples from Hayes, Severn, and Kwataboahegan Rivers give identical results and show that the only clay minerals present are chlorite and illite, and that they occur in a 1:1 ratio (R.N. Delabio, analyst). The origin of this clay is unknown, although intercalated marl bands indicate deposition in quiet fresh water. The leached upper portion of the clay in some sections where it is directly overlain by calcareous till (e.g. Severn River Section, above) may have resulted from an extended period of subaerial exposure after deposition and before subsequent glaciation.

The diamicton in the Hayes River Section is probably a subaqueous slump deposit because it has pinched out in other adjacent exposures.

Widespread exposures of sub-till stream gravel, such as that at the base of the Hayes River Section, invariably indicate a current direction the same as that of the present river. This is well displayed in an exposure on

Plate IIA. Sub-till stream gravels on the Fawn River indicating current flow from left to right, parallel with present river. (Shovel is 20 inches long) (GSC 138333; site 16 on Fig. 1)

the Fawn River (Plate IIA, site 16 on Fig. 1). These gravels commonly contain small waterworn marine shell fragments and are considered to be a facies analagous to the modern river sediments which contain shell fragments reworked from marine strata of post-glacial age exposed higher in the river banks.

Age and Rank of Interval

The age of this non-glacial interval is not yet known. Wood and peat samples from 7 different localities, shown in Table I, are all beyond the limit of radiocarbon dating. Results range from >29, 630 to >53, 000 C^{14}-years B.P. The fact that they are underlain by till allows their assignment to the Pleistocene. Because, as we shall see, they occupy a similar stratigraphic position throughout the Lowland, and because their occurrence in the Lowland is uniquely widespread, they are probably correlative with each other. This may or may not be born out by palynological investigation planned for the plant-rich strata.

Table I. Radiocarbon-dated sub-till sediments in Hudson Bay Lowland

Site No. (see Fig. 1)	Location	Material	C^{14} date	Lab. No.	Reference
1	Harricanaw R.	peat	>42,000	Y-1165	Stuiver, M., et al., 1963
2	Little Abitibi R.	wood	>43,600	GSC-435	Lowdon et al., 1967
7	Missinaibi R.	wood	>53,000	Gro-1435	Terasmae and Hughes, 1960
		wood	>38,000	W-242	Terasmae, 1958
		wood	>30,840	Y-270	Terasmae, 1958
		cellulose	>42,600	L-396B	Olson and Broecker, 1959
		wood	>40,500		
		peat	>29,630	Y-269	Terasmae, 1958
		peat	>38,000	W-241	Terasmae, 1958
6	Missinaibi R.	peat	>42,000	Gro-1921	Terasmae, pers. comm.
13	Attawapiskat R.	wood	>35,800	GSC-83	Dyck and Fyles, 1963
17	Severn R.	peat	>41,000	GSC-1011	McDonald, this report
18	Tributary of Echoing R.	wood	>37,000	GSC-892	McDonald, this report

Altitudes above present sea-level of these sub-till sediments have direct implications for the nature of this non-glacial interval. If glacier ice occupied Hudson Bay, thereby preventing drainage northward through Hudson Strait, a fresh-water body would have to be dammed in the Lowland to a sufficiently high level to overflow low points in the drainage divide to the south, east, or west. This level would have an altitude of more than 1,000 feet. But sub-till peats, which require a subaerial environment for development, are at altitudes as low as 250 feet. This strongly supports the idea that Hudson Bay was glacier-free, thereby allowing stream drainage northward. Sub-till stream gravels containing marine-shell fragments were invariably deposited from streams flowing northward, parallel to the present rivers. Altitudes as low as 200 feet for these gravels also support the idea of a glacier-free Hudson Bay.

Thus, these sub-till non-glacial strata are considered to be interglacial because:

(1) They are underlain and overlain by till;

(2) They include marine strata which require that Hudson Bay and Hudson Strait be sufficiently glacier-free to allow the influx of sea water;

(3) Subaerial environments at low altitudes, and streams, also at low altitudes, flowing toward the bay both require that Hudson Bay and Hudson Strait be glacier-free;

(4) Assuming that the earlier ice-caps developed and shrunk in a manner similar to that of the Wisconsin ice-cap, disappearance of glacier ice in Hudson Bay would indicate sufficient diminution of the ice-caps to merit calling the condition interglacial; and

(5) The pollen record in the Missinaibi River peats has led Terasmae and Hughes (1960, p. 11) to conclude that local vegetation during the non-glacial was "similar to that now present in the region".

Three further points related to the interglacial stage could be emphasized:

(1) The presence of interglacial marine beds in the Lowland indicates that Hudson Bay was a depression occupied by the sea at least as early as Sangamon time. Also, west of 86°W longitude Pleistocene marine shell fragments are present in all the tills. Whether these were transported inland from Hudson Bay or were picked up from local sub-till marine strata, the sea had to have occupied the Hudson Bay Basin prior to the glaciation.

(2) The similarity of interglacial facies relationships to post-glacial sedimentary facies suggests that events during the interglacial were grossly similar to those of the past 8,000 years.

(3) There is a crude separation between interglacial stream gravel in the northwest part of the Lowland, and peat beds in the southeast portion. Although this may in part reflect the dilute sampling, it could also indicate that the major rivers in the northwest have largely reoccupied their interglacial valleys, whereas the rivers in the southeast have cut new channels in post-glacial time.

GLACIAL GEOLOGY

Two tills overlie the interglacial strata on all rivers traversed. In the northwest and southeast parts of the Lowland, stratified sediments commonly separate the tills (Plate IIB). The stratified sediments were deposited in a proglacial lake and are apparently devoid of organic material. Tyrrell (1913, p. 201) noted the stratified sediments separating two tills in the northwest part of the Lowland. On the Gods River (Tyrrell's 'Shamattawa' River) he noted the presence in this unit of "... moss and wood, partly altered to lignite ...". Although organic material from this stratigraphic level could

Plate IIB. Section on the Hayes River exposing 20 feet of proglacial-lake sand overlain by 35 feet of till and underlain by 60 feet of till. Arrow indicates person for scale. (GSC 138351)

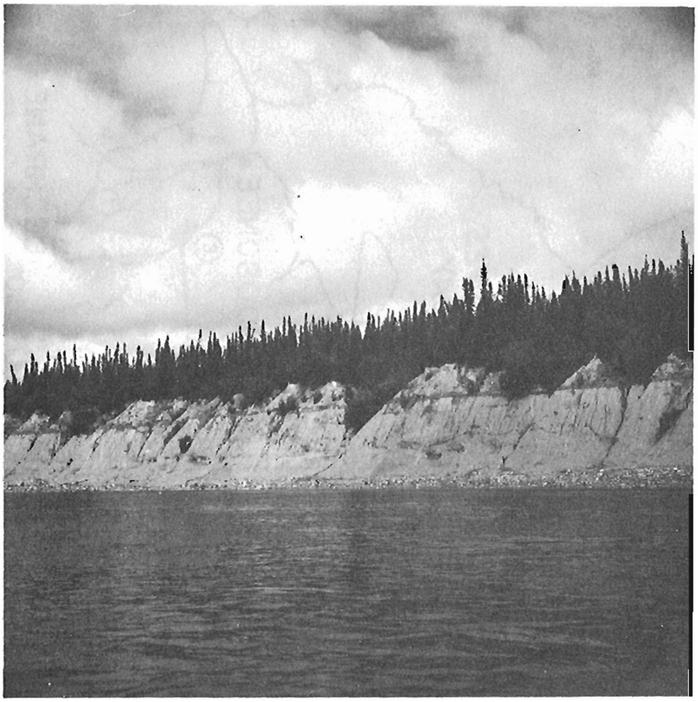


Plate IIIA. Two tills in contact on the Fawn River; upper till is 12 feet thick, lower till 34 feet thick. In the lower till, a contorted 2-inch sand layer is evident in the right half of the photograph. (GSC 138332)

provide a very important C^{14} date, we found no organic material in these sediments. In the central part of the Lowland the stratified-sediment unit is absent and the two tills are in contact with each other (Plate IIIA). The two tills are physically quite distinct when exposed in contact and the contact between them is sharp. Relative to the lower till, the upper till is generally finer grained, has a finer blocky structure, and is commonly a noticeably different colour.

Final documentation of the till stratigraphy must await laboratory analyses and will form the basis of a later report. Preliminary study of ice-flow directions based on bedrock striations, striated boulder pavements, fabric studies, ice-flow features exposed at the surface, and pebble counts, indicate ice-flow from northeast, north, and northwest. No acceptable evidence was found to support the contentions of Tyrrell (1913, 1916) that 'Patrician' glaciers flowed northward across the region.

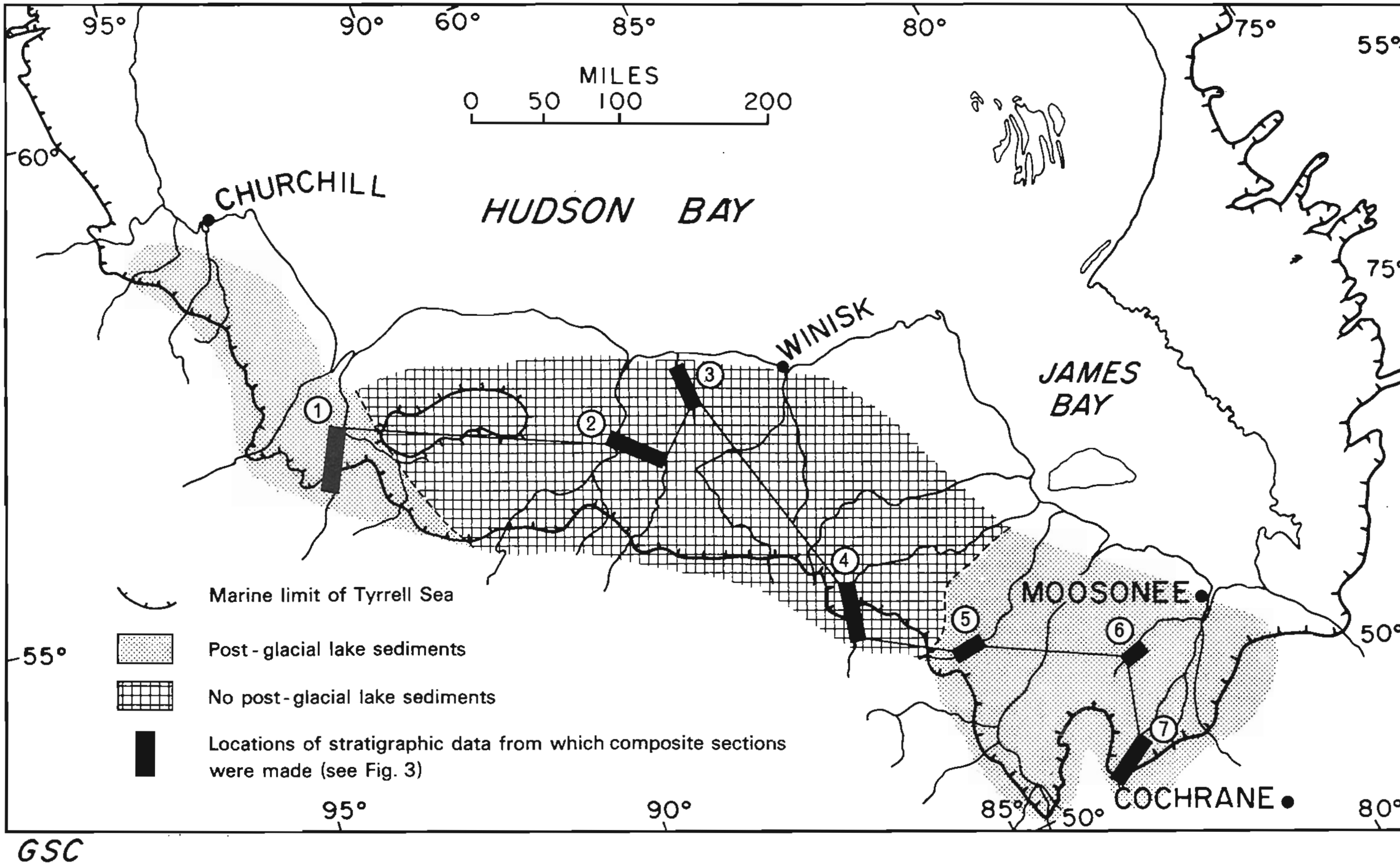


Figure 2. Hudson Bay Lowland, showing distribution of proglacial-lake sediments overlying uppermost till.

Cochrane till was not positively identified in the Hudson Bay Lowland. Hughes (1965) described the distinctive features of the type Cochrane till as a locally pinkish colour, well developed columnar jointing, and a clay- and silt-rich nature. He noted that Cochrane ice began its advance from north of 49°35'N latitude, but he interpreted the Cochrane episode as being of only local importance. Despite his field studies along the Missinaibi and Opasatika Rivers (Terasmae and Hughes, 1960), Hughes did not report Cochrane till in that area. Because of the abundance of reddish clastic Paleozoic bedrock types in that part of the Lowland (Norris, Sanford, and Bostock, 1967), it is unwise to assign all pinkish tills to the Cochrane. However, in the headwater region of the Albany River drainage basin east of 85°W longitude and south of 50°20'N latitude a few exposures of a three-fold till stratigraphy were examined in which the tills were in contact and the upper till exactly fit Hughes' description of the type Cochrane till. These exposures were unique in the Lowland; evidence for this upper facies was not seen elsewhere.

POST-GLACIAL LAKES

In the southeastern and northwestern parts of the Lowland (Fig. 2) silt and sand, rhythmically stratified and apparently of fresh-water origin, overlie the upper till but underlie fossiliferous sediments of the Tyrrell Sea (Plate IIIB). Current structures in the lake sediments invariably indicate weak current directions opposite to that of the present river and may indicate contribution of sediment and meltwater from a receding glacier. In the central part of the Lowland, evidence for this post-glacial lake phase is absent. Here, a few exposures of till interlensed with shell-bearing sand and gravel lead to the inference that the sea was in contact with glacier ice.

These lakes were post-glacial but pre-marine. Nothing is known about the lake surface altitudes except that they must have been above the subsequent marine limit. In view of the known distribution and stratigraphic position of glacial lakes south of the Hudson Bay Lowland (Elson, 1967; Boissonneau, 1966), it is reasonable that the lake in the northwest was the northern extension of Glacial Lake Agassiz and that the lake in the southeast was the northern extension of Glacial Lake Barlow-Ojibway. The lake phases shown on Figure 2 were not necessarily totally contemporaneous. If the sea entered the southeastern Hudson Bay Lowland first (Craig, this volume), then the southeastern lake would have ended first and the northwestern lake would have drained eastward to the sea (ice still occupied the Keewatin ice divide and the western portion of Hudson Bay). One area where a great influx of fresh water appears to have flowed eastward into the sea is in the upper reaches of the Fawn River near 88°15'W longitude (see next portion of this report). A marine shell date (GSC-877) would place this event shortly after about 7,400 C^{14}-years B.P.

As deglaciation proceeded, sea water spread northwestward to inundate the entire Lowland.

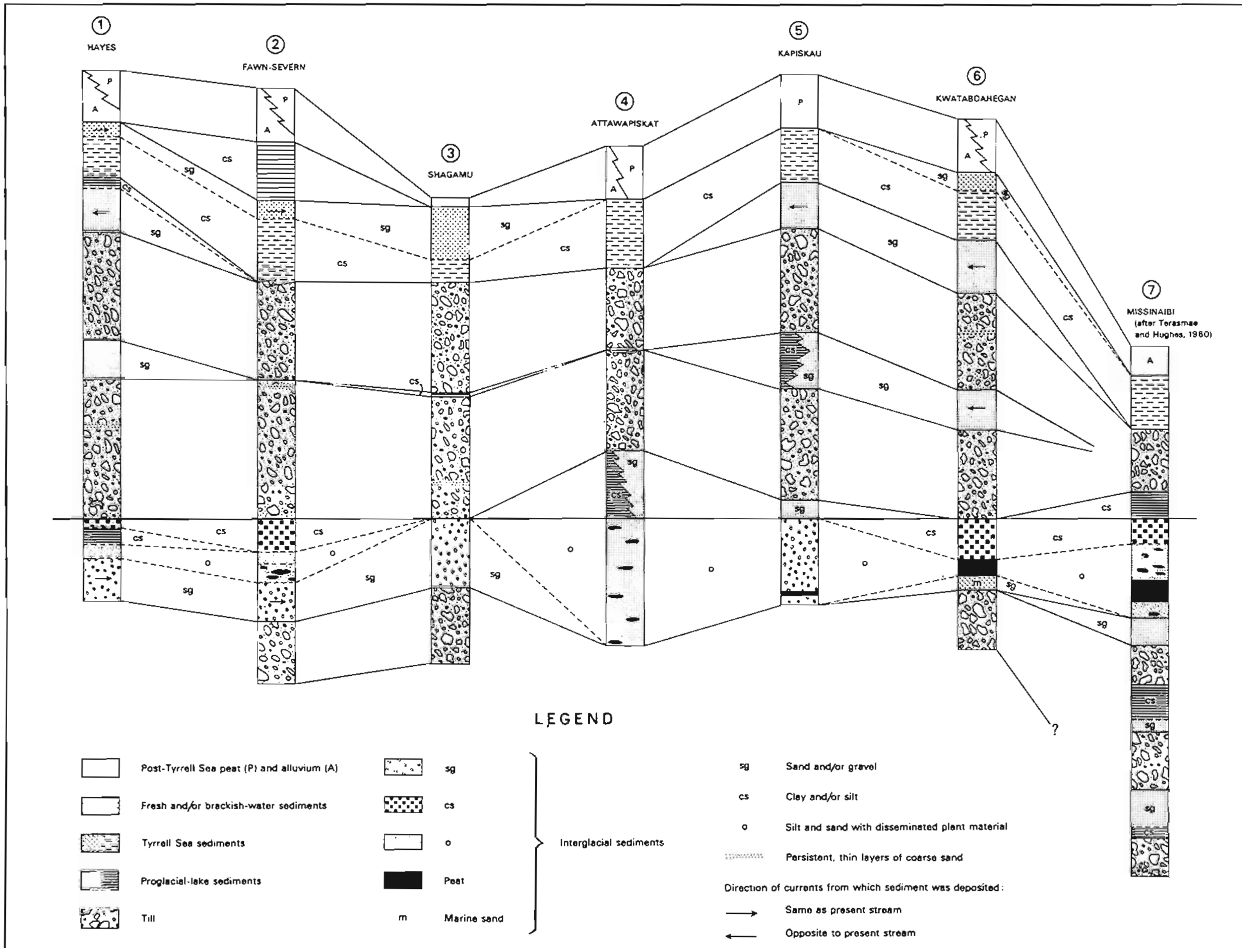


Figure 3. Quaternary stratigraphy, Hudson Bay Lowland.

STRATIGRAPHIC CORRELATION, HUDSON BAY LOWLAND

Composite sections have been made for several rivers along which abundant stratigraphic data were obtained. Six of these composite sections, together with a composite section condensed from Terasmae and Hughes (1960), are tentatively correlated in Figure 3 (see section locations on Fig. 2). The sections are arranged roughly from northwest on the left to southeast on the right. Distances between the composite sections vary, but the total distance from the Hayes to the Missinaibi is about 600 miles. The top of the interglacial sediments has been used as a marker bed.

Aspects of the correlation which should be noted in particular include:

(a) Interglacial sediments are widespread; they have a fairly consistent internal stratigraphy; and they are underlain by till.

Plate IIIB. Section on the Hayes River exposing 15 feet of proglacial-lake sand and silt beneath 30 feet of fossiliferous marine clay and silt. (GSC 138353)

(b) Two till units occur throughout the Lowland overlying the interglacial sediments.
(c) Post-glacial but pre-marine lake phases existed in the northwest and southeast parts of the Lowland, but appear to have been absent in the central part of the Lowland.
(d) The distribution of proglacial-lake sediments separating the upper tills is similar to the distribution of post-glacial lake sediments.
(e) A thick (30 to 40 feet) unit of very evenly stratified clay, silt, and sand overlies abundantly fossiliferous marine sediments for several miles along the upper reaches of the Fawn River. The current direction, as indicated by small-scale, delicate cross-stratification, was the same as that of the present Fawn River. There are only rare and very fragile barnacles in this material, and it is interpreted as a fresh- and/or brackish-water sediment. This may have resulted from a great influx into the Tyrrell Sea of fresh water from the west.

DISCUSSION

The Hudson Bay Lowland is an area of great interest because of the excellence and abundance of interglacial exposures. Glacial and non-glacial events in this area have unusual importance because of their location near the centre of the former ice-cap:

(a) Ice-flow directions associated with the various till units can provide useful data relevant to the growth and spread of former continental ice-sheets; and
(b) Non-glacial events here must correlate with significant non-glacial events in better known areas farther south.

The events outlined here probably affected the whole of the Hudson Bay region.

A disadvantage to palynological study of the interglacial sediments is the occurrence of these exposures in the broad boreal forest region of Canada. Terasmae and Hughes (1960) noted that the narrow vegetation zones farther south in Canada migrate in response to only minor climatic changes and thus the pollen spectra there provide detailed records of climatic variation. However, minor climatic changes may not influence local vegetation in the broad boreal forest, thus reducing the sensitivity of the pollen record there.

This demonstration of the Missinaibi interval as interglacial, rather than interstadial as advocated by Terasmae (1958, Pt. III; and 1960), encourages a new look at the stratigraphic position of the St. Pierre interval and the Bécancour till of the St. Lawrence Lowlands (Gadd, 1960; Terasmae, 1958, Pt. II). It is tempting to suggest correlation of the non-glacial interval between the two uppermost tills in the Hudson Bay Lowland and the Port Talbot interstadial (Dreimanis et al., 1966). Apparently, although parts of the Lowland were then ice-free, ice continued to occupy Hudson Bay. The presence of ice in Hudson Bay, instead of the present moderating effect of the sea, may be compatible with a boreal climate in southern Ontario.

There are many parts of the Hudson Bay Lowland which have not yet been examined on even a reconnaissance scale. Based on known exposures, areas in which detailed stratigraphic study could yield very interesting results include (a) the Moose River Basin generally, with emphasis on the Kwataboahegan and Abitibi Rivers near areas where interglacial marine sediments are known to occur; (b) the Kapiskau River; and (c) the Severn River near its confluence with the Fawn River.

REFERENCES

Bell, J.M.
1904: Economic resources of Moose River Basin; Ontario Bur. Mines, vol. 13, Pt. 1, 1904, pp. 135-179.

Boissonneau, A.N.
1966: Glacial history of northeastern Ontario: I. The Cochrane-Hearst area; Can. J. Earth Sci., vol. 3, pp. 559-578.

Bostock, H.S.
1964: A provisional physiographic map of Canada; Geol. Surv. Can., Paper 64-35.

Craig, B.G.
(in press): Late-glacial and post-glacial history of Hudson Bay region.

Dreimanis, A., Terasmae, J., and McKenzie, G.D.
1966: The Port Talbot interstade of the Wisconsin glaciation; Can. J. Earth Sci., vol. 3, pp. 305-325.

Dyck, W., and Fyles, J.G.
1963: Geological Survey of Canada radiocarbon dates II; Radiocarbon, vol. 5, pp. 39-55.

Dyer, W.S., and Crozier, A.R.
1933: Lignite and refractory clay deposits of the Onakawana lignite field; Ontario Dept. Mines, 42nd Ann. Rept., vol. 42, Pt. 3, pp. 46-78.

Elson, J.A.
1967: Geology of Glacial Lake Agassiz; in Life, Land and Water, edited by W.J. Mayer-Oakes, Univ. of Manitoba Press, pp. 36-95.

Gadd, N. R.
1960: Surficial geology of the Bécancour map-area, Quebec; Geol. Surv. Can., Paper 59-8.

Hogg, N., Satterly, J., and Wilson, A. E.
1953: Drilling in the James Bay Lowland: Part I, Drilling by the Ontario Department of Mines; Ontario Dept. Mines, 61st Ann. Rept., vol. 61, Pt. 6, 1952, pp. 115-140.

Hughes, O. L.
1965: Surficial geology of part of the Cochrane district, Ontario, Canada; in International studies on the Quaternary, edited by H. E. Wright, Jr., and D. G. Frey, Geol. Soc. Am., Spec. Paper 84, pp. 535-565.

Lowdon, J. A., Fyles, J. G., and Blake, W., Jr.
1967: Geological Survey of Canada radiocarbon dates VI; Radiocarbon, vol. 9, pp. 156-197.

McLearn, F. H.
1927: The Mesozoic and Pleistocene deposits of the lower Missinaibi, Opazatika, and Mattagami Rivers, Ontario; Geol. Surv. Can., Summ. Rept., 1926, Pt. C, pp. 16-44.

Montgomery, R. J., and Watson, R. J.
1929: Fire clay, kaolin, and silica sand deposits of the Mattagami and Missinaibi Rivers; Ontario Dept. Mines, 1928, vol. 38, pp. 81-120.

Norris, A. W., Sanford, B. V., and Bostock, H. H.
1967: Geology, Hudson Bay Lowlands; Geol. Surv. Can., Map 17-1967.

Olson, E. A., and Broecker, W. S.
1959: Lamont natural radiocarbon measurements V; Radiocarbon, vol. 1, pp. 1-28.

Prest, V. K.
1963: Red Lake-Lansdowne House area, northwestern Ontario; Geol. Surv. Can., Paper 63-6.

1966: Glacial studies, northeastern Ontario and northwestern Quebec; Geol. Surv. Can., Paper 66-1, pp. 202-203.

Stuiver, M., Deevey, E. S., Jr., and Rouse, I.
1963: Yale natural radiocarbon measurements VIII; Radiocarbon, vol. 5, pp. 312-341.

Taylor, F.C.
1961: Interglacial (?) conglomerate in northern Manitoba, Canada; Bull. Geol. Soc. Am., vol. 72, pp. 167-168.

Terasmae, J.
1958: Contributions to Canadian palynology: Part II, Non-glacial deposits in the St. Lawrence Lowlands, Quebec; Part III, Non-glacial deposits along Missinaibi River, Ontario; Geol. Surv. Can., Bull. 46.

Terasmae, J., and Hughes, O.L.
1960: A palynological and geological study of Pleistocene deposits in the James Bay Lowlands, Ontario; Geol. Surv. Can., Bull. 62.

Tyrrell, J.B.
1913: Hudson Bay exploring expedition, 1912; Ontario Bur. Mines, 22nd Ann. Rept., Pt. 1, pp. 161-209.

1916: Notes on the geology of Nelson and Hayes Rivers; Roy. Soc. Can. Trans., ser. 3, vol. 10, sec. 4, pp. 1-27.

Wilson, W.J.
1906: Reconnaissance surveys of four rivers southwest of James Bay; Geol. Surv. Can., Summ. Rept., 1902, Pt. A, pp. 222-243.

SUBMARINE PHYSIOGRAPHY, BOTTOM SEDIMENTS, AND MODELS OF SEDIMENT TRANSPORT IN HUDSON BAY

B.R. Pelletier
Atlantic Oceanographic Laboratory, Bedford Institute,
Dartmouth, Nova Scotia

Abstract

Chief control of submarine physiography in Hudson Bay is bedrock structure and lithology and secondarily, pre-Pleistocene subaerial erosion. Although the general bottom contours of Hudson Bay are concentric with the periphery of the bay, the regularity of the contours is disrupted by the radial pattern of an apparently submerged trunk system and a few major troughs and ridges whose trends appear to be controlled by geologic structure. Some of these valleys appear to be scoured by glaciers. A broad shelf zone extending from the shore to a point about 75 miles (120 km) offshore passes into a slope zone at 80 metres depth (264 feet). The slope zone extends to the upper margin of the deep zone at 160 metres (528 feet) and 150 miles (240 km) approximately from shore. The average lower depth of the deep zone is about 340 metres (792 feet).

Water studies reveal that bottom temperatures in Hudson Bay range uniformly between + 1.0°C and - 1.8°C, decreasing progressively from the shore to the centre of the bay. Content of dissolved oxygen is highest in shallow inshore areas (8 ml/litre) to lowest values in the deep central area (5.0 ml/litre). Salinity ranges from 30°/oo (parts per thousand) in the shallow areas to 34°/oo in the deeper areas. Currents move counterclockwise around the bay and ice apparently drifts in the same direction.

Ice-rafted sediments occur over all areas of the bay but are most common within the nearshore area. Its composition depends upon the nature of the underlying and bordering bedrock. On the east and northwest coast, crystalline igneous and metamorphic rocks are common while in other areas, Paleozoic carbonates and shales are dominant. Exclusive of ice-rafted sediments, the normal marine sequence of clastic sediments is present and consists of coarse sediments near shore grading progressively finer seaward to clays in the central deeper areas. Carbonate content is lowest in the eastern and western portions of the bay but is high in the central region particularly in the north. Content of organic carbon is highest in the deep parts generally.

Three models of sediment transport and dispersal show (1) that ice rafting is common in all areas of the bay regardless of hydrodynamic vigour at the site of deposition; (2) that with the gravel and boulder content removed from the distribution, the recalculated plot of the lithologic ratios shows the dispersal pattern conforming to the influence of topography and hydraulic vigour and (3) with an assumed amount of ice-rafted sediment removed from the remaining ternary plot of sand-silt-clay, the resultant model of sedimentary transport and dispersion results in a plot that resembles the ideal dispersion of sediments according to topographic zones and hydrodynamic vigour.

INTRODUCTION

Studies in submarine physiography in Hudson Bay together with a limited program of bottom sampling were carried out around the beginning of the present century by A.P. Low who worked on board D.G.S. 'NEPTUNE' on the east coast of Hudson Bay (Low, 1906). Soundings were taken much earlier by explorers, traders, and adventurers and as it was customary to arm the sounding lead with tallow, samples of the sea bottom were also obtained and the nature of the sea bottom was recorded and entered on navigational charts. With the advent of the echo sounder, bathymetric observations could be taken while the ships were underway which resulted in the production of continuous topographic profiles of the sea floor. Although this added immensely to the hydrographic coverage of the area under investigation it failed to augment the knowledge of either the geological formations beneath the sea floor or the unconsolidated sediments lying upon it.

The first major geological investigation in Hudson Bay was carried out in 1961 on the cruise of M/V THETA (Fig. 1) led by F.J. Barber (Barber and Glennie, 1964) who provided support for R.J. Leslie and B.R. Pelletier on their geological sampling program (Leslie, 1963; Leslie and Pelletier, 1965; and Pelletier, 1966). This cruise was followed by a more extensive two-ship program in 1965 (Figs. 2 and 3), which was co-ordinated by B.R. Pelletier (Pelletier, et al., 1968). As well as the research vessel CSS HUDSON and the support ship, M/V THERON, launches, a helicopter and a fixed-winged aircraft supported the project.

This report includes a brief description of the water mass adjacent to the sea floor, as well as an analysis of the submarine physiography and the bottom sediments from the area covered by the cruises of 1961 and 1965. More than 40,000 miles of soundings together with the field and, in many cases, the analytical data from 2,200 hydrographic and geological sampling stations are discussed. Approximately 800 bottom samples (Fig. 4) were texturally analyzed and 300 of these were analyzed for content of calcium carbonate and organic carbon. About 525 samples were chosen as representative of three major topographic environments and the textural analyses, particularly the lithologic ratios of the sample, were related to these physical environments. Because of the influence of ice rafting, models of sedimentary transport were drawn to illustrate the effects of both gravity deposition from suspension, as in the case of ice rafting, and current deposition, as in the case of longshore and offshore currents.

The writer thanks F.J. Barber for his support during the THETA cruise in 1961, and R.J. Leslie who carried out much of the geological and oceanographic sampling on that same cruise. Thanks are owed to J.M. Shearer and J.J. Stewart who supervised the sampling in the cruise of 1965 aboard CSS HUDSON and M/V THERON respectively. A debt of gratitude is owed to the three ships' masters who carried out their duties unstintingly: Captain Chris Maro of M/V THETA, Captain Harald Maro of M/V THERON and Captain John Vieau of CSS HUDSON. Numerous others deserve mention such as the senior hydrographer M.A. Hemphill, the seismic chiefs G.B. Hobson, M.J. Keen, A.C. Grant and H. MacAulay, the paleontologist Miss F.J.E. Wagner, the scientist-in-charge of the magnetic surveys P. Hood,

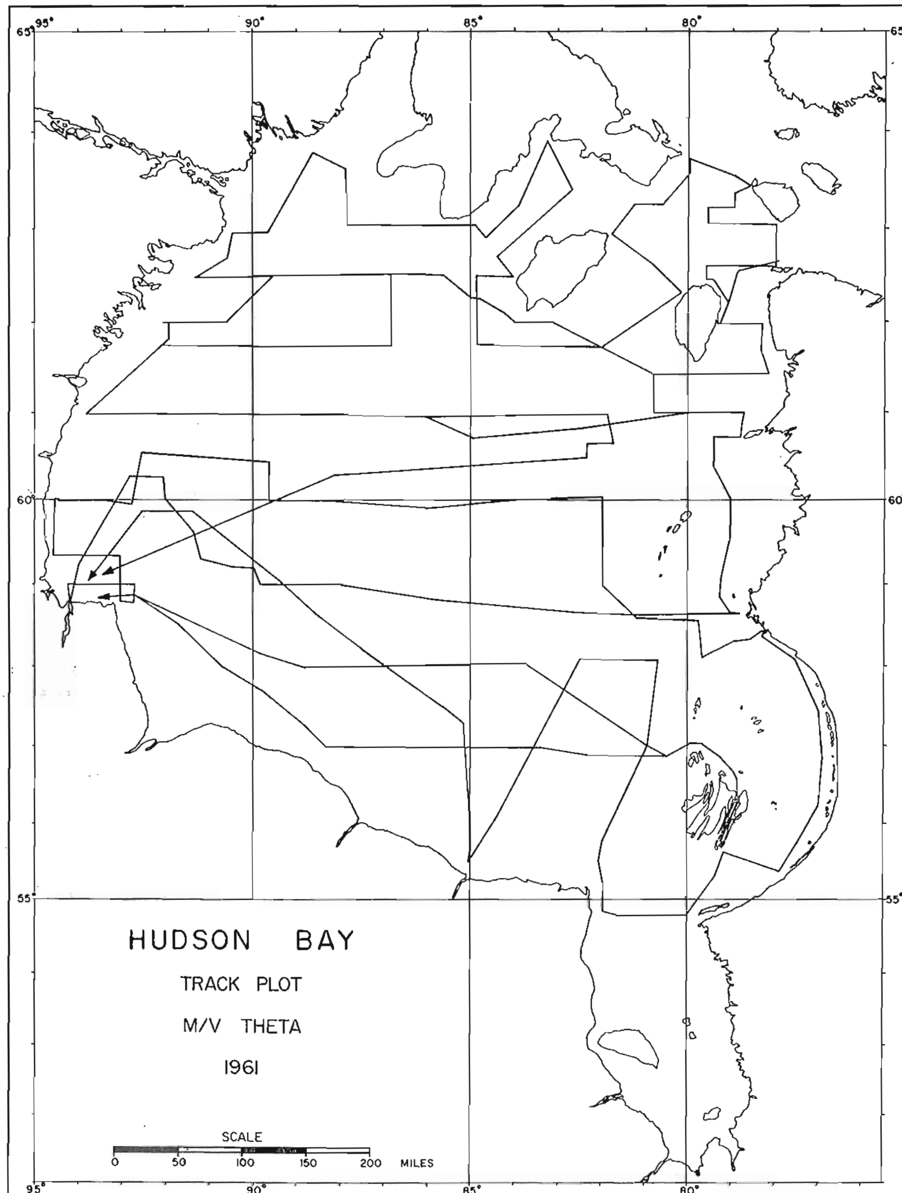


Figure 1. Track plot of M/V THETA on her oceanographic cruise into Hudson Bay, 1961. Arrows indicate the return of the vessel to Churchill during the cruise.

the chiefs in charge of the gravity survey H. Weber and A. Goodacre, the supervisor of the electronic geophysical data logger R. Cooper, our charting assistant Mrs. John Henderson (née P. Wise), and the many students, departmental technicians and ships personnel who made possible a successful completion of all the operations. Many thanks are due our marine geological technicians T. Holler, L. Brown, D. Clark and K. Robertson who carried out the laboratory analyses at the Bedford Institute. Finally I wish to thank my colleagues L.H. Loring, R.M. McMullen and F.J.E. Wagner for their critical reading of the manuscript, as well as for their many helpful discussions and suggestions.

SUBMARINE PHYSIOGRAPHY AND THE RELATIONSHIPS OF THE UNDERLYING BEDROCK AND THE RECENT BOTTOM SEDIMENTS

Submarine physiography in Hudson Bay is controlled predominantly by the nature and structure of the underlying bedrock and only secondarily by pre-Pleistocene subaerial erosion. Subsequent post-glacial sedimentation is even less important; in fact, in many shallow areas of the bay marine erosion is dominant, particularly in the western half, and sedimentation plays no part at all in shaping the submarine physiography.

Bathymetry

Bathymetric observations are amongst the earliest scientific records of Hudson Bay. From the days of the early explorers in the 17th century when the sounding lead was used, to the modern era of ice breakers and echo-sounding devices data has been continuously compiled for the purposes of scientific enquiry, navigation, and shipping interests. Most modern charts of Hudson Bay are based on the information compiled by the Canadian Hydrographic Service shown on its charts 5449 and 5003. From the cruises of 1961 and 1965, additional bathymetric data, supported by electronic navigational control, were obtained with the aid of precision depth recorders and echo-sounders operating from launches, ships and a helicopter. These data were compiled by M.A. Hemphill of the Bedford Institute, and form the basis of the present bathymetric chart (Fig. 5).

The average depth of water over the main area of Hudson Bay is about 100 metres (330 feet), although depths range to about 230 metres (750 feet) in the north-central region where depths increase progressively from the shoreline outward. The deepest areas of the bay however occur in troughs; one west of Ottawa Island is 300 metres (985 feet) deep and the other is adjacent to Digges Island near Cape Wolstenholme and is 550 metres (1805 feet) deep. Exclusive of these exceptionally deep troughs, the general bathymetric configuration of Hudson Bay is saucer-shaped. However, long ridges and valleys disrupt the concentric pattern of the general bathymetry and, in certain cases, these continuous, somewhat sinuous trends resemble a submerged trunk system, which is shown by the arrows in Fig. 5. The echograms clearly show steep-walled valleys up to 30 metres (100 feet) in height, which extend more than 80 miles (130 km) from present estuaries such as Chesterfield Inlet, and those of the Churchill, Nelson and Severn Rivers on the west and south coasts.

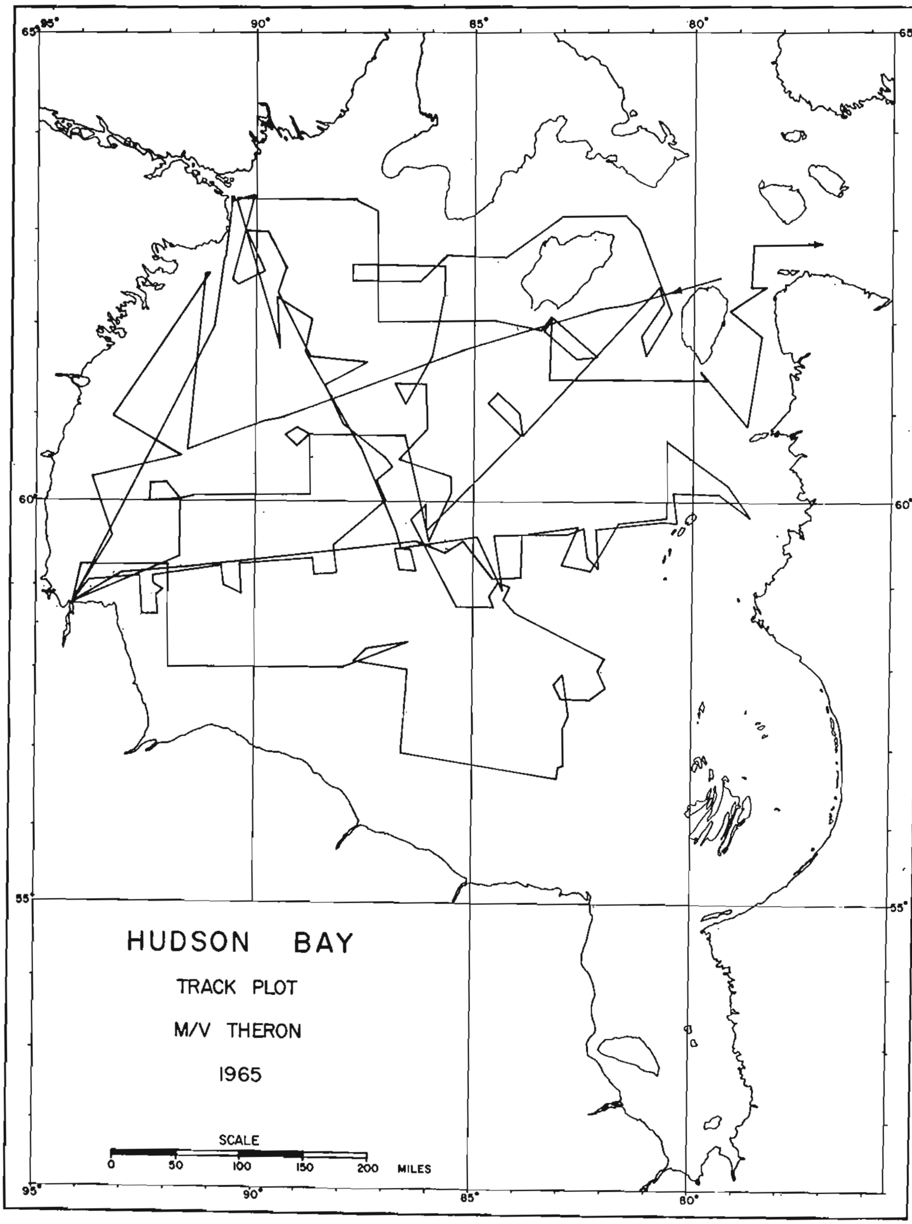


Figure 2. Track plot of M/V THERON on her oceanographic cruise into Hudson Bay, 1965. System of tracks radiating from centre of bay, with numerous short lines perpendicular to main track, was made to cover most of bay not previously surveyed. Survey plant also gave best coverage in limited time available for cruise.

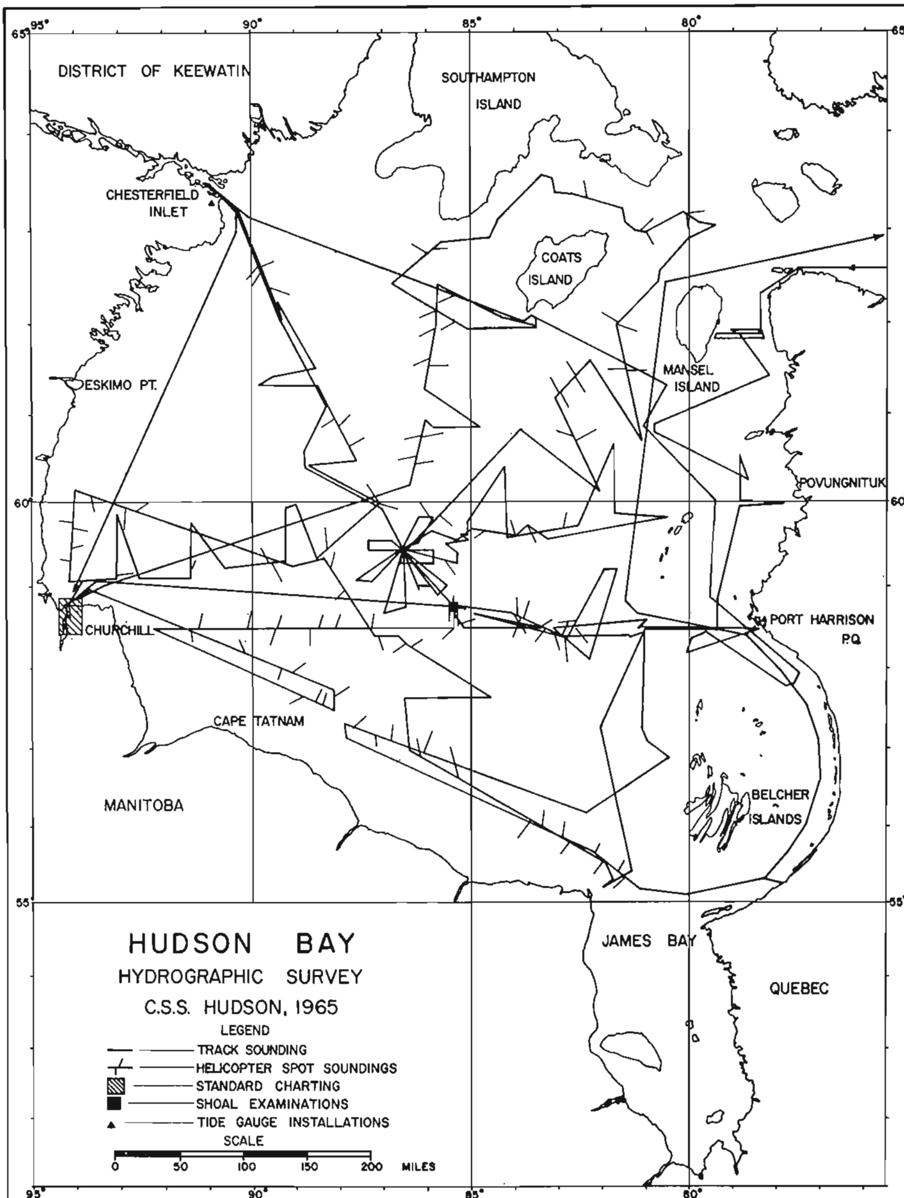


Figure 3. Hydrographic sounding lines from CSS HUDSON on her cruise into Hudson Bay, 1965. Soundings include those obtained from launches and helicopter. See Figure 2 for comments on ship's tracks.

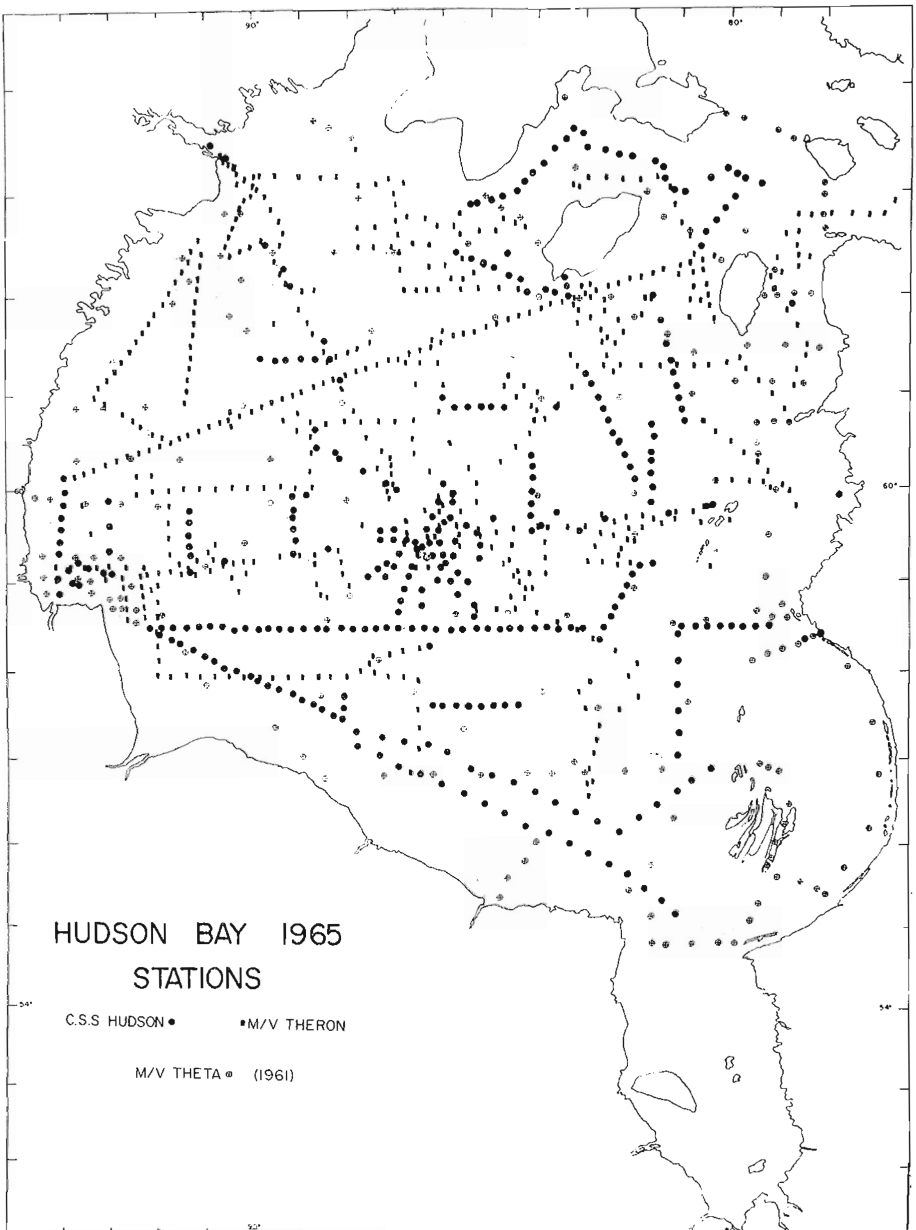


Figure 4. Location of geological, geophysical and oceanographic sampling stations of cruises of M/V THETA, 1961; M/V THERON, 1965; and CSS HUDSON, 1965. Actual breakdown of the work carried out at each station is not shown but each discipline was covered at approximately 800 stations although not necessarily at each one.

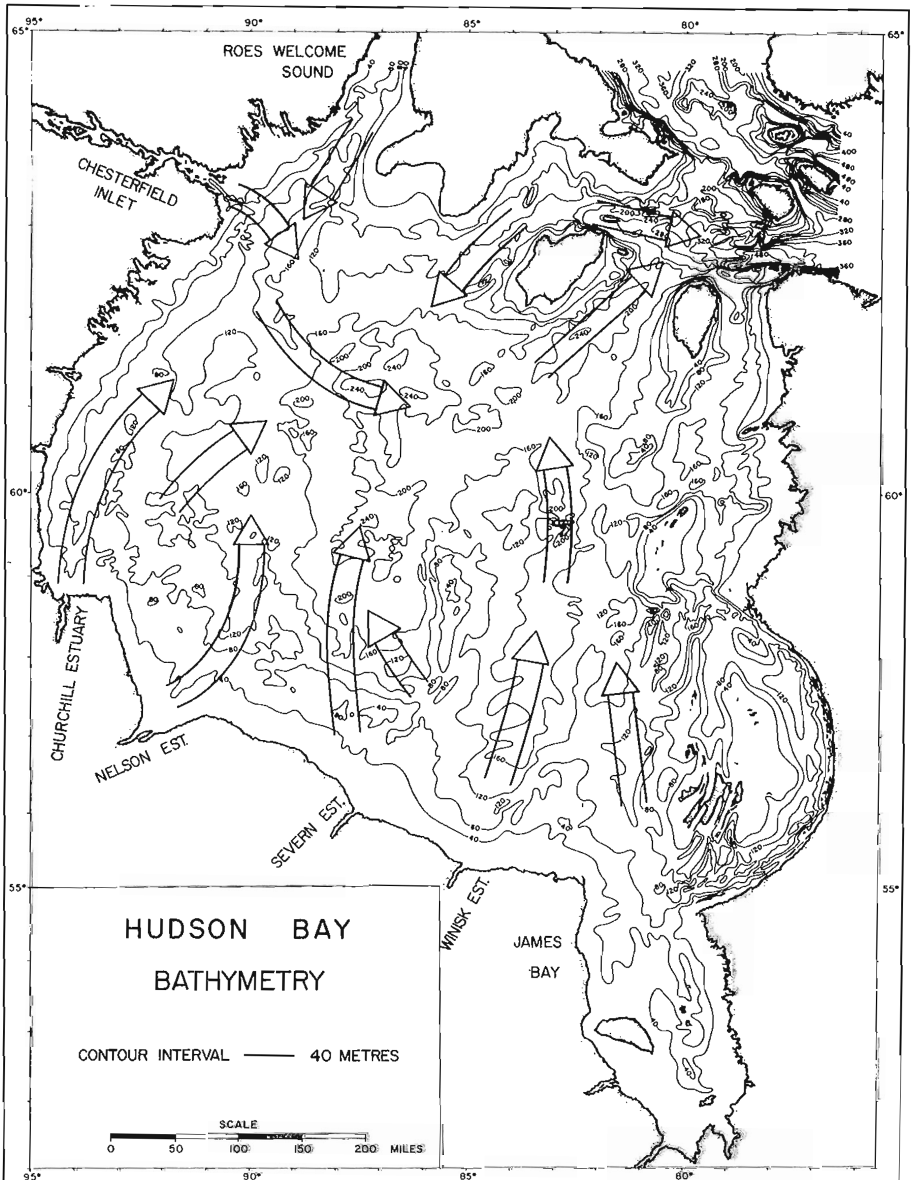


Figure 5. Bathymetric chart of Hudson Bay showing trends of a presumed older drainage system. The arrows indicate the approximate position of the earlier drainage system, and the probable direction of flow in the trunk system.

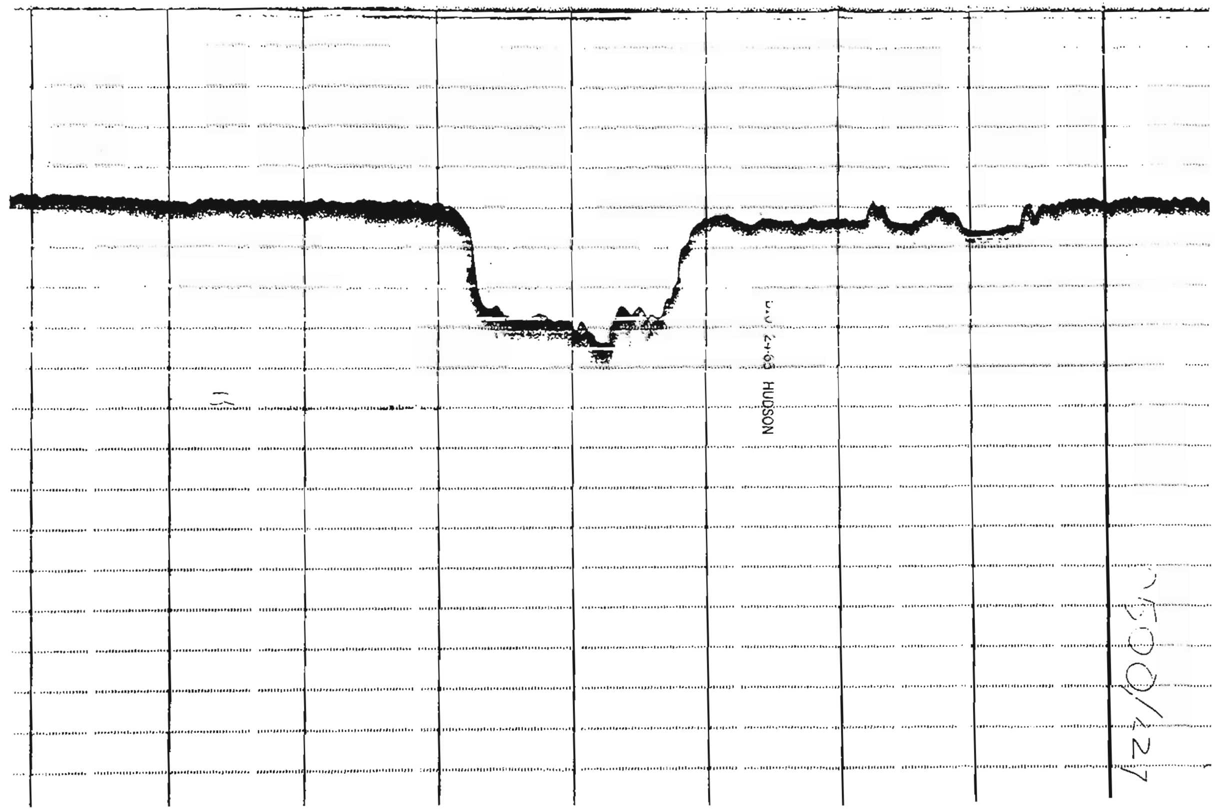


Figure 6. Bathymetric profile of deep submerged valley occurring west of Ottawa Islands. Depth of water is 600 feet over adjacent sea floor but trench itself is at least another 400 feet in depth. Note the occurrence of a minor valley dissected in the larger one. Two periods of erosion are indicated.

The floor of one valley, mentioned above, is located 80 miles (130 km) west of Gilmour Island (northern part of the Ottawa Islands) and appears to trend northerly from Winisk River, together with a sub-branch from James Bay. It lies 300 metres (985 feet) below sea level and is almost 200 metres (650 feet) below the adjacent level of the sea floor (Fig. 6). It is steep-walled and U-shaped in profile, and is more than 1 mile (1.6 km) in width. Paleozoic limestone was dredged from the west wall and, although the east wall was not sampled, the topographic expression of the sea floor directly east of the trough resembles a Precambrian terrain. This trough, or valley, appears to owe its configuration to subaerial erosion along a structural or geological contact.

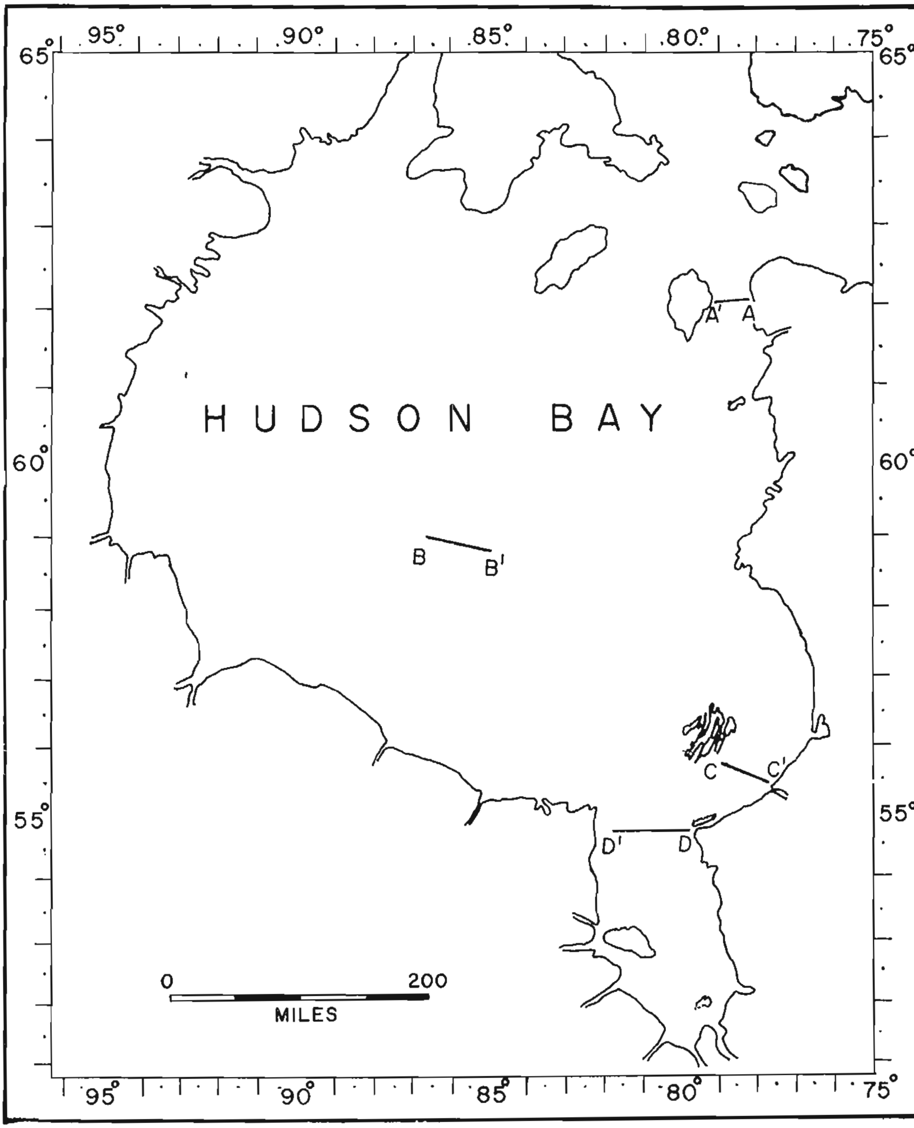
Other linear trends comprise topographic highs, the most striking of which is the northerly trending ridge which lies parallel to, and 75 miles (120 km) west of, the deep trough mentioned above. Originally this ridge was designated the "central shoals" where it was marked by a circled contour at a depth of approximately 30 metres (100 feet). Leslie and Pelletier (1965) showed that it was part of a larger feature extending as a broad arch some 50 miles (80 km) in width along an east-west line (Fig. 7, Section B-B'). The present chart (Fig. 5) shows a considerable southerly extension, and indicates a dominant underlying structural influence. Sub-bottom records obtained in 1965 clearly indicate that the trend of this ridge is controlled by geological structure (see Grant, this volume, Fig. 4).

A broad, low area occupies most of the western central region of the bay and appears to be the major confluence of submerged trunk systems originating from Fisher Strait and Roes Welcome Sound in the north, Chesterfield Inlet in the northwest, Churchill River in the west, and Nelson and Severn Rivers in the southwest. This area seems to have undergone considerable erosion by fluvial and perhaps glacial action. A number of small ridges and other features of higher elevations above the sea floor resemble submerged interfluvial areas, and are common on the east side of Hudson Bay as well.

One other notable physiographic feature is the trough that occurs in the northeastern part of Hudson Bay adjacent to Digges Island near Cape Wolstenholme. This trough is approximately 550 metres (1805 feet) deep, and is steep-walled and linear. Its origin is thought to be one of subaerial erosion involving dissection and glaciation along a geological contact such as a fault. A known fault occurs further to the east along this same trend. Overdeepening and steepening of this trough may be due to the passage of glaciers from Evans Strait and the submerged trunk system to the west at an earlier time before Hudson Bay was occupied by the sea.

Relationship of Physiography and Bottom Sediments To Geological Formations

From an examination of the echo-sounding records, a contrast was noted in the bottom physiography of various parts of Hudson Bay. On land, in the regions bordering Hudson Bay, correlation between physiography and bedrock geology is fairly obvious. The Paleozoic area to the southwest of the bay is called the Hudson Bay Lowlands, and is underlain by almost flat-lying strata. It is bordered by a low escarpment which separates it from the rolling Precambrian terrain to the south and west (Caley and Liberty, 1957). On Southampton Island a similar contrast was noted by



Index map for Figure 7.

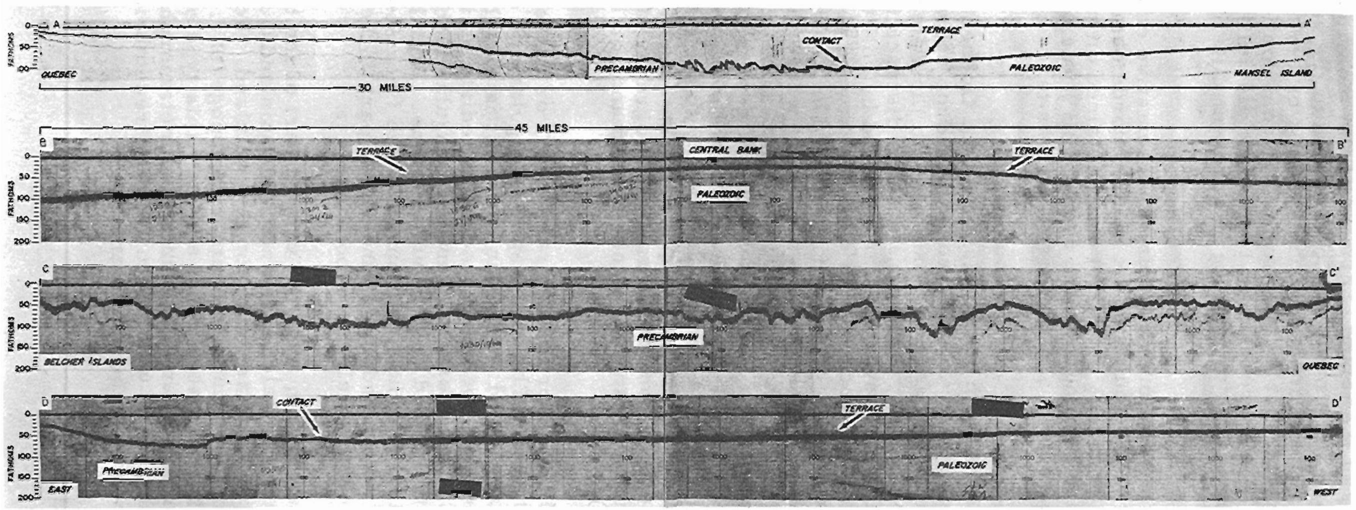


Figure 7. Selected fathograms of Hudson Bay to show the relationship of physiography to the underlying geological formations according to Leslie and Pelletier, 1965. The Paleozoic generally underlies a regular terrain whereas the Precambrian underlies a hilly and rolling terrain.

Bird (1953) when he observed that the interior and east coast consisted of highlands, and the remainder of the island consisted of flat monotonous lowlands. The same observations were made on Coats Island to the south by several officers participating in the oceanographic cruises of 1961 and 1965. According to Bird (1953) this contrast extends to the adjacent continental shelf, and is due essentially to the presence of two widely dissimilar rock types that have weathered and eroded to produce the present different landscapes.

To illustrate these relationships four representative echograms (or fathograms) (Fig. 7) were selected from the many records obtained from the cruise vessels. Two records (AA' and DD') were obtained on traverses over the Precambrian-Paleozoic boundary, one record (BB') was obtained on traverses solely over the Paleozoic, and another (CC') was taken only over the Precambrian.

Section A-A' extends from Mansel Island to the Quebec mainland. Mansel Island consists of Paleozoic carbonate rocks that drop seaward in a series of wide terraces. These terraces continue beneath the water and can be traced, by means of the echogram, for a considerable distance toward the Quebec mainland. The mainland however is characterized by rolling hills consisting of Precambrian granitic rocks which extend westward beneath the bay, and are also traceable by means of the echograms. The probable contact of these major geological terraces occurs at the point where the topography extended from either coast, changes abruptly. The same comparison and inference can be made for section D-D' which extends across the mouth of James Bay. The flat topography of the Hudson Bay Lowlands, which is underlain by Paleozoic strata, extends beneath James Bay to the east. Where this topography changes abruptly in the eastern part of James Bay, a geological contact is drawn. East of this contact the rolling topography of the Precambrian rocks of the Quebec mainland is encountered and continues eastward to the interior.

Section B-B' is drawn over the central shoals, or banks and appears to represent a broad arch. The topography is regular and smooth, and is similar to that of Mansel Island. For this reason it is thought to consist of Paleozoic strata. Dredging operations in the immediate vicinity of the central shoals recovered a considerable quantity of angular blocks of fossiliferous Paleozoic carbonate and red calcareous siltstone. Finally the results of the analyses to determine the lime content in the finer sediments led to the conclusion that the strata underlying the major part of the central region of the bay consists predominately of carbonates.

In contrast to this section, over the central part of the bay, the section C-C' extending between the Belcher Islands and mainland Quebec consists of hilly uneven topography similar to that on the mainland. For this reason the section appears to represent a Precambrian topography. Dredge hauls recovered elsewhere off the Quebec coast and over this type of topography contained fragments and boulders of granitic and metamorphic rocks, as well as some basaltic lavas, all of which occur in the Precambrian rocks of the Belcher Islands and nearby Quebec mainland.

Relationship of Physiography and Geological Structure to Thickness of Recent Sediments

Continuous graphical recordings of the thickness of the unconsolidated sediments, which overlie the bedrock beneath Hudson Bay, were obtained with the aid of conventional echo-sounders and electrical seismic sub-bottom profilers (see Grant, this volume). The thickness of this sediment varies from zero, on the boulder-strewn tidal flats off the west coast and again over the broken bedrock of the central shoals and areas adjacent to the northern islands, to more than 30 metres (100 feet) in the deeper central areas and major submarine troughs. In the vicinity of the Belcher Islands, as much as 25 metres (80 feet) of fine sediments are present within the confines of the synclines. This thickness decreases to less than 3 metres (10 feet) on the crests of folds due partly to more extensive winnowing by currents on the topographically higher areas, whereas the troughs are areas which are hydrodynamically less vigorous and would naturally receive more sediments. Over broad areas in the shallower northern and southern parts of the bay, which are underlain by flat-lying Paleozoic rocks, the cover of unconsolidated sediments averages 3 metres (10 feet) in thickness (Hood, 1966). The data are still insufficient to evaluate properly in order to make a regional interpretation of the thickness of unconsolidated sediments in Hudson Bay.

As shown by the sea-floor cores, much of the sedimentary material is derived from earlier glaciers, and much is strictly marine in nature and derived from normal stream discharge. The distribution pattern of the thicknesses clearly shows the same concentric trends outlined in the analyses of other oceanographic and sedimentological data. It appears that the thickness of the unconsolidated sediments increases progressively from shore to the deeper central areas exclusive of the central shoals. This is consistent with the concept of a longer but less turbulent sedimentary regime in deeper, quieter waters. Presumably a more complete record of sedimentation will be found when coring to bedrock is carried out in these deeper areas, and a fuller history of Hudson Bay can be constructed.

BOTTOM SEDIMENTS AND MODELS OF SEDIMENTARY TRANSPORT

Exclusive of the observations by Low (1902, 1906) on the nature of the sea floor of Hudson Bay, and the descriptions by Trask (1932) of sediments recovered from shallow waters near the east coast, the first major studies of Hudson Bay sediments were undertaken on the oceanographic cruises of 1961 and 1965, and estuarine studies in 1967. On these cruises bottom samples were obtained from approximately 1,000 localities (some estuarine localities not shown) covering representative areas of the bay. These samples were collected by means of snapper samplers, dredges, and corers. At each station observations were made on the water mass. On the THETA cruise of 1961 the entire water column was sampled at standard oceanographic depths. On the HUDSON and THERON cruise of 1965, only the bottom water was sampled. Analyses of the water mass were used to support the special studies involving biology, geology and geophysics carried out during the cruises.

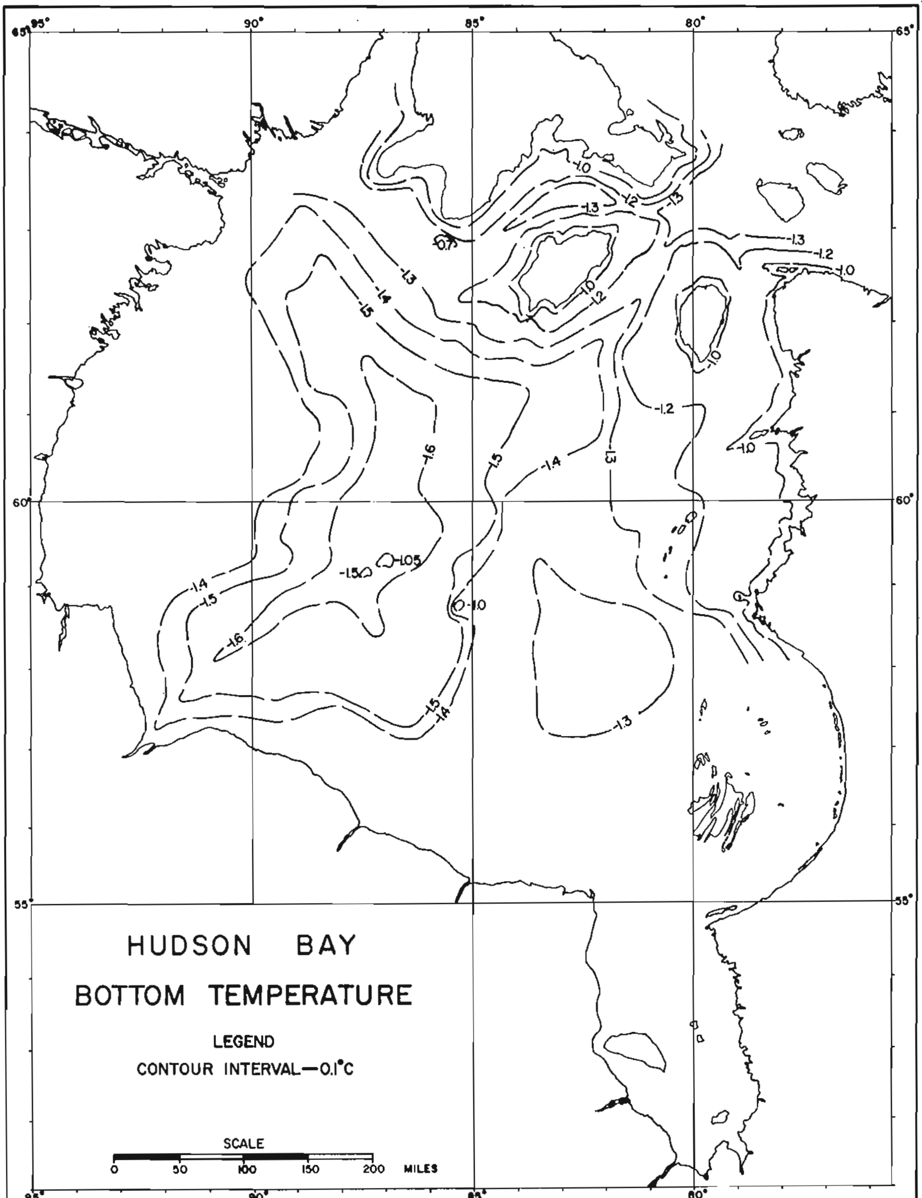


Figure 8. Temperature of bottom waters in Hudson Bay. Generally, deeper waters are colder.

Water Studies

Recent studies of the water mass in Hudson Bay are discussed by Hachey (1931, 1935), Barber and Glennie (1964), and Barber (1967). In this report only a basic description of the bottom water mass is given to present the oceanographic environment of sedimentary deposition. Investigations were restricted to temperature, amount of dissolved oxygen, degree of salinity and direction and velocity of currents. Depths of water are reported elsewhere (see bathymetry), and studies of the velocity of sound in water are given by the authors of the seismological investigations reported in this volume.

To obtain the temperature, oxygen content and salinity data, Nansen water bottles equipped with thermometers were lowered close to the sea floor. Upon returning to the surface, the bottles were brought aboard where samples were drawn and thermometers read. Determinations of the dissolved oxygen content were made in the chemistry laboratory on the ship. The remainder of the water sample was bottled and returned to the laboratories of the Bedford Institute in Dartmouth, Nova Scotia, where salinity determinations were made. All these observations were then plotted and the values contoured according to arbitrary intervals shown in the figures.

Temperatures of bottom waters in Hudson Bay were fairly uniform (Fig. 8). They ranged between +1.0°C and -1.8°C and decreased progressively from the perimeter of the bay to the centre. This concentric pattern is brought out clearly by drawing contours at intervals of 0.1°C. The water was relatively warmer over the shoals than over the deeps, thus reflecting seasonal warming in the near surface layer.

The content of dissolved oxygen in the bottom waters of Hudson Bay is shown in Figure 9. The values are highest in the inshore areas and decrease progressively from 8 ml/litre, along the coast to 5.0 ml/litre in the deeper, central areas of the bay. When the values are contoured at 0.5 ml intervals, this progressive decrease in oxygen content forms a concentric pattern about the centre of the bay. This pattern is disrupted by high values over the central shoals. However this is consistent with the previous observations that the dissolved oxygen content of bottom waters correlates with the depth of the water column.

Salinity determinations were carried out by W. Young at the Bedford Institute, and are shown in Figure 10. The results range from 30°/oo (parts per thousand) in the shallow areas, particularly near estuaries, to 34°/oo in the central, deeper areas of the bay, as would be expected from the known positive gradient of salinity with depth throughout most of the bay. When the results are contoured on an interval of 0.5°/oo, the concentric nature of the salinity distribution about the bay is immediately apparent. This pattern is disrupted over the central shoals where low results were obtained. Very low values down to 28°/oo were observed at one point along the east coast in shallow water, due no doubt to local river discharge.

Observations were made on the direction and velocity of the water circulation in Hudson Bay. The data obtained corresponds with the circulation in Hudson Bay as depicted by Hachey (1931, 1935) and is shown in Figure 11. This illustration is included here because inferences on the movement of

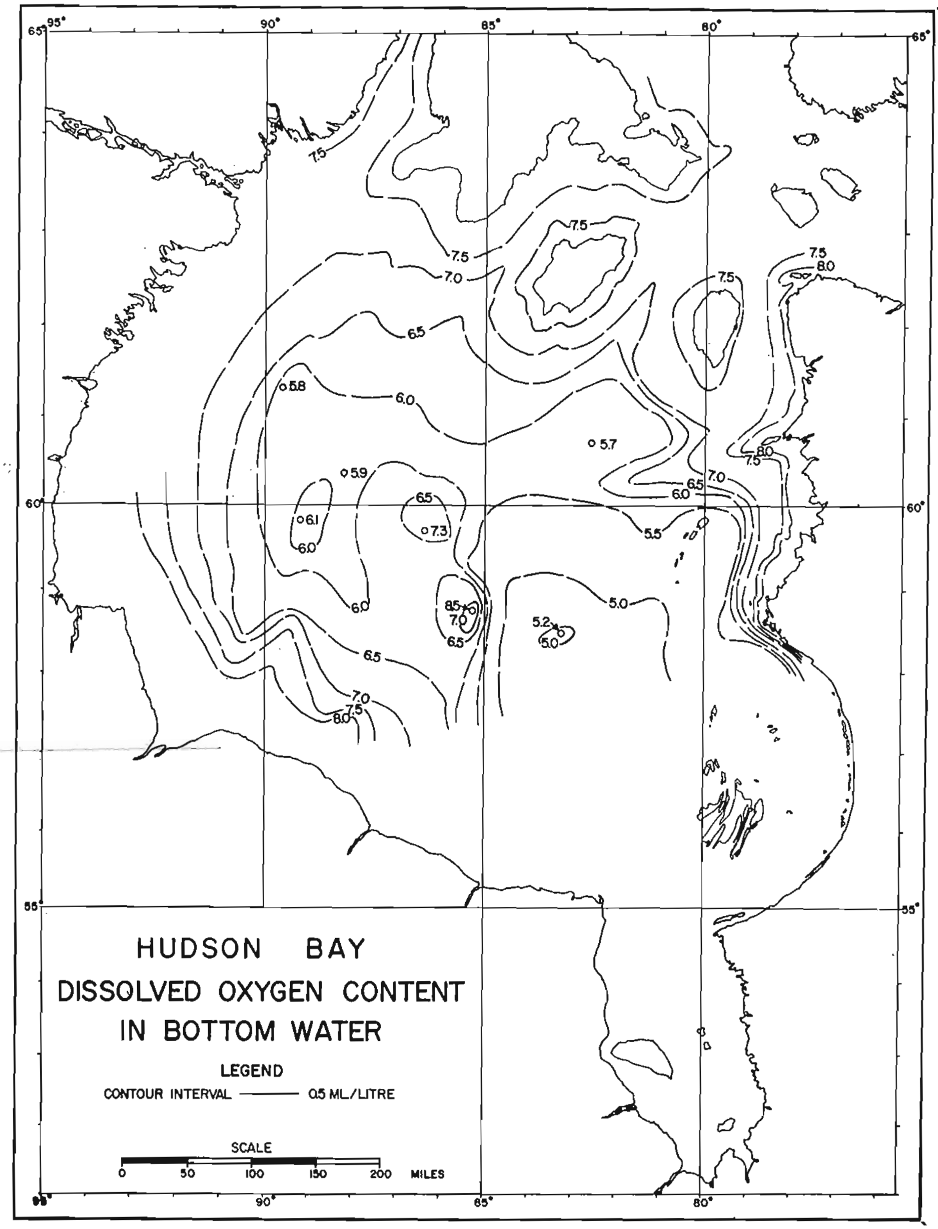


Figure 9. Dissolved oxygen content in bottom waters of Hudson Bay. Generally deeper waters contain less dissolved oxygen but there is no real deficiency of oxygen anywhere in the bottom waters.

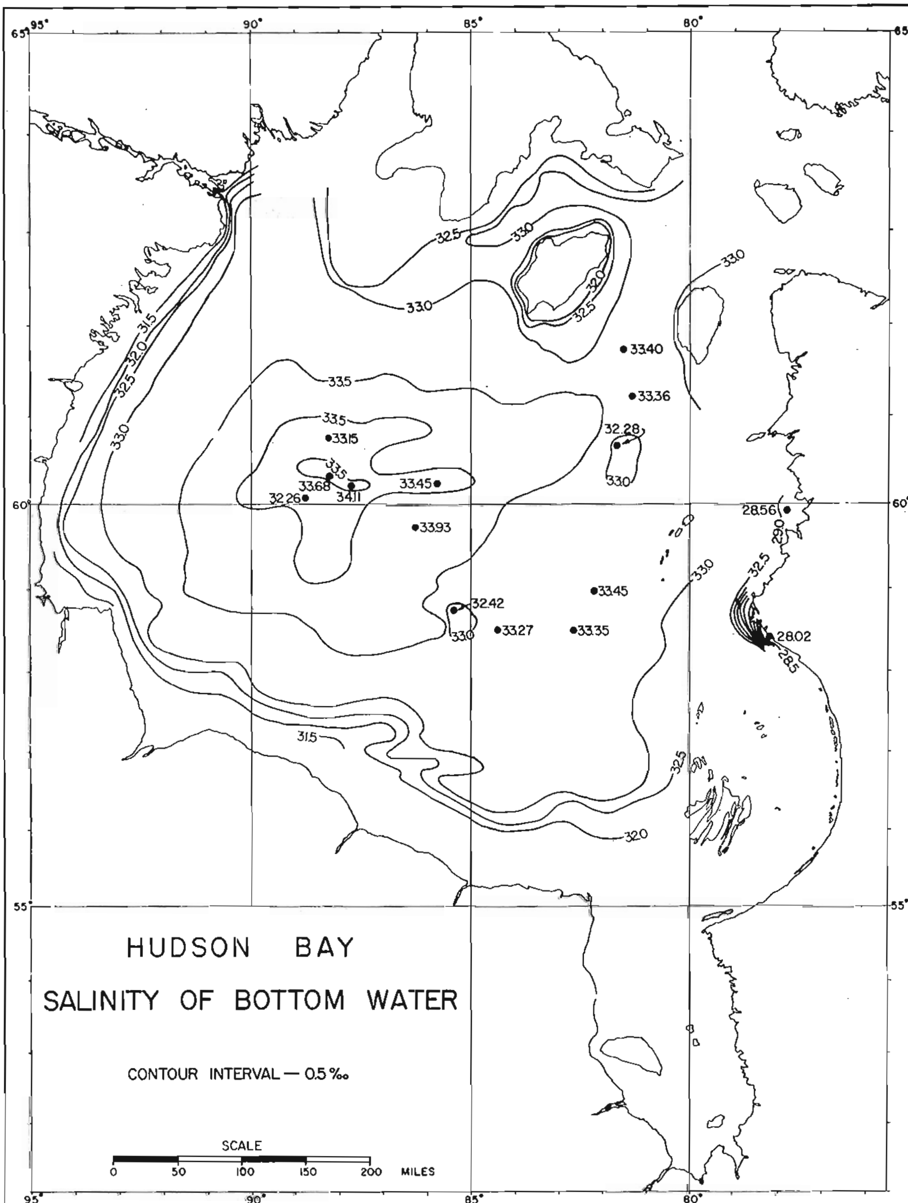


Figure 10. Salinity of bottom waters in Hudson Bay. Lowest values occur near shore due to the influence of fresh water from streams. Highest values present in deeper central area.

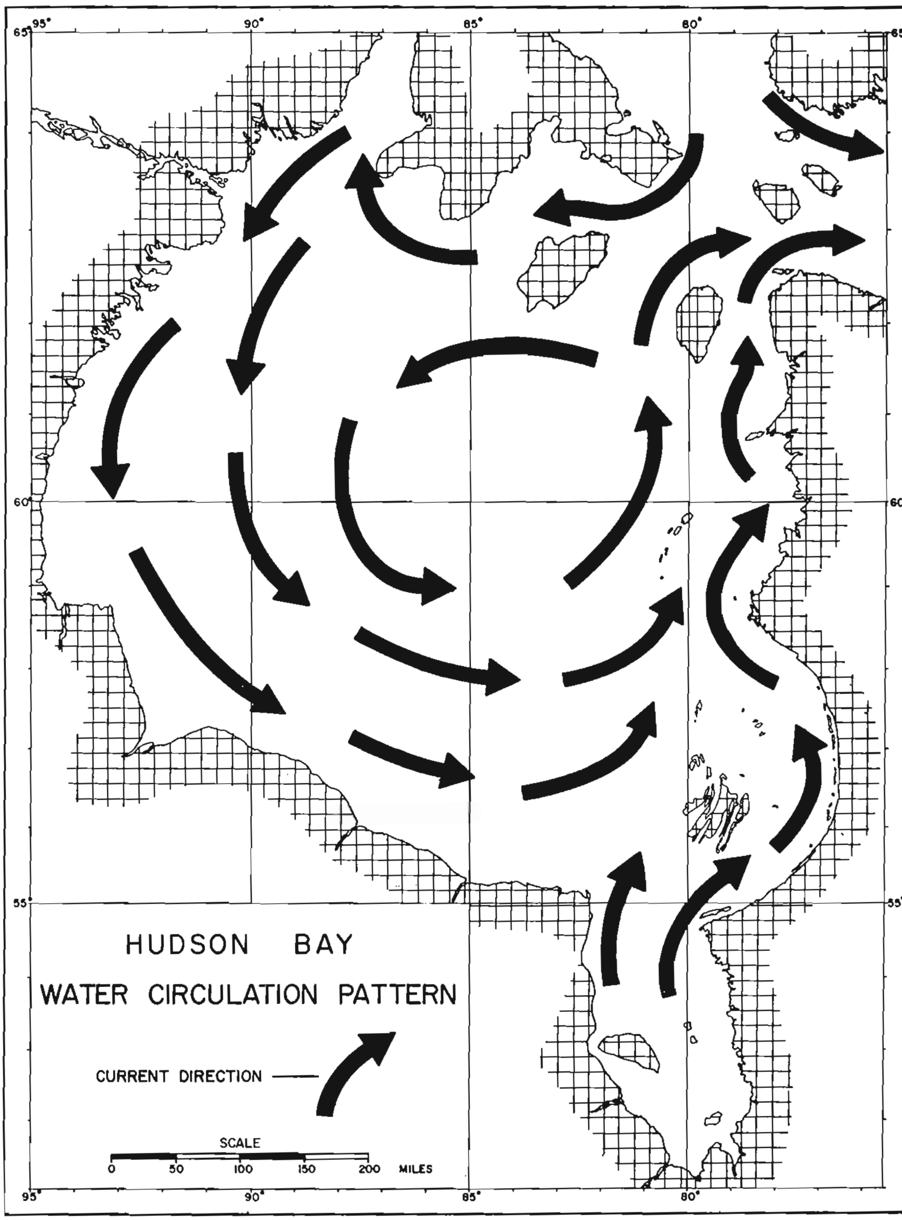


Figure 11. Water circulation in Hudson Bay as shown by H.V. Hachey (1935). The general direction of the circulation is counter-clockwise.

ice, and consequently the depositional distribution pattern of the sediments carried by the ice, must be based on this concept of the overall water circulation in the bay.

Ice-rafted Sediments

As Hudson Bay is ice-covered for several months of the year, a normal sedimentary discharge from streams flowing into the bay is inhibited. However much of the sedimentary increment is introduced by deposition from ice that has rafted sediments from the shoals adjacent to the coast. Shore ice has also removed material from the rocks and areas of unconsolidated sediments around the periphery of the bay. These deposits, which consist of boulders, angular blocks, and coarse gravels are strewn over the entire floor of Hudson Bay.

Generally the ice-rafted materials are most common within a few tens of miles from shore (Fig. 12), where currents are strongest and move the ice in a counter-clockwise direction around the bay. The areas of largest concentrations occur in the northwestern and southern parts of the bay, which areas coincide with the last refuge of winter ice. Campbell (1958) estimated that only 10 per cent of the ice in Hudson Bay actually passed out through Hudson Strait each year; therefore, a considerable portion is melted in the bay. Because much of this ice carries sediment, considerable deposition must result. Thus, ice moving off the shore and close to the coast would naturally deposit these sediments extensively in areas where the ice was so restricted and subsequently melted.

Composition of this ice-rafted debris depends in large part on the type of bedrock that occurs along the coast. On the east coast, crystalline granitic and metamorphic rocks and basic volcanic types are picked up by the ice which is moved over the adjacent sea floor by longshore currents. In the north and northwest, Paleozoic limestones are the chief contributors of sediment to the ice. In the west, additional crystalline metamorphic and granitoid rocks, as well as sedimentary formations, comprise the bulk of the contribution. Finally in the southwest and south, Paleozoic limestones and shales flank the coastline and are eroded over long distances by the ice due to higher tides and wider shoals. Because most of the ice circulation occurs during the late spring and summer, the time available for ice transportation is limited and therefore the sediments in the ice do not move great distances from their origin. This is apparent in a general sense in Figure 12, which shows the greatest concentration of ice-rafted sediments near shore.

Upon examination of the dredge hauls and snapper samples, the pebbles were sorted according to composition and angularity of shape. Because the carbonate pebbles (limestone, magnesium-rich limestone, and dolomites) were predominant, their percentage of the total number of pebbles in the sample was estimated for nearly 90 stations and plotted as Figure 13. In the central and northern areas of the bay, the carbonate pebbles are more abundant than in the extreme eastern and western regions. This is primarily due to the nature of the bordering and underlying bedrock, and is an indication that the underlying bedrock in Hudson Bay consists chiefly of carbonates. In the south, carbonate pebbles are not as prolific as would be expected considering that Paleozoic carbonate bedrock occurs along the south coast beneath the Hudson Bay Lowlands. However, the masking of carbonate pebbles by excessive increments of Precambrian pebbles has produced this

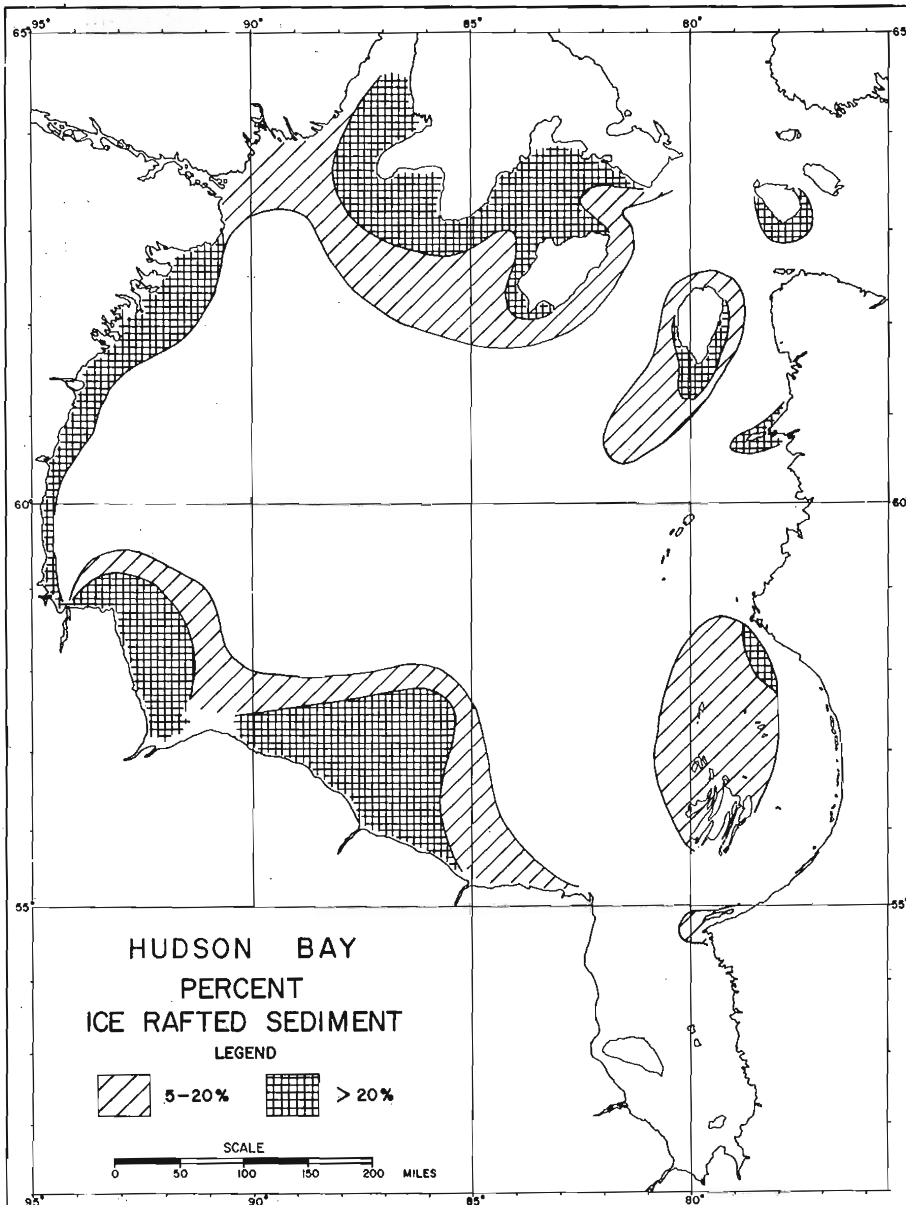


Figure 12. Distribution of ice-rafted sediments. Greatest concentration is in the southwest and north, which are areas that represent the last refuge of winter ice.

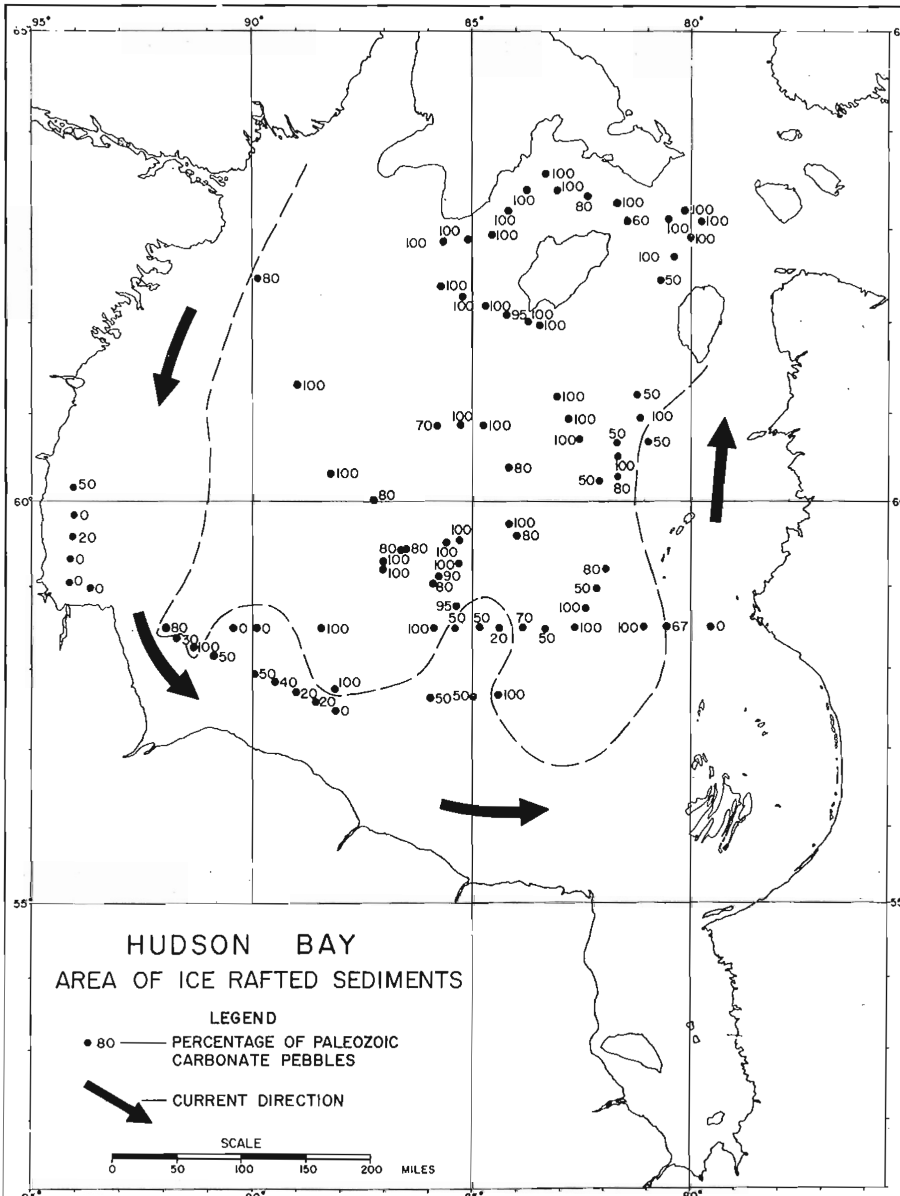


Figure 13. Percentage of Paleozoic carbonate pebbles in ice-rafted sediments. Dashed line indicates boundary between areas of high and low concentration of these pebbles. This line, exclusive of the southern boundary where masking by heavy increments of ice-rafted boulders occurs, is also the approximate boundary between the underlying Precambrian and Paleozoic rocks.

dilution. This phenomenon is expected along the south coast as it is a last refuge of winter shore ice that has picked up Precambrian pebbles and rock fragments from the west coast. Upon melting, the ice releases great quantities of Precambrian detritus to the sediments.

On the basis of shape and angularity it was possible to distinguish ice-rafted pebbles derived from distant areas, from blocks that were derived locally from bedrock. Thus Leslie and Pelletier (1965) were able to delineate broad areas in Hudson Bay underlain by different geological formations. In 1965 Shearer and Pelletier (Pelletier, 1968, in press) recognized the occurrence of a red calcareous siltstone in the central shoals in Hudson Bay, based on the fact that almost 100 per cent of the dredge hauls consisted of angular blocks. These blocks were derived from mechanically broken bedrock such as that which occurs in cases of frost shattering. Bedrock was again dredged beneath the northern waters of the bay, and consisted of broken blocks of Paleozoic limestone. These blocks were similar in shape, size and composition to the bedrock on land that had already undergone frost shattering. Therefore it is reasonable to assume that such action occurs in the bedrock comprising the central shoals, and at a time when these rocks stood above sea level and were exposed to a cold climate.

Sediment Types

Sediments obtained from Hudson Bay, apart from ice-rafted debris, are subdivided according to size as follows: gravel and blocks (greater than 2 mm in diameter), sand (1/16 to 2 mm), silt (1/256 to 1/16 mm), and clay (less than 1/256 mm). The distribution of these types is shown in Figure 14. The coarsest material occurs chiefly on the west and south coasts where currents are strongest and the tidal range is greatest. Also, several large streams contribute sediments directly to these areas of the bay whereas on the east and north coasts, the streams are small and lack the capacity for transporting large quantities of coarse material.

Coarse sediments also occur on the crest and flanks of the major topographic highs extending southerly from the central shoals. The absence of fine material here may be partly due to sedimentary by-passing, in which case the fine particles would settle in deeper water and under less turbulent hydrodynamic conditions. Also, winnowing by currents and waves at an earlier time when this shoal feature was in shallow water would result in the occurrence of a lag deposit consisting of coarse, sedimentary material.

The finer material is found in deeper waters such as in the northern and central parts of the bay, and in the broad depths extending toward Hudson Strait. In these areas currents are weakest and deposition of fine material takes place. Between the broad central area of fine sediments and the narrower coastal area of coarse sediments, lies an intermediate area of intermediate sizes. This phenomenon is expected as currents generally become weaker progressively from shore and are unable to transport large fragments. Accompanying this progressive lessening of hydrodynamic vigour is the occurrence of progressively deeper waters. Therefore the shore zone is the shallowest, most turbulent and receives the coarsest water-borne sediments, whereas the central area is the deepest, least turbulent and receives the finest water-borne sediments.

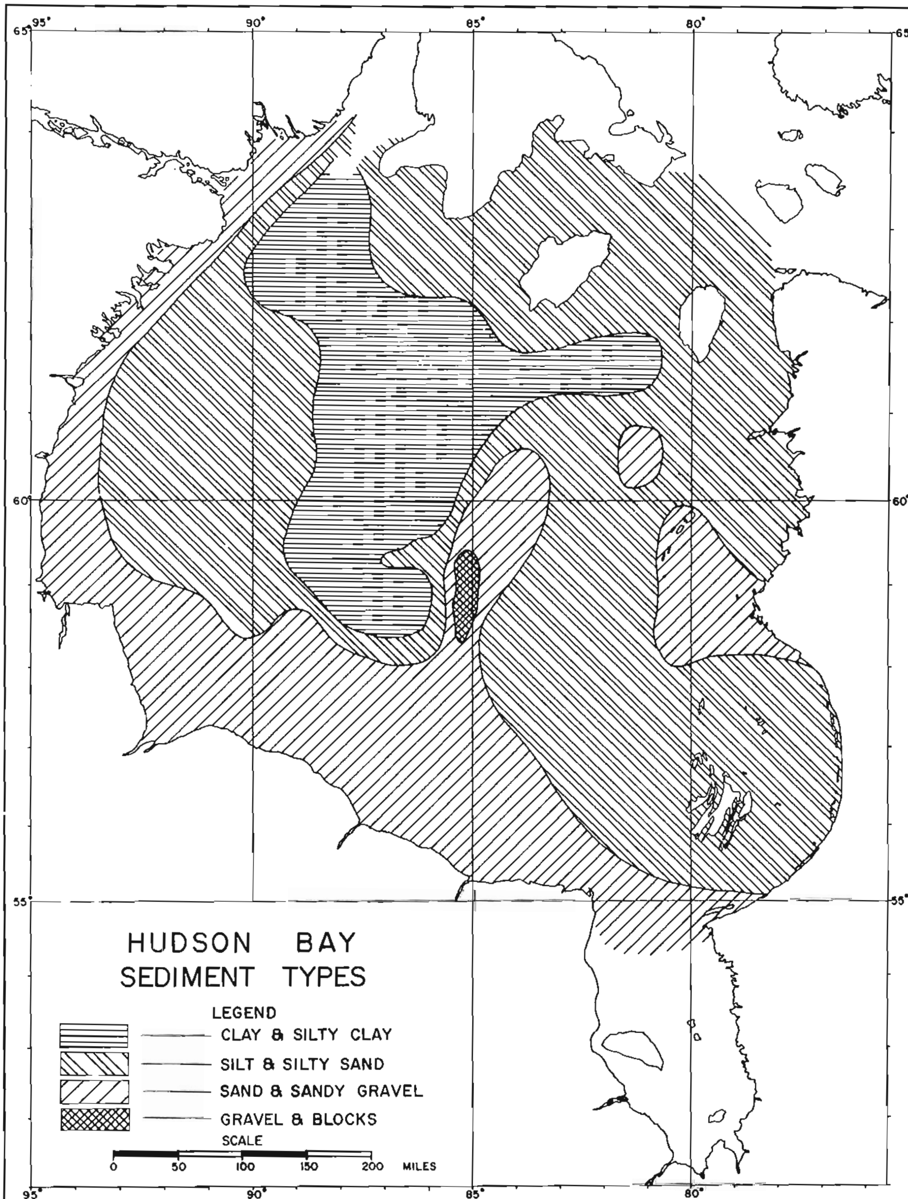


Figure 14. Distribution of various types of sediments in Hudson Bay. Generally coarser material occurs in the west, and finer in the east and central portion. However, coarse material does occur over the central shoals.

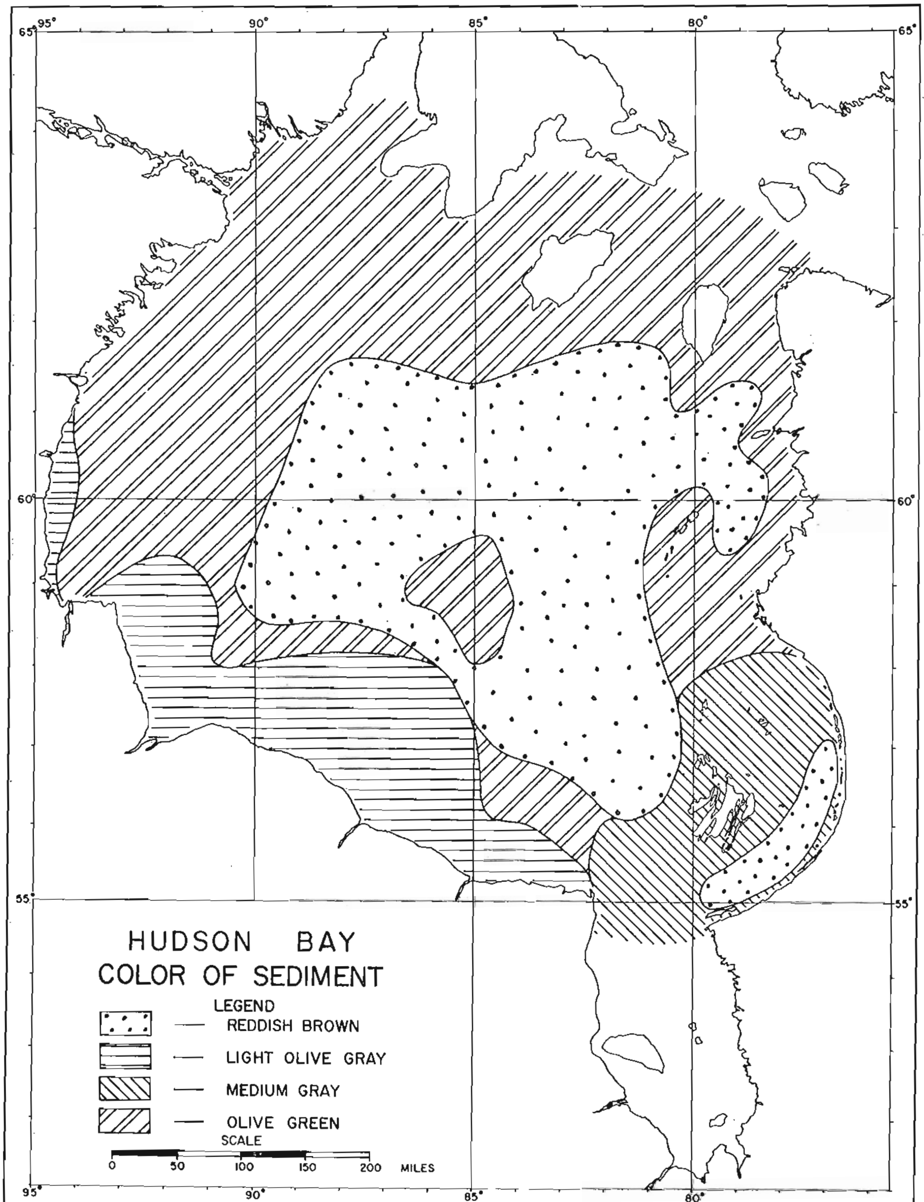


Figure 15. Colour of sediment in Hudson Bay. The deeper areas generally contain reddish brown sediments due to oxidation during a long, slow sedimentary descent of particles to sea bottom. Other areas are grey and greenish and reflect the nature of the source material bordering and underlying the bay.

Colour of Sediments

This aspect of sedimentation in Hudson Bay was reported first by Leslie (1963) and was observed further by Stewart, Shearer and Pelletier in 1965 (unpublished notes). The distribution pattern of the colour of the sediments is shown in Fig. 15. The bulk of the sediments in Hudson Bay are grey to olive green, and these are found in all areas exclusive of the central depths. These grey and olive green sediments consist chiefly of carbonate and shale fragments and are probably derived from the Paleozoic formations discussed previously. Thus nature of the source material appears to bear some relationship to the colour of the coarse silts and larger particles.

In the central depths and in the troughs adjacent to the Belcher Islands, the sediments are mainly reddish brown in colour. This colour extends through a depth of several inches, forming a thin veneer over much of the sea floor. Leslie attributed the origin of this layer to oxidation of slowly settling fine sediments in water of high oxygen content. Oxygen values for bottom waters (Fig. 9) indicate that no relationship exists between the content of oxygen and the colour of the sediment in the present immediate environment of deposition. However the effect of oxygen on the sediments over long periods of descent to the sea floor must not be discounted and is probably a more realistic interpretation of coloration of the fine sediments in these deeper waters.

Chemical Studies of the Sediments

The first chemical studies of the sediments in Hudson Bay were carried out by Leslie (1963). He determined the amount of calcium carbonate in the sediments as well as the content of organic carbon, and delineated several major areas in the bay of high and low values. These studies are augmented in the present report with data from an additional 200 analyses and the revised plots (Figs. 16 and 17) indicate similar areas of high and low values.

As in the case of the percentage of carbonate pebbles, the lowest values of carbonate content occur in the eastern and western region of the bay with high values in the central region (Fig. 16). The highest values are concentrated around the northern islands which consist predominately of Paleozoic limestones. The low values in the east and west are due to the proximity of non-calcareous rocks. The southern area should be richer in lime but due to excessive increments of ice-rafted material, the carbonate content in this area is considerably diluted. However the content of lime in this area is nevertheless considerably greater than in areas adjacent to the Canadian Shield.

In general, the areas adjacent to the northern islands, southern coast, and overlying the central shoals lie in close proximity to limestone bedrock, and all are in shallow water. It is therefore conceivable that these areas underwent subaerial erosion and weathering when they stood higher relative to sea level, and that lime products were contributed to the sediments at an earlier date. These areas are presently contributing mechanically eroded particles of fine sizes that would enrich the lime content of the sediments. Thus the high content of calcium carbonate in these areas is partly related to the nature of the underlying and bordering geological formations.

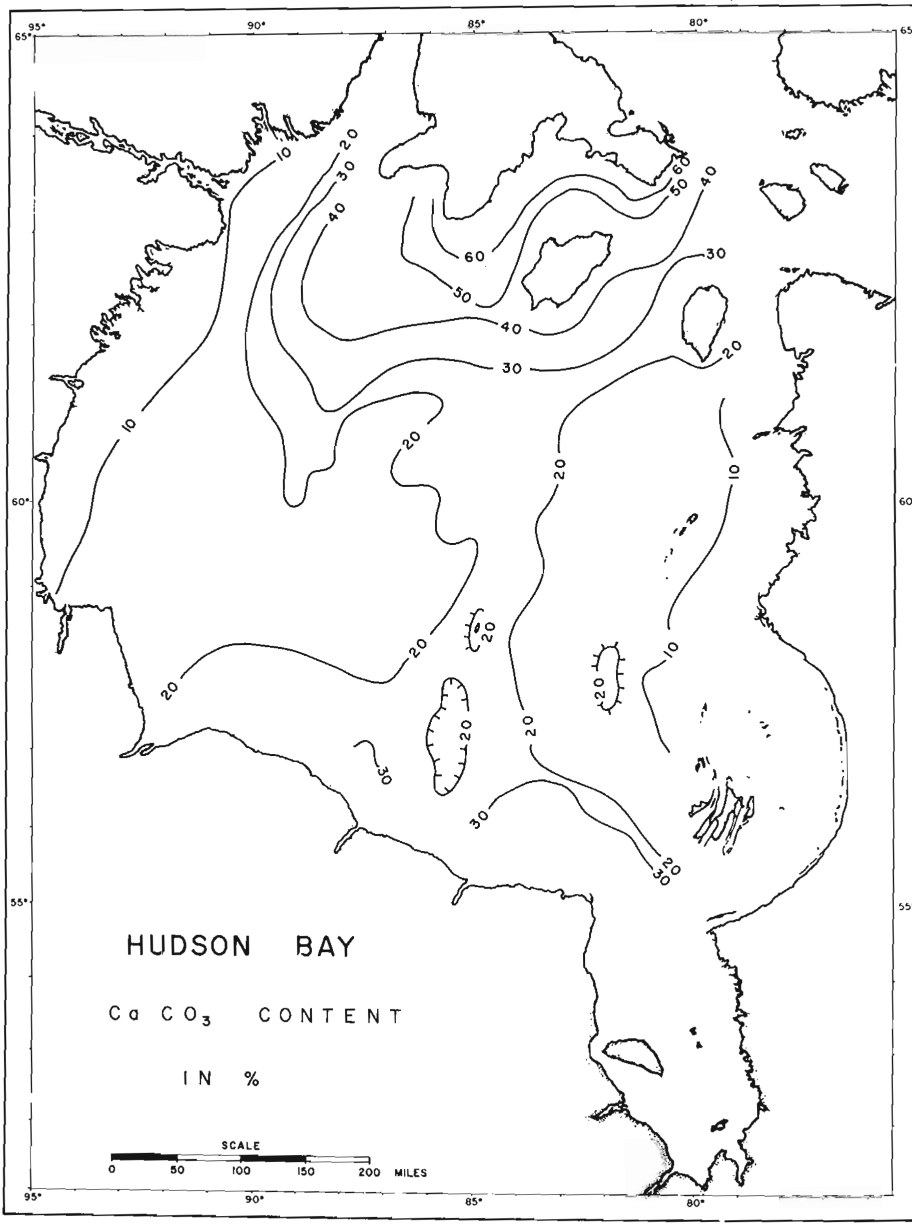


Figure 16. Distribution of calcium carbonate (lime) in the finer sediments in Hudson Bay. Generally the high lime content occurs in areas adjacent to, or underlain by Paleozoic limestones. Low values of lime are reported for the areas underlain by Precambrian rocks.

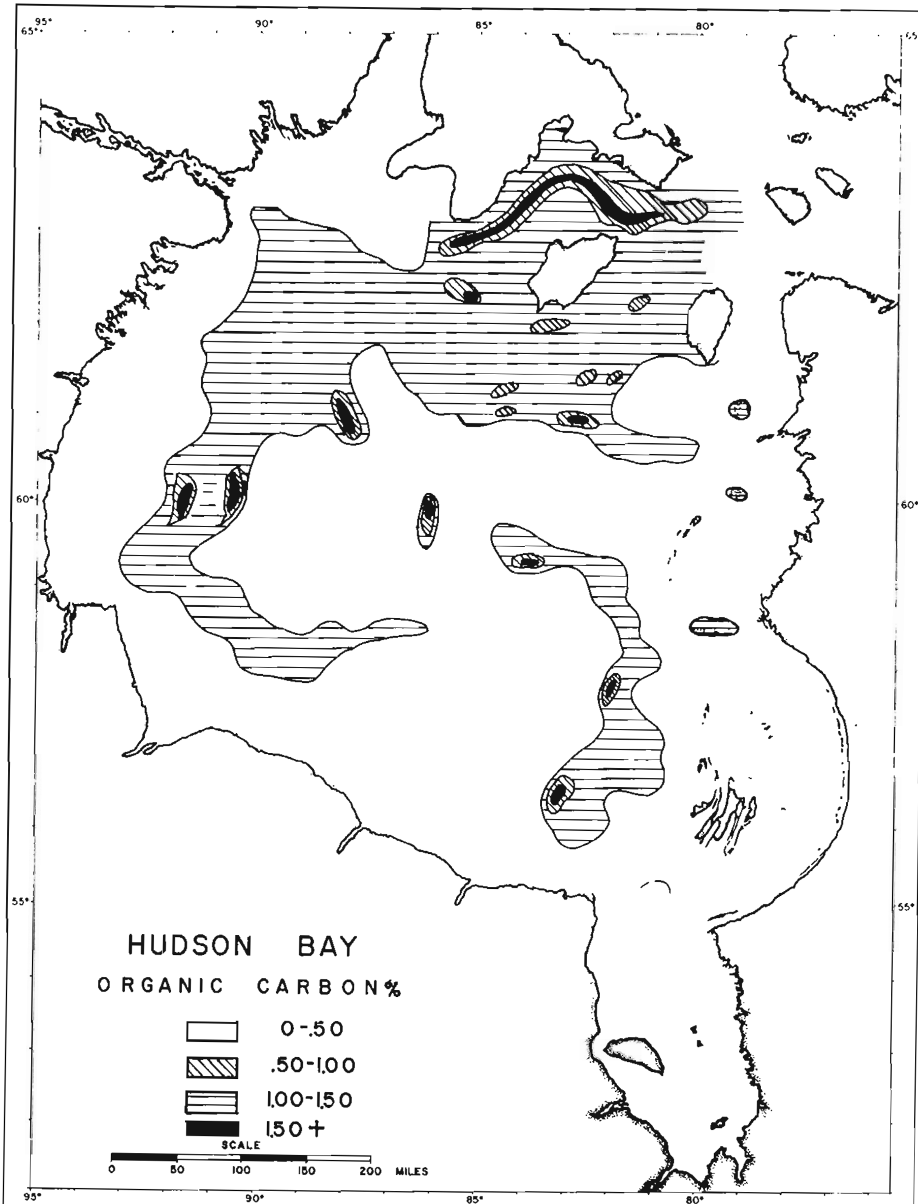


Figure 17. Content of organic carbon in the finer sediments in Hudson Bay. Highest values are associated with the finest sediments in the deepest areas. Lowest values occur close to shore where depositional processes are more rigorous and considerable masking by ice-borne debris occurs.

Increments of glacial flour consisting of finely comminuted carbonate rocks, sediments and shells, are derived from land and carried seaward to the central depths where they are deposited with other fine material. Foraminifera reported by Leslie (1963, 1965) and Wagner (this volume) would also account for some of the lime content. However the bulk of the calcium carbonate in the sediments appears to be derived mechanically, and to a lesser extent chemically, from the bordering and underlying areas of carbonate rocks.

Organic Carbon

The amount of organic carbon in the sediments from the floor of Hudson Bay ranges from 0.03 to 3.93 (analyses by K. Robertson and G. Duncan, Bedford Institute). However, the mean values for the four ranges of values shown in Fig. 17, are as follows: for the range 0-.50 per cent, the mean is .25; for .50-1.00 per cent, the mean is .71; for 1.00-1.50 per cent, the mean is 1.26; and for values greater than 1.50 per cent the mean is 2.2. The overall mean is .57. The highest values are associated with areas that receive fine sediments and this is expected, as the fine organic particles settle slowly with the fine clay particles. However in the deepest areas where clays are commonest, the organic carbon content is only intermediate in value. As these are broad areas occupied by the reddish brown sediments which are thought to be the oxidized particles of long sedimentation, it is further thought that organic carbon has also been oxidized during the descent to sea floor in this same, long sedimentary regime. Therefore in these localities carbon values would be somewhat lower. By the same reasoning, carbon values north of Coats Island are high as this is a shallow area receiving exceptionally large increments of fine sediments from the heavily laden Foxe Basin ice which drifts annually through this passage. Sedimentation is sufficiently rapid to inhibit long-continued oxidation of the particles containing organic carbon, and thus the value of organic carbon remains high.

Very low amounts of organic carbon occur in areas receiving the coarsest sediments in the bay, and in those areas affected greatly by increments of ice-rafted debris. Because the organic particles are associated with slowly settling fine particles it is not expected that high amounts of organic carbon will be associated with coarse, vigorous sedimentation.

It is interesting to note that no positive correlation of oxygen values with organic carbon values prevails for the sediments in Hudson Bay. High oxygen values are present in areas occupied by sediments of low carbon content such as in the south and west. High oxygen values are also present in areas which contain sediments of intermediate values of organic carbon, such as coastal areas in the east, at the central shoals, and the northern islands. Finally high oxygen values coincide with areas wherein sediments containing large amounts of organic carbon are found, such as in the northeastern trough near Hudson Strait and the area immediately to the south and off the east coast. Similar comparisons can be made for intermediate and lower values of dissolved oxygen content in the bottom waters of the bay. This lack of correlation is to be expected as the supply of oxygen in the water appears to be sufficient everywhere to support oxidation processes.

The overall distribution of the organic carbon content in Hudson Bay is most striking when related to the physiography of the sea floor. The mid-bay ridge in the south separates two basins in which the sediments contain high percentages of organic carbon. This relationship again shows the important and far-ranging influence of the ridge on oceanographic, geological, and chemical aspects of the sediments in Hudson Bay.

Models of Sedimentary Transport

The two main agents of sedimentary transport in Hudson Bay are marine currents and ice. Because the influences of these agents are superposed over physiographic features, bottom topography must be considered in the evaluation of suitable models to demonstrate sediment transport in the bay. A third factor, the sediments themselves, are so closely inter-related with transporting agents and physiography that they may be defined on either basis. Consequently, three topographic environments have been selected on the basis of depth and slope, and the sediments have been related to these environments. These environments and their arbitrary bathymetric limits are as follows: the shelf ranging in depth from 0 to 80 metres; the slope, ranging in depth from 80 to 160 metres; and the deeps, which exceed depths of 160 metres. These environments are further qualified in that some relatively deep areas and adjacent slopes may be found locally in the shelf zone but are not classified with shelf or deeps as they would present anomalous positions in the models. As this occurs in less than 10 per cent of the samples, the overall theory of the model can be considered valid for practical purposes.

Before attempting the construction of the models, the lithologic ratios of each sample, based on the textural analysis, was plotted on a ternary diagram (Fig. 18). This plot includes all sizes of particles and is based on the following limits; gravel (> 2 mm), sand (2 - .062 mm), and mud (< .062 mm). As well as plotting the sediments according to their mechanical composition, they were plotted according to the physiographic environment in which they were deposited. It became apparent immediately that the muddy sediments were found mainly in the deeps and lower slopes, while the deposits of sand and gravel were found mainly on the shelf and upper slope. However, the widespread distribution of the textural plot of the sediments over the entire diagram indicated that a normal progression of sedimentary textures from coarse to fine did not prevail particularly as so many analyses were plotted on the gravel-mud side. If progressive sorting by marine currents had acted solely on these sediments during sedimentary transport, the ideal plot would show the distribution of the sediments along the gravel-sand-mud boundary, that is, in an anticlockwise direction around the diagram from the gravel apex. The fact that it is otherwise suggests that coarse sediments were deposited from suspension, such as in ice-rafting, and that this mechanism produced anomalous marine deposits over most of the bay.

Arbitrarily the sediments coarser than 2 mm were designated, as ice-rafted material and removed from the analysis. New lithologic ratios consisting of sand (2 - .062 mm), silt (.062 - .004 mm) and clay (< .004 mm), were calculated and plotted in a second ternary diagram (Fig. 19). The new plot was revealing in that the distribution of the sediments was now clustered closer to the sand-silt-clay sides than to the sand-clay side. This indicated a more ideal dispersion in that progressive sorting from high energy areas such as the shelf, to low energy areas such as the deeps, was taking place. Also apparent were fewer occurrences of sediments released from the ice as

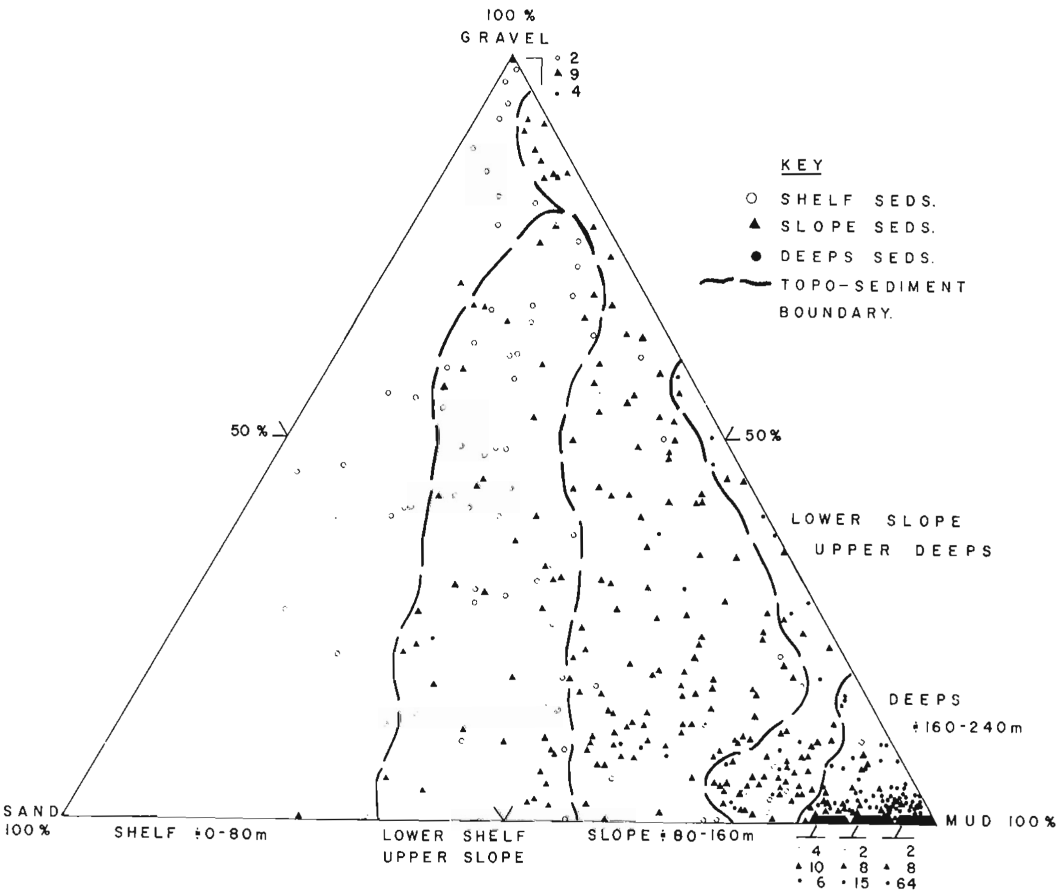


Figure 18. Ternary diagram of lithologic ratios of all size grades of Hudson Bay bottom sediments and their relationship to topographic environments Heavy dashed lines arbitrarily separate various topographic-sediment fields showing natural division of coarser sediments in shallow waters and finer in deeps. Effect of ice-rafting is apparent as some coarse material is found in deeps. Numerals in lower right indicate samples not plotted individually.

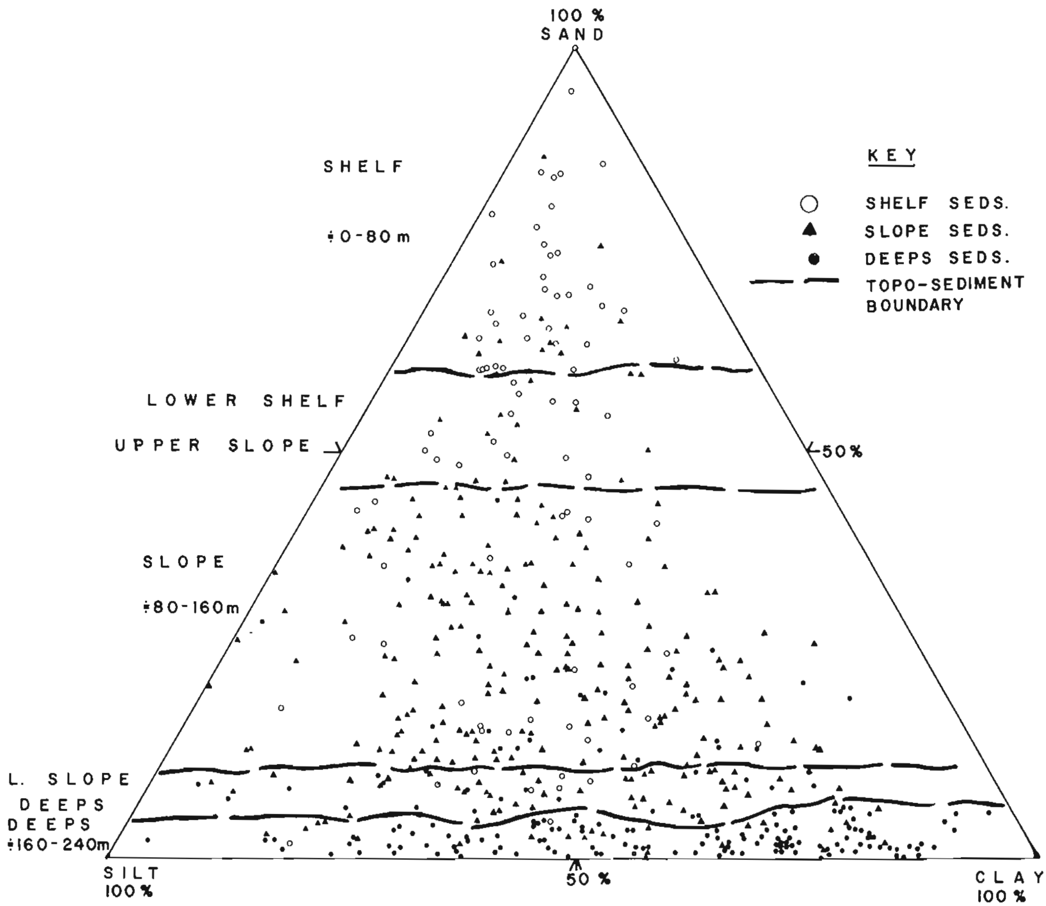


Figure 19. Ternary diagram of lithologic ratios of sand and smaller sizes in sediment samples from Hudson Bay. With removal of gravel content, ratios plot at some distance from sand-clay side which is axis representing material deposited from suspension. A more clearly defined series of topographic - sediment fields emerges.

the latter circulated around the bay. However it is certain that sand, silt and clay were transported in variable amounts by this means according to the proximity of the ice-route to the shore.

As most of the ice transportation takes place in peripheral areas of the bay with minor movement across the bay during early summer when the bay becomes free of ice, more sediments of ice-rafted origin should be found in the shelf zone and less in the deeps. This was considered when recalculating the lithologic ratios to show the plot of that proportion of sediments affected only by marine currents. Also considered was the fact that the bulk of the material transported, by weight, consisted of pebbles and boulders. In the shelf zone, from Figure 12, at least 20 per cent of the material is ice-rafted; in the slope zone, the amount varied from 5-20 per cent with the higher figure representing the sediments from the upper slope; in the deeps the amount varied from 0 to 5 per cent.

It is difficult to estimate from each fraction the amount that was ice-rafted and deposited from suspension, and the amount that was dispersed by marine agencies along the sea floor. By assuming an ideal situation in which no sediments would be deposited from suspension, the resulting ternary plot of sand-silt-clay would show an absence of sediments along the sand-clay side. This would be based on the premise that progressive sorting occurred from regions of high energy to those of low energy as represented by the shelf environment in which sand predominates, to the slope where silt predominates, to the deeps where clay predominates. Thus the theoretical dispersal pattern for sediments related to such a hypothetical sea floor would be a single-line plot along the sand-silt and silt-clay sides only.

Based on the observation that more coarse than fine material is ice-rafted, mainly because the sediment is picked up by the ice in near-shore zones where the sediments are coarser, the recalculation of lithologic ratios was next made on the sand fraction. By subtracting 20 per cent in the shelf zone, 5-20 per cent in the slope zone and less than 5 per cent in the deep zone, the remaining silt and clay fractions were correspondingly increased. This had the effect of moving the dispersal pattern of the sediment on the ternary plot further from the sand-clay side and closer to the ideal dispersal pattern of sediments transported by marine currents only. This is shown in Figure 20. The left panel shows that ice-rafting together with marine currents were responsible for the dispersal pattern shown on this diagram. This should be compared with Figure 18 from which it was inferred. In Figure 20, the centre panel shows the effect of partial ice-rafting in that the gravel (and coarser sizes) have been removed from the plot. This should be compared to Figure 19 from which this construction was inferred. In Figure 20, the panel on the right represents the situation wherein only the agency of marine currents produces the dispersal pattern of the sediments. This model is based on the ternary plot in Figure 19, and represents the position of the deeply curved sand-clay boundary after the ice-rafted sand was removed from the analysis.

SUMMARY AND CONCLUSIONS

The dominant physiographic trends in Hudson Bay are the concentric bathymetric contours which parallel the peripheral areas of the bay and trend seaward around the long mid-bay ridge that terminates at the central shoals. This ridge is easily the most dominant physiographic feature in

MODELS OF SEDIMENTARY TRANSPORT IN HUDSON BAY

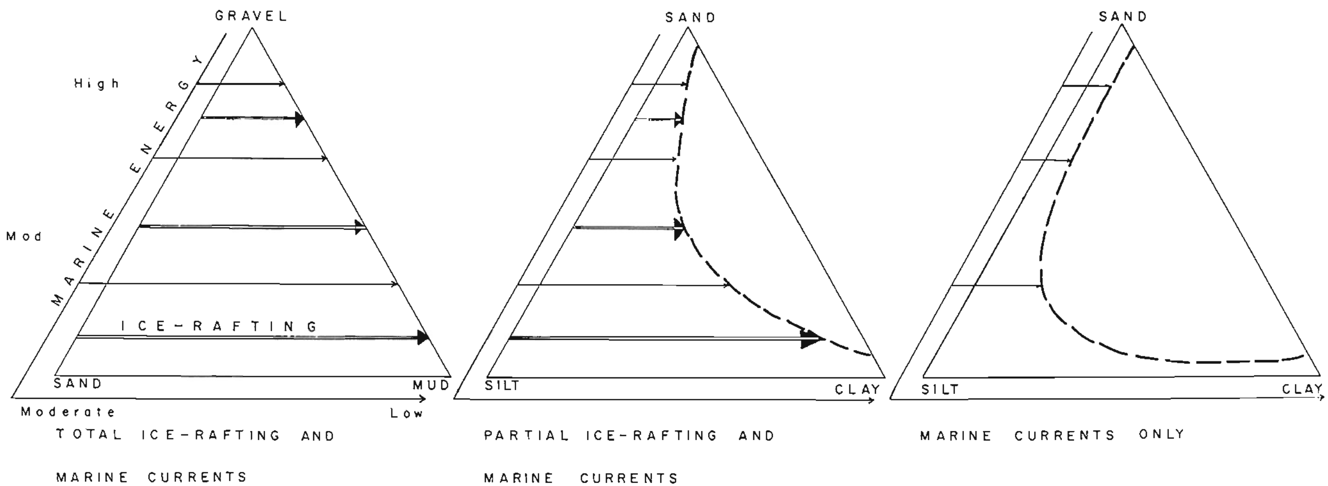


Figure 20. Sediment transport with reference to ice-rafting and marine currents is shown in relationship to the ternary lithologic diagrams. In left panel, gravel apex represents sediments deposited from a high energy zone, whole sand and clay apices represent progressively decreasing energy zones. Gravel-clay side represents deposition from suspension, hence arrows depicting ice-rafting cross entire diagram as ice is active over all topographic fields. Similarly marine energy is active over all fields and decreases progressively toward deeps. Centre panel shows dispersion area of sediments removed from sand-clay side, as gravity deposition from ice (gravels removed here) becomes less important. Right panel shows dispersion area of sediments removed almost entirely from sand-clay side when ice-rafting is absent.

Hudson Bay as it influences the origin of subsidiary physiographic features, such as a preglacial drainage pattern, and divides the southern part of the bay into two major basins of almost equal depth. The ridge separates the bottom water mass into two separate areas of low temperature, low dissolved oxygen content, and high salinity values. It also separates areas of sediments which contain relatively high amounts of organic carbon and relatively low content of calcium carbonate, from areas of low oxygen carbon content and high percentages of calcium carbonate. Over this ridge the sediments are thinner and coarser than the basinal sediments on its flanks.

The deep linear troughs appear to represent terrestrial erosion and glaciation along a pre-existing river channel which owes its location to some structural dislocation in the earth's crust. Subsidiary trunk systems with more subdued relief appear to be the relics of a submerged drainage system that existed in Hudson Bay prior to the period of Pleistocene glaciation. In shallow areas, this trunk system is less modified by glacial action and may have been exposed during part of the glacial epoch. Frost heaved blocks in the shoals suggest that this may have occurred.

Sediments in Hudson Bay owe their origin primarily to fluvial increments with subsequent dispersal brought about by means of marine currents, and secondarily, to ice-rafting which has disrupted the normal marine sedimentary sequence and has produced many anomalous occurrences of extremely coarse sediments forming an admixture with clays and silts in areas of hydrodynamically quiet sedimentation. The models of sedimentary transport, based on lithological ratios, topographic depth zones, and agents of sedimentary transport show the influence of ice-rafting over all energy zones and topographic environments. By removing the ice-rafted debris, a recalculated plot of the lithologic ratios in relationship to the energy zones shows the dispersal pattern of the sediment to approximate that found on a hypothetical sea floor underlying zones of similar hydrodynamic vigour.

REFERENCES

Barber, F.G.
1967: A contribution to the oceanography of Hudson Bay; Marine Sci. Br., Can. Dept. Energy, Mines, Resources, Ms. Rept. Ser. No. 4, p. 69.

Barber, F.G., and Glennie, C.L.
1964: On the oceanography of Hudson Bay, an atlas presentation of data obtained in 1961; Marine Sci. Br., Can. Dept. Mines, Tech. Surv., Ms. Rept. Ser. No. 1, p. 98.

Bird, J.B.
1953: Southampton Island; Geograph. Br., Can. Dept. Mines, Tech. Surv., Mem. 7.

Caley, J.F., and Liberty, B.A.
1957: The St. Lawrence and Hudson Bay Lowlands, and Paleozoic Outliers; in Geology and economic minerals of Canada, Geol. Surv. Can., Econ. Geol. Ser. 1, 4th Ed., pp. 207-246.

Campbell, N.J.
1958: The oceanography of Hudson Strait; Fisheries Res. Board Can., Ms. Rept. No. 12, p. 60.

Hachey, H.B.
1931: The general hydrography and hydrodynamics of the waters of the Hudson Bay Region; Contrib. Can. Biol. Fish., n.s., vol. 7, No. 9, pp. 93-118.

1935: The circulation of Hudson Bay water as indicated by drift bottles; Science, vol. 82, pp. 275-276.

Hood, P.
1966: Geophysical reconnaissance of Hudson Bay; Geol. Surv. Can., Paper 65-32, p. 42.

Leslie, R.J.
1963: Foraminiferal study of a cross-section of Hudson Bay, Canada; Geol. Surv. Can., Paper 63-16, p. 28.

1965: Ecology and paleoecology of Hudson Bay Foraminifera; Bedford Inst. Oceanog., Rept. 65-6, p. 192.

Leslie, R.J., and Pelletier, B.R.
1965: Bedrock geology beneath Hudson Bay as interpreted from submarine physiography; Bedford Inst. Oceanog., Rept. 65-12, p. 18.

Low, A.P.
1903: Report on an exploration of the east coast of Hudson Bay from Cape Wolstenholme to the south end of James Bay; Geol. Surv. Can., Ann. Rept., n.s., vol. 13 (1900), Pt. D, p. 84.

1906: Report on the Dominion Government expedition to Hudson Bay and the Arctic Islands on board D.G.S. Neptune, 1903-04; Geol. Surv. Can., Pub. No. 905, p. 355.

Pelletier, B.R.
1966: Marine geology of the Canadian Arctic Archipelago and Baffin Bay; Hudson Bay and Approaches. Encyclopedia Earth Sci., vol. 1, pp. 157-168, 359-363.

Pelletier, B.R., Wagner, F.J.E., and Grant, A.C.
1968: Marine geological investigations in Hudson Bay; in Science, History and Hudson Bay, vol. II, Chapt. 9, Pt. III, Can. Dept. Energy, Mines, Resources, pp. 557-613.

Trask, P.D.
1932: Origin and environment of source sediments of petroleum; Gulf Pub. Company, Houston, Texas, p. 323.

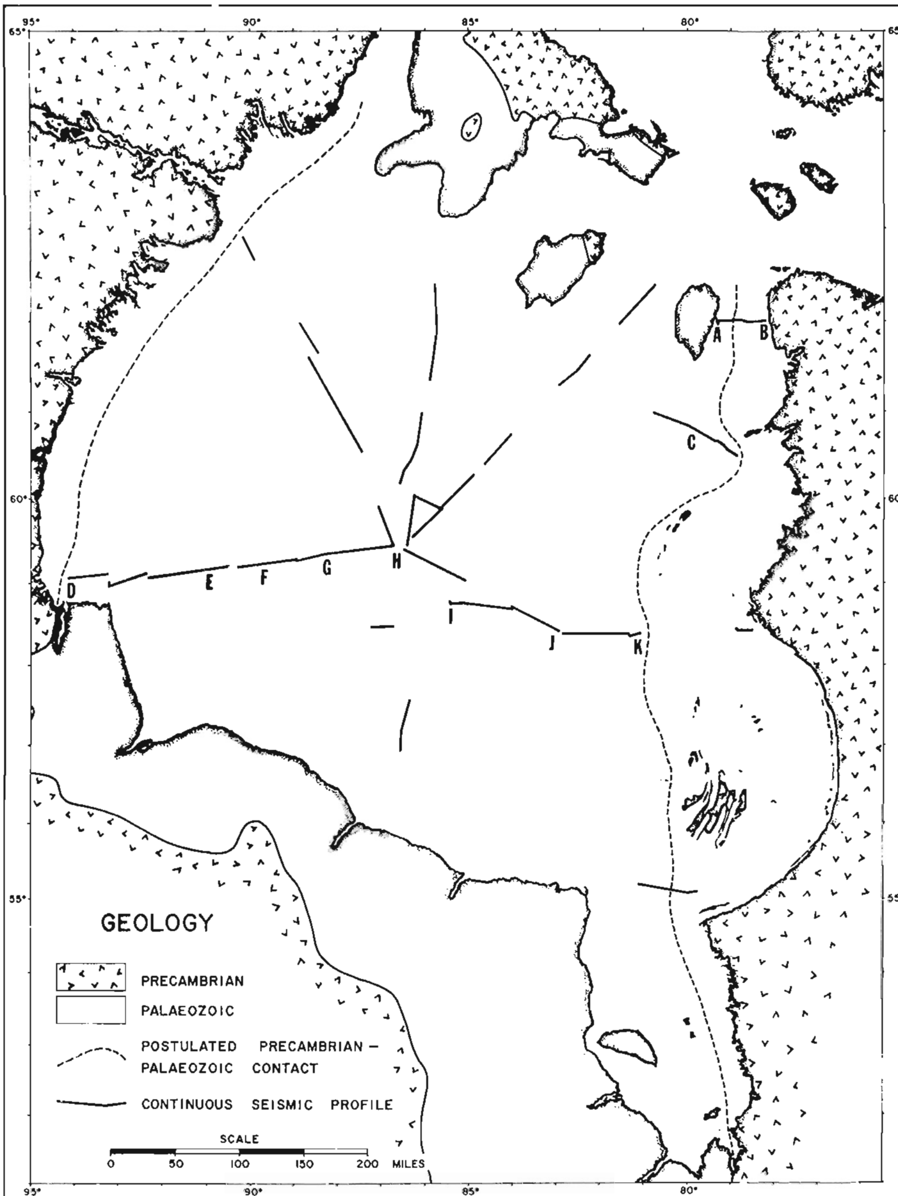


Figure 1. Generalize geology of Hudson Bay region showing postulated Paleozoic-Precambrian contact beneath Hudson Bay. The heavy lines indicate the location of continuous seismic profiles described in this paper.

SOME ASPECTS OF THE BEDROCK GEOLOGY OF HUDSON BAY AS INTERPRETED FROM CONTINUOUS SEISMIC REFLECTION PROFILES

A. C. Grant
Atlantic Oceanographic Laboratory, Bedford Institute
Dartmouth, Nova Scotia

Abstract

Continuous seismic reflection profiles indicate that the Paleozoic sedimentary rocks beneath Hudson Bay comprise a basinal structure. Regional strike determinations indicate north-south elongation of this basin, and the major topographic trends are considered to be a reflection of bedrock structure. In particular, the western slope of the 'central shoal' feature is a dip slope, and the eastern side is an erosional escarpment truncating the west-dipping beds. Structure imposed subsequent to the deposition of the Paleozoic sediments in Hudson Bay may have influenced the development of drainage features. These features were the centres of considerable drift accumulation during Pleistocene time.

INTRODUCTION

During the summer of 1965 more than 1,100 miles of continuous seismic profiling was obtained in Hudson Bay as a contribution to the Hudson Bay Oceanographic Project of the Department of Energy, Mines and Resources. This survey method was applied in order to study the bathymetry, the thickness and composition of the unconsolidated bottom sediments, the configuration of the underlying bedrock surface, and the lithology and structure of the bedrock. Slightly more than half of the continuous seismic profile coverage was obtained with an Alpine Model 501-200 'Sparker', and the remainder with a Huntec Model 2A 'Hydrosonde'. The energy output of these two units is rated at 200 and 160 joules respectively. Under favourable operating conditions sub-bottom reflectors were traced to depths of several hundred feet. This paper deals with the results of this survey mainly as they pertain to the bedrock structure in Hudson Bay.

RESULTS

Figure 1 shows the general geology of the Hudson Bay region, and also indicates the location of the survey lines of continuous seismic profiling. In particular, this figure shows the postulated limit of the distribution of Paleozoic rocks within Hudson Bay. The Paleozoic-Precambrian contact was verified on profiles A-B and X-Y (Fig. 1) by continuous seismic profiling; elsewhere in the bay the location of the contact has been interpreted on the basis of submarine physiography as drawn from echo-sounding records (Pelletier and Leslie, 1965).

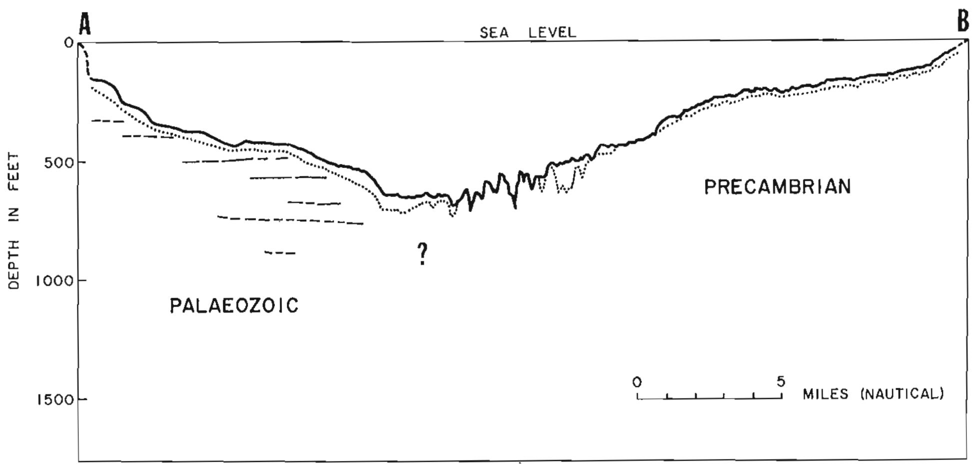


Figure 2. Seismic cross-section derived from profile between Mansel Island on left and Quebec mainland on right. (See Fig. 1 for locations). Vertical to horizontal scale exaggeration approximately 50 to 1.

Cross-section A-B (Fig. 2) is a generalized interpretation of one of the profiles across the Paleozoic-Precambrian contact, between Mansel Island and the Quebec mainland to the east. Although the vertical scale is greatly exaggerated - approximately 50 to 1 - this section illustrates the characteristic change in bottom physiography commonly encountered in traversing from Paleozoic to Precambrian bedrock, and also shows the apparent difference in penetration of seismic energy into the Paleozoic sedimentary rocks as opposed to the Precambrian crystalline rocks. The near-horizontal lines on the Paleozoic side of the section represent reflecting horizons. The dotted line on the section indicates the approximate thickness of unconsolidated bottom sediment. Based mainly upon refraction seismic information (Hobson, 1964, 1966) velocities of 7,500 ft/sec and 15,000 ft/sec have been applied to bottom sediment and bedrock respectively, in order to effect a better approximation of the depth to sub-bottom reflectors on the cross-section.

Bathymetrically, Hudson Bay is a shallow basinal feature (Fig. 3), with gradual increase in depth to about 240 metres at its centre. A prominent shoal area (the so-called 'central shoal') strikes northward into the Bay at about latitude 59° north, longitude 85° west. Most of the continuous seismic profiles extend along several lines that radiate from the approximate geographical centre of the bay. Apparent dips observed in the sub-bottom bedrock along these lines, with the exception of a few minor reversals, are

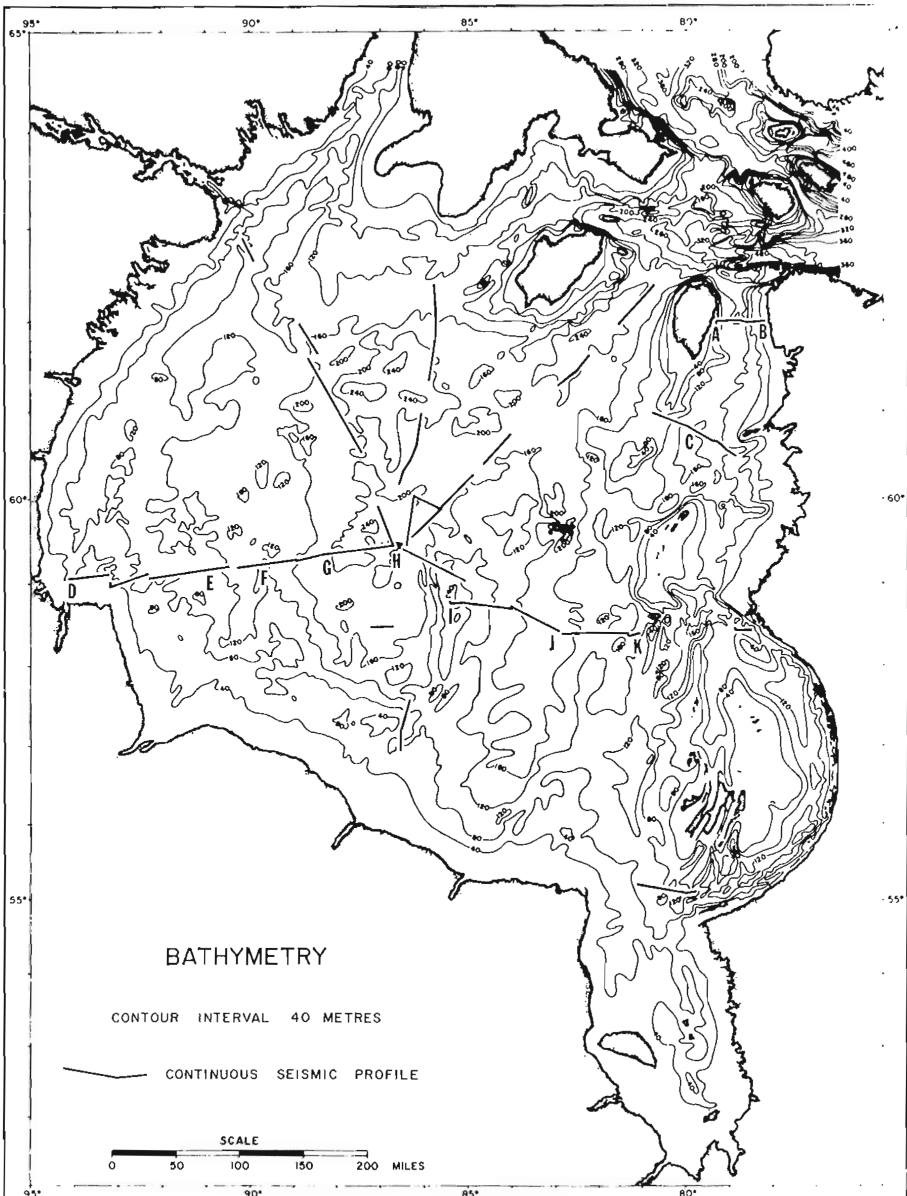


Figure 3. Bathymetry of Hudson Bay with locations of continuous seismic profiles.

practically all at a low angle toward the centre of the bay. On a broad scale, therefore, the Paleozoic sedimentary rocks beneath the waters of Hudson Bay – like the bay itself – appear to comprise a basinal structure.

Cross-section D-K (Fig. 4) is compiled from the series of continuous seismic profiles that afford nearly uninterrupted coverage east-west across Hudson Bay. A number of points along the section have been lettered to indicate their position on the regional maps. The vertical scale on this section is exaggerated by a factor of approximately 340 to 1, and the sub-bottom velocity considerations mentioned above have been applied in order to derive dips. Reference to the dip scale appearing on the section shows that few of the indicated dips exceed 30 feet per mile, which is less than one-half degree. Even locally few dips were observed that were greater than 3 or 4 degrees. The depth to which data have been plotted on the section is a rough indication of the depth to which sub-bottom information was recorded. Although there is considerable generalization of data in such a presentation, the section does serve to illustrate the regional picture of bedrock structure in Hudson Bay as interpreted from the continuous seismic profiler records.

From the western end of the section (D) eastward to point G the continuous seismic profiles generally show sub-bottom reflectors dipping at a low angle to the east, with a few localized areas of reversal and distortion. From point G to the centre of the bay (H) the sub-bottom reflectors are apparently flat-lying, until west-dipping reflectors are encountered as the bottom rises toward the 'central shoal' feature (I). Record quality deteriorates somewhat to the east of this point and the sub-bottom reflectors become irregular and discontinuous. Westward dip appears to predominate, however, until Precambrian rocks are encountered on the eastern side of the bay (K). The 'central shoal' would appear to be an erosional escarpment, with truncation of strata along its eastern flank. Although it is not readily apparent on the section, it was observed that on the western flank of this structure the deeper reflectors dip more steeply to the west than do the shallower horizons. The net effect is an eastward convergence of reflectors, or thinning of strata, of approximately 9 feet per mile. An eastward component of thinning is also apparent on the continuous seismic profiles that extend northeast from the centre of the bay, as well as on the profile (C) located west of Cape Smith. Examination of the several profiles converging at the centre of the bay enabled a local calculation of regional strike. This proved to be slightly west of north, approximately on trend with the northern end of the 'central shoal' which projects into the centre of the bay from the south. As closely as can be determined the thinning described above also appears to have this same general strike.

On a very broad scale several additional points may be noted on section D-K that further indicate a broad relationship between bedrock structure and the main physiographic trends in Hudson Bay. It can be seen that areas of most pronounced flexure of sub-bottom reflectors generally coincide with the more prominent bathymetric features (e.g. E, F, I). Throughout

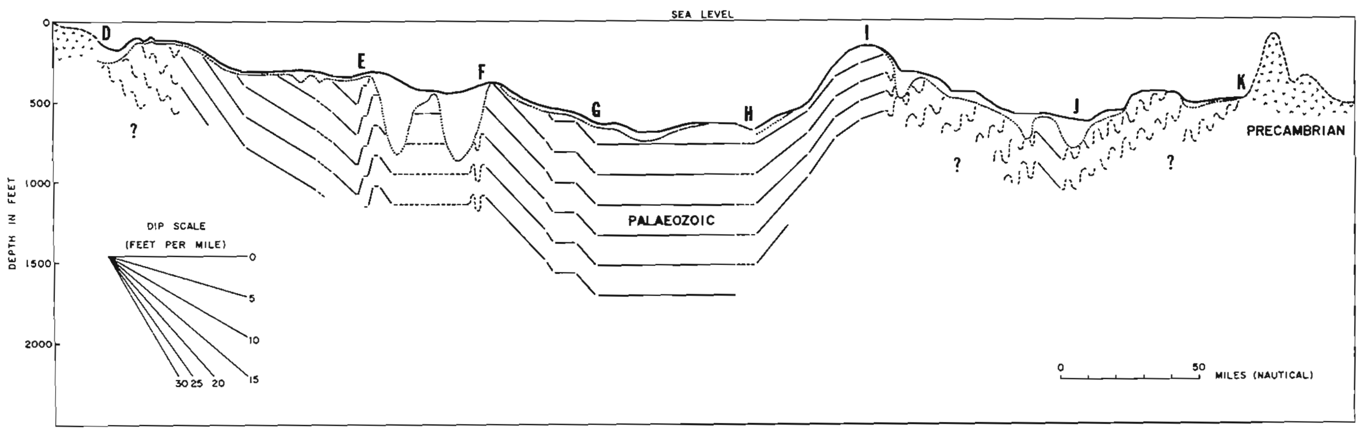


Figure 4. Seismic cross-section derived from profiles affording east-west coverage of Hudson Bay. Vertical to horizontal exaggeration approximately 340 to 1.

the bay it was also observed that the more continuous bottom slopes were usually underlain by bedrock layers that dip in the same direction as the slope. It may perhaps be inferred, then, that the regional alignment of bedrock structure in Hudson Bay is reflected in the general north-south trends of the bathymetry. There is also an obvious general coincidence of areas of thick bottom sediment with zones of folding adjoining topographically low trends (E, F, J). Presumably this sediment accumulated during Pleistocene time in pre-existing drainage features, and it would appear that the latter were perhaps regionally related to bedrock structure.

Finally, it is rather interesting to employ the dips observed on the western half of section D-K to estimate the total thickness of the underlying Paleozoic strata. For this calculation it was assumed that point D defined the western limit of the Paleozoic Basin, and that point H marked the centre of the basin. In areas where distortion, reversal, or questionable data occur an average regional dip of 18.5 feet per mile to the east was applied. On this basis the resultant thickness of Paleozoic strata in the centre of the bay is about 2,300 feet. Applying the value for average regional dip to areas where the continuous seismic profile shows approximately flat-lying strata the maximum thickness attainable is in the order of 3,900 feet. The latter figure is still considerably less than thicknesses predicted on the basis of magnetic (Hood, 1964) and refraction seismic surveys (Hobson, 1968). It should be borne in mind, however, that this estimate from continuous seismic profiling data is based mainly upon information from only the top few hundred feet of section.

Data to the east of the 'central shoal' on section D-K are not sufficiently reliable to attempt a similar calculation for the eastern side of the basin. As mentioned, there is considerable distortion of reflectors, but an apparent predominance of west dip. The profile west of Cape Smith (C) affords the best information from the east side of the bay. In that area west dip of about 11 feet per mile is indicated, with eastward convergence of reflectors in the order of 6 feet per mile. Applying this dip from K to H on section D-K gives about 1,900 feet of Paleozoics at the centre of the bay. The thinning of 6 feet per mile could account for an additional 1,000 feet of section.

CONCLUSION

Observed dips along the radial lines of continuous seismic profiling are toward the centre of the bay, indicating that the Paleozoic sediments in Hudson Bay comprise a basinal structure. The estimated regional strike indicates north-south elongation of this basin, and the major submarine topographic trends are considered to be a reflection of bedrock structure. Thinning observed east and north from the centre of the bay appears to have the same general strike as the regional structure. Bedrock structure appears to have been a controlling factor in the development of Pleistocene drainage features. These depressions were filled with drift during Pleistocene time.

REFERENCES

Hobson, G. D.
1964: Nine reversed refraction seismic profiles Hudson Bay Lowland, Manitoba; in Summ. of Activities: Office and Laboratory, 1963, Geol. Surv. Can., Paper 64-2, pp. 33-40.

1966: Seismic investigations in Hudson Bay; in Rept. of Activities, May to October, 1965, Geol. Surv. Can., Paper 66-1, pp. 193-196.

1967: A reconnaissance seismic refraction survey in Hudson Bay, Canada; Seventh World Petroleum Congress, vol. 2, pp. 813-826.

Hood, P.
1964: Sea magnetometer reconnaissance of Hudson Bay; Geophysics, vol. 29, pp. 916-921.

Leslie, R. J., and Pelletier, B. R.
1965: Bedrock geology beneath Hudson Bay as interpreted from submarine physiography; Bedford Inst. Oceanog., Rept. 65-12.

RIVERS OF THE HUDSON BAY LOWLANDS

L. M. Cumming
Geological Survey of Canada
Ottawa, Ontario

Abstract

The distribution of Precambrian and Paleozoic formations and the pre-glacial history of the Hudson Bay Lowlands are geological influences which helped to shape the character of individual rivers and streams of the Lowlands. These geological influences upon various individual rivers of the Hudson Bay Lowlands are described and summarized.

The rivers of the Hudson Bay Lowlands are an important and unique natural resource. Aspects of the transportation and hydroelectric potential of some of the rivers are summarized.

INTRODUCTION

Rivers which flow across the Hudson Bay Lowlands are part of an enormous drainage system whose tributaries extend to the watershed of streams flowing into the Arctic, Pacific and Atlantic Oceans, as well as the Gulf of Mexico.

This paper discusses that part of the drainage system which is within the confines of the Lowlands. In particular, the aspects of the rivers which are related to the general geology of the Hudson Bay Lowlands are discussed and some illustrations of individual rivers are given.

During Operation Winisk (see Norris and Sanford, 1968) the writer had the opportunity of observing at first hand many of the rivers of the Hudson Bay Lowlands (see Fig. 1). Base camps were established on the Moose, Kenogami, Attawapiskat and Gods Rivers. The writer made boat traverses on parts of the Harricanaw, Kattawagami, Birthday (Malouin), Little Current, Drowning, Kenogami, Atikameg, Ekwan, Gods, Nelson, Weir and Churchill Rivers; and helicopter traverses were made along parts of the South Knife, Churchill, Gods, Echoing, Sachigo, Muketei and Albany Rivers as well as Herriot Creek. During the course of the summer's work starting at Moosonee and terminating at Churchill, five flights in an Otter aircraft were made. These flights, totalling over 800 miles, were from Moosonee to Albany Forks; Albany Forks to Attawapiskat, Hawley Lake to Shamattawa; Shamattawa to the Precambrian contact on the Nelson River; and Nelson River (at Weir River junction) to Churchill.

Traverses, totalling over 900 miles, were made in a Cessna 180 aircraft during a systematic search for outcrop in the Hudson Bay-James Bay watershed area, southwest from Hawley Lake (see Fig. 4). In addition, short traverses were made on foot along Joncas, Atikameg and Angling Rivers, Fossil Brook and Hidden, Surprise, Caution and Chasm Creeks.

GENERAL FEATURES

Major rivers of the Hudson Bay Lowlands include the Harricanaw, Moose, Albany and Attawapiskat which flow into James Bay; and the Winisk, Severn, Hayes, Nelson and Churchill which flow into Hudson Bay (see Fig. 1). The source area of these rivers is mainly in Precambrian higher ground bordering the Lowlands, the average elevation of which is about 1,000 feet. For example, Lake Winnipeg, the source of the Nelson River is at an elevation of 712 feet and the source of the Churchill at Methy Lake, Saskatchewan, is at an elevation of 1,467 feet. The relatively slight elevation of this watershed, which borders the Hudson Bay Lowlands, is characteristic of these rivers, which typically have low gradients.

The Precambrian highland rim is missing only in the Hudson Straits area. J.B. Bird (1967) has recently suggested that the whole area (see Fig. 2) was once above sea-level and that the Paleozoic cover over the Shield was once more extensive and that in early Tertiary time, rivers with sources in the western Cordillera carried sediment across what is now the Prairie Provinces toward Hudson Strait and out into the Atlantic. With additional uplift of the land, these rivers removed part of the Paleozoic cover by erosion. The Mackenzie drainage system then began to develop and captured and diverted much of the flow to the north. The Hudson Bay area was left with a foreshortened drainage system which tended to converge toward the centre of Hudson Bay (see Fig. 2). The theory that there once existed a late Tertiary radial drainage pattern across the Hudson Bay Basin (Hudson Platform of Puminov, 1967) fits into the general pattern of evolution of drainage in the Arctic Islands which was initiated by a Cretaceous uplift (Fortier and Morley, 1956). One line of evidence for an older drainage system across the Hudson Bay Lowlands is a buried river channel discovered by drilling at Campbell Lake (see Fig. 2). There, 700 feet of Cretaceous, Upper and Middle Devonian strata have been eroded away in a narrow valley which was subsequently filled with Pleistocene drift (Hogg et al., 1953, p. 117).

Also Sutton and Hawley Lakes (see Figs. 2 and 4) appear to be remnants of a single large northward flowing river (Dowling, 1902b; Hawley, 1926, p. 7). These two lakes occupy a deep narrow valley and soundings of Sutton Lake show that the bottom of the lake is 310 feet below the surface of the surrounding clay plain (Dowling, 1902a, p. 113).

A third line of evidence for a preglacial drainage system across the Hudson Platform is found in the bottom configuration of Hudson Bay (B.R. Pelletier, Bedford Institute of Oceanography, personal communication). Bathymetric contours show an extremely deep trench southwest of Cape Dufferin (position C, Fig. 2). This trench has a U-shaped cross-section which could have been produced by a major river at a time when the land stood

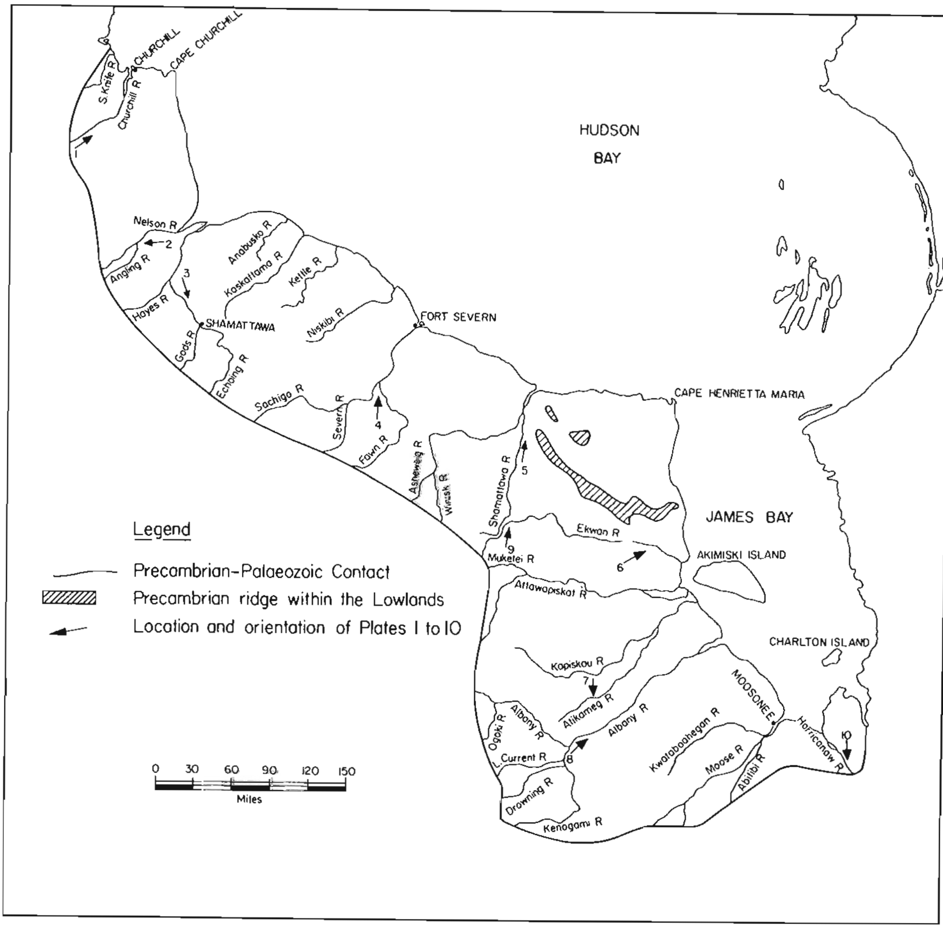


Figure 1. Sketch map of Hudson Bay Lowlands showing some of the major rivers.

1000 feet higher. Also, the general submarine physiographic pattern of Hudson Bay is dendritic, and may have been formed by a preglacial river system (B.R. Pelletier, personal communication).

The preglacial topographic setting of the Hudson Bay Lowlands has been summed up by Kupsch (1967, p. 158):-

> "Although, therefore most of the Hudson Bay region was probably no longer below sea level just prior to the first Pleistocene glaciation, it was lower in elevation than western Canada. It is generally held that the preglacial drainage from that part of the North American continent was to the

northeast toward the lowland now covered by the sea water of Hudson Bay (Barton et al. 1965, pp. 195, 197; Flint 1957, p. 170). It follows from this that a depression of the topographic surface of the earth's crust already existed between western Canada and the Hudson Bay region before the continental glacier developed. The weight of the ice emphasized this bowl-shape but did not create it. . . ."

A general comment that can be made about the rivers of the Hudson Bay Lowlands is that their erosional effects are far less than for other North

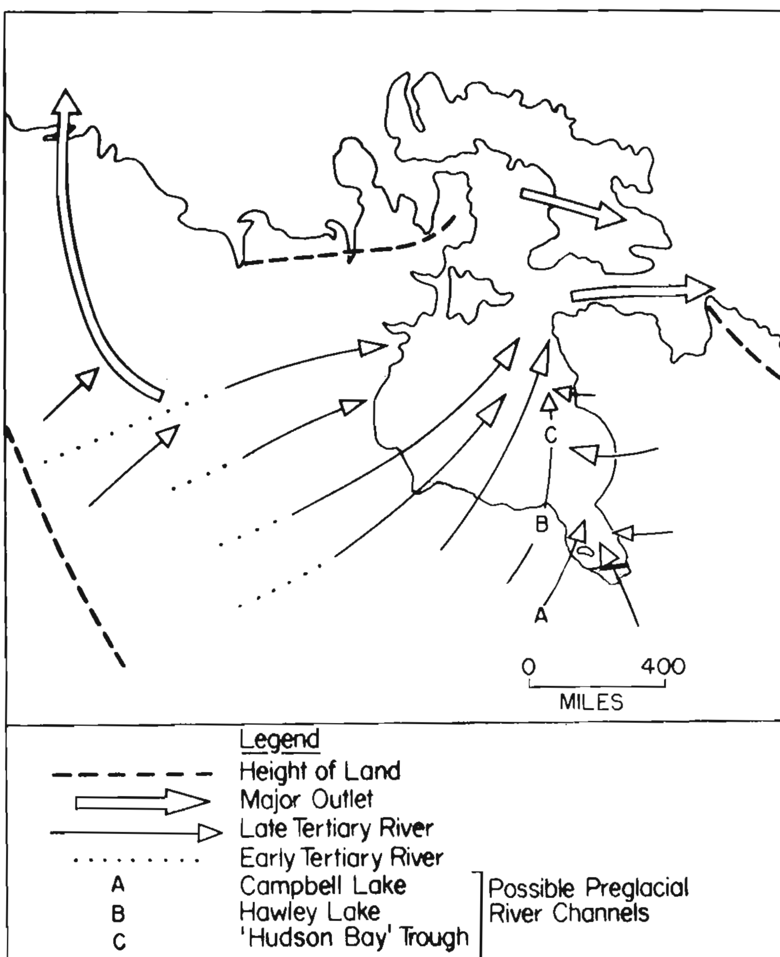


Figure 2. Tertiary drainage pattern across the Hudson Bay Lowlands, (modified after J.B. Bird, 1967).

American river systems. Dole and Stabler (1909) estimated that the approximate rate of erosion was only 28 tons per year per square mile of drainage basin. This is 1/4 to 1/6 less than for other river systems, such as in the Appalachian or Cordillera regions. Reasons for this low rate of erosion are to be found in the low gradient of the rivers and also the difficulty of eroding into bedrock which tends to form smooth pavement, where the regional dip of the bedding surfaces is approximately 15 feet per mile.

The Hudson Bay Lowlands represent a composite of parts of two sedimentary basins: (1) the Moose River Basin in the south, with a northeast axis of elongation and which underlies part of James Bay, and (2) a larger Hudson Bay Basin to the north, which is a circular feature about 600 miles across and which underlies most of Hudson Bay. Present day river systems reflect these two large-scale basinal features. Rivers of the Lowlands whose outlet is Hudson Bay show a large-scale radial drainage system. In contrast, rivers of the Lowlands whose outlet is James Bay have become adjusted to the structures of the underlying sedimentary rocks of the southern basin. The divide between these two present day drainage systems follows the axis of a broad Precambrian basement high which forms the Cape Henrietta Maria Arch (see Fig. 1).

RIVERS DRAINING INTO HUDSON BAY

The following statements deal with individual rivers within the Lowlands which flow into Hudson Bay, and these are treated in a north to south sequence. Plates 1-5 are photographs of some of the rivers whose outlet is Hudson Bay, and their locations are shown on Figure 1. For the locations of other smaller rivers the reader is referred to GSC map 17-1967 (scale 1 inch to 15.78 miles).

In the northernmost part of the Lowlands, the North and South Knife Rivers (Fig. 1) and Herriot Creek are three small rivers with shallow bedrock channels. A view of the South Knife River is shown by Nelson (1963, pl. 3, fig. 2). These three rivers are confined to an area underlain by Ordovician strata, and probably originated as post-Pleistocene or as interglacial streams.

The Churchill River is the second largest river of the Hudson Bay Lowlands. It is 1,000 miles long with its source in Methy Lake, Saskatchewan. Only 90 miles of that length is in the Lowlands. The Churchill is the only river of the Lowlands where geological conditions provide a natural harbour at its mouth. At the coast, a Precambrian ridge composed of subgreywacke and some conglomerate (Churchill quartzite) trends west-southwest across the river mouth. The river, flowing north across relatively soft Silurian beds, breaches these older and more resistant rocks; the lee side forming the natural harbour discovered by Jens Munck in 1619.

Downstream from the western Precambrian granitic contact, the Churchill River flows in a northeast direction for 55 miles (see Plate I). This part of the river probably represents part of the preglacial radial drainage system and forms a channel across Ordovician limestone. Below Red Head Rapids, near the eastern end of the Ordovician outcrops, the river channel reaches the less resistant Silurian sedimentary rocks and the channel swings abruptly to the north. It is assumed that an extension of the probable bedrock channel lies buried beneath Pleistocene deposits. This channel should reach the coast near Cape Churchill. In 1879 Robert Bell surveyed the Churchill River and in 1884 served as pilot for the first steamship to enter Churchill Harbour.

The waters of the Nelson River which funnel through the Hudson Bay Lowlands represent runoff from 414,000 square miles of drainage area. This is clearly one of the continents largest river systems (including the North and South Saskatchewan, the Assiniboine, the Red and the Winnipeg Rivers). The high to low runoff ratio of the Nelson River is 6 to 1, with a maximum discharge of the Lowlands of over 140,000 cubic feet per second. Large natural storage reservoirs within the watershed (e.g. Lakes Winnipeg, Winnipegosis and Manitoba) help to maintain this relatively small variation between maximum and minimum flows producing a highly reliable supply.

A small tributary, the Angling River, enters the Nelson about halfway across the Lowlands, and this junction is near the Ordovician-Silurian contact. A view from this point of the Nelson River, showing its broad valley along the skyline, is shown on Plate 2.

The stretch of the Hayes River flowing through the Hudson Bay Lowlands traverses a region of thick Pleistocene drift in which Paleozoic bedrock is not exposed (GSC Map 17-1967). The Hayes River route to the interior (Hudson Bay to Lake Winnipeg) was the first choice of the early travellers and traders (Gans, 1925 p. 162). This route represents a late stage (northeastward) outlet of glacial Lake Agassiz as postulated by Upham (1895, p. 226).

Elson (1967, figs. 2, 4, 13, and p. 44) also speculated that the Hayes and adjacent rivers were possible outlets (about 7500 B.P.) during the Pipun (or final) phase of Lake Agassiz. (Ibid. p. 44)

> "Lake Agassiz drainage must have been through channels represented now by cross-axial stream systems draining north into Hudson Bay, such as Sachigo River, Echoing River(?) Hayes River, Bigstone River, and perhaps finally in the north, the east-flowing Limestone River (Lat. 56°35', Long. 95°)."

The Hayes River was surveyed by Robert Bell of the Geological Survey of Canada in 1877. O'Sullivan, also of the Survey, in 1906 completed a canoe trip from Norway House to York Factory in 14 days. York Factory (now abandoned) at the mouth of the Hayes River was the great warehouse depot for the Hudson's Bay Company (Rich, 1967). For over two centuries, until

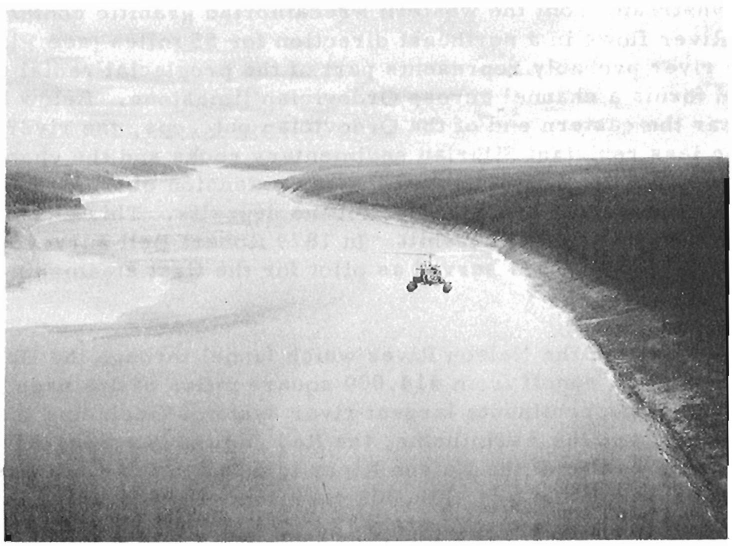


Plate 1. Churchill River, view from lat. 57°56'30" N., long. 95°01'30" W., towards Hudson Bay. River direction is North 45° E. (GSC 200807-I)

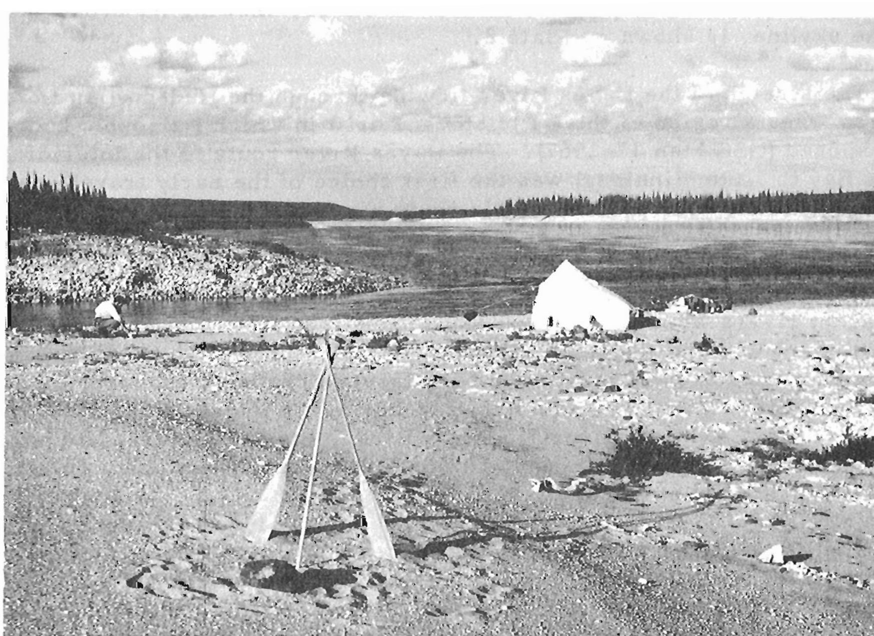


Plate 2. Nelson River, view upstream from Angling River junction. (LMC 53-6-67).

Plate 3. Gods River, view upstream 15.4 miles northwest of lat. 56°00'N. Pleistocene deposits here rise 120 feet above river level. (LMC 44-11-67).

the building of the Canadian Pacific Railway in 1885, York Factory was the centre of distribution for western Canada.

Gods River (formerly called Shamattawa River; Savage and Van Tuyl, 1919) is a major tributary of the Hayes and unlike the Hayes displays numerous exposures of Paleozoic (Ordovician) limestone. These exposures are scattered in the stretch of river from the Precambrian-Paleozoic contact to the village of Shamattawa, at the junction with Echoing River. Typically, much of the bedrock of this stretch of the Gods River is covered by glacial drift. However, for 20 miles downstream from the village of Shamattawa there are abundant exposures of Upper Ordovician limestone. This northwest flowing section of the Gods River coincides roughly with the Ordovician-Silurian boundary. Plate 3 is a view of the river below the last Ordovician outcrop, in a region characterized by a thick cover of Pleistocene drift.

The distance along the coast of Hudson Bay from York Factory, at the mouth of the Hayes River, to Severn River is 240 miles. Along this stretch of the coast four good-sized rivers enter the Bay (O'Sullivan, 1906).

Anabusko (Broad) River	78 miles from York
Kaskattama River	95 " " "

Kettle River	126 miles from York
Niskibi (Goose) River	196 " " "

Of these the Kaskattama is the largest and its pre-capture headwaters are probably represented by the stretch of the Gods River above the junction with the Echoing River (see Fig. 1). The Kaskattama enters Hudson Bay by three channels, forming two large islands at its mouth.

The Severn River (Plate 4) drains a rectangular area roughly 400 miles long and 100 miles wide. It decends 1,014 feet from its source in Sandy Lake to Hudson Bay, a distance of 610 miles. In its upper reaches, the river flows through a chain of lakes connected by short channels containing numerous falls and rapids. A change in river gradient coincides with the Precambrian-Paleozoic contact and across the Lowlands the gradient flattens and becomes more uniform. Two large tributaries, the Sachigo and Fawn Rivers, enter the Severn in its lower reaches. The Sachigo River enters from the west about 105 channel miles upstream from Fort Severn. The Fawn River drains out of Big Trout Lake and enters from the east approximately 40 channel miles downward from the mouth of the Sachigo River. Near the mouth of the Fawn River (Plate 4) are abundant exposures of the white weathering Silurian Severn River Formation.

Limestone Rapids, formed near the middle of the exposures of the resistant Silurian Attawapiskat (limestone) Formation, marks the last fall of the Severn to the typical low marshy plain underlain by softer and less resistant Silurian beds of the Kenogami River Formation. Captain Thomas James named the river the 'New Severn' in 1631.

Fur traders occasionally used the Severn River route to Lake Winnipeg, but other routes were generally preferred because of the numerous rapids on the Severn. The Fawn River was used as a fur trade route to Big Trout Lake (Macfie, 1953).

The Winisk River is the last major river draining the Lowlands north of Cape Henrietta Maria. Its drainage basin is roughly trapezoidal in shape and has an area of approximately 26,000 square miles. The Winisk River near the Precambrian-Paleozoic contact is characterized by the splitting off of two large channels, one to the east and a shorter one to the west. The first of these begins and flows northward about 6 miles from Lake Winisk, where the river divides to the eastward through the Winiskisis Channel. About 20 miles farther downstream a second split, the Tabasokwia Channel, leaves the river westward. This channel rejoins the main branch of the Winisk 38 miles below its point of exit. The Winiskisis Channel returns 8 miles farther downstream or 66 miles below its point of exit. About 25 miles downstream from the mouth of the Tabasokwia Channel (i.e. approximately equal to the width of the Ordovician belt) a major tributary, the Asheweig River, (with a drainage area of 6,000 square miles) enters from the west. The lower junction of the Tabasokwia Channel is near the Precambrian-Paleozoic contact,

Plate 4.

Aerial view of Severn River at junction with its tributary the Fawn River. (GSC 200807-H).

Plate 5.

Aerial view of Shamattawa River, Sutton Lake map area, meander is at lat. 54° 40'N., long. 81°27'W., junction of Winisk River in background. (GSC 200807-8).

Figure 3. Part of Hudson Bay map by N. Bellin, 1744. (Map H 12/1101, Public Archives of Canada).

the lower junction of the Winiskisis Channel is near the Middle(?)-Upper Ordovician contact, and the Ashaweig junction is near the Ordovician-Silurian contact.

The 150-mile downstream course of the Winisk River from the junction of the Asheweig River to Hudson Bay is characterized by a broad zig-zag as the river flows across the area of low relief which is underlain by the Silurian Severn River Formation and the river gradient is only about one foot per mile. This zig-zag course is north for 35 miles, east for 70 miles and then northeast for 45 miles, and reflectsthe impounding effect caused by the unexposed massive reefal limestone of the Attawapiskat Formation which lies north of the zig-zag.

The Shamattawa River drains radially towards the centre of Hudson Bay, across the flat plain underlain by the Severn River Formation. The junction of the Shamattawa River with the Winisk River may be seen in the background of Plate 5. At this junction is a small inlier of Proterozoic sedimentary rocks, representing an extension of the elongate Precambrian ridge shown on Figure 1.

AREA BETWEEN WINISK AND EKWAN RIVERS

An inland canoe route between James Bay and Hudson Bay is shown on Bellin's 1744 map (Trudel, 1961). This inland route around Cape Henrietta Maria was shown on many subsequent historical maps of the Hudson Bay area. This historic map (Fig. 3), distortedly showed a lake draining both into the Ekwan and Severn Rivers. This distortion of direction may have been due to the presence of strongly magnetic sediments at the base of the diabase sills on Sutton Lake, reported by Hawley (1926 p. 5). Actually the route is between the Ekwan and Winisk Rivers via the Shamattawa River and Shamattawa Lake (see Fig. 4). This route can now be interpreted as drainage that skirts around a resistant Precambrian ridge which is 110 miles long.

Two additional portage routes make it possible to travel by canoe from James Bay to Hudson Bay and yet avoid the unpredictable conditions offshore along the extensive tidal flats near Cape Henrietta Maria, and these are shown on Figure 4. Both Dowling and Hawley used the Washagami River route and portaged east across the watershed to a small stream which flowed into the south end of Sutton Lake. Another route, used by the Indians, is by the Little Ekwan River and small streams and lakes forming its headwaters.

In th.s area the Ontario Department of Lands and Forests in April, 1968, established a new wilderness game preserve and sanctuary to be known as Polar Bear Provincial Park. The northwest boundary of this park is the Kinushseo River and the southern boundary is the Ekwan River. The park, the second largest in Canada, encompasses an area of over 7,000 square miles and includes Cape Henrietta Maria and portions of the coastlines of James Bay and Hudson Bay. The western boundary of the park is at

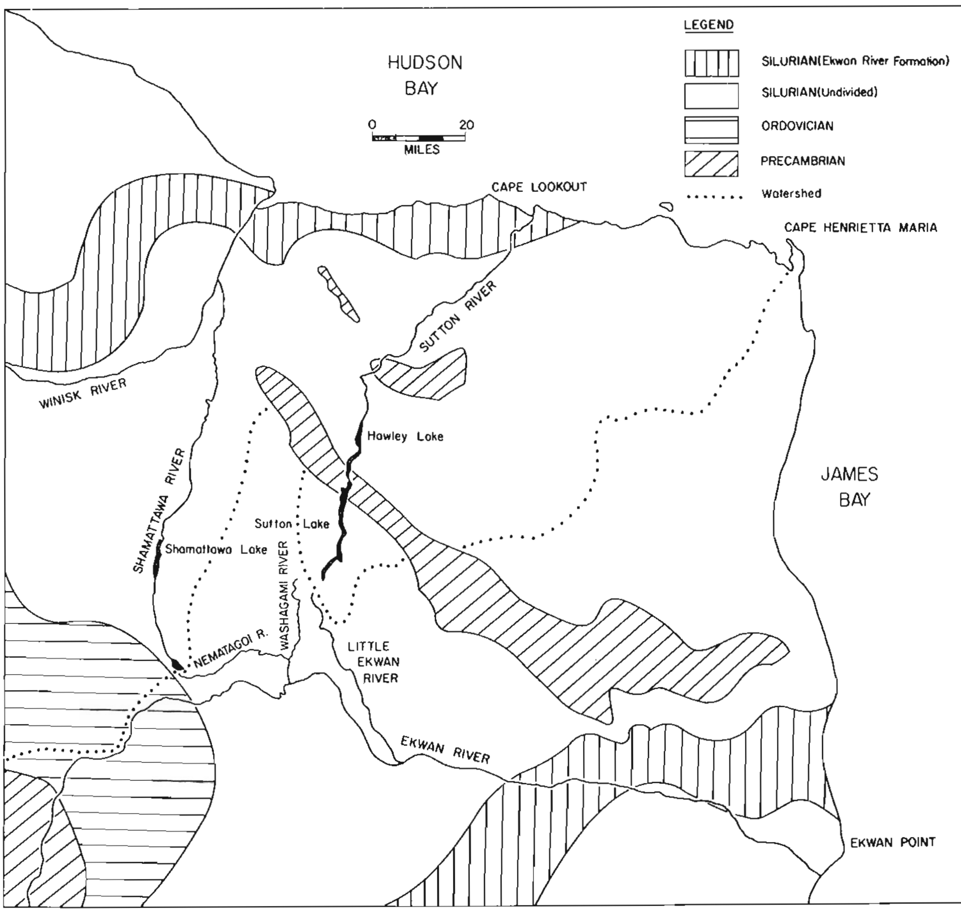


Figure 4. Sketch map of the Hudson Bay Lowlands watershed between the Winisk and Ekwan Rivers (from GSC Map 17-1967), showing geological control of inland water routes between Hudson Bay and James Bay.

longitude 83°40'W. Access to the park by aircraft, may be made at a landing strip of the abandoned radar base near Cape Henrietta Maria.

RIVERS DRAINING INTO JAMES BAY

The following comments deal with individual rivers within the Hudson Bay Lowlands whose outlet is James Bay. Plates 6 to 10 show some parts of these rivers whose positions are also shown on Figure 1.

Plate 6. Ekwan River at lat. 53°26'40"N., long. 82°55'25"W.; view to north-east. Rapids formed by massive reefal limestone beds of the Attawapiskat Formation. (GSC 200807-A).

The Ekwan is the first major river draining the Hudson Bay Lowlands to the south of Cape Henrietta Maria. The river enters the Lowlands near the axis of the Precambrian Cape Henrietta Maria Arch. The Ekwan River follows a northeast course for the 40 miles between the Precambrian-Paleozoic and Ordovician-Silurian contacts. Many stretches of the upper part of the Ekwan are locally controlled by the direction of a prominent system of jointing (Plate 9). Intense jointing is typical of Ordovician strata of Hudson Bay Lowlands which are stratigraphically close to the Precambrian basement. Downstream from the Ordovician-Silurian contact the river flows east and then southeast as it skirts around the Precambrian ridge shown on Figure 1. The lower reaches of the Ekwan River cut across the northern part of resistant and massive Middle Silurian reefal beds of the Attawapiskat Formation. Bedrock exposures of these limestones occur between 28 and 40 miles from the river mouth (Plate 6) and this lower stretch of the river is characterized by several rapids.

The Attawapiskat River drainage basin comprises about 19,000 square miles and extends for 420 miles westward from James Bay. In its lowermost 260 miles, the channel of the Attawapiskat drops 600 feet at an uniform rate of 2-3 feet per mile. Thus Robert Bell (1887, p. 29) reported "It is a remarkable fact that we did not require to make a single portage in the whole distance from this lake, (Attawapiskat Lake), to the sea, ..." Near the Precambrian-Paleozoic contact, the Muketei River flows parallel to the main channel along its north side and then enters from the northwest. From the Muketei River junction, the Attawapiskat follows a slightly south of east course for 150 miles to James Bay. This stretch of the river angles across Silurian carbonate formations and the river is unique in that it flows for 40 miles across the greatest development of the massive reefal limestone of the Attawapiskat Formation, which was not represented in the Albany River exposures. This characteristic stretch of the river was described by Robert Bell (1887, p. 27) as follows: "....the river flows with a rapid current, between cliffs, and among almost innumerable islands of yellowish limestone, all having an average height of about forty feet." Forty miles from its mouth and near the end of the continuous exposure of reefal limestone, the river divides into two channels, a main northern channel and a smaller southern channel. The marshy delta of the river provides grasses such as 'wild rice' and is populated by migratory ducks and geese. The Attawapiskat Settlement at the mouth of the river is populated mainly by Cree Indians.

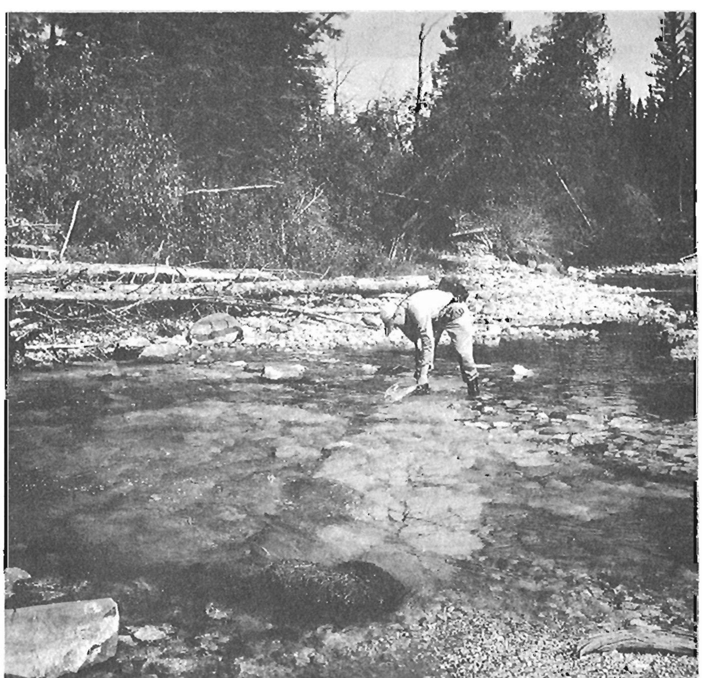


Plate 7. Atikameg River at lat. 51°40'N., long. 84°06'W. View to southeast, showing submerged strata of Silurian Kenogami River Formation. (GSC 200807-G).

Plate 8. Aerial view of Albany River looking downstream with mouth of Henley River at the left. This locality is a former site of Henley House, one of the first inland trading posts of the Hudson's Bay Company. (GSC 200807-E).

The direction of the lower parts of both the Kapiskau River and the Atikameg River is controlled by the northeast strike of soft, red and green shales and siltstones of Member 3 (of Martison, 1953) of the Silurian Kenogami River Formation. Plate 7 shows a typical submerged bedrock surface of this formation on the Atikameg River. These smooth bedrock 'pavement' surfaces are typical of many of the rivers of the Hudson Bay Lowlands.

The Albany River drainage basin has an area of 53,000 square miles of which 1/3 lies within the Hudson Bay Lowlands. The Albany River flows east across the Precambrian-Paleozoic contact, and then turns southeasterly for 20 miles to the mouth of the Ogoki River which enters from the south. In the next 20 miles the river flows almost due east, then turns southeast for 60 miles to the Forks where the Kenogami River enters from the south. Because the lower part of the Albany River is controlled by the northeast strike of Devonian sedimentary formations, in the remaining 165 miles to James Bay the river channel is narrow and there are no large tributaries. This lower stretch of the Albany River is confined, for the most part, to the narrow belt of the Devonian Stooping River Formation.

The Albany River is an excellent river for tranportation because it follows the northeast trend of the southern sedimentary basin where it has a uniform gradient with no difficult rapids. Plate 8 is a view of the river 150 miles from its mouth.

Fort Albany, at the mouth of the river, was established for the Hudson's Bay Company by Charles Bayly shortly before 1679.

Rivers flowing east into the Kenogami, such as the Little Current and the Drowning Rivers are characterized by broad meanders, formed in an intensely jointed rock unit within the upper part of the Silurian succession especially Members 2 and 3 (of Martison, 1953) of the Kenogami River Formation. This joint system may have resulted from leaching of evaporites and subsequent compaction of beds within this red bed sequence.

The Kenogami, Kabinakagami and Squirrel Rivers in succession follow the curvature of the Silurian-Devonian contact of the southwest side of the southern basin for over 90 miles. The Kenogami River in particular follows

Plate 9. Aerial view of Ekwan River at lat. 53°45'N., long. 85°39'W.; view downstream showing jointing controlling river direction. (GSC 200807-D).

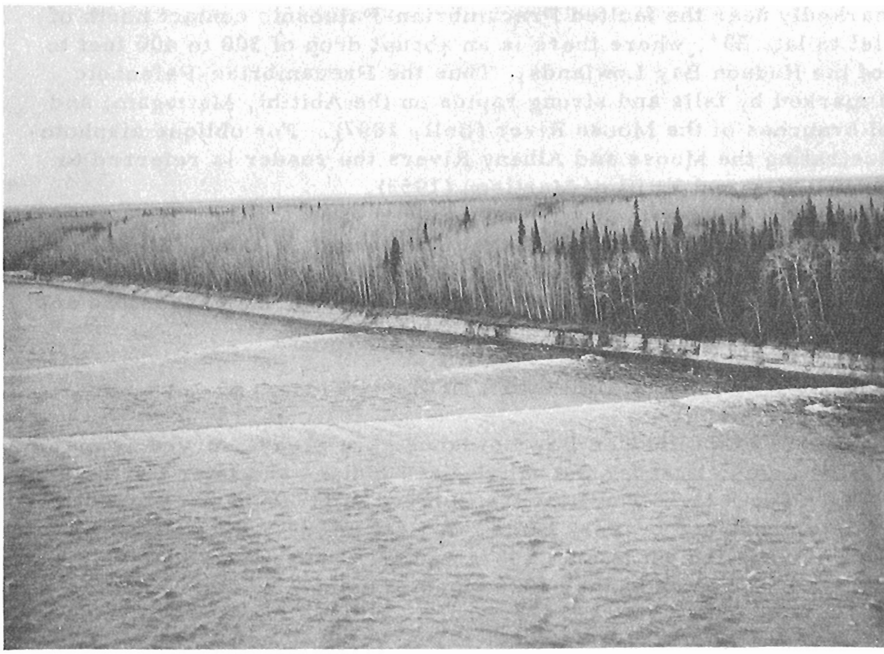


Plate 10. Harricanaw River, Quebec, view upstream from lat. 50°49'N., long. 79°20'W. Rapids formed by resistant limestone beds of the Silurian Ekwan River Formation striking across river. (GSC 200807-F).

the Silurian side of the contact. The river position is controlled by the occurrence of cherty beds at the base of the Devonian (Stooping River Formation). The Kenogami River can be used for transportation because its direction is strike-controlled and therefore does not contain rapids.

The Kwataboahegan River originates on and drains the northern part of the extensive plain underlain by soft Cretaceous sedimentary rocks of the central part of the Moose River Basin. The lower 30 miles of the river flows southeast across more resistant Devonian formations and then enters the Moose River 12 miles above Moosonee.

The term "Moose River" applies only to the 63 miles of channel between James Bay and the confluence of the Missinaibi and Mattagami Rivers. The Abitibi River enters this reach at mid point from James Bay. These four rivers make up the Moose River drainage basin with a total area of 41,900 square miles. The Moose River itself follows the northeast trend of the southern sedimentary basin.

The stream gradients of tributary streams of the Moose River system steepen markedly near the faulted Precambrian-Paleozoic contact north of and parallel to lat. 50°, where there is an abrupt drop of 300 to 400 feet to the level of the Hudson Bay Lowlands. Thus the Precambrian-Paleozoic contact is marked by falls and strong rapids on the Abitibi, Mattagami and Missinaibi branches of the Moose River (Bell, 1897). For oblique airphotographs illustrating the Moose and Albany Rivers the reader is referred to plates VI, VIII, XIV and XVIII of Martison (1953).

The Harricanaw River flows largely in Quebec, with only its lower reaches in Ontario. The Harricanaw, below the Precambrian-Paleozoic contact, cuts a broad channel across the strike of Ordovician sandstone and Silurian limestones (*see* Plate 10).

TRANSPORTATION

The rivers of the Hudson Bay Lowlands have always served as major transportation routes, first for the native Cree Indians and later for the fur traders. Fur trade freight was first transported in birch-bark canoes but these were later replaced by York boats. A fleet of 800 York boats once carried the fur trade freight (Main, 1967a and b). There were four major canoe and York boat routes (Gans, 1926, map 3) using:

1) Hayes River,
2) Severn River and Fawn River,
3) Albany River (2 branches), and
4) Moose River (3 branches).

York boats navigated the Albany River for 250 miles. These flat-bottomed boats, 24 to 40 feet long and 7 to 8 feet wide, were rolled over portages on logs to give access to waters draining west into Lake Winnipeg.

Robert Bell (1872, p. 111) described the Albany River as a transportation route as follows - "As shewing its freedom from obstructions, I may mention that the Hudson Bay Company's boats, in descending, are allowed to drift all night with the stream, in any part of this distance, the submerged top of a fir tree being sufficient to keep them in the channel".

Martin's Falls is a former Hudson's Bay Company Post located on the Albany River about 250 miles from the rapids at the mouth of the river. Martin's Falls is at the western border of the mapped Precambrian rocks as shown on Map 17-1967. The "distance" referred to by Bell is from Martin's Falls to the mouth of the Albany.

Today in the James Bay region, supplies are transported by truck and scow from railhead (Moosonee) to Moose Factory, located on an island in the middle of the river. Also, larger barges, with capacity of 1,000 tons, are used to supply the northern coastal villages, such as Albany and Attawapiskat.

This heavy equipment is winter-stored at Paint Hills on the east side of James Bay, because the only other southernmost harbour on the west side of Hudson Bay is at the mouth of the Churchill River.

In 1920 Revillon Frères blasted boulders from beds of the Pagwachuan River below Pagwa, thus removing obstruction to shallow draft vessels during high water stages between Pagwa and Fort Albany. Power boats were used to tow 15-ton barges of lumber from Pagwa to Fort Albany. These boats returned upstream leaving the barges to be broken up for building purposes.

It would be possible, during spring floods, for large boats to navigate and carry freight on the lower reaches of most of the larger rivers of the Lowlands (Bell, 1910, p. 74). By this method, the Moose and its west branch, the Missinaibi, might be ascended for 130 miles; the Albany and Attawapiskat for 250 miles; the Kapiskau for 50 miles; and the Ekwan, Winisk, Severn and Hayes for about 130 miles each. It might be feasible to use the rivers for transporting heavy equipment such as drill rigs and supplies to inland sites in the southern part of the Lowlands. In addition, most of the rivers of the Lowlands make ideal routes for transportation by hovercraft vehicles. In winter, an average of three to four feet of ice covers the rivers and they then can be used as tractor-train transportation routes.

HYDROELECTRIC POWER AND RIVER DIVERSIONS

Hydroelectric power is developed on the Abitibi River where Otter Rapids has a head of 107 feet and an installed capacity of 240,000 horsepower, and on Mattagami River where Smoky Falls has a head of 113 feet and an installed capacity of 56,250 horsepower. Martison (1953, Table I, p. 8) gives additional information on other power sites of the Abitibi and adjacent rivers. McInnes (1913, p. 11) drew attention to the power potential of the Nelson River and pointed out that Kettle, Long Spruce and Limestone rapids each dropped 50 feet within a mile or so of distance. He compared the volume of flow of the Nelson as being four times that over the Chaudière Falls at Ottawa.

By 1980 it is expected that more than one-half of the electrical energy used in Manitoba will come from the Nelson River which entails transmission of the power 560 miles to southern Manitoba. There is a 712-foot total drop between Lake Winnipeg and Hudson Bay and the Nelson River Programming Board considers that 628 feet of this total drop can be developed by power generating sites. The Kettle Rapids power site now under construction (on the Precambrian near the Paleozoic contact) is the Phase 1 Development. Additional downstream power sites are at Long Spruce Rapids, Limestone Rapids and Gillam Island. These power sites (Hurdle et al., 1967) have the following potential:

	Net Head in Feet	Installed Capacity in Megawatts
Kettle Rapids	98.5	1,018
Longspruce	78.0	806
Limestone	169.5	1,840
Gillam Island	80.5	832

The ultimate potential of the Nelson River is 6 million kilowatts.

A number of diversion schemes are possible for the development of the rivers of the Hudson Bay Lowlands. These schemes could serve to enhance the value of power sites and allow more efficient use of the rivers by controlled water storage and water regulation. Some of the diversion schemes are described by McIntyre (1966 MS), and the following three projects give an indication of the scope of future engineering projects in the Hudson Bay Lowlands.

1. Diversion of the Winisk River into the Fawn south of lat. 55°. This scheme would consist of dams on both the Fawn and Winisk Rivers, forming a reservoir in the low ground between the two streams. Nearly 20,000 square miles of drainage would be added to the Severn River basin by this project, which would greatly enhance the value of power sites on the lower Fawn and Severn Rivers.

2. An alternative plan would be the reverse of that mentioned above (i.e. diversion of the Fawn River into the Winisk River just south of lat. 55°). This scheme would be of interest in connection with power development of the lower Winisk River.

3. Diversion of the Attawapiskat River to the Albany River at about long. 86°20'. This diversion scheme would consist of a dam near long. 86°20' and some dyking north of the Attawapiskat to prevent overflow into the Muketei River and channel excavation through low ground southward to the Albany River. This scheme would be of interest in connection with power developments of the Albany River or with pumped diversion to the Great Lakes basin.

An estimate of mean flows available for these diversions has been given by McIntyre (1966), based upon isopleths of mean annual runoff.

Within the next few years it is proposed to divert part of the water of the Churchill River Basin into the adjacent Nelson River. This diversion will take place in the Precambrian area west of the Lowlands. A watershed area of 90,000 square miles will thus be transferred to the Nelson River System, increasing the reservoir potential for the Kettle Rapids power site. The resulting decrease in volume of fresh water entering Hudson Bay at the mouth of the Churchill is expected to substantially increase the shipping season at Port Churchill. The build up of slush ice in the harbour is expected to be delayed by several weeks by the expected more brackish nature of water in the harbour area. This slush ice development is the critical factor in terminating wheat shipments for the winter season.

REFERENCES

Alcock, F. J.
1916: The Churchill River; Geogr. Rev., vol. 2, pp. 433-448.

Barton, Ritt., et al.
1965: Quaternary; in Geological history of western Canada; Atlas Alberta Soc. Petrol. Geol., edited by R. G. McCrossan and R. P. Glaister, Calgary, pp. 195-200.

Bell, R.
1872: Report of the country between Lake Superior and the Albany River; Geol. Surv. Can., Rept. Progress, 1871-72, pp. 101-114.

1887: An exploration of portions of the Attawapiskat and Albany Rivers, Lonely Lake to James Bay; Geol. Nat. Hist. Surv., Canada, 1886, pt. G, pp. 5-38.

1897: Recent explorations to the south of Hudson Bay; Geograph. J., vol. 10, No. 1, pp. 1-19, and Map.

1910: The Hudson Bay route to Europe; Scot. Geograph. Mag., vol. 26, pp. 64-76.

Bird, J. B.
1967: The physiography of Arctic Canada; John Hopkins Press, Baltimore, pp. 81-116.

Cox, L.
1936: Rivers without end; Can. Geograph. J., vol. 14, No. 2, pp. 82-95.

Dole, R. B., and Stabler, H.
1909: Papers on the conservation of water resources; U.S. Geol. Surv., Water Supply Paper 234, pp. 78-93.

Dowling, D. B.
1902a: The west side of James Bay; Geol. Surv. Can., Sessional Paper No. 26, Summ. Rept. 1901, pp. 107-115.

1902b: Report on an exploration of Ekwan River, Sutton Mill Lakes, and part of the west coast of James Bay; Geol. Surv. Can., Summ. Rept. 1901, pt. F, pp. 1-60.

Elson, J. A.
1967: Geology of Glacial Lake Agassiz; in Proc. 1966 Conference on environmental studies of the Glacial Lake Agassiz region, edited by W. J. Mayer-Oakes, Univ. Manitoba Press, pp. 36-105.

Flint, R. F.
1957: Glacial and Pleistocene geology; Wiley and Sons, New York.

Fortier, Y. O., and Morley, L. W.
1956: Geological unity of the Arctic Islands; Trans. Royal Soc. Can., Ser. 3, vol. 50, pp. 3-12.

Hawley, J. E.
1926: Geology and economic possibilities of Sutton Lake area, District of Patricia; Ontario Dept. Mines, Ann. Rept., 1925, vol. 34, pt. 7, and map.

Hogg, N. et al.
1953: Drilling in the James Bay Lowland, Part I., Ontario Dept. Mines, vol. 61, pt. 6, pp. 115-140.

Hurdle, H. L., MacGregor, G., and Storey, T. E.
1967: The selection of +450 KV, DC for the transmission of power from the Nelson River; Engineering J., vol. 50, No. 10, pp. 17-21.

Inland Waters Branch
1967: Surface water data, Manitoba, water year 1965; Dept. Energy, Mines Resources.

Kuiper, E.
1965: Water resources development; Butterworth and Co., London.

Kupsch, W. O.
1967: Postglacial uplift - A review; in Proc. 1966 Conference on environmental studies of the Glacial Lake Agassiz region, edited by W. J. Mayer-Oakes, Univ. Manitoba Press, pp. 155-185.

Macfie, J.
1953: Fawn River — an early fur trade route; Sylva, vol. 9, pp. 3-7.

Main, J. R. K.
1967a: Early transportation in Canada: the canoe in commerce: The Dot, Dept. Transport, March-April, 1967, pp. 12-13.

1967b: Early transportation in Canada: Part II, the York boat: The Dot, Dept. Transport, May-June, 1967, pp. 14-15.

Martison, N. W.
1953: Petroleum possibilities of the James Bay Lowland area; Ontario Dept. Mines, vol. 61, pt. 6, pp. 1-95.

McIntyre, D.
1966MS: Preliminary report on northern Ontario water resources; Water Resources Branch, Dept. Energy, Mines Resources, unpubl. MS.

Nelson, S. J.
1964: Ordovician stratigraphy of northern Hudson Bay Lowland, Manitoba; Geol. Surv. Can., Bull. 108.

Nelson, S. J., and Johnson, R. D.
1966: Geology of Hudson Bay Basin; Bull. Can. Petrol. Geol., vol 14, No. 4, pp. 520-578.

Norris, A. W. et al.
1967: Geology, Hudson Bay Lowlands; Geol. Surv. Can., Map 17-1967.

Norris, A. W., and Sanford, B. V.
1968: Operation Winisk, Hudson Bay Lowlands, Ontario, Manitoba, Quebec, District of Keewatin; in Report of Activities, Part A - May to October, 1967, Geol. Surv. Can., Paper 68-1A, pp. 207-208.

Ont. Dept. Lands, Forests
1966: Locations of dams, Northern Ontario; Map D.266.

O'Sullivan, O.
1906: A survey of the coast of Hudson Bay from York Factory to Severn River; Geol. Surv. Can., Summ. Rept. 1905, pp. 73-76.

Puminov, A. P.
1967: A chart of the recent tectonics of the Arctic; Dok. Akad. Nauk SSSR, vol. 175, No. 4, pp. 901-910; translated by E. R. Hope, Defence Research Board T487R.

Rich, E. E.
1967: The fur trade and the Northwest to 1857; McClelland and Stewart, Toronto.

Savage, T. E., and Van Tuyl, F. M.
1919: Geology and stratigraphy of the area of Paleozoic rocks in the vicinity of Hudson and James Bay; Bull. Geol. Soc. Am., vol. 30, pp. 339-377.

Spencer, L., and Holland, H.
1968: Northern Ontario, a bibliography; Univ. Toronto Press.

Trudel, M.
1961: Atlas Historique du Canada Français; Les Presses de l'Université Laval, p. 40, re: Carte de la Baye de Hudson (1744) and Lac des deux Décharges.

Tyrrell, J. B.
1917: Early explorations of the Churchill River; Geograph. Rev., vol. 3, pp. 375-381.

Upham, W.
1895: The Glacial Lake Agassiz; U.S. Geol. Surv., Monograph 25.

PALEOZOIC AND MESOZOIC GEOLOGY OF THE HUDSON BAY LOWLANDS

A.W. Norris and B.V. Sanford
Geological Survey of Canada
Ottawa, Ontario

Abstract

This paper summarizes some of the preliminary results of Operation Winisk, an air-supported reconnaissance survey of the Hudson Bay Lowlands completed in 1967. The area studied is a coastal plain largely covered by muskeg which borders the southwest side of James and Hudson Bays in Quebec, Ontario, and Manitoba, embracing an area in excess of 130,000 square miles.

Remnants of two major Phanerozoic sedimentary basins are present in the Lowlands comprising the Moose River Basin in the south with an embayment extending into Quebec on its east side, and a much larger, Hudson Bay Basin, in the north, only part of which is represented on the mainland. Separating the two basins is a northeast trending positive area, the Cape Henrietta Maria Arch, where Archean and Proterozoic rocks are exposed in several inliers surrounded by a thin veneer of Silurian rocks.

In the Moose River Basin, Ordovician, Silurian, Devonian and Lower Cretaceous rocks are present with a total thickness of about 2,500 feet in the central part of the basin. In the Hudson Bay Basin rocks of Ordovician, Silurian and Devonian ages are represented on the mainland. The total succession in the central part of the latter basin covered by water of Hudson Bay is estimated by geophysical studies to be about 6,000 feet thick.

Rocks of Upper Ordovician age unconformably overlie the Precambrian and consist of a basal sandstone overlain by limestone and dolomitic limestone. They outcrop in a belt along the western and southeastern margins of the Lowlands where they have been subdivided into the Bad Cache Rapids and Churchill River Groups, and Ordovician undivided.

Middle and Upper Silurian rocks are represented in both basins by four major rock units, the Severn River, Ekwan River, Attawapiskat, and Kenogami River Formations. They consist largely of marine carbonate rocks with a capping of red clastic sedimentary rocks with minor evaporites.

Rocks of Lower, Middle, and Upper Devonian ages comprising the Stooping River (or its non-marine equivalent Sextant Formation), Kwataboahegan, Moose River, Murray Island, Williams Island and Long Rapids Formations are present in the Moose River Basin. In the Hudson Bay Basin only the Stooping River and Kwataboahegan Formations are present on the mainland.

Dykes and sills of lamprophyric and kimberlitic composition intrude the Sextant, Stooping River and Kwataboahegan Formations at Sextant and Coral Rapids at the southern edge of the Moose River Basin.

The Lower Cretaceous Mattagami Formation consists of clay, sand and lignite. It outcrops only in the southern part of the Moose River Basin where it unconformably overlaps rocks ranging in age from Upper Devonian to Precambrian.

INTRODUCTION

The present paper summarizes some of the preliminary results of Operation Winisk on the Paleozoic and Mesozoic geology of the Hudson Bay Lowlands. Operation Winisk (Norris and Sanford, 1968) was an air-supported geological reconnaissance survey of the Lowlands completed by the Geological Survey of Canada during the summer of 1967. The main objectives of the operation were to study and map (1) the Phanerozoic rocks, (2) the Precambrian rocks within and around the periphery of the Lowlands, and (3) the Quaternary surficial deposits.

Geological Survey of Canada personnel participating and their individual responsibilities were: A. W. Norris - head of operation, H. H. Bostock - Precambrian, L. M. Cumming - Ordovician, B. S. Norford - Silurian, B. V. Sanford and A. W. Norris - Devonian, L. L. Price - Mesozoic, and B. G. Craig and B. C. McDonald - Quaternary.

The area studied (see Fig. 1) is a relatively flat coastal plain the physiography of which has been described by Coombs (1954). The region is largely covered by muskeg and bog and borders the south and west sides of James and Hudson Bays. It lies within the provinces of Quebec, Ontario, and Manitoba, and District of Keewatin, and embraces an area in excess of 130, 000 square miles. Almost all of the Phanerozoic bedrock exposures are confined to river channels and scattered localities along the coast. Figure 2 is a photograph taken from the air showing a string bog, a very wet type of muskeg terrain which is common throughout much of the area. The Hudson Bay Lowlands is probably one of the larger bog areas of the world (see Falconer, 1958) which accounts in large part for the slow growth of settlement in the area and makes inland exploration exceedingly difficult and costly.

In this paper, the distribution, thickness and facies of most of the Phanerozoic formations are illustrated by a series of maps compiled from all known outcrop and available subsurface data. For this reason descriptions are restricted mainly to the more pertinent and gross regional features of each formation. For more detailed accounts of the stratigraphy of various parts of the Lowlands the reader is referred to Johnson and Nelson (this volume), Martison (1953), Nelson (1963, 1964), Nelson and Johnson (1966), Remick, Gillain and Durden (1963), Savage and Van Tuyl (1919), and Sanford,

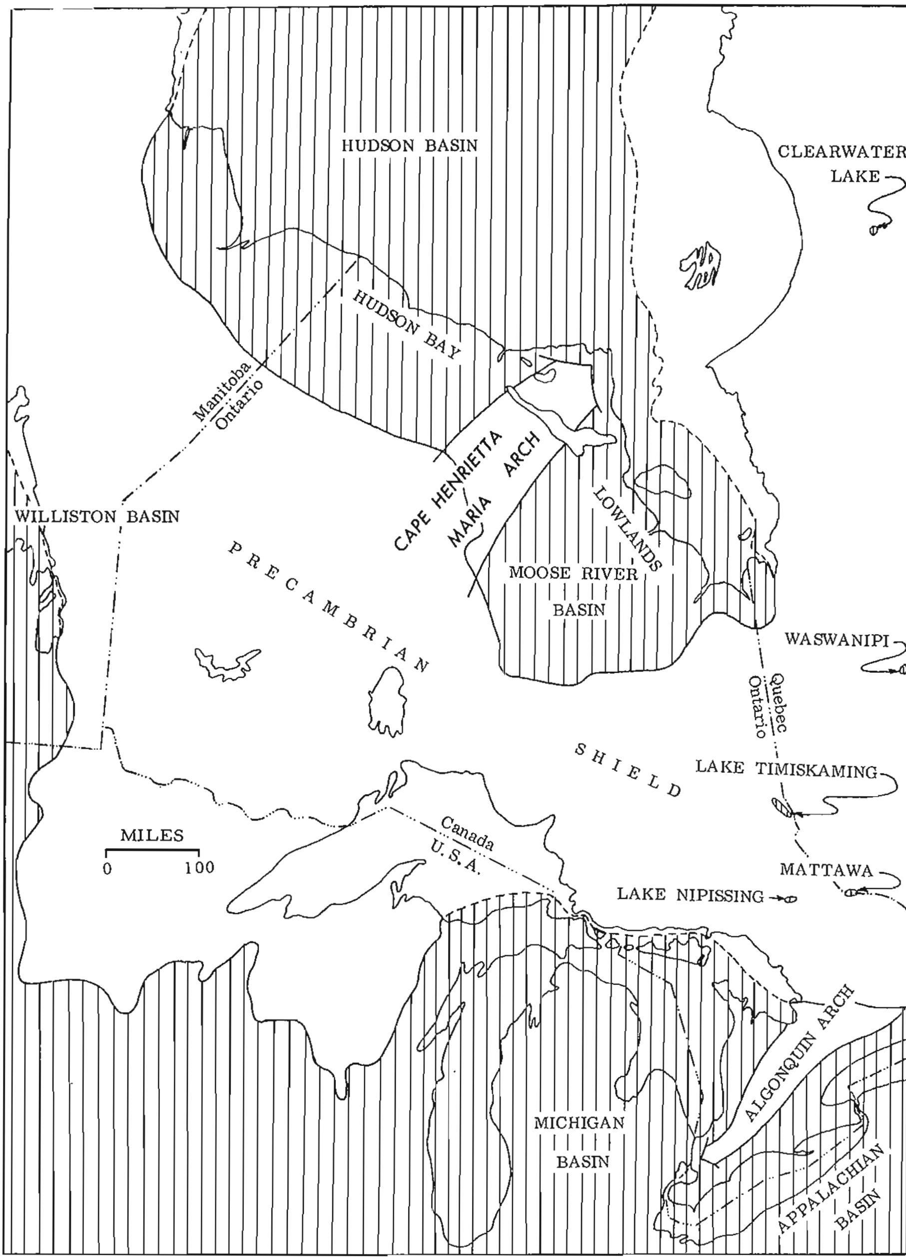


Figure 1. Index map showing Hudson Bay Lowlands and adjacent geological provinces.

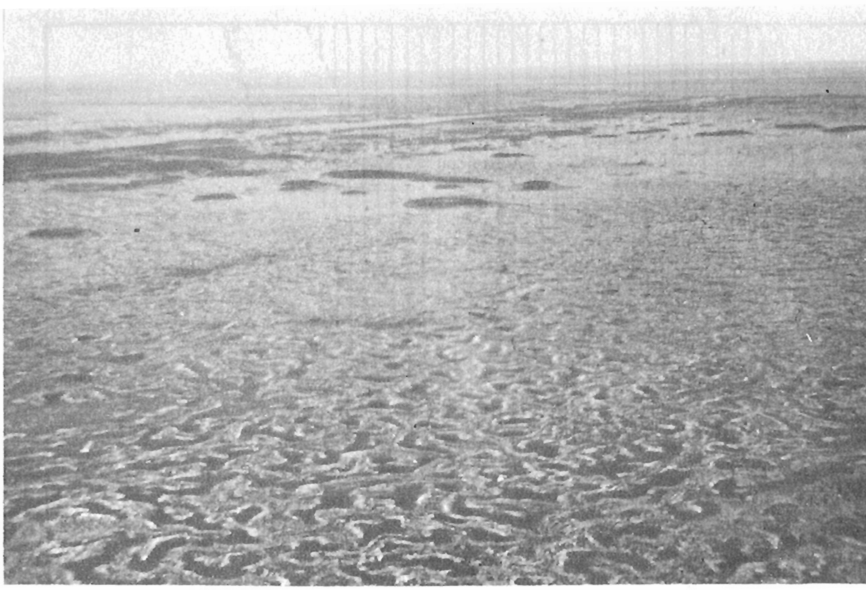


Figure 2. Aerial view of a string bog. (GSC 200841-0).

Norris and Bostock (1968). Locations of outcrops and wells mentioned but not illustrated in this paper are shown on the Geological Survey of Canada, geological Map 17-1967 of the Hudson Bay Lowlands at a scale of 1: 1 million.

Very few fossil collections of Operation Winisk have as yet been examined and identified, consequently conclusions presented are tentative. Preliminary fossil determinations by M. J. Copeland, D. C. McGregor, G. W. Sinclair, and T. T. Uyeno are gratefully acknowledged.

For assistance and many courtesies received while preparing for and mounting of Operation Winisk the writers wish to thank the representatives of Aquitaine Company of Canada Limited, Banff Oil Limited, Sogepet Limited, and associated companies, Drs. J. F. Davies and H. R. McCabe of the Manitoba Mines Branch, Dr. A. S. MacLaren of the Geological Survey of Canada, Dr. S. J. Nelson of the University of Calgary, Consolidated Morrison Explorations Limited, Imperial Oil Enterprises Limited, the Hydro-Electric Power Commission of Ontario, and Officers of the Ontario Department of Mines.

GEOLOGY

The Phanerozoic rocks of the Hudson Bay Lowlands are present in the remnants of two fairly large intracratonic sedimentary basins (see Fig. 1), the Moose River Basin in the south with an embayment extending into Quebec, and a much larger, Hudson Bay Basin[1], in the north, only part of which is present on the mainland. Separating the two basins is a northeast trending Precambrian basement high, referred to as the Cape Henrietta Maria Arch. Because of the close similarity of facies and faunas, both of the basins were almost certainly connected with the Williston, Michigan and Appalachian Basins to the south during various intervals of Paleozoic time. The presence of Paleozoic outliers (Caley and Liberty, 1957, pp. 237-238) at Clearwater Lake (Kranck and Sinclair, 1963), Waswanipi (Clark and Blake, 1952), Lake Timiskaming (Hume, 1925), Mattawa, Lake Nipissing, and others, tends to support this hypothesis.

In the Moose River Basin (see Fig. 3), Paleozoic rocks of Ordovician, Silurian and Devonian ages are represented by a variety of shallow marine facies consisting of sandstones, shales, limestones, dolomites, and evaporites. These are succeeded by non-marine clastic rocks of Lower Cretaceous age. In the Hudson Bay Basin to the north, only rocks of Ordovician, Silurian and Lower and early Middle Devonian ages are represented on the mainland. A more complete section, comparable to the Moose River Basin, is believed to be present offshore in the central part of this basin.

Figure 5 shows the general topography of the Precambrian surface and distribution of Archean crystalline and Proterozoic sedimentary rocks. The deepest part of the Hudson Bay Basin on the mainland near Cape Tatnum is about 3, 000 feet below sea level. The basement slope is towards the centre of Hudson Bay Basin and is about 25 feet per mile.

The deepest part of the Moose River Basin is 2, 500 feet. The Precambrian basement rises abruptly to the surface along the southern margin of the basin to form an escarpment rising above the plain of the Lowlands. In the subsurface of the southern part of the basin the Precambrian appears to have been uplifted as a horst about 1, 500 feet along major faults which presumably occurred during Lower Devonian time.

It is apparent that the basement crystalline rocks of Archean and questionable Proterozoic ages underlie a large part of the Hudson Bay Lowlands (Fig. 5). Proterozoic rocks, consisting mainly of gently deformed sediments, appear to have a more restricted distribution in the Lowlands.

---

[1] Although indicated as the Hudson Basin on Figures 1, 4 and 25, the more appropriate term for this structure is the Hudson Bay Basin which has priority (see Nelson and Johnson, 1966).

The latter outcrop as inliers on the Cape Henrietta Maria Arch and in the vicinity of Churchill where they dip mainly into the subsurface beneath Hudson Bay. Proterozoic rocks are presumed to underlie a large part of James Bay and to occur as scattered outliers over the southwestern part of the arch. This interpretation is suggested by the unusually thick depths to basement (up to 1, 600 feet) indicated by seismic studies (Hobson, 1964, 1967) over Akimiski Island and the Cape Henrietta Maria Arch, areas in which the Paleozoic sequences are known to be relatively thin.

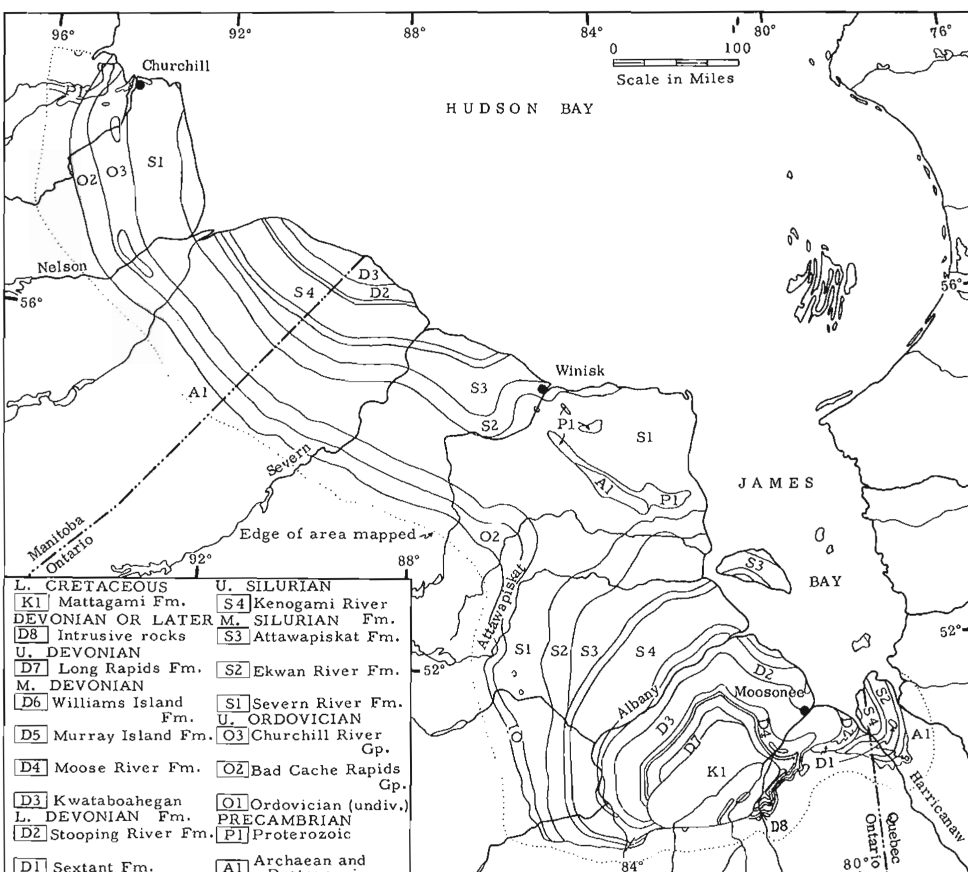


Figure 3. Geological map of the Hudson Bay Lowlands.

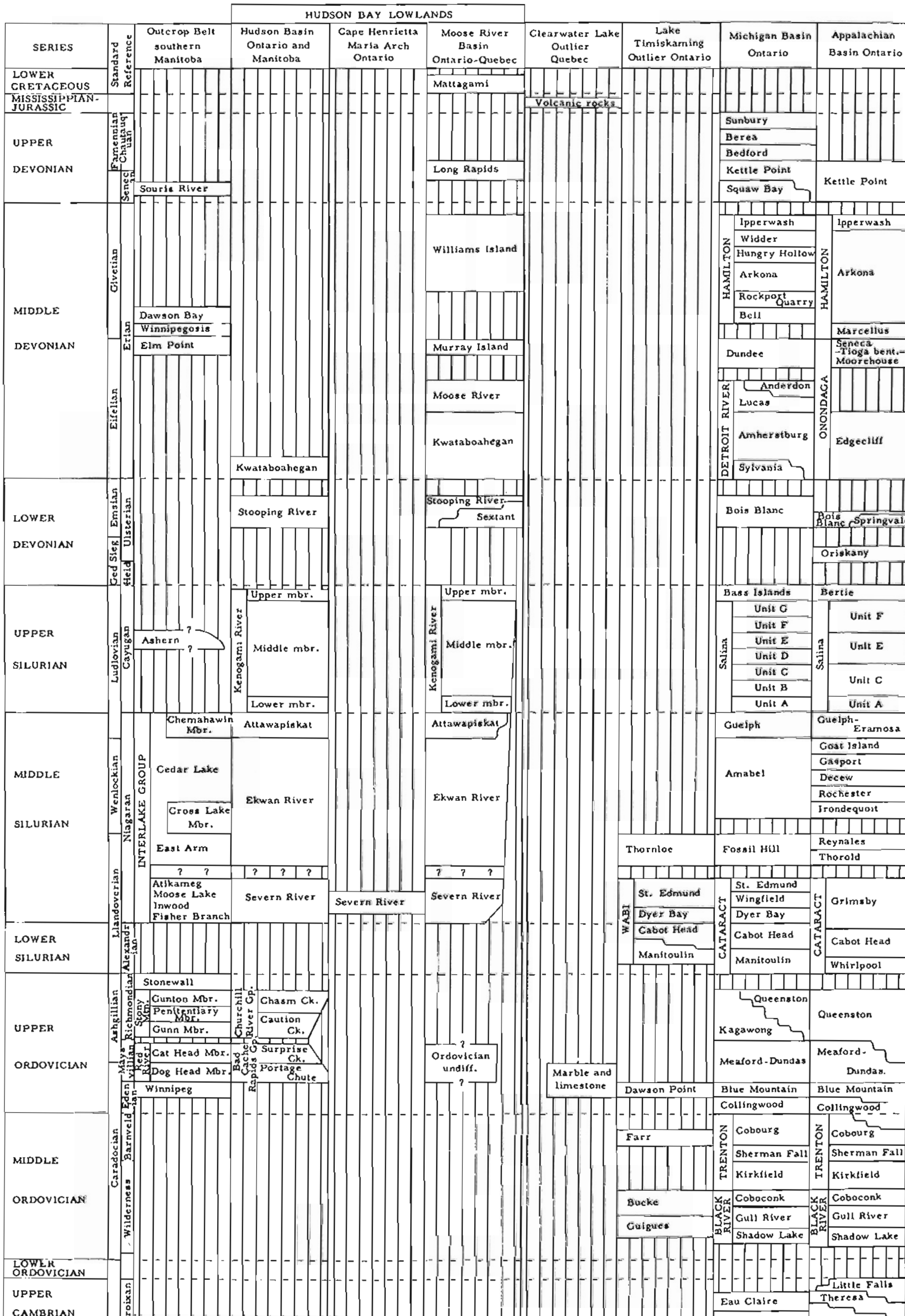


Figure 4. Formational nomenclature of the Hudson Bay Lowlands and related areas.

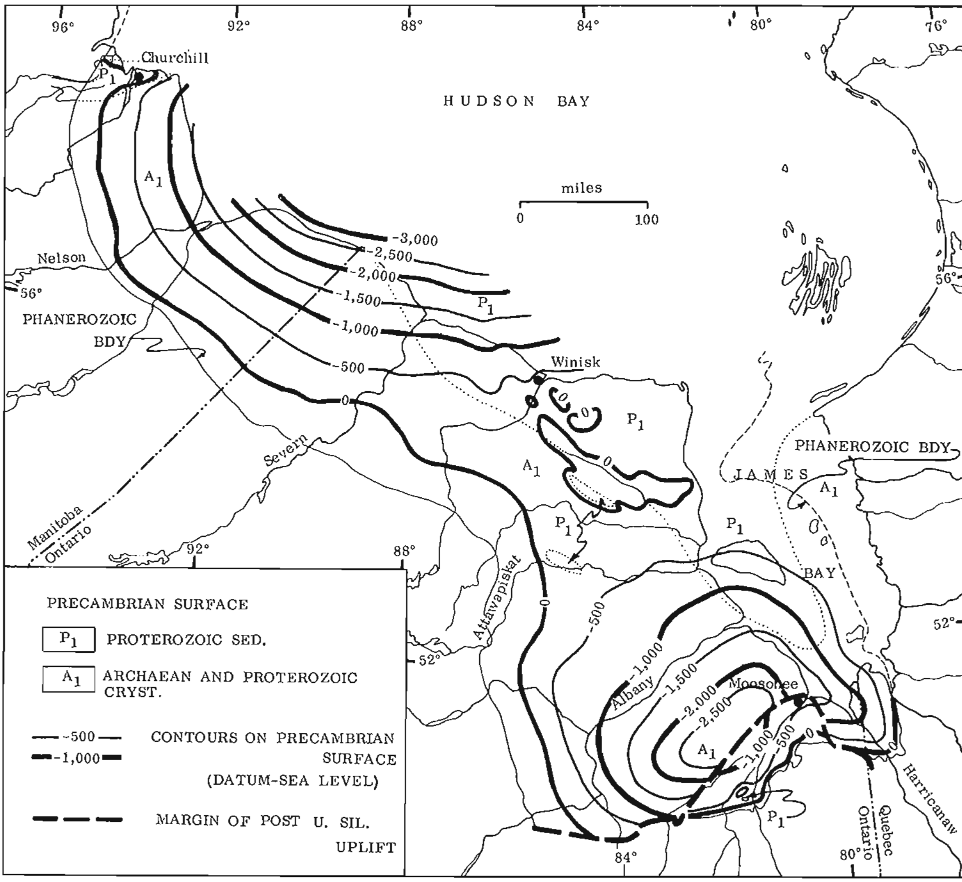


Figure 5. Contours on Precambrian surface, Hudson Bay Lowlands.

Because of the relative flatness of the Lowlands, Figure 5 also provides a rough indication of the thickness of Phanerozoic rocks covering the Precambrian.

The regional structural attitudes of the Phanerozoic rocks as determined by mapping (see Fig. 3) are very nearly parallel to the basement contours. Beds dip basinward fairly uniformly at 15 to 25 feet to a mile. However, where Archean and Proterozoic rocks project through the Paleozoic cover, compaction dips in the onlapping strata vary from 17 to 25 degrees.

Upper Ordovician

The oldest known Paleozoic rocks in the Hudson Bay Lowlands are of late Middle or early Upper, and late Upper Ordovician ages (Fig. 6). They consist of a basal sandstone, overlain by limestones and dolomitic limestones. In the Hudson Bay Basin they reach a known thickness of 400 feet, but probably exceed this thickness towards the centre of the basin. In this region the Ordovician rocks are subdivided into two mappable units, named by Nelson (1963) the Bad Cache Rapids and Churchill River Groups. These units outcrop in a narrow belt along the western margin of Hudson Bay Basin.

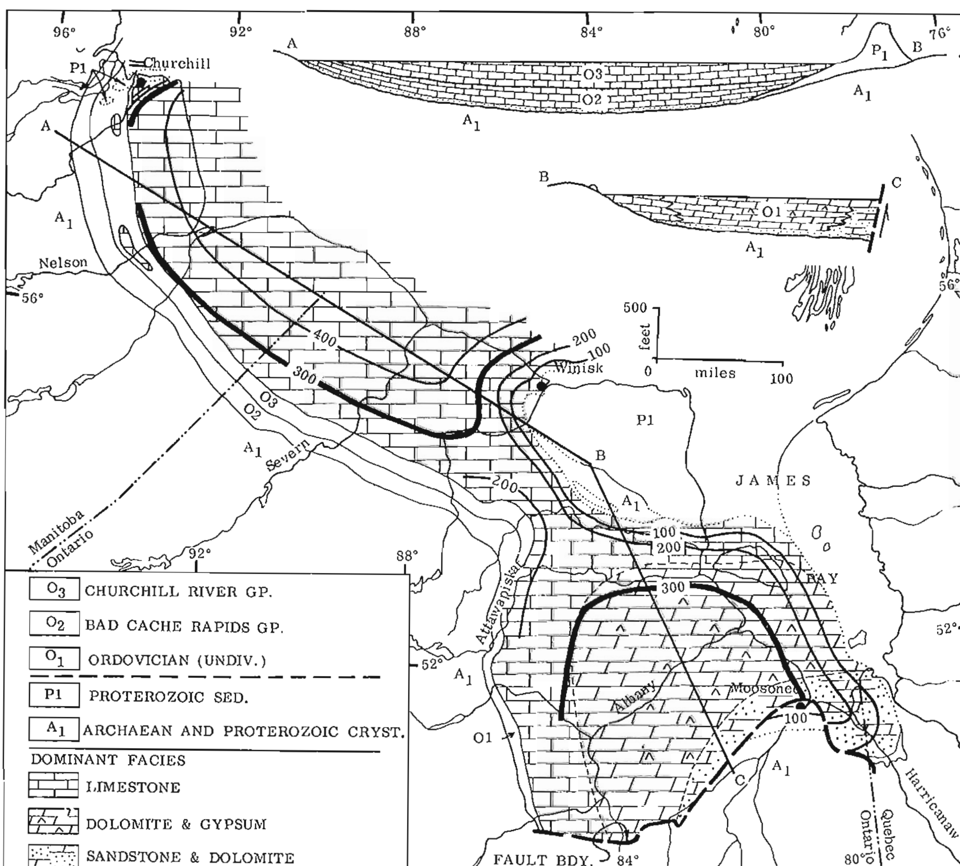


Figure 6. Facies and isopachous map of Ordovician rocks in Hudson Bay Lowlands.

Ordovician rocks outcrop also along the western and southeastern margins of the Moose River Basin where they lose their identity and are tentatively mapped as Ordovician undivided.

Bad Cache Rapids Group

The Bad Cache Rapids Group rests on the peneplaned surface of the Precambrian. Perhaps one of the best exposures of these beds is on the Churchill River as shown in Figure 7. The group in this area is about 140 feet thick and contains a basal transgressive orthoquartzite sandstone varying from 5 to 15 feet thick, overlain by dolomitic limestone.

Fossils from this group studied by Nelson (1963, 1964) indicate a correlation with the Red River Formation of the Lake Winnipeg area in Manitoba.

Churchill River Group

The Churchill River Group disconformably overlies the Bad Cache Rapids Group and is composed primarily of mottled, light yellowish grey and brown fragmental limestones. It has a maximum known thickness of 290 feet in the Kennco No. 5 well. Figure 8 shows a typical exposure of these strata on the South Knife River.

The faunal succession within the group indicates correlation with the Stony Mountain Formation of Manitoba (Nelson, 1963, 1964).

Ordovician Undivided

Ordovician strata in the Moose River Basin are poorly exposed and consequently not as well known as they are to the north, and are left unnamed (unit O_1 of Fig. 6). In the western part of this basin they consist of limestone and dolomitic limestone with a thin basal sandstone. In the central part of the basin they consist of dolomite with some interbeds of gypsum. Towards the truncated southern margin of the basin the dolomite contains an increasing amount of clastic material consisting of quartz and arkosic sand and pebbles of granite. In the Quebec Embayment clastic rocks are the dominant facies.

Thickness of Ordovician strata penetrated in the Puskwuche Point well is 271 feet.

A few fossils from the western margin of the basin (upper Muketei and Albany Rivers) suggest that at least part of the Bad Cache Rapids Group is represented in the sequence.

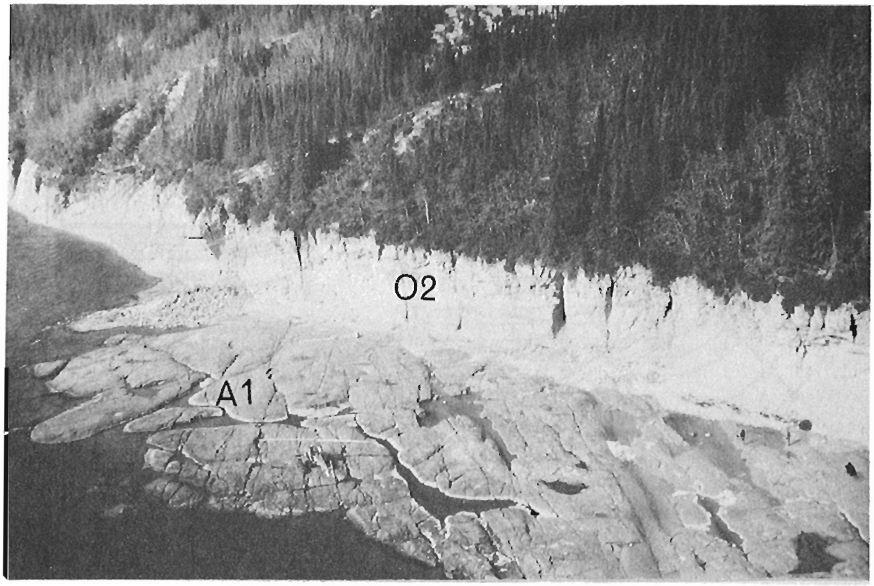


Figure 7. Aerial view of Bad Cache Rapids Group (O_2) resting on the Precambrian (A_1) on Churchill River. (GSC 200841-B).

Figure 8. Dolomitic limestone of Caution Creek Formation of Churchill River Group outcropping on South Knife River. (GSC 200841-K).

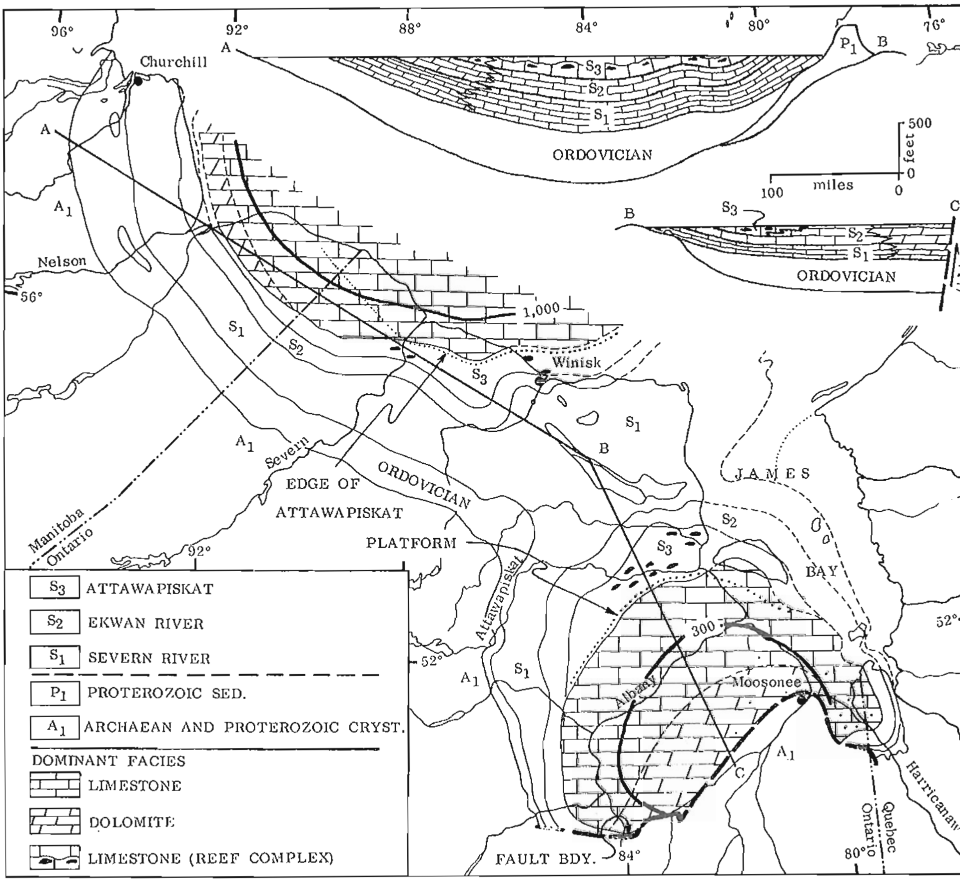


Figure 9. Facies and isopachous map of Middle Silurian rocks in Hudson Bay Lowlands.

Middle Silurian

Although rocks regarded as Lower Silurian in age are preserved in the Lake Timiskaming outlier (see Fig. 4), the sea depositing similar rocks apparently did not extend north to the Hudson Bay Lowlands. The oldest Silurian rocks of the Lowlands contain the brachiopod Virgiana decussata (Whiteaves) which is of an early Middle Silurian age (Bolton, 1953). Rocks containing this species disconformably succeed the Ordovician. Middle Silurian (Niagaran) rocks of the region comprise the Severn River, Ekwan River and Attawapiskat Formations (see Fig. 9). They outcrop along the western margins of the Moose River and Hudson Bay Basins and form the youngest Paleozoic strata across the intervening Cape Henrietta Maria Arch. They

Figure 10. Beds of Severn River Formation (S_1) exposed along coast immediately east of Churchill. (GSC 200841-G).

are truncated along the southern margin of the Moose River Basin by a major fault where they are in contact with Precambrian crystalline rocks. Parts of the sequence also outcrop in the Quebec Embayment and on Akimiski Island on the southeast and northeast margins of the basin. The total thickness of Niagaran strata in the central part of the Moose River Basin is about 300 feet. In the Hudson Bay Basin to the north Niagaran strata would appear to have a considerably greater thickness, perhaps more than a thousand feet as indicated by Figure 9.

The Middle Silurian sequence is composed mainly of limestone with the exception of two areas where the predominant facies is dolomite. These latter areas are (1) in the southern half of the Moose River Basin, and (2) in the southwestern part of the Hudson Bay Basin.

Severn River Formation

The term Severn River Formation was proposed by Savage and Van Tuyl (1919) for beds exposed along Severn River above its junction with the Fawn River. In the present paper it also includes beds of the Port Nelson Formation, named by Savage and Van Tuyl (1919), and the upper member of the Red Head Rapids Formation of Nelson (1963).

Throughout most of the Lowlands light brown or tan, fine textured limestones and dolomites of the Severn River Formation disconformably overlie Ordovician carbonate rocks. Over the Cape Henrietta Maria Arch and near Churchill the Severn River Formation overlaps the Ordovician to rest directly on the Proterozoic. Figure 10 shows Severn River dolomite on the north flank of a ridge of 'Churchill Quartzite' 1 mile east of Churchill where the beds dip northward beneath Hudson Bay. The quartzite ridge (P_1) can be seen in the background.

The Severn River Formation at one time buried the ridges of 'Churchill Quartzite' as indicated by fissure fillings of dolomite and quartz pebble conglomerate found at scattered localities on the north flank of the ridge. One such fissure filling is shown in the photograph (Fig. 11).

Figure 11.

Severn River dolomite present as a fissure filling in 'Churchill Quartzite'. (GSC 200841-N).

Known maximum thickness of the Severn River Formation in the Moose River Basin is 148 feet in the Puskwuche Point well. In the Hudson Bay Basin to the northwest, 169 feet were penetrated in the Kennco No. 5 well where the formation is incomplete.

Ekwan River Formation

The term Ekwan River limestones was proposed by Savage and Van Tuyl (1919) for beds typically exposed along Ekwan River. This name is used here in preference to Dyer's (1930) Pagwa River Formation because the latter includes beds in part equivalent to the Ekwan River Formation and the lower member of the Kenogami River Formation. The Ekwan River succeeds the Severn River and is overlain by the Attawapiskat reefal beds and in places by the Kenogami River Formation.

The Ekwan River consists of grey, cream and brown, fine to medium crystalline, thin to thick bedded limestone and dolomite which locally form massive biostromal lenses.

Figure 12 shows about four feet or more of biostromal limestone outcropping and extending part way across Albany River to form rapids.

Thicknesses of the Ekwan River Formation penetrated in the Puskwuche Point and Jaab Lake wells are 177 and 66 feet (base not reached) respectively.

This formation is in places richly fossiliferous and is lithologically similar to the Fossil Hill and Amabel Formations of southwestern Ontario, and the Thornloe Formation of the Lake Timiskaming outlier, and are presumed to be roughly equivalent in age.

Attawapiskat Formation

Completing the Middle Silurian sequence is the Attawapiskat reef complex. Although reef development along the lower reaches of the Attawapiskat River was first described by Bell (1887), the term Attawapiskat Coral Reef was first proposed by Savage and Van Tuyl (1919). Figure 13 shows a stretch of the lower reaches of the Attawapiskat River along which this formation is typically exposed. Most of the islands in the foreground are held up by small bioherms of massive yellowish tan and brown, vuggy, cavernous limestone that weather ash grey. Flanking the bioherms are thick beds of coarse bioclastic limestone dipping steeply away from the cores. These beds become finer in texture and thinner bedded where they grade into the inter-reef facies. Associated with the bioherms are thick, high energy biostromal beds, 18 to 24 inches thick, and these form a fairly high percentage of the formation around the margins of the basins.

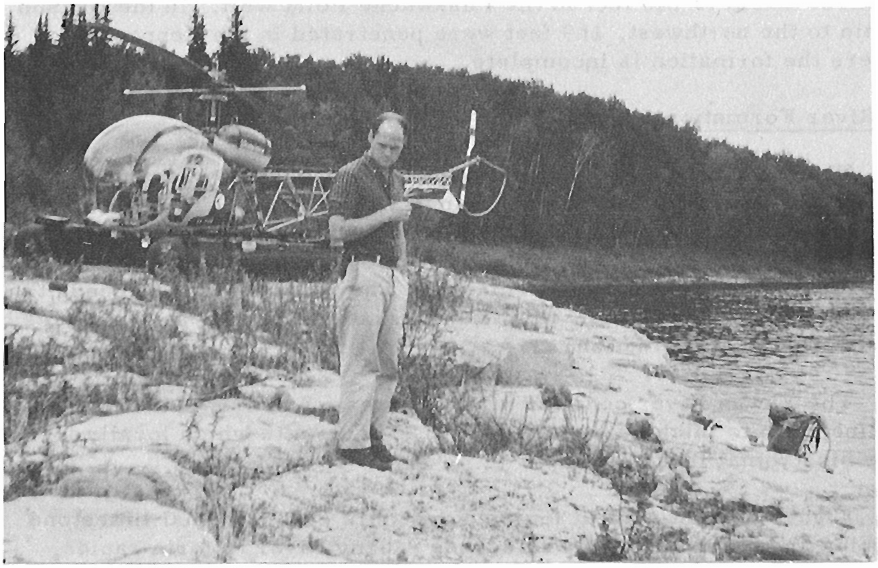


Figure 12. Outcrop of biostromal limestone of Ekwan River Formation on Albany River. (GSC 200841-M).

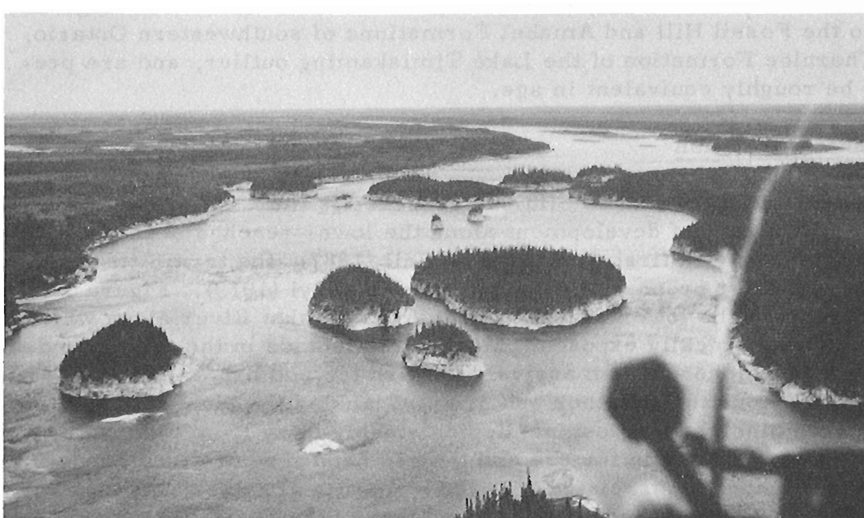


Figure 13. Aerial view looking down river of Attawapiskat reefal and associated beds outcropping along Attawapiskat River. (GSC 200841-C).

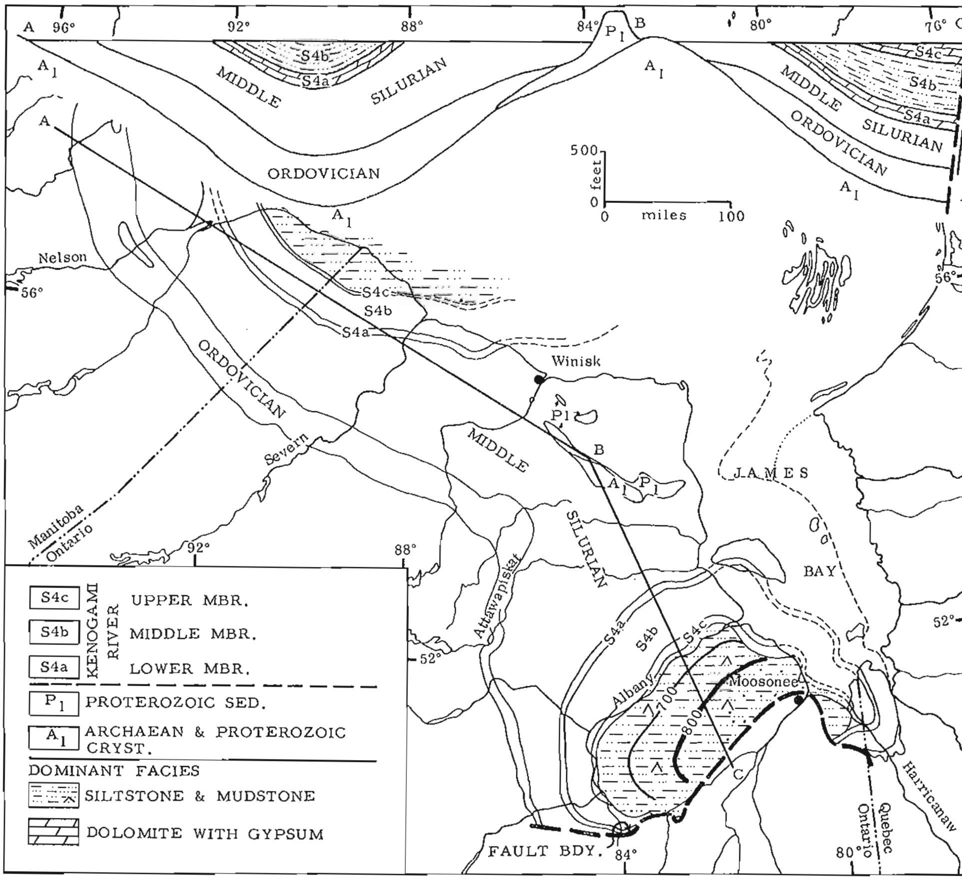


Figure 14. Facies and isopachous map of Upper Silurian rocks in Hudson Bay Lowlands.

The areas flanking the Cape Henrietta Maria Arch apparently acted as stable platforms on which the Attawapiskat Formation developed as a barrier reef complex. For comparison one may mention the Michigan Basin where a barrier reef complex completely surrounds that basin. In the Lowlands the bioherms high on the platform are small and of low relief, presumably due to lack of subsidence. Perhaps lower in the Moose River and Hudson Bay Basins subsidence was sufficiently rapid to have permitted the development of pinnacle bioherms which would be worth searching for as possible sources of oil and gas.

Estimated maximum thickness of this formation in the outcrop areas is in excess of 100 feet.

The Attawapiskat reef complex is very similar in character to the Guelph Formation of the Great Lakes region of Canada and the United States, and is tentatively correlated with that formation (Fig. 4).

Upper Silurian

Kenogami River Formation

The youngest Silurian rocks (Fig. 14) of the Lowlands named by Dyer (1930a) the Kenogami River Formation are of probable Upper Silurian age. This formation overlies the Attawapiskat and in places the Ekwan River, and is disconformably succeeded by the Lower Devonian Stooping River Formation. An entirely different sedimentary regime is indicated by these rocks. The formation consists of a lower member of dolomite and evaporites, a middle member of evaporitic red beds of mudstone, siltstone, sandstone and dolomite, and an upper member of oolitic dolomite and dolomite breccia.

It has a known maximum thickness of 850 feet in the Moose River Basin and its thickness and lithology in the Hudson Bay Basin is presumably closely comparable.

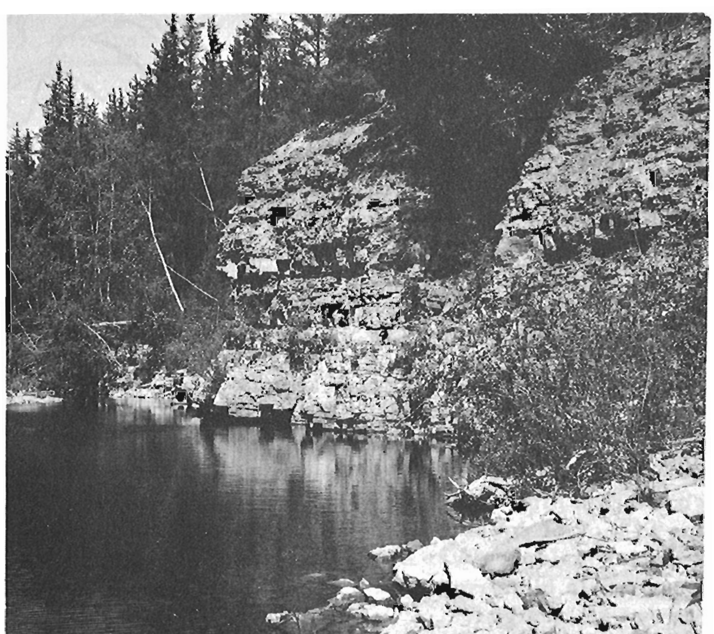


Figure 15. Parts of the lower and middle members of the Kenogami River Formation outcropping on Coal River. (AWN 2-1-67).

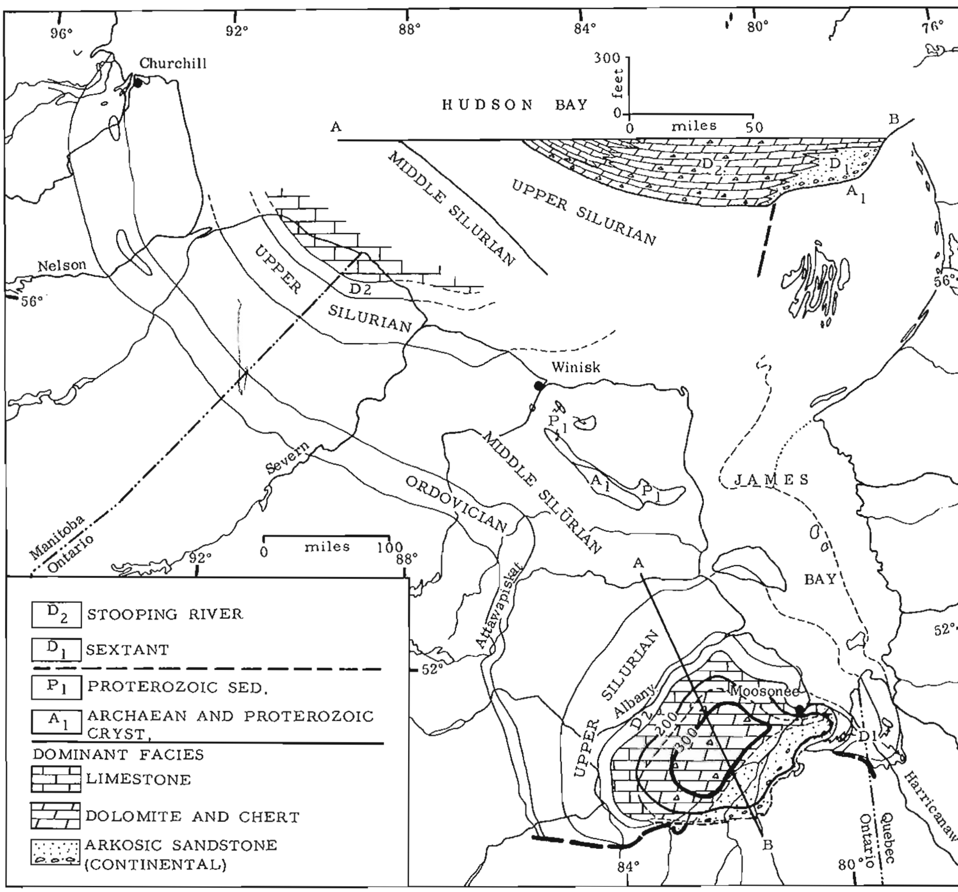


Figure 16. Facies and isopachous map of Lower Devonian rocks in the Hudson Bay Lowlands.

Figure 15 shows parts of the lower and middle members of the formation outcropping on Coal River at the southern margin of the Moose River Basin where it is in fault contact with Precambrian rocks which outcrop nearby.

Although Kenogami River strata are sparsely fossiliferous, they are presumably coeval with the Upper Silurian Salina and Bass Islands Formations of southwestern Ontario, and the Ashern Formation of southern Manitoba.

Lower Devonian

Lower Devonian rocks of the Hudson Bay Lowlands are represented by continental beds of the Sextant Formation and equivalent marine carbonate rocks of the Stooping River Formation (Fig. 16).

Sextant Formation

The Sextant Formation named by Savage and Van Tuyl (1919) is known only in the southeastern part of the Moose River Basin. At Sextant Rapids on Abitibi River it rests directly on the Precambrian, and grades laterally basinward to marine carbonates of the Stooping River Formation, where it is transgressively succeeded and overlapped by that formation. In the Quebec Embayment outliers of the Sextant Formation disconformably overlie beds of the Ordovician undivided, Ekwan River and Kenogami River Formations respectively (see Fig. 3).

Figure 17 shows the lower part of the Sextant Formation (D_1) intruded by basic dykes (D_8) at Sextant Rapids on the Abitibi River. The formation consists of terrigenous clastic beds of sandstone, siltstone, shale and conglomerate, and locally contains plant remains described by Lemon (1953).

Maximum known thickness is 175 feet recorded in the Coral Rapids well.

Spores from the Sextant Formation have been dated by D. C. McGregor of the Geological Survey of Canada as late Lower Devonian (Emsian) age.

Stooping River Formation

The name Stooping River Formation was proposed by Sanford and Norris in Sanford et al. (1968) for Lower Devonian limestones and dolomites typically exposed at the junction of the Stooping and Albany Rivers, and at nearby Fort Albany.

In the northern part of the Moose River Basin and in the Hudson Bay Basin, this formation consists mainly of finely crystalline and locally fragmental limestones. In the central part of the Moose River Basin it consists of cherty dolomite and limestone which becomes increasingly argillaceous and sandy where it intertongues with and overlaps the Sextant Formation. The latter facies is shown in the photograph (Fig. 18) where beds of this formation (D_2) outcropping at Coral Rapids on Abitibi River are overlain by the Kwataboahegan Formation (D_3).

Maximum known thickness of the Stooping River Formation is 309 feet recorded in the Jaab Lake well.

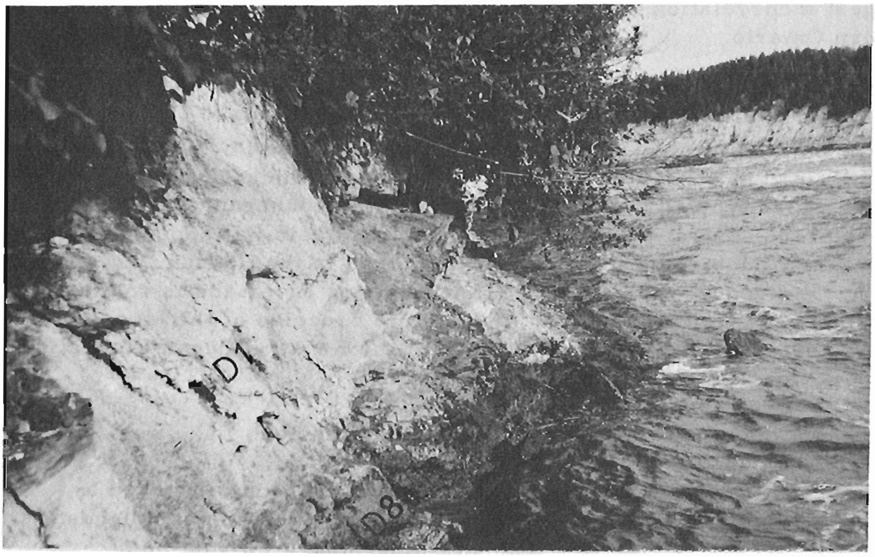


Figure 17. Lower part of Sextant Formation (D_1) intruded by lamprophyric dykes (D_8) outcropping at Sextant Rapids on Abitibi River. (GSC 200841-J).

Figure 18. Beds of Stooping River Formation (D_2) overlain by more resistant cliff-forming beds of Kwataboahegan Formation (D_3) outcropping at Coral Rapids on Abitibi River. (GSC 200841-H).

Lower Devonian fossils, including Amphigenia sp., in the Stooping River suggest a correlation with the Bois Blanc Formation of Michigan and southwestern Ontario.

Middle Devonian

The name Kwataboahegan Formation was proposed by Sanford and Norris, in Sanford et al. (1968) for the cliff-forming, thick-bedded, coral-bearing limestones typically exposed along the Kwataboahegan, Abitibi, and other rivers of the central part of the Moose River Basin. It appears to be the youngest formation represented on the mainland in the Hudson Bay Basin to the north. It disconformably overlies the Stooping River and is conformably overlain by evaporitic limestone or dolomite breccias of the Moose River Formation. Figure 20 shows resistant beds of the Kwataboahegan Formation outcropping at Coral Rapids on the Abitibi River.

It has a maximum thickness of 403 feet in the Jaab Lake well.

The rich coral fauna of the Kwataboahegan, in part discussed by Fritz and Cranswick (1953) and commented upon by Oliver (1966), suggests a correlation with the early Middle Devonian Amherstburg Formation of Michigan and southwestern Ontario, and the Edgecliff Member of the Onondaga Formation of New York State and Niagara Peninsula region of Ontario.

Moose River Formation

The Moose River Formation was named by Dyer (1928) and here applies to gypsum and associated unfossiliferous carbonate rocks that overlie the Kwataboahegan, and are succeeded by fossiliferous limestones of the Murray Island Formation. In the central part of the Moose River Basin it consists of aphanitic limestones and dolomites with thick interbeds of white gypsum (area indicated by dotted line on Fig. 19). Along the southern margin of the basin a large part of the gypsum has been removed by solution leaving the collapsed carbonate rocks severely contorted and brecciated.

Figure 21 shows a typical exposure of massive gypsum of the Moose River Formation on Cheepash River.

Maximum known thickness of the formation is 108 feet in the Jaab Lake well.

Although unfossiliferous the stratigraphic position of the Moose River Formation suggests that it correlates roughly with the Lucas Formation of Michigan and southwestern Ontario.

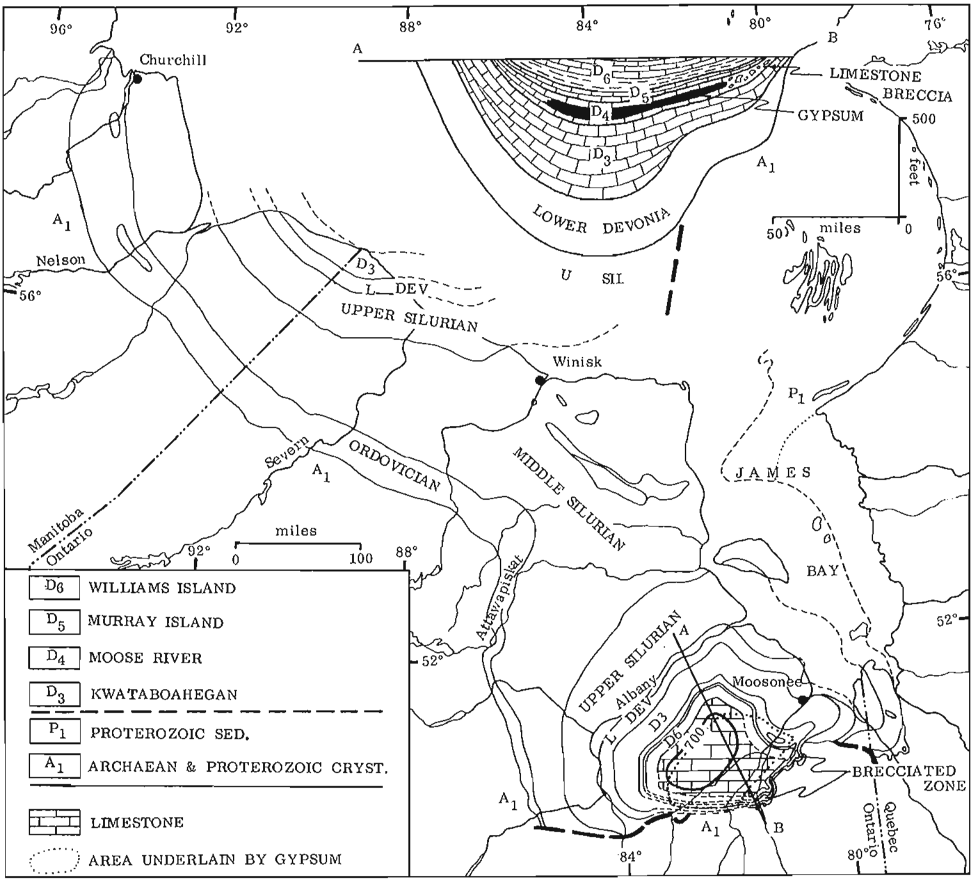


Figure 19. Facies and isopachous map of Middle Devonian rocks in Hudson Bay Lowlands.

Figure 20. Cliff-forming beds of Kwataboahegan Formation at Coral Rapids on Abitibi River. (GSC 200841-I).

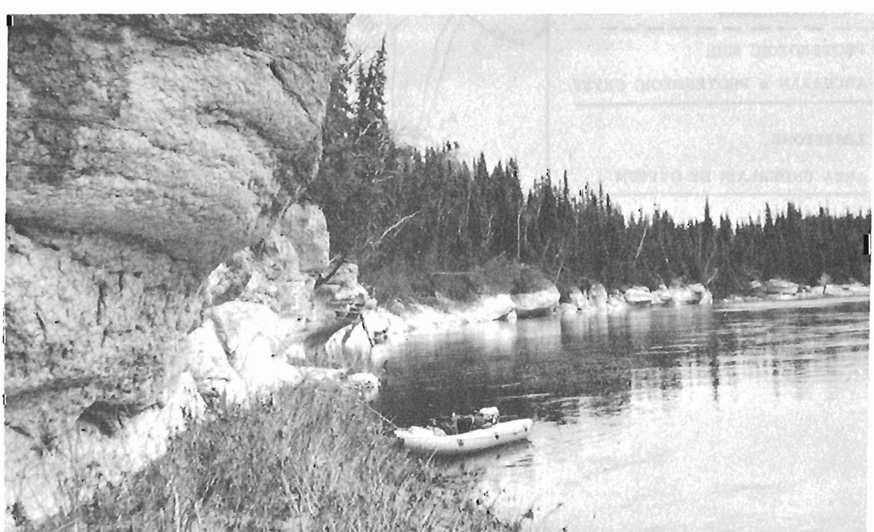


Figure 21. Gypsum of Moose River Formation outcropping on Cheepash River. (GSC 200841-F).

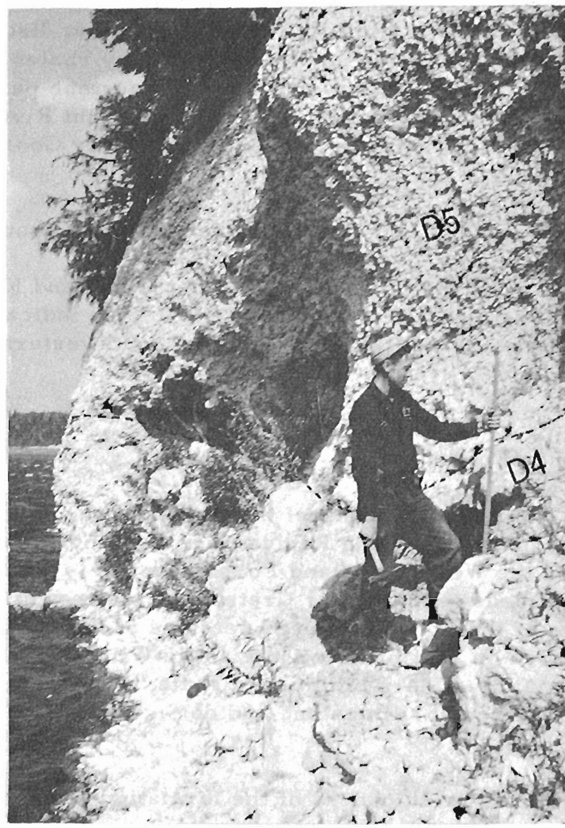


Figure 22.

Closely jointed limestone beds of the Murray Island Formation (D5), overlying brecciated carbonate beds of the Moose River Formation (D4), near upper end of Long Rapids on Abitibi River. (GSC 200841-A).

Murray Island Formation

The name Murray Island Formation was proposed by Sanford and Norris in Sanford et al. (1968) for fossiliferous limestones that disconformably overlie the Moose River Formation and are succeeded by shales and limestones of the Williams Island Formation. The type section is at the head of Murray Island on Moose River. Figure 22 shows the typical closely jointed character of the Murray Island Formation (D 5) overlying brecciated carbonate beds of the Moose River Formation (D 4) outcropping near the upper end of Long Rapids on Abitibi River.

It has a maximum thickness of 20 feet in the Jaab Lake well.

The presence of Desquamatia arctica (Warren) and other fossils in this formation suggest a correlation with the Elm Point Formation of Manitoba. Lithologically it is remarkably similar to the Dundee Formation of southwestern Ontario and Michigan.

Williams Island Formation

The uppermost unit of the Middle Devonian succession of the Moose River Basin is the Williams Island Formation which was named by Kindle (1924). It consists of limestones and shales that disconformably overlie the Murray Island Formation and is succeeded by shales of the Long Rapids Formation. Figure 23 shows the upper limestone part of the formation exposed at the head of Williams Island on Abitibi River. Part of the lower shale beds of the formation are exposed at Grey Goose and Mike Islands on Moose River.

Estimated thickness of the formation is about 200 feet.

Brachiopods listed by Williams (1920) and Kindle (1924), and corals described by Fritz, Lemon and Norris (1957), indicate a correlation with the late Middle Devonian Hamilton Group of southwestern Ontario.

Upper Devonian

Long Rapids Formation

The uppermost unit of the Devonian succession in the Moose River Basin was named the Long Rapids Formation by Savage and Van Tuyl (1919). It overlies the Williams Island Formation and is unconformably succeeded by continental beds of the Lower Cretaceous Mattagami Formation. Figure 24 shows one of the thicker exposed sections of the Long Rapids Formation in the type area on Abitibi River just above Williams Island. The formation consists mainly of dark bituminous shale, with some interbeds of greyish green shale, nodular limestone and dolomite, and scattered clay ironstone nodules.

Maximum thickness of the formation is 285 feet in the Onakawana well.

The Long Rapids Formation, on the basis of published fossil lists (Kindle, 1924; Martison, 1953; and others) contains a peculiar mixture of Upper and Middle Devonian forms. Until the fossils are restudied the formation is tentatively correlated with the lithologically similar Upper Devonian Kettle Point Formation of southwestern Ontario.

Devonian or Later

Intrusive Dykes and Sills

Of unusual interest is the presence of basic dykes and sills that outcrop at Sextant and Coral Rapids on Abitibi River at the southern edge of the Moose River Basin (see Fig. 3 and Geological Survey of Canada Map 17-1967). These have been examined and described by a number of geologists and the

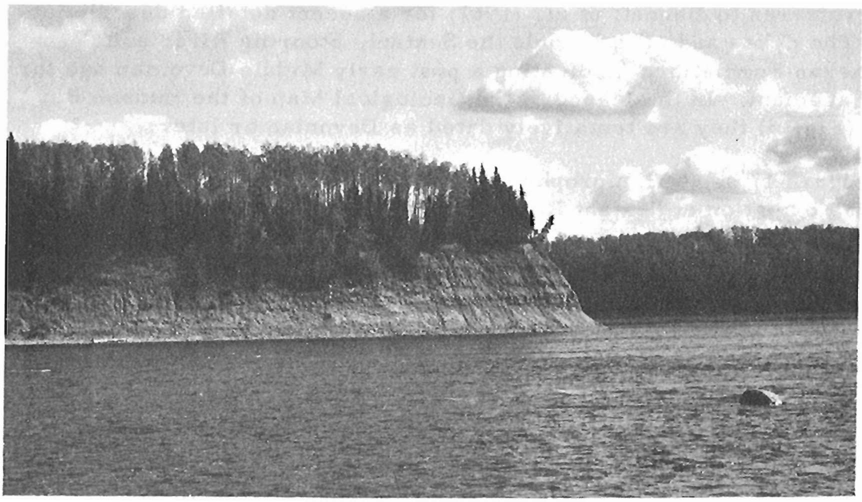


Figure 23. Upper beds of Williams Island Formation exposed on southern end of Williams Island in Abitibi River. (AWN-1953).

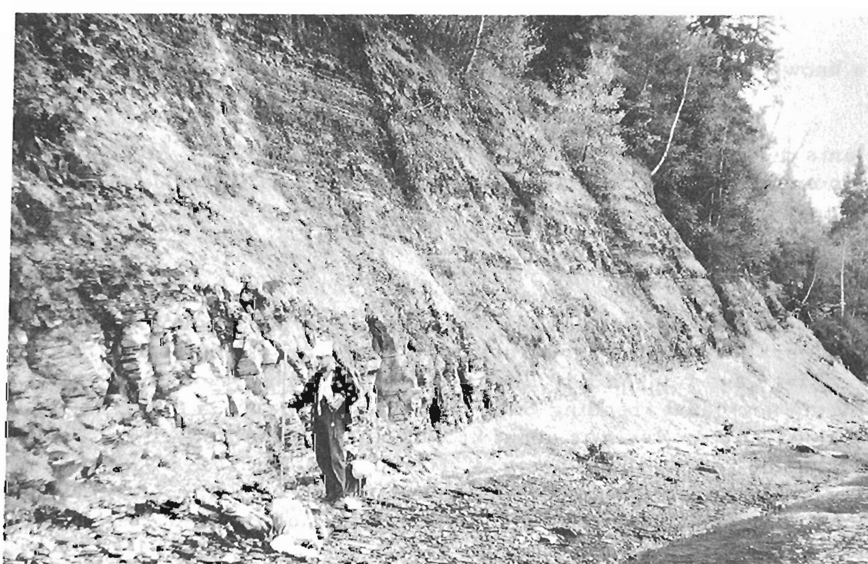


Figure 24. Shale beds of Long Rapids Formation outcropping on Abitibi River just above Williams Island. (GSC 200841-L).

reader is referred to Bennett et al. (1967) for a recent detailed description of them. The dykes and sills intrude the Sextant, Stooping River and Kwataboahegan Formations, indicating a post early Middle Devonian age for their emplacement. In the legend of the Geological Map of the Hudson Bay Lowlands (Fig. 3) they are tentatively dated as Devonian or later.

Figure 17 shows lamprophyric dykes (D_8) cutting continental beds of the Sextant Formation at Sextant Rapids.

Lower Cretaceous

Mattagami Formation

The Mattagami Formation (unit K_1 of Fig. 3) consisting of continental beds of sand, clay and coal unconformably overlaps the bevelled edges of various formations of Middle to Upper Devonian ages to rest directly on the Precambrian along the southern margin of the Lowlands. It is unconformably overlain by beds of Pleistocene age. The formation was informally named by Keele (1920) for beds exposed along the Mattagami River, and later studies and mapping by McLearn (1928), Dyer (1931), Martison (1953), and others, have shown that it is restricted to the southern part of the Moose River Basin (Fig. 3). Possible equivalents mapped by Remick, Gillain and Durden (1963) in the Quebec Embayment are here tentatively included in the Sextant Formation.

Its known maximum thickness at Onakawana is 170 feet as determined by drilling.

Plants described by W. A. Bell (1928) and spores (D. C. McGregor, personal communication) from this formation are dated as Upper Jurassic or Lower Cretaceous, with preference given to the latter age.

SUMMARY

To summarize the stratigraphic succession of the Lowlands one may refer to the generalized northwest structure section across the central parts of the Moose River and Hudson Bay Basins (Fig. 25). The two basins are separated by the northeast trending Cape Henrietta Maria Arch. Maximum depth of the Moose River Basin is about 2, 500 feet which is floored by Archean crystalline rocks. This basin is truncated in the south by major faults where the basement rises nearly 1, 500 feet to be in juxtaposition with rocks of Ordovician and Silurian ages. In the subsurface this feature is overlapped by Devonian and Cretaceous rocks.

The Hudson Bay Basin in the north is much larger with only the southwest part of it present on the mainland. Its maximum depth down to Archean crystalline rocks is estimated by geophysical studies (Hood, 1964; Hobson, 1967) to be about 6, 000 feet. It is possible that the lower part of the

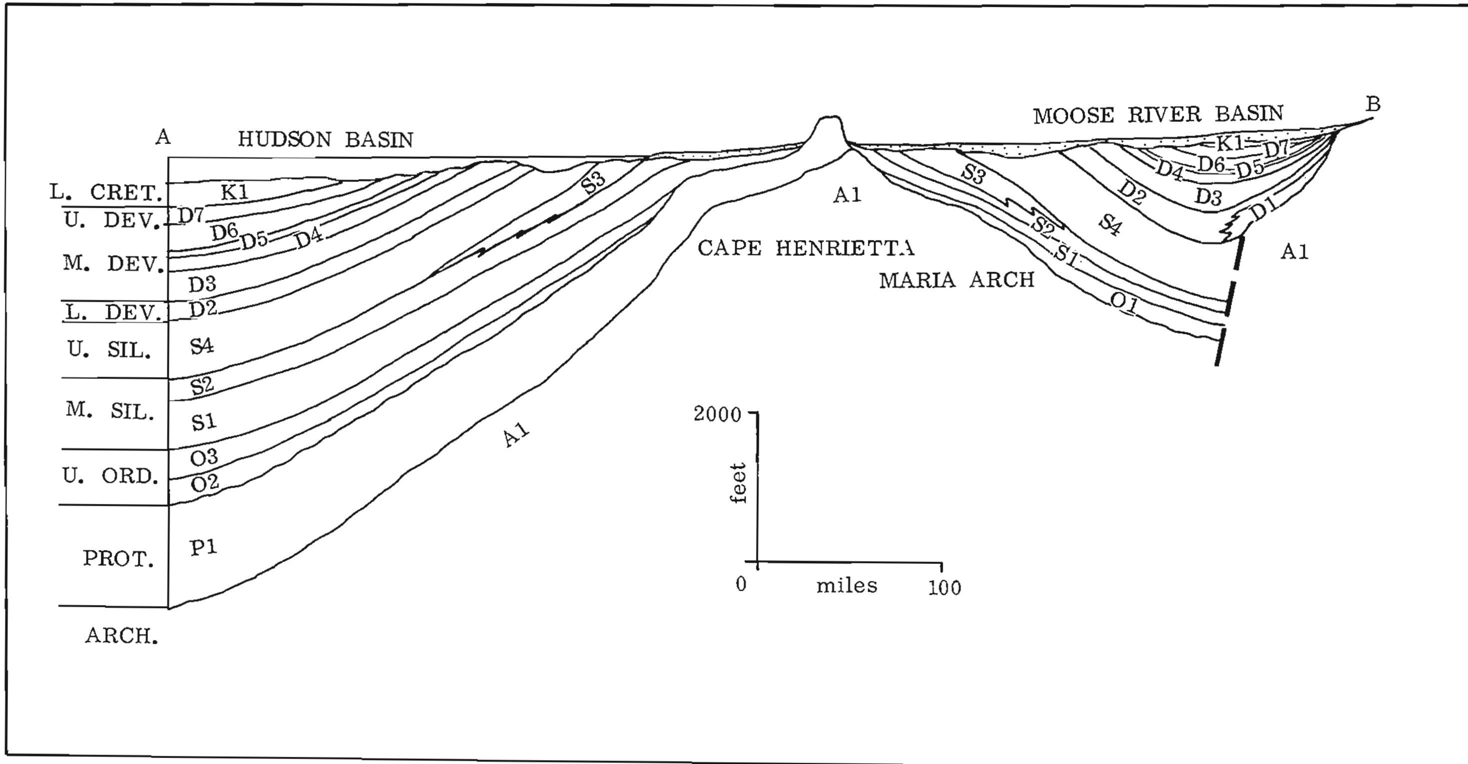


Figure 25. Generalized cross-section across Moose River and Hudson Bay Basins.

6,000 feet may be represented by a relatively thick sequence of Proterozoic sedimentary rocks. Judging from the incomplete succession on the mainland it is presumed to contain a Paleozoic and Mesozoic succession analogous to that in the Moose River Basin to the south.

Rocks of late Middle or early Upper, and Upper Ordovician ages unconformably overlie the Precambrian and consist of a basal sandstone overlain by limestone and dolomite. They outcrop in a belt along the south-western margin of the Hudson Bay Basin where they have been mapped as the Bad Cache Rapids and Churchill River Groups. In the Moose River Basin, Ordovician rocks outcrop in a narrow belt along the western and southeastern margins of the basin where they have been mapped as Ordovician undivided.

Middle Silurian rocks are represented in both basins by three major carbonate rock units, the Severn River, Ekwan River and Attawapiskat Formations. On the stable platform flanking the Cape Henrietta Maria Arch, biostromal development started in the Ekwan River Formation and reached a climax in the Attawapiskat Formation to form a barrier reef complex. Pinnacle reef development may be expected in the deeper parts of the two basins.

The Upper Silurian Kenogami River Formation consisting of a uniform sequence of red beds of mudstone, siltstone, sandstone, dolomite and evaporites reflects an entirely different sedimentary regime. The predominance of fine clastics points to the erosion of a highland area some distance away.

The Lower Devonian is represented by the continental Sextant Formation, present only in the southern part of the Moose River Basin, and its marine equivalent, the Stooping River Formation, present in both basins.

Middle Devonian rocks comprise the Kwataboahegan, Moose River, Murray Island, and Williams Island Formations. These formations consist mainly of marine carbonate rocks with some gypsum present in the Moose River, and some shale present in the Williams Island.

The Upper Devonian Long Rapids Formation consisting mainly of dark bituminous shale of marine origin points to another profound change in sedimentation caused presumably by more rapid subsidence of the basin.

A long hiatus separates the Lower Cretaceous Mattagami Formation from the underlying beds. The Mattagami consists of continental beds of clay, sand and lignite, and overlaps beds ranging in age from Upper Devonian to Precambrian. It outcrops only in the southern part of the Moose River Basin.

BIBLIOGRAPHY

Baillie, A. D.
1951: Devonian geology of Lake Manitoba - Lake Winnipegosis area; Manitoba Mines Branch, Publ. 49-2.

Bell, J.M.
1904: Economic resources of Moose River Basin; Ontario Bur. Mines, vol. 13, Pt. 1, pp. 135-179.

Bell, R.
1887: Report on an exploration of portions of the Attawapiskat and Albany Rivers, Lonely Lake to James Bay; Geol. Surv. Can., Ann. Rept. 1886, vol. 2, Pt. G, pp. 1-39.

Bell, W. A.
1928: Mesozoic plants from the Mattagami Series, Ontario; in Contributions to Canadian Paleontology, Can. Dept. Mines, Bull. No. 49, Geol. Ser. No. 48, pp. 27-30, pls. 14-18.

Bennett, G., Brown, D. D., and George, P. T.
1966: Operation Kapuskasing, District of Cochrane; Ontario Dept. Mines, Summ. of Field Work, 1966, by the Geological Branch, edited by E. G. Pye, P. R. 1966-1, pp. 42-47.

Bennett, G., Brown, D. D., George, P. T., and Leahy, E. J.
1967: Operation Kapuskasing; Ontario Dept. Mines, Misc. Paper 10.

Bolton, T. E.
1953: Silurian Formations of the Niagara Escarpment in Ontario; Geol. Surv. Can., Paper 53-23.

Bostock, H. H.
1962: Geology Lansdowne House, Ontario; Geol. Surv. Can., Map 4-1962.

1968: Reconnaissance of Precambrian rocks of the James Bay and southwestern Hudson Bay Lowlands (37J, O); in Report of Activities: May to October, 1967; Geol. Surv. Can., Paper 68-1, Pt. A, pp. 121-122.

Caley, J. F., and Liberty, B. A.
1957: The St. Lawrence and Hudson Bay Lowlands, and Paleozoic outliers; in Geology and Economic Minerals of Canada, Geol. Surv. Can., Econ. Geol. Ser. 1 (4th ed.), pp. 207-245.

Camsell, C.
1905: Country around the headwaters of the Severn River; Geol. Surv. Can., Summ. Rept. 1904, pp. 143-152.

Clark, T.H., and Blake, D.A.W.
1952: Ordovician fossils from Waswanipi Lake, Quebec; The Canadian Field-Naturalist, vol. 66, No. 5, pp. 119-121.

Coombs, D.B.
1954: The physiographic subdivisions of the Hudson Bay Lowlands south of 60 degrees north; Dept. Mines Tech. Surv., Geogr. Branch, Bull. No. 6, pp. 1-16.

Davies, J.F., Bannatyne, B.B., Barry, G.S., and McCabe, H.R.
1962: Hudson Bay Lowlands; in Geology and mineral resources of Manitoba; Manitoba Dept. Mines Nat. Resources, pp. 148-149.

Dowling, D.B.
1901: Report on an exploration of Ekwan River, Sutton Mill Lakes, and part of the west coast of James Bay; Geol. Surv. Can., Summ. Rept. 1901, Pt. F, pp. 1-60.

1902: The west side of James Bay; Geol. Surv. Can., Summ. Rept. 1901, pp. 109-117.

Duffel, S., MacLaren, A.S., and Holman, R.H.C.
1963: Red Lake-Lansdowne House area, northwestern Ontario; bed-rock geology, geophysical and geochemical investigations (Parts of 42, 43, 52, 53); Geol. Surv. Can., Paper 63-5, with Maps 2-1963, 3-1963.

Dyer, W.S.
1928: Geology and economic deposits of the Moose River Basin; Ontario Dept. Mines, vol. 37, Pt. 6, pp. 1-69.

1930a: Paleozoic geology of the Albany River and certain of its tributaries; Ontario Dept. Mines, vol. 38, Pt. 4, pp. 47-60.

1930b: The Onakawana lignite deposit, Moose River Basin; Ontario Dept. Mines, vol. 39, Pt. 6, pp. 1-14; (also published as) The lignite deposit at Onakawana, Moose River Basin, Ontario; Bull. Can. Inst. Mining Met., vol. 33, pp. 450-472.

1931: Stratigraphy and structural geology of the Moose River Basin, northern Ontario; Trans. Roy. Soc. Can., Ser. 3, sec. IV, vol. 25, pp. 85-99.

Dyer, W.S. (cont'd)
1932: Stratigraphy and oil and gas prospects of Moose River Basin; in Oil and gas in eastern Canada, edited by G.S. Hume; Geol. Surv. Can., Econ. Geol. Ser. 9, pp. 89-103.

Dyer, W.S., and Crozier, A.R.
1933: Lignite and refractory clay deposits of the Onakawana lignite field; Ontario Dept. Mines, vol. 42, Pt. 3, pp. 46-78.

Dyer, W.S., and Gerrie, W.
1953: Re-log of Onakawana drillhole A; Ontario Dept. Mines, vol. 61, Pt. 6, Appendix C to Martison, 1953, pp. 87-95.

Ehlers, G.M., and Kesling, K.V.
1957: Silurian rocks of the northern peninsula of Michigan; Michigan Geol. Soc., Ann. Geol. Excursion Field Guidebook.

Falconer, Jessie
1958: Rock outcrop and drift cover of the Canadian Shield; (insert to) Glacial Map of Canada; published by Geol. Assoc. Canada.

Fritz, M.A., and Cranswick, J.S.
1953: Lower and Middle Devonian of the James Bay Lowland; Proc. Geol. Assoc. Can., vol. 6, Pt. 1, pp. 69-74.

Fritz, M.A., Lemon, R.R.H., and Norris, A.W.
1957: Stratigraphy and paleontology of the Williams Island Formation; Proc. Geol. Assoc. Can., vol. 9, pp. 21-40, pls. 2-4.

Guillet, G.R.
1964: Gypsum in Ontario; Ontario Dept. Mines, Industrial Mineral Rept. No. 18.

Gussow, W.C.
1953a: Silurian reefs of James Bay Lowland, Ontario; Bull. Am. Assoc. Petrol. Geol., vol. 37, No. 10, pp. 2422-2424.

1953b: Southern part of James Bay Lowland, Ontario, by Ontario Department of Mines - Reviews and new publications; Bull. Am. Assoc. Petrol. Geol., vol. 37, No. 10, pp. 2425-2426.

Hobson, G.D.
1964: Ontario - Hudson Bay Lowlands, thickness of sedimentary section (Paleozoic to Cretaceous) from reconnaissance seismic refraction survey; Ontario Dept. Mines and Geol. Surv. Can., Prelim. Map No. P243.

Hobson, G. D. (cont'd)
1967: A reconnaissance seismic refraction survey in Hudson Bay, Canada; Proc. Seventh World Petrol. Congress, Mexico City, April 2-8, 1967, pp. 813-826.

Hogg, N., Satterly, J., and Wilson, A. E.
1953: Drilling in the James Bay Lowland, Part I - Drilling by the Ontario Department of Mines; Ontario Dept. Mines, vol. 61, Pt. 6, pp. 115-140.

Hood, P.
1964: A sea magnetometer reconnaissance of Hudson Bay; Geophysics, vol. 29, No. 6, pp. 916-921.

Hume, G. S.
1925: The Paleozoic outlier of Lake Timiskaming, Ontario and Quebec; Geol. Surv. Can., Mem. 145.

Innes, M. J. S.
1960: Gravity and isostasy in northern Ontario and Manitoba; Dominion Observatory Can., Publ., vol. 21, No. 6.

Innes, M. J. S., and Argun-Weston, A.
1966: Crustal uplift of the Canadian Shield and its relation to the gravity field; Ann. Acad. Sci. Fennicae, Ser. A III, Geologica-Geographica 90, pp. 169-176.

Jackson, G. D.
1962: Geology Fort Hope, Ontario; Geol. Surv. Can., Map 6-1962.

Keele, J.
1920: Clay and shale deposits of the Abitibi and Mattagami Rivers; Ontario Bur. Mines, vol. 29, Pt. 2, pp. 31-56.

Kindle, E. M.
1924: Geology of a portion of the northern part of Moose River Basin, Ontario; Geol. Surv. Can., Summ. Rept. 1923, Pt. C1, pp. 21-41.

Kranck, E. H.
1951: On the geology of the east coast of Hudson Bay and James Bay; Acta Geograph. 11, No. 2, pp. 1-71.

Kranck, S. H., and Sinclair, G. W.
1963: Clearwater Lake, New Quebec; Geol. Surv. Can., Bull. 100.

Lemon, R. R. H.
1953: The Sextant Formation and its flora; unpubl. M.A. thesis, University of Toronto.

Leslie, R. J.
1964: Sedimentology of Hudson Bay, District of Keewatin (34, 44, and 54); Geol. Surv. Can., Paper 63-48.

Leslie, R. J., and Pelletier, B. R.
1965: Bedrock geology beneath Hudson Bay as interpreted by submarine physiography; Bedford Inst. Oceanography, Report 65-12.

Manitoba Mines Branch
1965: Geological map of Manitoba; Manitoba Dept. Mines Nat. Resources, Geol. Div., Map 65-1.

Martison, N. W.
1953: Petroleum possibilities of the James Bay Lowland area; Ontario Dept. Mines, vol. 61, Pt. 6, pp. 1-58, appendices (pp. 59-95).

McLearn, F. H.
1927: The Mesozoic and Pleistocene deposits of the lower Missinaibi, Opazatika, and Mattagami Rivers, Ontario; Geol. Surv. Can., Summ. Rept. 1926, Pt. C, pp. 16-44.

Nelson, S. J.
1963: Ordovician paleontology of the northern Hudson Bay Lowland; Geol. Soc. Am., Mem. 90.

1964: Ordovician stratigraphy of northern Hudson Bay Lowland; Geol. Surv. Can., Bull. 108.

Nelson, S. J., and Johnson, R. D.
1966: Geology of Hudson Bay Basin; Bull. Can. Petrol. Geol., vol. 14, No. 4, pp. 520-578.

Norris, A. W., Sanford, B. V., and Bostock, H. H.
1967: Geology, Hudson Bay Lowlands; Geol. Surv. Can., Map 17-1967.

Norris, A. W., and Sanford, B. V.
1968: Operation Winisk, Hudson Bay Lowlands, Ontario, Manitoba, Quebec, District of Keewatin; in Report of Activities, May to October, 1967; Geol. Surv. Can., Paper 68-1, Pt. A, pp. 207-208.

Norris, A. W., Sanford, B. V., and Bell, R. T.
1968: Bibliography on Hudson Bay Lowlands; Geol. Surv. Can., Paper 67-60.

Oliver, W. A.
1966: Bois Blanc and Onondaga Formations in western New York and adjacent Ontario; New York State Geol. Assoc. 38th Ann. Meeting, 1966, preprint, pp. 32-43.

Potter, R. R.
1962: Gods River map-area, Manitoba; Geol. Surv. Can., Paper 62-8.

Remick, J. H., Gillain, P. R., and Durden, C. J.
1963: Geology of Rupert Bay - Missisicabi River area, Abitibi and Mistassini Territories; Quebec Dept. Nat. Res., Geol. Surv. Branch, Prelim. Rept. No. 498.

Sanford, B. V.
1968: Devonian of Ontario and Michigan; Alberta Soc. Petrol. Geol., International Symposium on the Devonian System, vol. 2, pp. 973-999.

Sanford, B. V., Norris, A. W., and Bostock, H. H.
1968: Geology of the Hudson Bay Lowlands; Geol. Surv. Can., Paper 67-60.

Satterly, J.
1953: Drilling in the James Bay Lowland; Part II - Results of other drilling; Ontario Dept. Mines, vol. 61, Pt. 6, pp. 141-157.

Savage, T. E., and Van Tuyl, F. M.
1919: Geology and stratigraphy of the area of Paleozoic rocks in the vicinity of Hudson and James Bays; Bull. Geol. Soc. Am., vol. 30, pp. 339-377.

Sinclair, G. W.
1959: Succession of Ordovician rocks in southern Manitoba, 62, 63, parts of; Geol. Surv. Can., Paper 59-5.

1965: Succession of Ordovician rocks at Lake Timiskaming; Geol. Surv. Can., Paper 65-34.

Skinner, R.
1966: Geology of part of Moose River (42I) map-area; in Report of Activities, May to October, 1965; Geol. Surv. Can., Paper 66-1, p. 158.

Stearn, C. W.
1956: Stratigraphy and paleontology of the Interlake Group and Stonewall Formation of southern Manitoba; Geol. Surv. Can., Mem. 281.

Williams, M. Y.
1920: Paleozoic rocks of Mattagami and Abitibi Rivers, Ontario; Geol. Surv. Can., Summ. Rept. 1919, Pt. G, pp. 1-12.

1921: Paleozoic stratigraphy of the Pagwachuan, lower Kenogami, and lower Albany Rivers; Geol. Surv. Can., Summ. Rept. 1920, Pt. D, pp. 18-25.

1948: The geological history of Churchill, Manitoba; Western Miner, vol. 21, No. 6, pp. 39-42.

Wilson, Alice E.
1953: A report on fossil collections from the James Bay Lowland; Appendix A of Martison, 1953; Ontario Dept. Mines, vol. 61, Pt. 6, pp. 59-81.

Wilson, W. J.
1906a: The Nagagami River and other branches of the Kenogami; Geol. Surv. Can., Ann. Rept., vol. 15, 1902-1903, Pt. A, pp. 109-120, Map 847.

1906b: The Little Current and Drowning Rivers, branches of the Albany, east of Lake Nipigon; Geol. Surv. Can., Ann. Rept., new ser., vol. 16, 1904, Pt. A, pp. 164-173.

PRECAMBRIAN SEDIMENTARY ROCKS OF THE HUDSON BAY LOWLANDS

Hewitt H. Bostock
Geological Survey of Canada
Ottawa, Ontario

Abstract

Reconnaissance mapping by the Geological Survey of Canada during 1967 has extended known areas of Precambrian sedimentary rocks west of Churchill, Manitoba, and in the Cape Henrietta Maria area of the Hudson Bay Lowlands.

In the Churchill area coarse- to fine-grained clastic sediments form an east-west belt, extending through Churchill, that is probably continuous beneath the Paleozoic cover with similar rocks exposed to the west.

In the Cape Henrietta Maria area, Precambrian sedimentary rocks including iron formation are exposed in a narrow discontinuous southeast trending belt extending from Winisk River to near James Bay, and in an inlier on Aquatuk River. Elsewhere over the Cape Henrietta Maria Arch, the Paleozoic cover is believed to be thin or absent. Similar Precambrian rocks, extend across the mouth of James Bay, and probably continue west beneath Paleozoic rocks for some distance beyond the Winisk inlier.

Precambrian sedimentary rocks are widely distributed around the margins of Hudson Bay, and their geology suggests that they underlie a significant part of the Bay and its adjacent lowlands. Reconnaissance mapping by the Geological Survey of Canada in 1967 has more accurately delineated their distribution in two areas; 1) around Churchill, Manitoba, and 2) in the Cape Henrietta Maria area (see Fig. 1 and GSC Map 17-1967).

In the Churchill area the Precambrian sedimentary rocks outcrop in an east-west trending discontinuous belt up to 12 miles wide extending from 10 miles east of Churchill to beyond the western limit (96th meridian) of the area mapped. To the north of this main belt outliers of these rocks are also known on Seal River and between the Knife Rivers. The southern limit of the belt is obscured by overburden.

Precambrian sedimentary rocks in the Churchill area consist mainly of subgreywacke, siltstone, and slate, associated with some quartzite, greywacke, and conglomerate. In the vicinity of the town of Churchill the section consists mainly of subgreywacke with minor beds and lenses of conglomerate. Isolated cobbles commonly 2 inches in diameter are widespread. These rocks form an arcurate range of hills some 30 miles long slightly concave to the south. Conglomerate beds are most prominent near the east end of the hills and apparently near the base of the section. Crossbedding on a large scale is abundant and forms a conspicuous feature of the subgreywacke (see Fig. 2). These rocks are probably continuous with siltstone, slate and subgreywacke that outcrop along North Knife River to the west beyond the Paleozoic cover (see GSC Map 17-1967).

At Churchill the rocks are folded to form a northward overturned syncline that trends nearly east-west. The northern limb of this syncline is crumpled about a north-south axis to form a subsidiary syncline that plunges steeply southward. The structure of the south limb is obscured by overburden. On the presumed western continuation of the same belt, along North Knife River, the rocks are steeply dipping and in part closely folded.

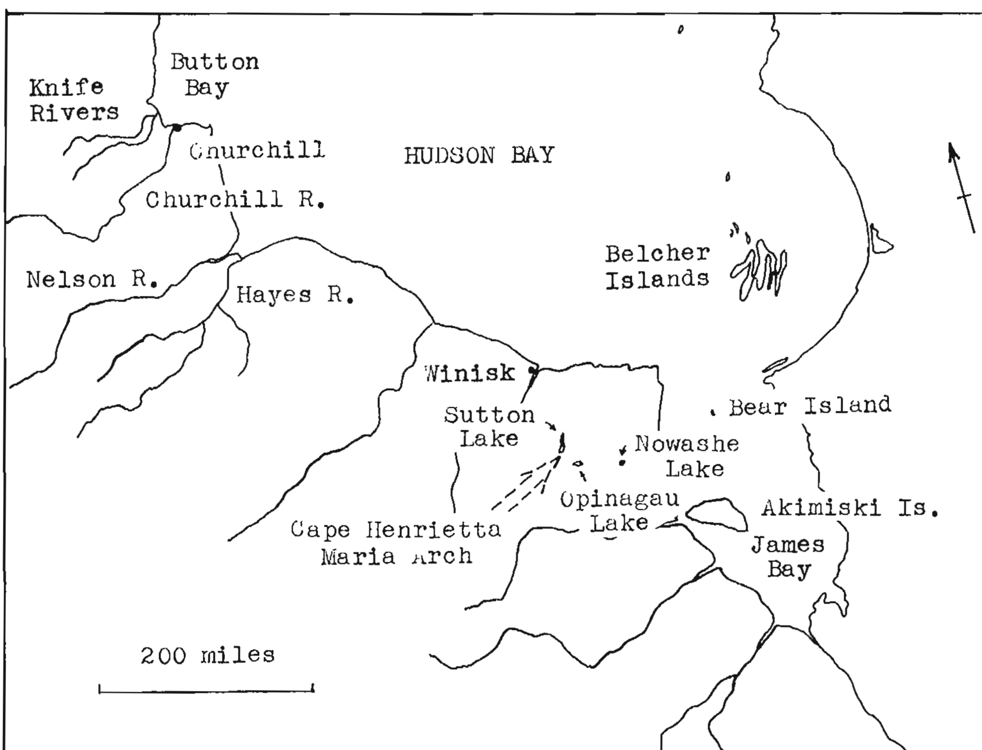


Figure 1. Index map of southern Hudson Bay.

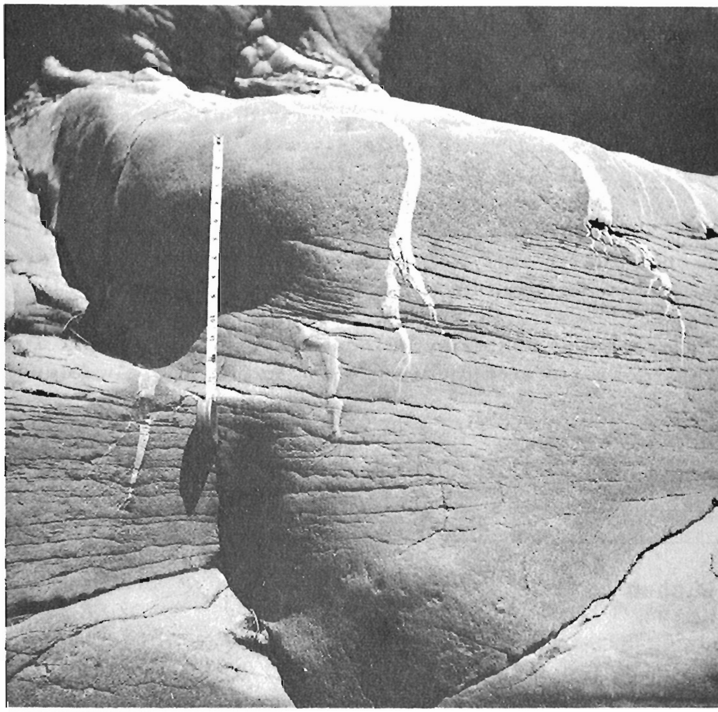


Figure 2. Crossbedding cut by quartz veins in subgreywacke near Churchill. (GSC 138286).

Aeromagnetic anomally trends are eastward and are approximately parallel to the major fold axis at Churchill. Some 40 miles to the east these trends swing northward perhaps reflecting an eastward limit to the eastward striking folded rocks at Churchill.

The precise age of the Precambrian sedimentary rocks in the Churchill area is uncertain, however, some evidence indicates that granitic rocks both older and younger than these sedimentary rocks may be present. Bluish quartz is present locally as small pebbles and quartz eyes in greywacke along North Knife River, and similar quartz is present in coarse-grained foliated granitic rocks to the north. This suggests that the sedimentary rocks were derived from and are therefore younger than the granitic rocks to the north. Still farther southwest porphyroblastic gneisses that are possibly metamorphosed equivalents of the sedimentary rocks along North Knife River are intruded by fresh massive pegmatite. Fresh, non-foliated, garnet-muscovite-biotite-bearing granitic rocks exposed nearby may therefore be younger than the sedimentary rocks to the north and east.

In the Cape Henrietta Maria area Precambrian sedimentary rocks outcrop in a narrow discontinuous southeast trending belt extending from Winisk River through Nowashe Lake to near James Bay (see GSC Map 17-1967). The orientation of this belt is nearly perpendicular to the northeast trending axis of the Cape Henrietta Maria Arch. Similar and obviously related rocks outcrop in an inlier on Aquatuk River some 27 miles north-northeast of Sutton Lake. Elsewhere on the arch, bedrock is concealed by a veneer of overburden, but the Paleozoic cover is believed to be thin or absent for the following reasons. 1) Beds of the Middle Silurian Severn River Formation that directly overlie the Precambrian in a Paleozoic remnant at Sutton Lake, also outcrop around the flanks of the arch. 2) Where these same rocks outcrop at Cape Henrietta Maria they show irregular dips presumably caused by compaction over an irregular buried Precambrian topography. 3) Several isolated bodies of diabase project through the muskeg along the northwest margin of the arch and thereby suggest that Paleozoic cover is thin or absent in that vicinity.

The Precambrian sedimentary section in the Cape Henrietta Maria area consists of a lower dolomitic unit (see Fig. 3), which is stromatolitic

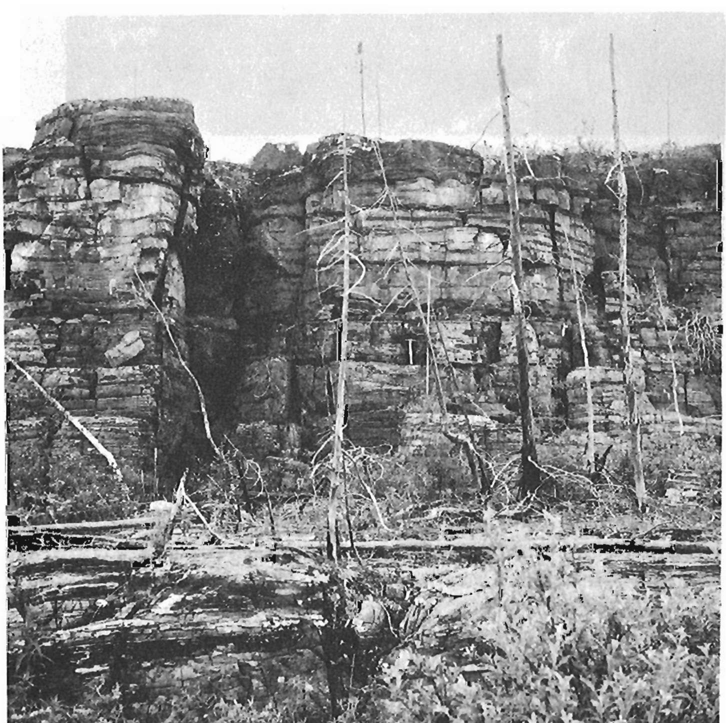


Figure 3. Stromatolitic dolomite near Sutton Lake. (GSC 138233).

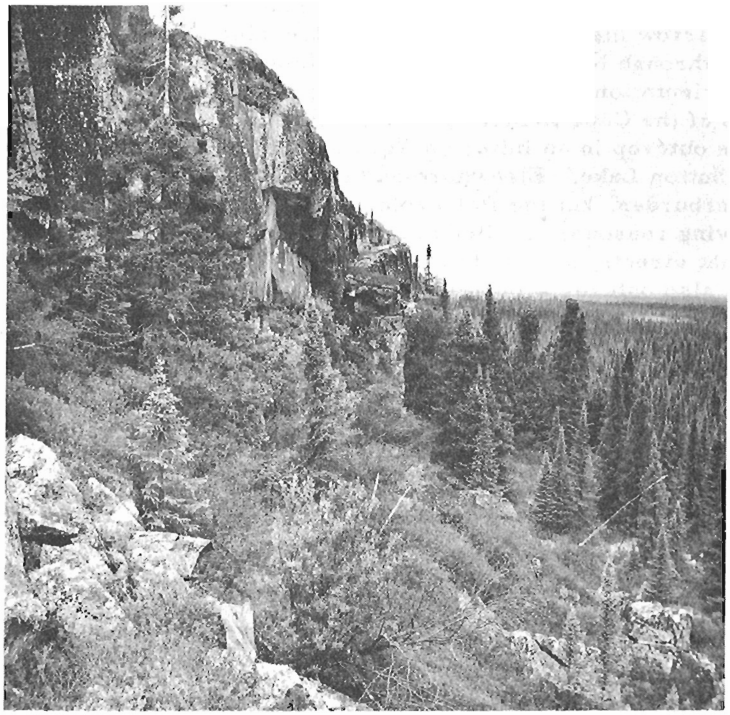


Figure 4. Diabase sill overlying iron formation near Aquatuk River, Sutton Lake area. (GSC 138262).

at Sutton and Nowashe Lakes, overlain by a unit consisting of iron formation, greywacke, argillite, quartzite, chert, and minor carbonate and conglomerate. At Sutton Lake irregular lenses of chert breccia and conglomerate are present at the base of the upper unit suggesting a disconformable contact. To the southeast quartzite is present in this interval.

Thicknesses of the two units in the Nowashe Lake area are estimated as follows: 250 feet or more for the lower unit, and 230 feet or more for the upper unit.

The structure of the Precambrian sediments over the axis of the Cape Henrietta Maria arch and its southern flank appears to be broadly homoclinal with northeastward dips generally 10 degrees or less. Dips are reversed about what appears to be a domal structure on Aquatuk River (Sutton Lake area), and attitudes of the sediments near diabase intrusions are locally tilted 50 degrees or more. In a small isolated outcrop of Precambrian sedimentary rocks on Winisk River on the northwest flank of the arch the trend of the folding is 110 degrees (see Fig. 6). These folds plunge gently westward and their axial planes dip to the south.

Seismic results of Hobson (1967) may be interpreted to indicate 1,000 feet or more of sedimentary rocks beneath the Paleozoic cover near Akimiski Island. This suggests that a trough of Precambrian sedimentary rocks similar to those at Nowashe Lake may extend southward beneath Akimiski Island. In the Moose River No. 1 drillhole in the southern part of the Hudson Bay Lowlands, Satterly (1953) reported 59 feet of red argillite associated with basic volcanic rocks presumably of Precambrian age (see Fig. 5). Rocks of

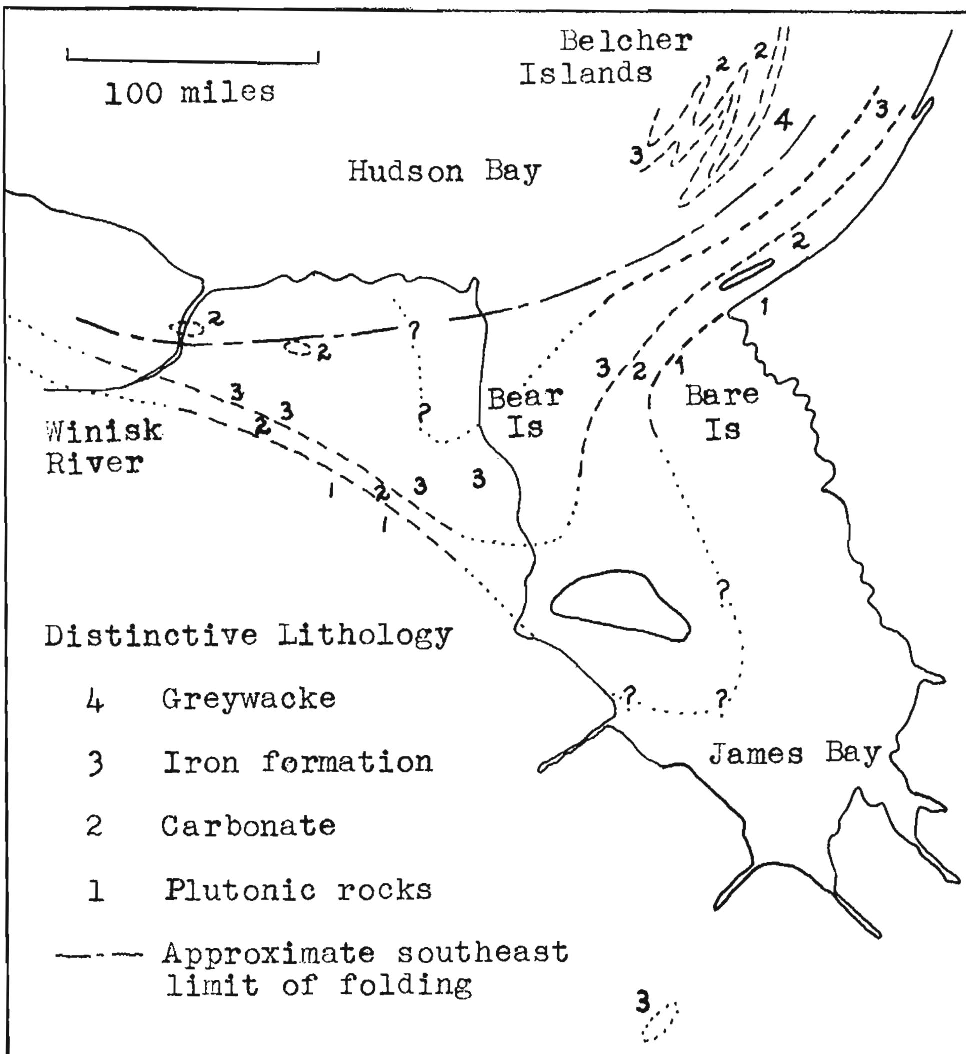


Figure 5. Map showing the distribution of Precambrian sedimentary rocks, southeast Hudson Bay, with Paleozoic cover removed.

this type, however, appear to be absent in nearby drillholes. From the above evidence it appears that much of the Moose River basin was at one time covered by rocks of the Nowashe Lake type, but these were presumably in large part removed prior to the Paleozoic.

On Bear Island in northern James Bay, Burns (1952) has reported quartzite, iron-stained greywacke, and minor limy sandstone, and Coates (1951) has reported the presence of slate. The beds strike southeasterly and dips are gentle. On Sunday Island to the east, Burns (1952) reported limestone dipping gently northward. On Bare Island still farther east Coates (1951) has reported granitic rocks. It would appear that the Precambrian sedimentary sequence comprising carbonates overlain by iron formation and clastic rocks, which overlies the northeastern part of the Cape Henrietta Maria Arch, extends northeastward across the mouth of James Bay. This sequence also resembles parts of the section on Belcher Islands which, however, is much thicker. The rapid northeast thickening of the sedimentary part of the section is from about 500 feet over the Cape Henrietta Maria Arch to at least 20,000 feet (Jackson, 1960) on Belcher Islands.

The northwest strike of the Precambrian sedimentary outcrop belt to near Winisk River, and the presence of folds trending east-west in the Winisk River inlier (see Fig. 6) suggest that similar rocks persist beneath the

Figure 6. View looking eastward of folding in interbedded dolomitic argillite and dolomite on Winisk River. (GSC 138222).

Paleozoic cover for some distance northwest and west of their exposed limits. Many early explorers including McInnes (1913), Tyrrell (1916), Bell (1879), and officers of the Hudson Bay Company have remarked on the presence of erratics of sedimentary rocks of Precambrian aspect in till and alluvium on Winisk, Hayes, Nelson and Churchill rivers, and in Button Bay. These rocks are mostly quartzites but include red conglomerate, banded jaspilites, and "stones that look like iron". Bell noted that the dominant lithologies of boulders seen in Button Bay were those of the unaltered rocks that outcrop in the neighbourhood of Manitounuk and Nastapoka Sounds on the east coast of Hudson Bay. It is therefore possible that sedimentary rock types represented in the boulders may be present beneath the drift or below sea-level. These rocks have not been recognized in the drill cores from the Nelson and Weir River areas.

REFERENCES

Bell, R.
1880: Report on explorations on the Churchill and Nelson rivers and around God's and Island Lakes; Geol. Surv. Can., Reports of Explorations and Surveys 1878-79, Pt. C, pp. 1-44.

Burns, C.A.
1952: Geological notes on localities in James Bay, Hudson Bay, and Foxe Basin visited during an exploration cruise, 1949; Geol. Surv. Can., Paper 52-25.

Coates, D.F.
1951: Mapping the North (establishing the land control for aerial survey on James Bay); Can. Geograph. J., vol. 43, pp. 58-69.

Hobson, G.D.
1967: A reconnaissance seismic refraction survey in Hudson Bay, Canada; Proc. 7th World Petroleum Congr., pp. 813-826.

Jackson, G.D.
1960: Belcher Islands, N.W.T.; Geol. Surv. Can., Paper 60-20.

Keep, F.E.
1961: Amphibole asbestos in the Union of South Africa; Trans. 7th Commonwealth Mining and Metallurg. Congr., vol. 1, pp. 90-121.

McInnes, W.
1913: Basins of Nelson and Churchill rivers; Geol. Surv. Can., Mem. 30.

Norris, A.W., Sanford, B.V., and Bostock, H.H.
1967: Geology, Hudson Bay Lowlands; Geol. Surv. Can., Map 17-1967.

Satterly, J.
1953: Drilling in the James Bay Lowlands, Pt. 2; Ontario Dept. Mines, vol. 61, Pt. 6, p. 157.

Tyrrell, J.B.
1916: Notes on the geology of Nelson and Hayes rivers; Trans. Roy. Soc. Can., ser. 3, vol. 10, sect. 4, pp. 1-27.

SOGEPET-AQUITAINE KASKATTAMA PROVINCE NO. 1 WELL, HUDSON BAY LOWLAND, MANITOBA

Ronald D. Johnson and Samuel J. Nelson
R.D. Johnson & Associates, and
The University, Calgary, Alberta

Abstract

The Sogepet-Aquitaine Kaskattama Province No. 1 well, drilled during 1966 and 1967, is located on the west shore of Hudson Bay in the central Hudson Bay Lowlands at latitude 57°14' 18.487" and longtitude 90°10' 29.408". The well was drilled to a total depth of 2941 feet. The Phanerozoic, comprising Ordovician, Silurian, Devonian and overburden, is 2913 feet thick and rests on Precambrian crystalline rocks. In ascending order, Phanerozoic strata comprise: Upper Ordovician carbonates, 634 feet thick, of Bad Cache Rapids and Churchill River Groups; Lower? to Middle Silurian, partly reefal carbonates, 1203 feet thick, of Port Nelson, Severn River, Ekwan River and Attawapiskat Formations; Upper? Silurian red clastics, 653 feet thick, of Kenogami River Formation; Middle Devonian carbonates, 400 feet thick, of Abitibi River Formation; and overburden, 23 feet thick.

A seismic refraction profile at wellsite shows velocities of 10,500, 13,000, 18,200, and 20,000 feet/second with interfaces near the base of the Middle Devonian, near the top of the Middle Silurian and near the top of the Upper Ordovician. No refractor was found at the Phanerozoic-Precambrian contact. A velocity survey shows interval velocities of 10,300 feet/second to 13,600 feet/second for the Middle Devonian with velocities as low as 9,500 feet/second in the Upper? Silurian increasing to averages of 16,500 feet/second in the Middle Silurian and 22,500 feet/second in the Upper Ordovician.

INTRODUCTION

General Statement

The Sogepet-Aquitaine Kaskattama Province No. 1 well is located on the west coast of Hudson Bay in the central Hudson Bay Lowlands near the mouth of the Kaskattama River (Fig. 1). It was spudded on September 16, 1966, suspended at 2,880 feet for six months over the winter, reactivated and finally abandoned at 2,941 feet on July 13, 1967. Precambrian basement was penetrated at 2,913 feet after drilling through Devonian, Silurian and Ordovician strata (Fig. 2).

The present paper describes the stratigraphy, paleontology and geophysics of the well, and outlines engineering and logistical data. Because of the confidential nature of much of the information, generalized descriptions are commonly given.

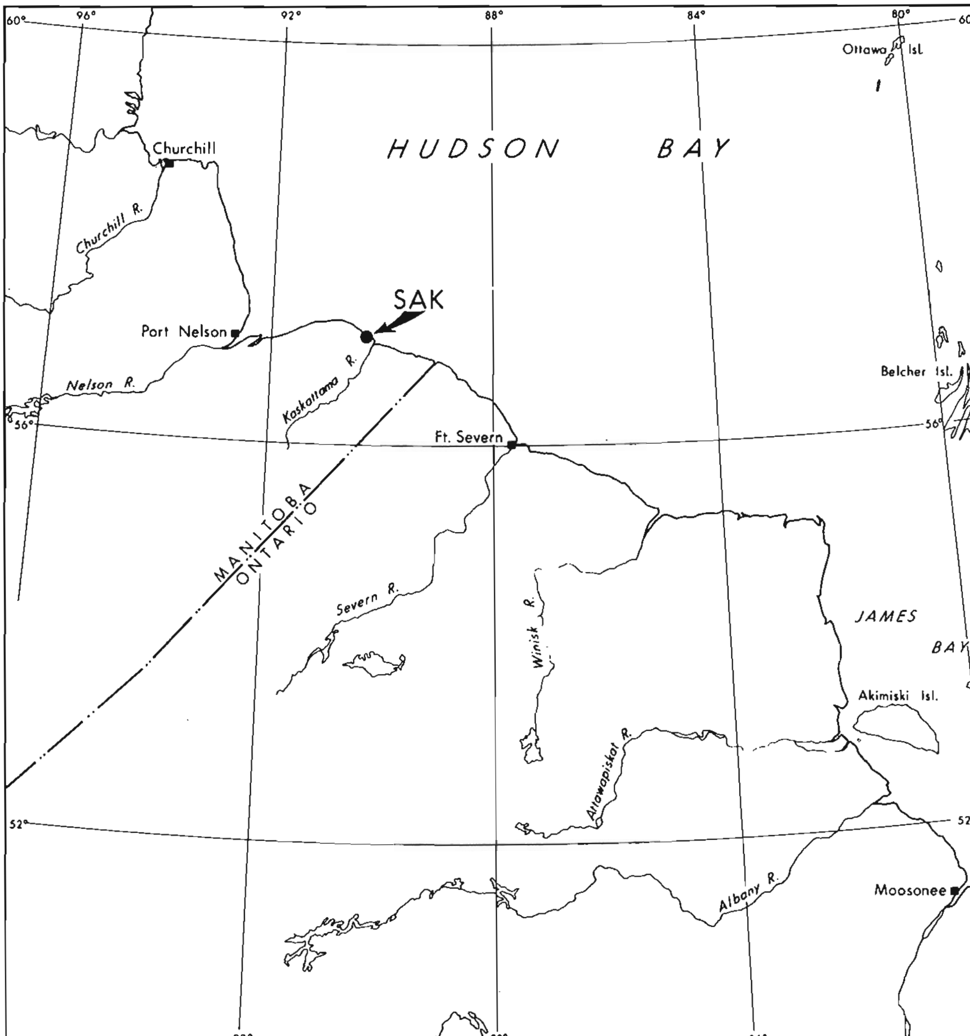


Figure 1. Location map of the Sogepet-Aquitaine Kaskattama Province No. 1 well ("SAK").

The Kaskattama well is in an area devoid of surface exposure; essentially no outcrops occur over a 100 mile radius. The well is therefore important in that it provides the first comprehensive subsurface control for the vast area of Hudson Bay Basin. It also confirms the presence of Devonian strata within the basin, previously interpreted by Nelson and Johnson's (1966) rubble studies.

Acknowledgments

The authors are indebted to the land owners, namely: Sogepet Limited, Aquitaine Company of Canada Limited, Bralorne Petroleum Limited, French Petroleum Company of Canada Limited, Elf Exploration and Production Canada Limited, Texas Gulf Sulphur Company, Sun Oil Company, Western Decalta Petroleum Limited, and Teck Corporation Limited, for their cooperation and release of data. Particular thanks are given to F.R. Joubin of Sogepet and R. Bonafoux of Aquitaine for their encouragement, and to W. Taylor and C. Kostashuk of Banff Oil Limited for their help and criticism relating to geophysical and geological interpretation. J. LeFevre of Pau, France identified Devonian conodonts, ostrocods and tentaculitids from the well.

Historical Sketch

In 1962 Sogepet Limited was formed to examine petroleum prospects in the Hudson Bay region. In August of that year, Sogepet filed on the petroleum and natural gas rights over approximately half a million acres in Manitoba and two million acres of Federal lands offshore between Cape Tatnam and the Ontario boundary. These permits were the first issued in what is now referred to as the Hudson Bay Basin (Nelson and Johnson, 1966).

Prior to 1962, all technical data on the area was limited. Only geological reconnaissance and minor gravity and magnetic observations were available. During 1963 and 1964 investigations by Sogepet included geological reconnaissance of both the Hudson Bay Lowlands and northern islands of Hudson Bay by the authors (Nelson and Johnson, ibid.). Other activities included examination of shore ice conditions and reconnaissance aeromagnetic and refraction seismic studies of the lower Kaskattama River area. During the same period, the Geological Survey of Canada produced considerable magnetic and seismic data (Hood, 1964; and Hobson, 1964). Late in 1964, Richfield Oil Corporation (now Atlantic-Richfield Company) acquired offshore rights to approximately 50 million acres. Transalta Minerals Limited and Mill City Petroleums Limited separately acquired approximately 2.5 million acres offshore. In 1965, the Geological Survey, Richfield and Sogepet all carried out surveys of various types, principally geophysical.

Sogepet's work indicated that the maximum onshore stratigraphic section, approximating 3,000 feet, was in the Kaskattama River delta area (Nelson and Johnson, 1966) and a stratigraphic test hole was proposed for this location. Surface work suggested that it would contain Devonian, Silurian

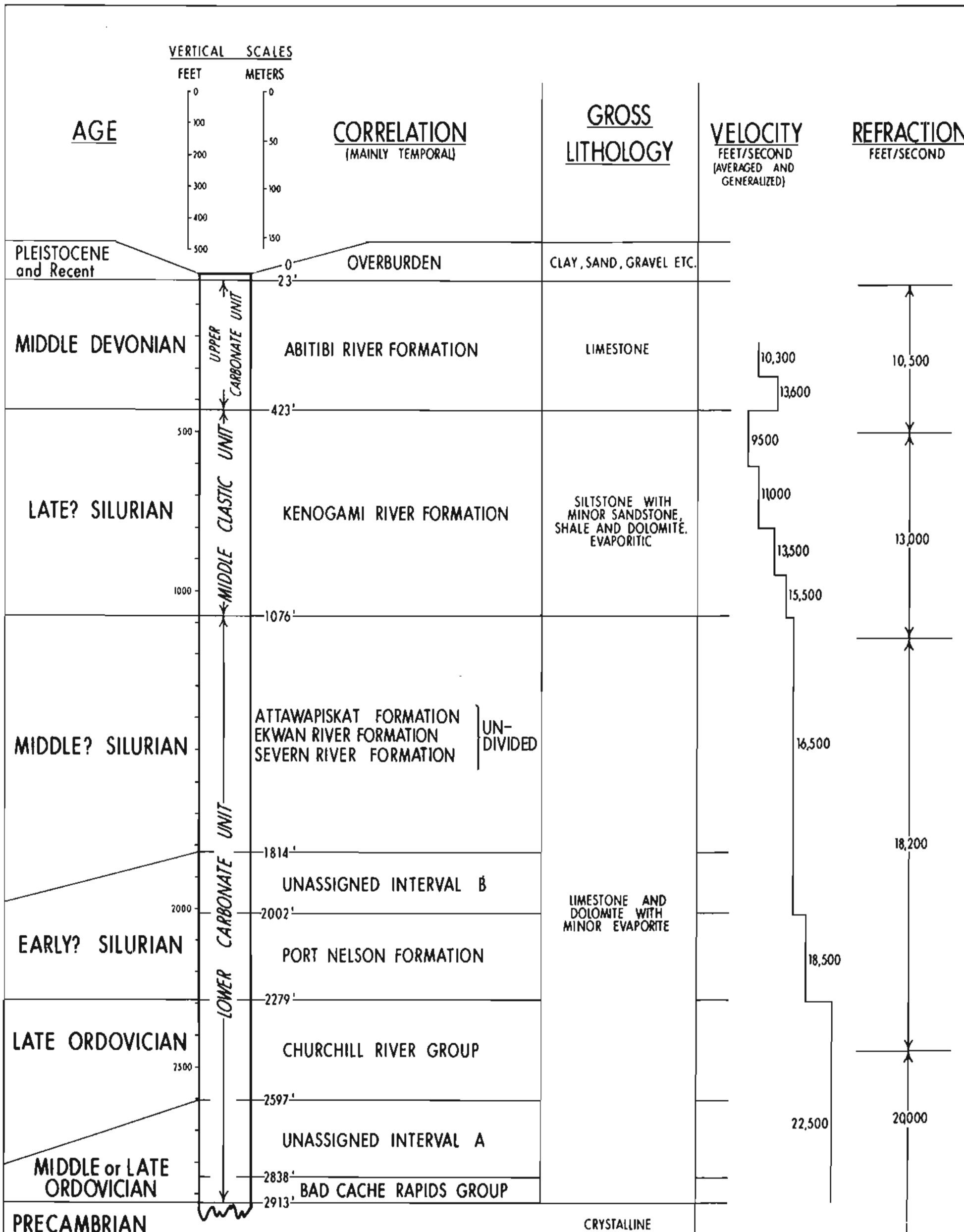


Figure 2. Generalized correlations, lithology and geophysics of the Sogepet-Aquitaine Kaskattama Province No. 1 well.

and Ordovician strata. Sogepet was joined by Bralorne, then by Aquitaine and others (see Acknowledgments) and the hole was scheduled for the fall of 1966. Banff Oil acted as operator on behalf of Aquitaine, and Big Indian Drilling Company Limited was the contractor.

The present group of companies now hold permits over approximately 1.5 million acres in Manitoba, one million acres in Ontario and four million acres of Federal lands in the Bay. A seismic survey is presently in progress on the onshore area.

LOCATION AND LOGISTICS

The primary location for the Kaskattama stratigraphic test was picked on the north shore of the northwest arm of the Kaskattama River delta as available data suggested this to be the position of maximum onshore stratigraphic thickness (Nelson and Johnson, 1966, p. 570). Logistical problems of the site, particularly sea and air access caused the final location to be moved some five miles to the northwest along the coast to latitude 57°14' 18.487" and longitude 90°10' 29.408". Ground elevation is 15.8 feet with Kelly Bushing elevation at 29.5 feet above sea level respectively.

The logistical problems encountered in drilling the Kaskattama hole provide object lessons in the amount of planning and time considerations required in such an endeavour. Land costs and other considerations dictated that the test be drilled in the fall of 1966 while planning of the well by Aquitaine could not commence until early July of that year. The resulting short planning and mobilizing period resulted in extra costs. Nevertheless, the operator and the contractor accomplished a successful stratigraphic test to the basement without serious accident.

In early July, 1966 Big Indian Drilling Company Limited of Calgary was appointed drilling contractor and a Failing 1500 rig was selected as the most suitable for the assignment. All materials, about 275 tons, were marshalled in Calgary and arrived at Churchill on August 13. The Canadian Coast Guard Ship Raven was chartered and started unloading by barge at the mouth of Kaskattama River on August 24. An unloaded D4 Caterpillar bulldozer became mired in the tidal flat and was lost making further loading impractical and forcing the Raven to return to Churchill with the balance of the cargo.

On August 28, a Bristol "170" Freighter aircraft landed a D4 Caterpillar on a raised beach some five miles northwest along the coast from Kaskattama River. On September 8, the C.C.G.S. Eider, standing two and three-quarters miles offshore lightered bulky equipment and camp facilities. A second load ashore was attempted on September 13 but high seas forced the Eider to withdraw and it had to return to Churchill. By September 16, the Bristol Freighter had flown twenty-six trips using a 5,500 foot landing strip prepared by the bulldozer. The well was spudded on that date. By

October 15, the Bristol had flown an additional twenty-three trips. When drilling was suspended on December 17, ten more trips were required to remove equipment and crews.

Besides the Bristol Freighter, a helicopter and several other light aircraft were used on occasion for special purposes. Personnel changes, grocery supplies, mail service and core transportation were generally handled by a Piper Aztec aircraft.

Operations to reactivate drilling began in mid-June 1967 and the required materials were shipped to Gillam, Manitoba. By July 1, a De Havilland Twin Otter had flown seven loads to the wellsite and reconditioning of the hole commenced. Drilling started on July 5 and final total depth of 2,941 feet was reached on July 13. Cement plugs were run and the hole abandoned on July 16, 1967.

Twelve trips by the Bristol Freighter were required to withdraw equipment and men to Churchill from whence the rig was shipped by rail to Calgary. The bulldozer and camp were left at the wellsite in anticipation of the seismic program the following winter.

ENGINEERING SUMMARY

A Failing "1500" rig was used because it could be easily adapted to use either pipe or drilling rods, giving practical depth capacity of 3,500 feet. An 8 3/4-inch diameter hole was drilled to 330 feet, 4 11/16-inch to 1,732 feet, and 2 5/16-inch to 2,941 feet. Seven-inch diameter surface casing was set to 330 feet with 3 1/2-inch intermediate casing set to 1,729 feet. Approximately two-thirds of the hole was cored; 16.5% of the section above 1,000 feet, and 88.5% below. Core diameter varied from 2 3/16 to 1 7/8 inches and recovery was excellent. Drilling fluid used was in part with mud and in part with water.

Deviation of the hole was no greater than one degree. Various surveys of the hole included: Induction Electrical Log (326-1633 feet), Sonic Log (326-1633feet), Gamma Ray-Neutron Log (0-2877 feet), Temperature Log (0-2877 feet), Electrical Log (1729-2877 feet). No logs were run after the hole was deepened from 2,880 to 2,941 feet. A velocity survey and a refraction survey were shot at the wellsite.

STRATIGRAPHY

The Phanerozoic rocks in the Kaskattama well rest on the Precambrian and comprises Upper Ordovician, Lower? to Upper? Silurian, Middle Devonian, and overburden. The hole penetrated 28 feet of Precambrian crystalline rocks. The Phanerozoic section is 2,913 feet thick, of which 23 feet is overburden, and consists of 634 feet of Ordovician, 1,856 feet of Silurian, and 400 feet of Devonian (<u>see</u> Fig. 2).

The designated sequence in the well may be subdivided into three broad lithological subdivisions informally as lower carbonate unit, a middle clastic unit, and upper carbonate unit. The lower carbonate unit is 1,873 feet thick and contains Upper Ordovician and Lower? to Middle Silurian limestones and dolomite. The middle clastic unit consists of Upper? Silurian siltstones, shales and argillaceous dolomite, 653 feet thick. The upper carbonate unit consists of 400 feet of Middle Devonian limestone.

Lower Carbonate Unit

The lower carbonate unit extends from the Precambrian contact at 2,913 feet up to 1,076 feet, with the lower 634 feet Upper Ordovician and the upper 1,203 feet Lower? and Middle Silurian. Both the Ordovician and Silurian show essentially the same assemblage of limestones and dolomites with sporadic evaporites, generally related to the latter lithology. The limestones and dolomites are brown and grey-brown and each exhibits a rather rhythmic monotonous sequence between a fine-grained calcarenitic bioclastic with nodular to well bedded aspect, alternating with a cryptocrystalline, finely fragmental facies. The latter variant is most common.

Limestones dominate the Ordovician part of the unit. An eighty-foot partly evaporitic dolomite is present between 2,685 and 2,605 feet and a cyclic sequence of microcrystalline limestones, banded dolomites, minor anhydrites and thin shales occur through the upper 171 feet, into the lower 89 feet of the Silurian.

A sequence similar to the Ordovician carbonate is present in the Silurian, with limestones, alternating with dolomites which are commonly anhydritic. Above 1,800 feet dolomite becomes minor but the same basic lithologies continue upward into the upper part of the Middle Silurian, where the limestones become reefal in character.

The basal part of the lower carbonate unit comprises a thin sandstone followed by shale. Coring recovered 4 feet of grey to brown, fine to medium-grained, friable, partly shaly sandstone followed by 3.5 feet of dark green to brown, soft fissile shale.

The Silurian-Ordovician contact is tentatively picked at 2,279 feet in the lower carbonate unit, on a rather marked thin very dark grey shale break, a position supported by paleontological data. Minor shale breaks are found over a 100-foot interval both above and below this contact. The position of these shales is rather similar to those at the Silurian-Ordovician contact, the "oil shale interval", on Southampton Island (Nelson & Johnson, 1966).

Paleontological evidence within the lower carbonate unit suggests that temporal correlatives of the Late Ordovician Bad Cache Rapids and Churchill River Groups, Early? Silurian Port Nelson, and the Middle Silurian Severn River, Ekwan River and Attawapiskat Formations are present. In the well these formations cannot generally be differntiated because of the rather monotonous character of the lithologies.

The 75-foot interval from the base of the well up to 2,838 feet is correlated with the Bad Cache Rapids Group of Churchill River (Nelson, 1963) on the basis of one poorly preserved Maclurites sp., suggestive of M. manitobensis (Whiteaves) at 2,838 feet. More precise correlations with the Portage Chute and Surprise Creek Formations within the group are not possible. The top of the Bad Cache Rapids Group is arbitrarily placed at the 2,838-foot Maclurites occurrence although this boundary probably occurs higher within an interval here; referred to as unassigned interval A (see Fig. 2). From outcrop studies the Bad Cache Rapids Group is dated as late Middle or early Late Ordovician (Nelson, 1963), with preference given to the latter age.

The strata from 2,838 to 2,497 feet do not bear diagnostic fossils and are arbitrarily included in the unassigned interval A. The fauna comprises mainly strophomenid brachiopods and cup corals.

From 2,597, to 2,279 feet at the top of the Ordovician, fossils indicate correlation with the late Late Ordovician (Richmondian and/or Gamachian) Churchill River Group on Churchill River. The most diagnostic elements are Bighornia bottei Nelson, B. patella (Wilson), Lobocorallium trilobatum (Whiteaves) and Palaeofavosites spp. This fauna definitely establishes correlation with the Churchill River Group but is not sufficiently diagnostic to establish more discrete relationships with its contained Caution Creek and Chasm Creek Formations (see Nelson, 1963).

No lithologic or faunal representatives of the Red Head Rapids Formation (Nelson, 1963), the youngest outcrop Ordovician unit in the Hudson Bay Lowlands, have been identified in the Kaskattama well.

Strata considered possibly correlative with the Lower? Silurian Port Nelson Formation of Nelson River (Nelson, 1964) occur from the Ordovician-Silurian contact at 2,002, to 2,279 feet. Most common species are Tryplasma gracilis (Whiteaves), ?Angopora manitobensis Stearn and particularly Virgiana decussata (Whiteaves). This correlation is based partly upon abundance of V. decussata in both well and outcrop and partly upon stratigraphic position.

The status of the Port Nelson Formation is a doubtful one (Nelson and Johnson, 1966, p. 540) and the correlation of the interval from 2,002 to 2,279 feet should be treated with caution. The age of the formation has been variously interpreted as Early or Middle Silurian. The former is questionably accepted here.

From 2,002 to 1,814 feet is an interval that is rather unfossiliferous with some rare and undiagnostic rhynchonnellid brachiopods. It cannot at present be correlated with outcrop formations and is informally designated as the unassigned interval B.

Fossils from 1,814, to 1,076 feet at the top of the lower carbonate unit are largely tabulate corals belonging to species of _Halysites_, _Favosites_ and _Multisolenia_, with rare _Catenipora_, _Alveolites_, _Lyellia_, septate corals and brachiopods.

Among the species recognized are _Favosites_ sp., cf. F. _niagarensis_ Hall, _F._ sp., cf. _F._ _hisingeri_ Milne-Edwards and Haime, _F._ sp., cf. _F._ _favosus_ (Goldfuss), _Halysites_ sp., ex. gr. _H._ _catenularius_ Linnaeus, _H._ sp., ex. gr. _H._ _nexus_ Davis, _H._ sp., cf. _H._ _agglomeratus_ Hall, _H._ _magnitubus_ Buehler, _H._ sp., ex. gr. _H._ _sussmilchi_ Etheridge, _Multisolenia_ _tortuosa_ Fritz, _Lyellia_ _affinis_ (Billings), _Catenipora_ sp., ex. gr. _C._ _gothlandica_ (Yabe), _Synamplexoides_ _varioseptatus_ Stearn.

These, particularly the species of _Favosites_ and _Halysites_, are closest to those found in outcrops of the Severn River, Ekwan River and Attawapiskat Formations, particularly the Ekwan River Formation. The age of this assemblage is generally interpreted as Middle Silurian (_see_ Nelson and Johnson, 1966).

Middle Clastic Unit

The middle clastic unit, extends from 1,076 to 423 feet (653 feet thick). It is considered Late? Silurian in age and correlates with the Kenogami River Formation of the southern Hudson Bay Lowlands. This unit is strikingly coloured dark red with some green mottling and consists mainly of gypsiferous siltstones and shaly siltstones with minor beds of shale and sandstone. The lower 140 feet of this clastic unit is a light grey somewhat argillaceous and gypsiferous dolomite which may be genetically more closely related with the underlying lower carbonate unit. This dolomite is arbitrarily grouped with the former because of its similarity to dolomite in the lower Kenogami River Formation of the southern Hudson Bay Lowlands.

The correlation of the middle clastic unit with the Kenagomi River Formation of Late? Silurian age (Bolton, 1966) is based on lithology and stratigraphic position; in the Kaskattama well this unit is almost completely devoid of organic remains.

Upper Carbonate Unit

The upper carbonate unit of mainly light grey limestones extends from 423 feet to the base of overburden at 23 feet. These limestones are considered early Middle Devonian in age and correlate with the Abitibi River Formation of the southern Hudson Bay Lowlands (Martison, 1953; Nelson and Johnson, 1966). Three distinct limestone lithologies are present within the unit. The lower 23 feet, from 423 to 400 feet depth consists of light buff to grey, chalky crypto-crystalline dolomitic limestone. The interval between 400 and 154 feet (246 feet thick) consists of dense, grey-brown, unfossiliferous, partly sucrosic fine-grained to microcrystalline to finely crystalline limestone. The third lithology extends from 154 feet depth to the base of overburden (131 feet thick), and is composed of buff to light grey, bioclastic, fossiliferous cryptocrystalline to finely crystalline limestone.

An unconformable relationship between the lower and middle limestones is suggested by several thin, anomolous chert conglomerate beds between 378 and 398 feet in the lower part of the middle limestone. This suggests that the lower chalky limestone may belong to an appreciably older horizon; perhaps to the Late? Silurian Kenogami River Formation. Faunal evidence, however, indicated that the lower limestone are Middle Devonian and temporally related to the middle limestones.

The unit is sparsely fossiliferous. Fossils occur mainly in the upper limestones and include the following forms: Thamnopora sp., cf. T. martisoni Fritz, Lemon and Norris, Productella concentrica (Hall), Atrypa sp., cf. A. rustica Stainbrock and A. scutiformis Stainbrook. These are undiagnostic and serve only to indicate a Devonian age for the unit. The microfauna including conodonts, ostracods and tentaculitids are more useful and suggest an early Middle or possible late Early Devonian age. They also are most abundant in the upper limestone unit and include the following: ?Viriatellina spp., Kirkbyella sp.?, Icriodus sp., ?Acontinodus sp., Angulodus sp., Hindeodella sp., Polygnathus linguiformis Hinde and Oneatodus sp. ?. The same species of ?Viriatellina occur in the lower and middle limestones suggesting their close temporal relationships to each other and to the upper limestones.

The Devonian surface rubble in the area about the Kaskattama well is of two main lithologies. One type consists of grey fragmental limestone, lithologically similar to that occurring between 23 and 154 feet in the well. The other type of lithology is a reddish, shaly limestone reminiscent of the strata referred to the completely unfossiliferous Silurian Kenogami River Formation between 423 and 1,076 feet. Both the red and the grey rubble are fossiliferous and bear a fauna of late Middle or early Late Devonian age which correlates with the Williams Island Formation of the southern Hudson Bay Lowlands (see Nelson and Johnson, 1966, p. 562). Future drilling in the Hudson Bay Lowlands should take into account that strata of the Williams Island Formation may be present in subcrop and that grey and red lithologies may be penetrated, not temporally related to the grey and red lithologies in the Kaskattama well between 23 - 423 and 423 - 1,076 feet, respectively.

GEOPHYSICS

A conventional downhole velocity survey using miniaturized equipment was run on the Kaskattama well before it was suspended over the winter months. This survey, in which twenty-two check shots were used, provided velocity control from 310 to 2,844 feet depth. The Devonian upper carbonate unit has a velocity of 10,300'/sec. at the top, ranging to 13,600'/sec. at the base. The Upper? Silurian middle clastic unit has velocities increasing from

9,500'/sec. in the upper more silty members to approximately 13,500'/sec. in the middle more shaly parts. The velocity of the lower dolomite in the unit is unknown but is between 13,800'/sec. and 17,500'/sec., probably averaging about 15,500'/sec. In the lower carbonate unit Middle Silurian velocities range from 15,000'/sec. to 20,000'/sec. with an approximate average velocity of 16,500'/sec. Velocities below the Middle Silurian interval appear erratic and unreliable, presumably due to the small intervals over which measurements were made. However, they do increase and reach values in excess of 20,000'/sec. The plot of the indicated values for the Lower? Silurian range between 17,500 and 22,500'/sec. averaging 18,500'/sec., with Upper Ordovician values ranging from 17,500'/sec. to 27,500'/sec. An average velocity indicated for the latter is of the order of 22,500'/sec.

A survey carried out at the wellsite indicated three refractive horizons. The uppermost interface plotted out at 460 feet depth between a velocity of 10,500'/sec. and 13,000'/sec. This marker is presumed to be actually above the 423 feet depth and within the Devonian upper carbonate unit. The second interface was between 13,000'/sec. and 18,200'/sec. and was placed at 1,130 feet depth. This refractor is at or near the top of the Middle Silurian of the lower carbonate unit. The third refractor, between 18,200'/sec. and 20,000'/sec., was placed at 2,420 feet depth near the top of the Upper Ordovician. Subsequent drilling indicated that the 20,000'/sec. marker, sometimes considered to be basement (Hobson, 1964) was an Ordovician marker in the Kaskattama well. Basement is nearly five hundred feet deeper than the deepest refractive horizon. In summary the three refractors in the Kaskattama well appear to be near the base of the Middle Devonian, at or near the top of the Middle Silurian and Upper Ordovician respectively.

Hodgkinson (this volume), in a separate evaluation of the sonic log, velocity survey and refraction survey from the Kaskattama well presents an independent interpretation of the data. His interpretation shows Middle Devonian carbonate velocities of 10,500'/sec. to 13,500'/sec., with 11,000'/sec. for the Upper? Silurian middle Kenogami River siltstones and shales, to 16,700'/sec. for the Middle and Lower? Silurian carbonates, and 23,000'/sec. for Upper Ordovician carbonates. Hodgkinson relates his four refractive horizons to the base of the drift, near the base of the Middle Devonian, near the top of Middle Silurian, and to the top of Upper Ordovician.

REFERENCES

Bolton, T. E.
1966: Illustrations of Canadian fossils, Silurian faunas of Ontario; Geol. Surv. Can., Paper 66-5.

Hobson, G. D.
1964: Nine reversed refraction seismic profiles Hudson Bay Lowland, Manitoba; in Summary of activities: Office and Laboratory, 1963, Geol. Surv. Can., Paper 64-2.

Hood, P.
1964: Sea magnetometer reconnaissance of Hudson Bay; Geophysics, vol. 29, No. 6, pp. 916-921.

Martison, N. W.
1953: Petroleum possibilities of the James Bay Lowland area; Ontario Dept. Mines, vol. 61, pt. 6, pp. 1-58, and appendices pp. 59-95.

Nelson, S. J.
1963: Ordovician paleontology of the Northern Hudson Bay Lowland; Geol. Soc. Am., Mem. 90.

1964: Ordovician stratigraphy of Northern Hudson Bay Lowland; Geol. Surv. Can., Bull. 108.

Nelson, S. J., and Johnson, S. J.
1966: Geology of Hudson Bay Basin; Bull. Can. Petrol. Geol., vol. 14, No. 4, pp. 520-578.

SEISMIC REFRACTION RESULTS FROM THE HUDSON BAY REGION

George D. Hobson
Geological Survey of Canada
Ottawa, Ontario

Abstract

Onshore refraction seismic surveys were conducted by the Geological Survey of Canada in 1963 in Manitoba and in 1964 in Ontario in cooperation with the Ontario Department of Mines in the Hudson Bay Lowlands area. These surveys were extended to the offshore areas by marine refraction surveys during August and September 1965. Considerable interest has been generated in this major sedimentary area of Canada by previous magnetometer surveys and the comprehensive survey of 1965 which encompassed the fields of geophysics, geology and oceanography.

Hitherto unpublished seismic data from the 1964 onshore survey are presented as cross-sections to permit closer correlation between these seismic surveys and their interpretation with the results of the 1967 geological survey Operation Winisk. The geological map resulting from Operation Winisk does not show the Precambrian topographic high deduced from the interpretation of seismic data in the region of the Winisk River near latitude 54°N and between longitudes 87° and 89°W. The only way that the geophysical interpretation can be changed to agree with the geological interpretation is to grant that the Ordovician and Silurian Formations are too thin to transmit seismic energy or that the high velocities assumed to represent Precambrian rocks actually should be identified as the Ordovician and Silurian carbonates. However, the correlation between geology and geophysics is so good elsewhere that it is difficult to recognize this as other than a possibility. No rock outcrops have been mapped in the Winisk River area.

It may also be difficult to correlate the seismic interpretation with the geology in the area of Precambrian outcrop near and southeast from Hawley Lake. Similarly it may be difficult for the geologists and geophysicists to agree on a representation of subsurface structure along the axis of the Cape Henrietta-Maria Arch from these Precambrian outcrops to that Cape. There must be either faults on both sides of the Precambrian outcrop or severe erosion of the Precambrian surface with the present Precambrian outcrop being explained as an erosional remnant.

There appears to be considerable structure within the Hudson Bay sedimentary basin. The presence of lower and intermediate values of seismic velocities indicates the probable presence of Mesozoic sediments overlying the Paleozoic section. The thickness of sediments overlying the Proterozoic strata is calculated to be about 6, 000 feet.

INTRODUCTION

An extensive and comprehensive survey of Hudson Bay was undertaken during August and September 1965 by the Department of Mines and Technical Surveys now the Department of Energy, Mines and Resources. The program, encompassing the fields of geology, hydrography, oceanography and geophysics, was designed to support a substantial reconnaissance of Hudson Bay for the purposes of obtaining regional scientific information, to add to man's knowledge of the history of the earth and specifically the crustal rocks in that part of Canada. This paper will be confined to a discussion of the results of both the conventional marine seismic program undertaken during the 1965 program and to the earlier onshore program in the Manitoba and Ontario Lowlands during 1963 and 1964.

Onshore refraction seismic surveys were conducted by the Geological Survey of Canada in 1963 in Manitoba, Hobson (1964a), and in 1964 in Ontario in cooperation with the Ontario Department of Mines, Hobson (1964b). These surveys were extended to the offshore areas by marine refraction surveys during the 1965 Hudson Bay project and have been reported elsewhere by Hobson (1967a and b). Considerable interest has been generated in this major sedimentary area of Canada by previous magnetometer surveys and the comprehensive survey of 1965.

Seismic investigations comprised a major part of the 1965 cruise. Three different types of seismic surveys were conducted: one using conventional marine seismic techniques to investigate the unconsolidated and consolidated sediments overlying the crystalline basement complex and another a crustal experiment to study the crust or outer shell of the earth down to the mantle or Mohorovicic discontinuity while a third employed a repetitive spark source to investigate the unconsolidated sediments overlying bedrock and stratification within the bedrock to a shallow depth. All three seismic programs will be discussed in this symposium.

The geology of Hudson Bay will not be discussed in this paper. It is sufficient to say that Hudson Bay is part of an ancient sedimentary basin that extends over an area considerably larger than that of the bay itself. Hudson Bay is bordered on the south and north by gently-dipping Paleozoic sandstones, limestones or dolomite rocks. They are conformable and dip towards the bay from the Precambrian-Paleozoic contact. Rocks on the east and west sides form part of the Canadian Shield. The Hudson Bay Basin, therefore, is set in a typical shield environment and the bay itself may be likened to a large lake or sea which will eventually become no more than a small lake on the Shield when isostatic equilibrium has been regained, Innes and Weston (1965). Raised beaches on the periphery of Hudson Bay indicate a relatively fast rate of rebound.

Manitoba Lowlands 1963 Seismic Survey

In 1963, nine reversed refraction seismic profiles were shot in the Hudson Bay Lowlands area of Manitoba, Hobson (1964a). It was the first attempt to use this geophysical tool to determine the geological column in this area. The project was carried out using a helicopter to transport men and equipment to selected lakes and rivers where the seismic investigations were carried out. This survey pointed out two important conclusions: firstly, the Silurian and Ordovician Formations cannot always be distinguished by a characteristic seismic velocity since they are both predominantly carbonates, and secondly, there is considerable topographic relief on the Precambrian Shield surface. Seismic locations one to nine of Figure 1 were shot during the 1963 program.

Ontario Lowlands 1964 Seismic Survey

The seismic program begun in 1963 was continued in March and April of 1964 by a crew under contract to the Geological Survey of Canada. Forty-one reversed refraction profiles were shot in the Lowlands of Ontario as a joint venture between the Ontario Department of Mines and the Geological Survey of Canada (Hobson, 1964a; Hobson, 1965). These locations extended from the Precambrian-Phanerozoic sediment contact south of James Bay northwestwardly to the Ontario-Manitoba boundary. Seismic locations 10 to 53 of Figure 1 comprised this program. The seismic instruments for this program were carried in the cabin of an Otter aircraft which was landed on the frozen lakes and rivers to carry out the seismic program.

Seismic profiles were also shot near three diamond-drill holes drilled by the Ontario Department of Mines in 1951 and reported by Martison (1953). The depths obtained seismically at the Jaab Lake hole agree very favourable with the drill logs. Glacial drift was drilled to a depth of 147 feet while seismic methods indicate a drift thickness of 154 feet. One interface between strata with velocities of 12,000 and 15,000 feet per second computes to a depth which ties very closely to the logged top of the Abitibi Formation of Devonian age. Total depth to basement at this hole was calculated from seismic data to be 1,865 feet – just 55 feet below the depth at which the hole was abandoned in the Pagwa River Formation of the Silurian. The profiles shot near the drillhole at Puskwuche Point and Mike Island also correlate reasonably well with the drill logs.

The thickness of glacial drift overlying bedrock in the Lowlands area of Ontario varies considerably from a few feet to over 700 feet in the north-westerly regions. As contemplated in earlier publications and then shown seismically in 1964, a Precambrian arch divides the James Bay and Hudson Bay Lowland areas. This is revealed by a relatively thin cover of sedimentary rocks overlying basement in the Cape Henrietta-Maria region. The thickest section of sediments within the onshore portions of the Hudson Bay Basin appears to be located in the region of the Sogepet-Aquitane-Kaskattama

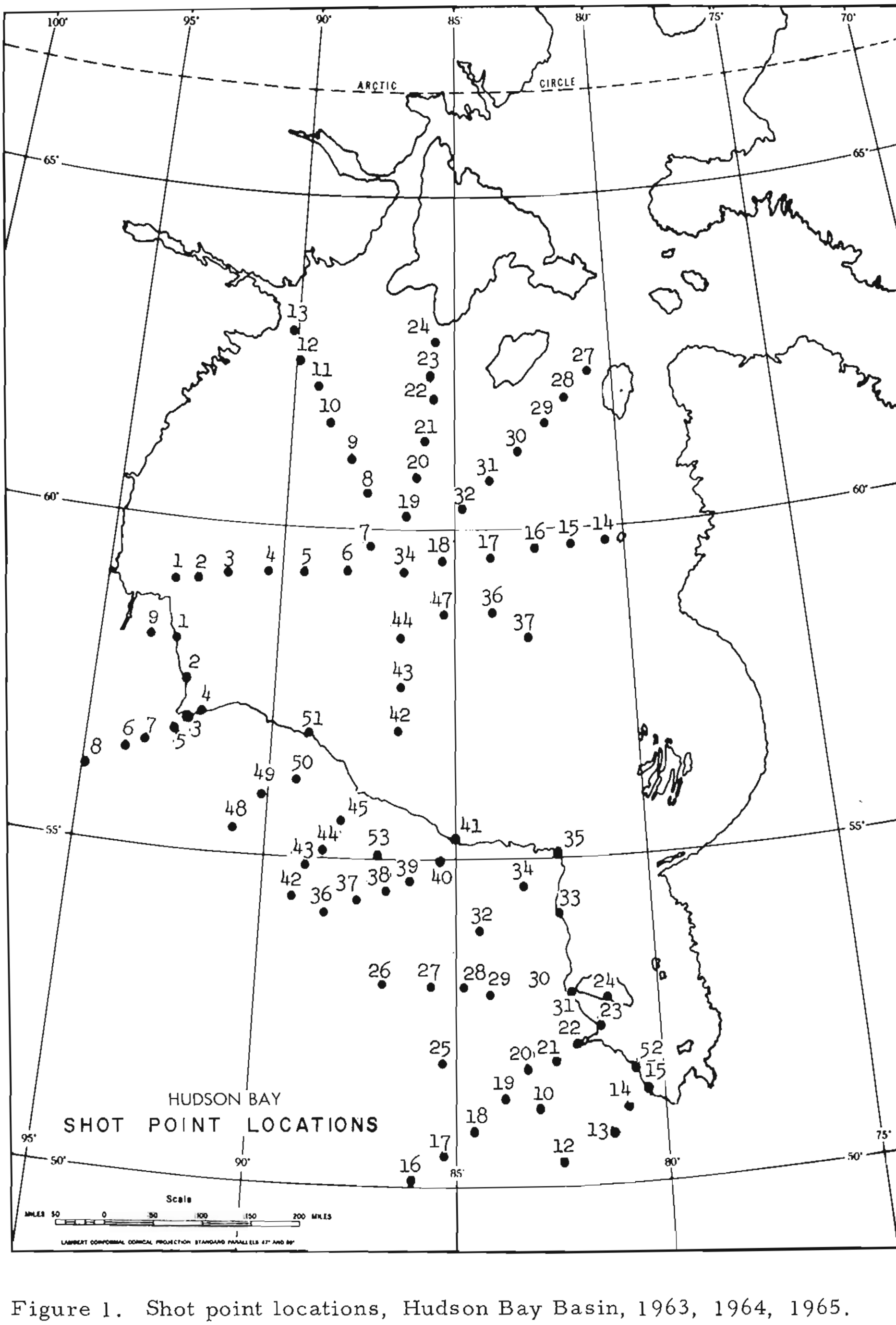


Figure 1. Shot point locations, Hudson Bay Basin, 1963, 1964, 1965.

Province No. 1 hole. Akimiski Island in James Bay appears to be situated over and is probably a reflection of a Precambrian ridge although the seaward side of this feature has not been studied seismically. With the publication of the Geological Survey of Canada Map 17-1967 the opportunity has been presented to tie the seismic profiles of the 1963 and 1964 programs more closely to mapped geology. This discussion will be presented below.

Conventional Marine Seismic Program 1965 in Hudson Bay

Seismic investigations comprised a major part of the 1965 cruise in Hudson Bay and as indicated above, all aspects of these investigations will be presented in the symposium. The conventional marine refraction seismic program was designed to give information about the thickness and nature of the geological strata overlying the Precambrian basement, to outline the extent of the sedimentary basin, to delineate if possible the extent and thickness of Proterozoic sediments underlying younger rocks and to investigate in a reconnaissance manner the extent of structure within the geologic section. Such matters as seismic refraction theory, field procedures, instrumentation and computation procedures will not be discussed in this paper. It is sufficient to note that nothing particularly novel was attempted in order to obtain the seismic data.

Discussion of Data

Precambrian Topography

The basement depths obtained from all seismic programs conducted in the Hudson Bay Basin are presented in Figure 2. This map indicates the general character of the Precambrian topography underlying Hudson Bay. The greatest depth obtained, namely 6, 585 feet, is located in the west central part of the bay where the water depth is 680 feet. The extent of the sedimentary basin is outlined in Figure 2 where it can be seen that the Precambrian contact in the northwestern part of the bay follows the shoreline rather closely while southward the shorelines of Hudson Bay and James Bay are not closely related to the boundary of the sedimentary basin. On the east the Paleozoic edge of the basin departs markedly from the shoreline of Hudson Bay while approaching it more closely in James Bay. From seismic data it is evident that there is considerable relief on the Precambrian Shield surface which however is not defined in detail by the reconnaissance nature of the marine seismic survey of 1965.

Cross-sections across Hudson Bay

Several cross-sections are presented in Figures 3, 4, 5 and 6 wherein strata are divided on the basis of refraction seismic velocities. Variations in the velocity data indicate that there is considerable structure within the sedimentary section. Indications of faulting have been observed on the seismic records but not in sufficient detail to permit the introduction of this structure into the cross-sections with reasonable conviction.

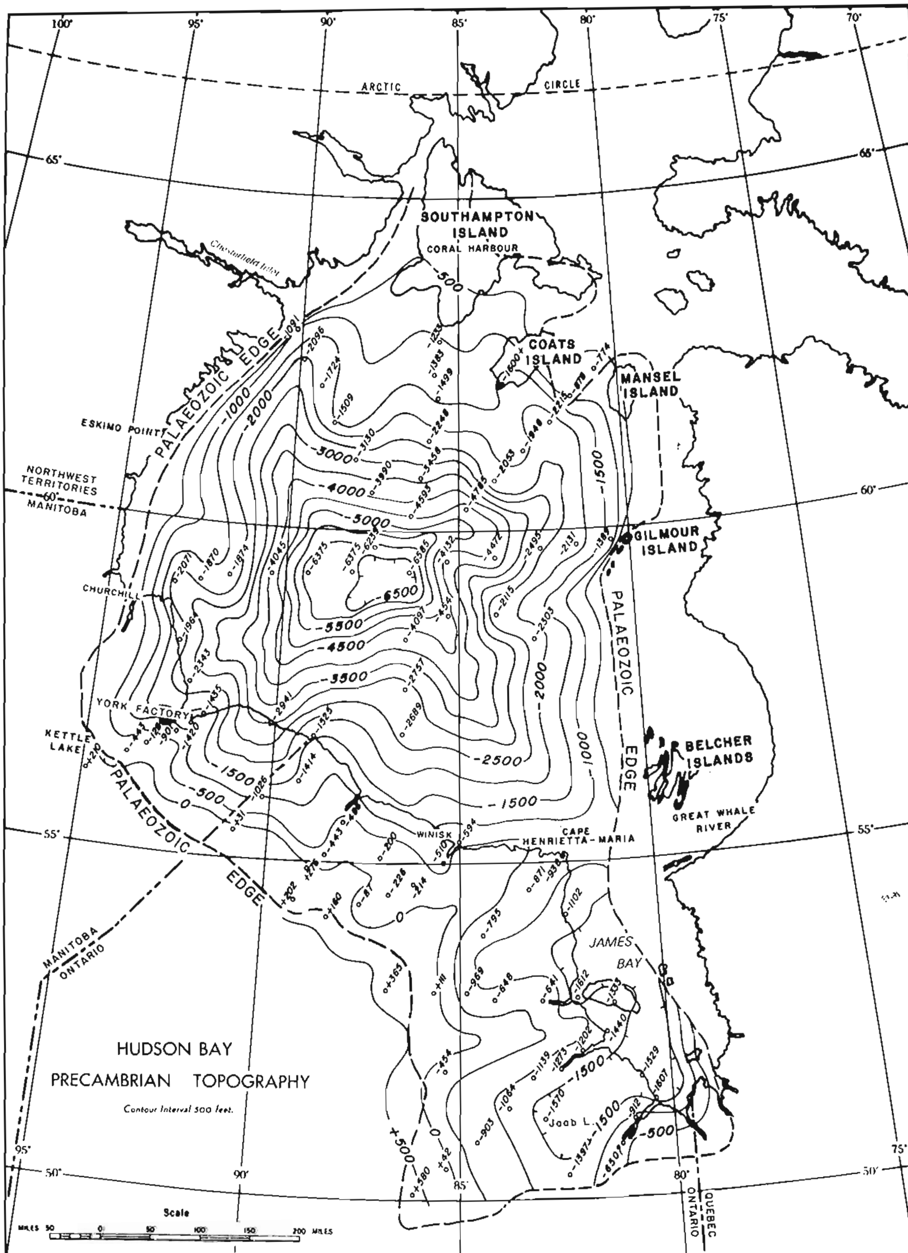


Figure 2. Precambrian topography, Hudson Bay Basin.

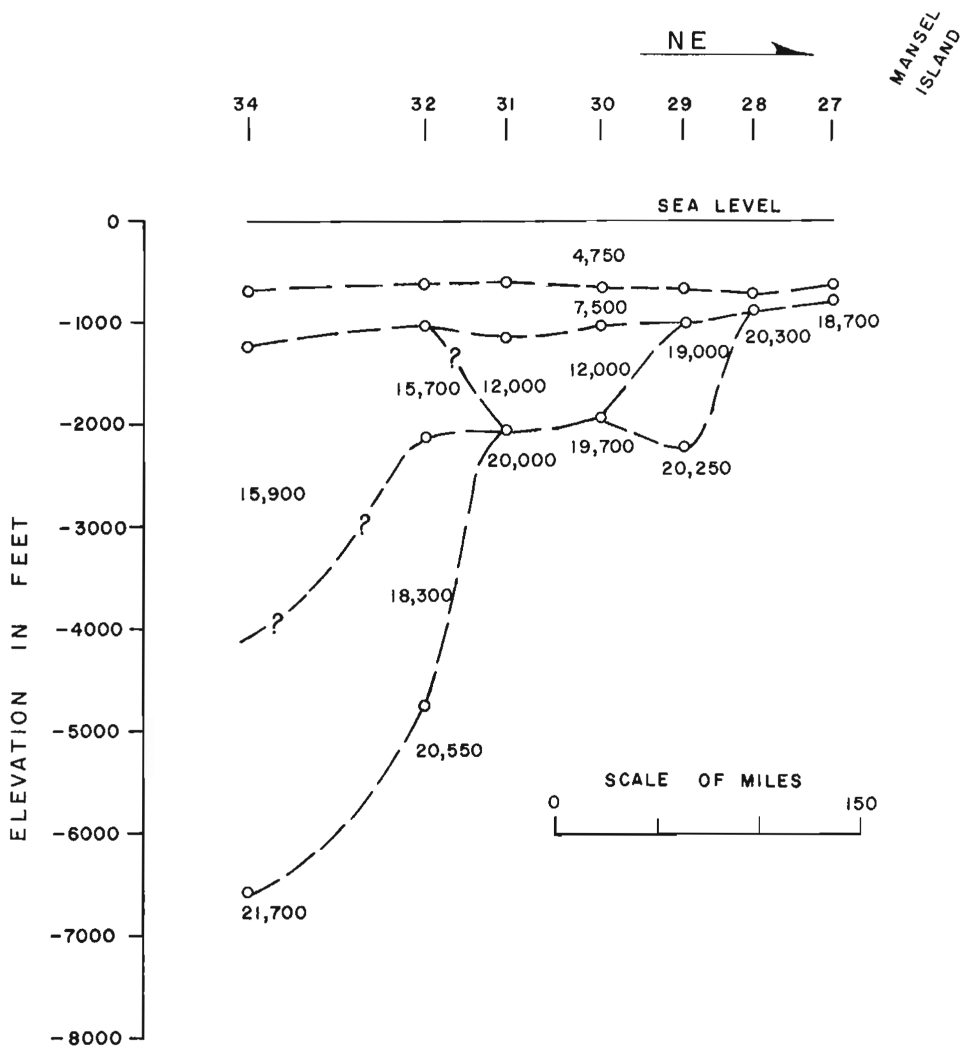


Figure 3. Section, centre of bay northeast to Mansel Island, Hudson Bay Basin. Seismic velocities are given in feet per second.

On these four cross-sections six different velocity ranges can be observed. The presence of lower and immediate range velocities, that is, less than 13, 500 feet per second indicates the probable presence of Mesozoic sedimentary rocks overlying the Paleozoic section. These formations are probably Lower Cretaceous or younger in age. The undulating nature of the 11, 300 to 13, 600 feet per second velocity layer beneath the assumed 7, 500 foot per second layer is thought to be real but not necessarily as depicted.

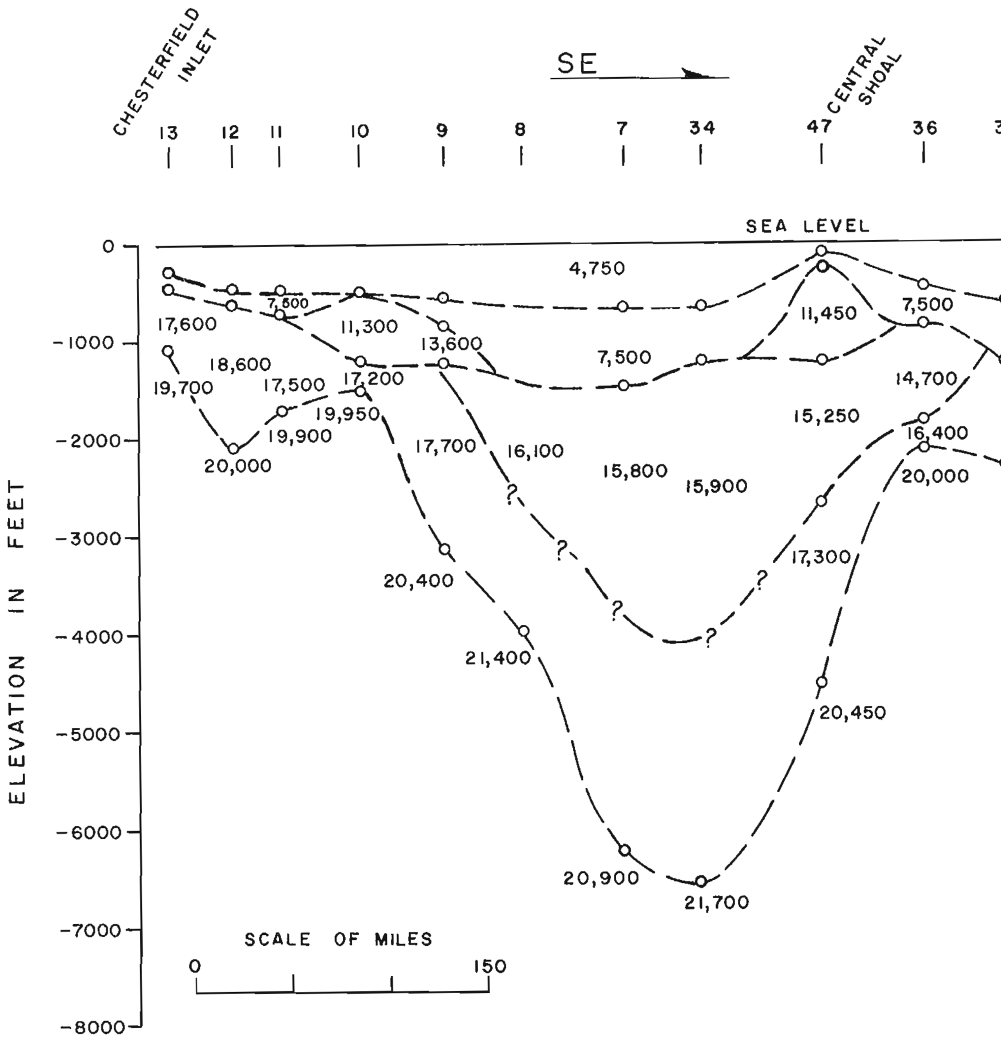


Figure 4. Section, central shoal northwest to Chesterfield Inlet, Hudson Bay Basin. Seismic velocities are given in feet per second.

It could be more persistent than shown on the depth sections, being present as a masked layer undetectable by the techniques employed. The repetitive spark profiles show a similar undulating surface beneath the sea floor where the conventional refraction data indicate this layer. The velocity layer 14, 500 to 16, 200 feet per second is the thickest stratum observed in the geological column, thicknesses as great as 3, 000 feet having been calculated. This layer is believed to be Lower or Middle Devonian in age.

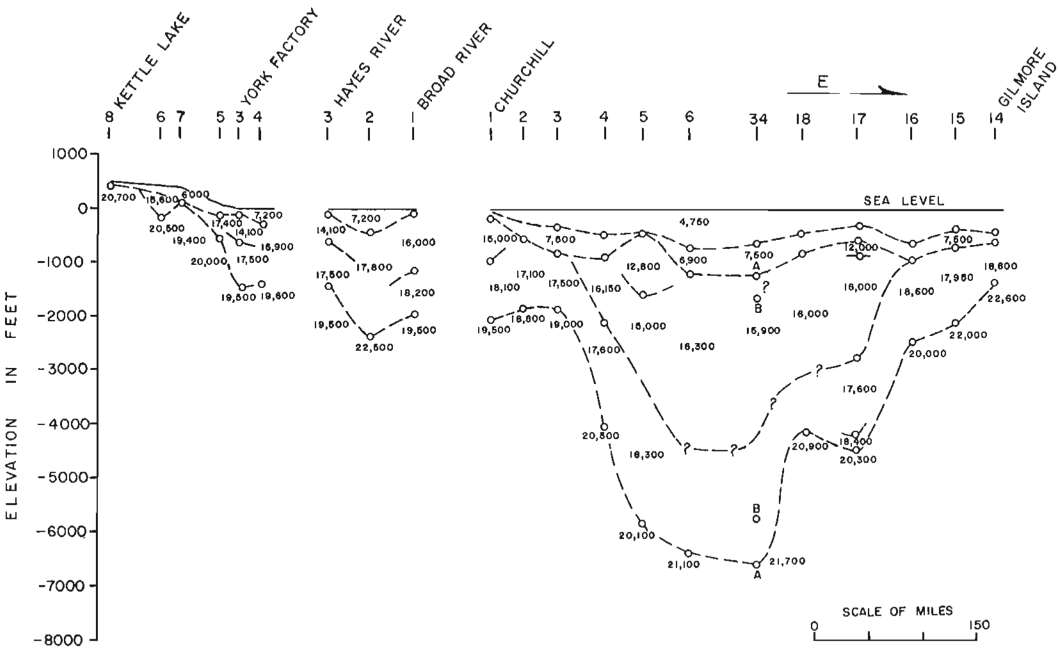


Figure 5. East-west section across Hudson Bay Basin. Seismic velocities are given in feet per second.

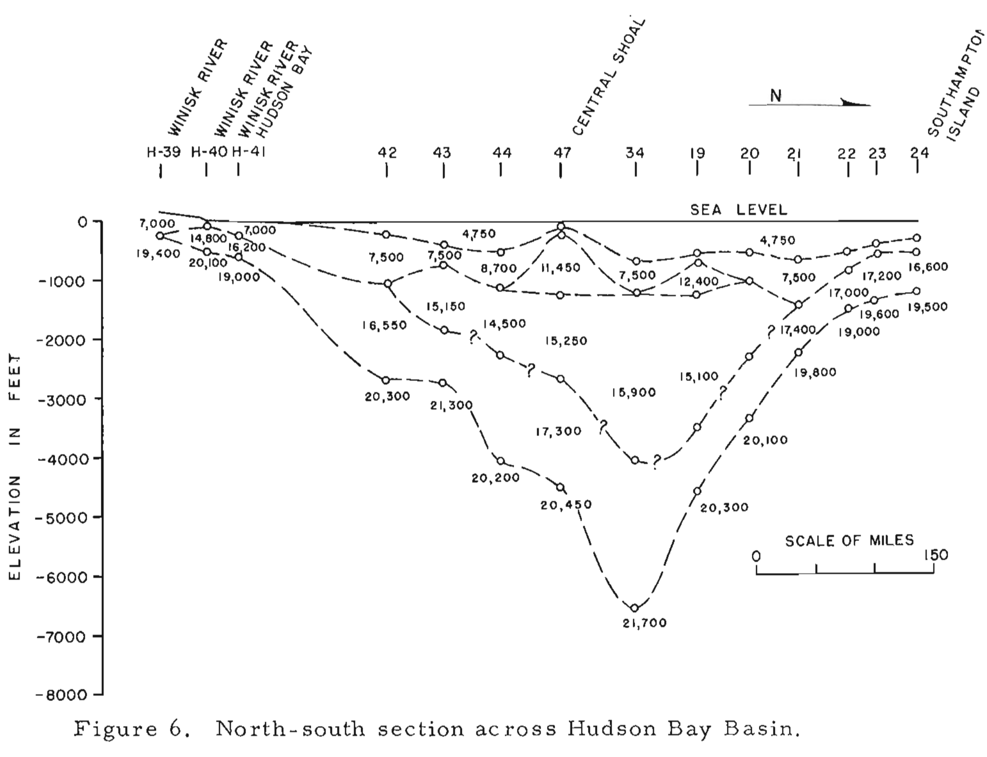


Figure 6. North-south section across Hudson Bay Basin.

The strata represented by the velocity range of 16, 400 to 19, 000 feet per second are probably undifferentiated Silurian and Ordovician carbonates. It is most often associated with the thinner sedimentary section but it must also be noted that sufficient evidence has been recorded as first and secondary seismic arrivals of energy to support its presence within the thicker section.

The basement velocity observed at numerous locations in the bay and Lowlands varies between 18, 800 and 22, 600 feet per second. This is acknowledged to be broad range, perhaps a greater range than would be expected from the steepest dips determined in the interpretation of the seismic data, but possibly not excessive if accountable by local structure on the Precambrian surface. It is concluded that the change in velocity represents a change in lithology. Most noteworthy is the generally high velocities observed under the east side of the bay compared with those on the west which are considered to be normal velocities for the Canadian Precambrian Shield.

The section northeast to Mansel Island, Figure 3, in no place shows the complete velocity or geologic section. Ice flows between Coats and Mansel Islands prohibited procurement of seismic data to confirm or deny the fault or graben postulated by Hood (1964) to exist north of these two islands. Of particular interest on Figure 4 is the depression in the basement at the northwest end of the line, a feature which correlates with a magnetic low postulated by Hood (1964). The Precambrian-Paleozoic contact was observed on the northern side of the refraction profile closest to Chesterfield Inlet. Figure 5 is an east-west section across the Hudson Bay Basin and shows all velocity strata including the possible differentiation of the Silurian and Ordovician Formations beneath location 17. This is the only location at which the marine seismic method was able to differentiate the two carbonates. Figure 6 is a north-south section across the Hudson Bay Basin traversing the central shoal.

Cross-sections of Manitoba and Ontario Lowlands

Hitherto unpublished seismic data from the 1963 and 1964 onshore surveys are presented below as sections to permit a closer correlation between these seismic surveys and their interpretation with the results of the geological mapping project Operation Winisk of 1967. The publication of Geological Survey of Canada,Map 17-1967 for Operation Winisk has permitted a very interesting reappraisal of the seismic sections; these sections will be discussed in detail below.

Figure 7 is a seismic cross-section which extends southwesterly from York Factory in Manitoba. The Silurian and Ordovician carbonates are undifferentiated beneath this profile except at location 6 where only the Ordovician is present and beneath location 3 where two velocities might indicate both Silurian and Ordovician. Reference to Map 17-1967 indicates that location 7 should have detected both Silurian and Ordovician but such was not

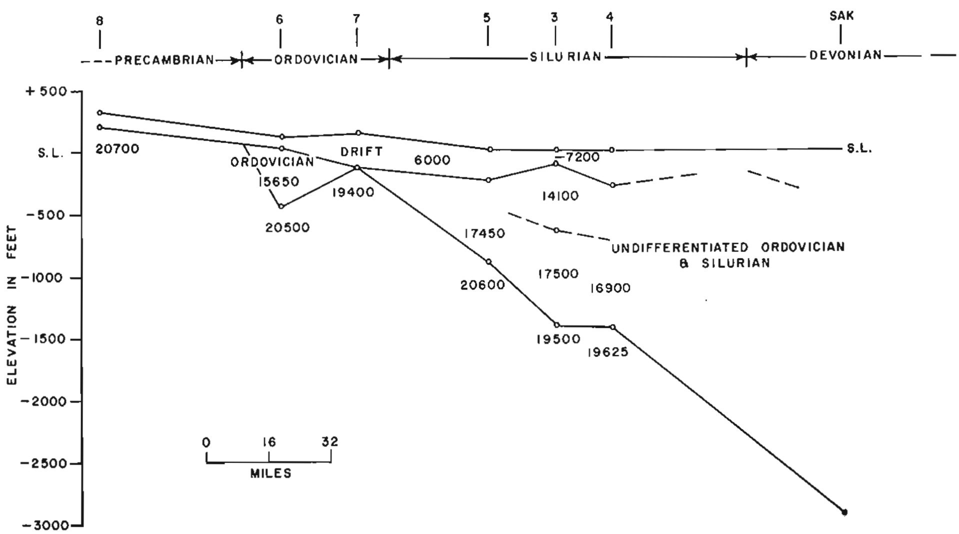


Figure 7. Section, southwest from York Factory, Hudson Bay Lowlands, Manitoba.

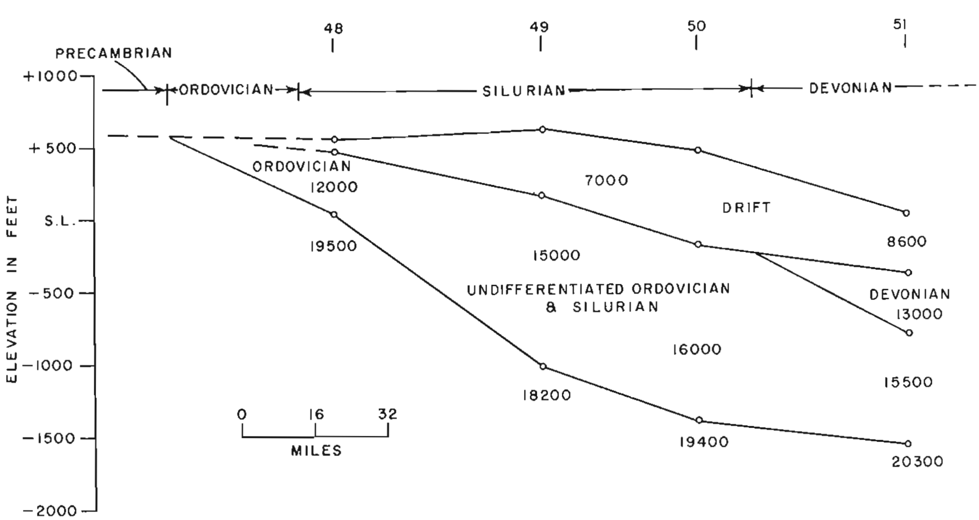


Figure 8. Section along Manitoba - Ontario boundary, Hudson Bay Lowlands.

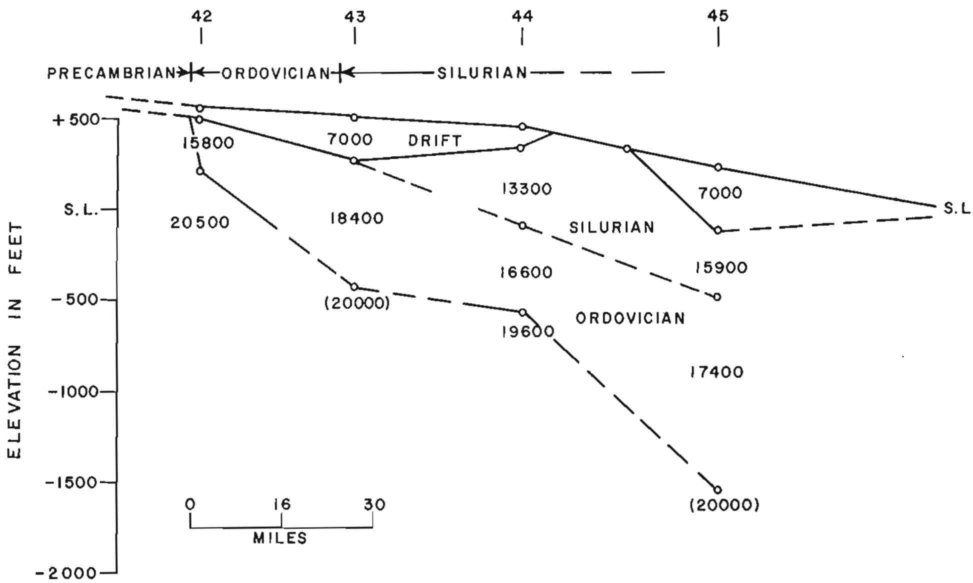


Figure 9. Section, southwest from Fort Severn, Hudson Bay Lowlands, Ontario.

the case. Seismically, location 7 appears to be located on a Precambrian high. This section has been extended to include the Sogepet-Aquitane-Kaskattama hole indicating only the Precambrian surface at that location.

Figure 8 is located along the Manitoba-Ontario boundary. The Silurian and Ordovician Formations are undifferentiated beneath this profile and appear to have been detected in normal thickness except beneath location 51. The thickness of these strata detected beneath location 51 appears to be anomalous since the carbonate should thicken towards the coast. Seismically there is a good velocity contrast between the carbonates and the basement and the computations are believed to be accurate from good records. The presence of the Devonian Formation is detected at location 51. Of particular interest over this profile is the very thick layer of drift probably due to considerable weathering on the upper Silurian Formations. These upper Silurian Formations are very soft in nature and if highly weathered would be detected seismically as part of the drift.

Figure 9 extends southwest from Fort Severn. The Silurian and Ordovician carbonates have been differentiated beneath this profile but only since the publication of Geological Survey of Canada, Map 17-1967. An earlier interpretation would have correlated the Silurian velocities with Devonian Formations. The thicknesses indicated beneath locations 43 and 45 are minimal since penetration was not achieved at these locations.

Figure 10 is a profile southwest from Winisk. This section is very interesting because two interpretations can be presented, one directly from the seismic data and a second when Geological Survey of Canada, Map 17-1967 is considered. Figure 10A is the original interpretation from the seismic data. It must be admitted that originally on this section the Proterozoic outcrop near location 40 was not included in the interpretation. This outcrop was not known at the time the profile was shot and it was fortuitous that location 40 was established near this outcrop because the project was undertaken during the winter months. It is interesting to consider the lower part of Figure 10 wherein it is indicated that the undifferentiated Silurian and Ordovician carbonates may be present as a seismically hidden layer as much as 420 feet thick. Velocity contrasts are such as to permit such a section to be undetected by the seismic technique. As pointed out however this was not the interpretation originally considered for the data. Figure 11 indicates the possible geophysical contact compared with the contact shown between the Paleozoics and Precambrian on Geological Survey of Canada, Map 17-1967. The area is drift covered and only a hole drilled to the Precambrian would resolve this problem.

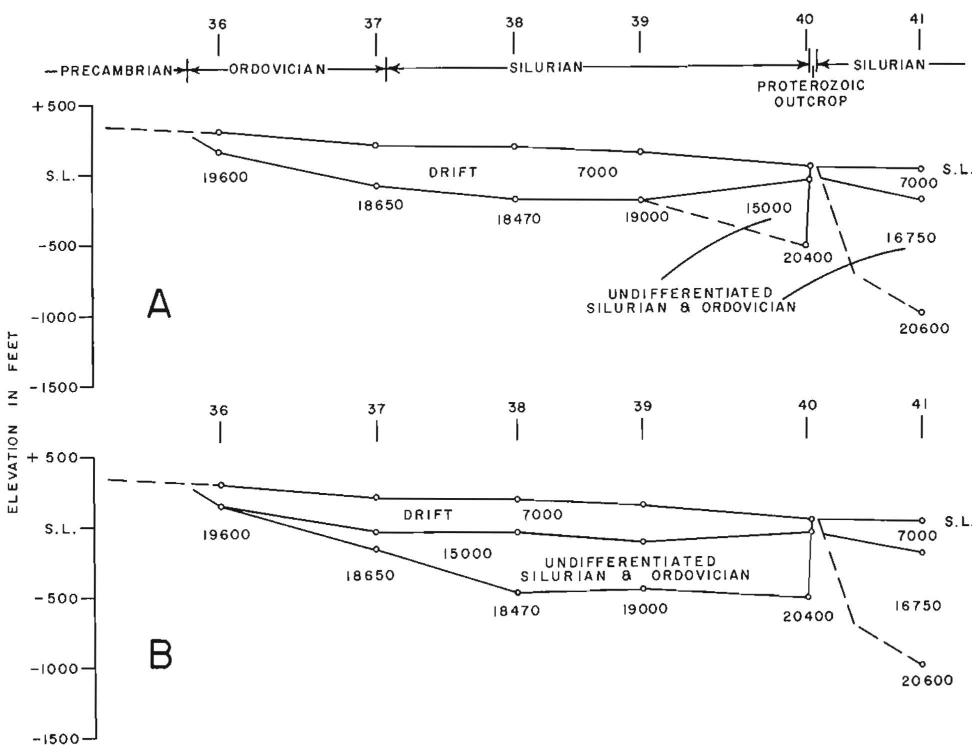


Figure 10. Section, southwest from Winisk, Hudson Bay Lowlands, Ontario.

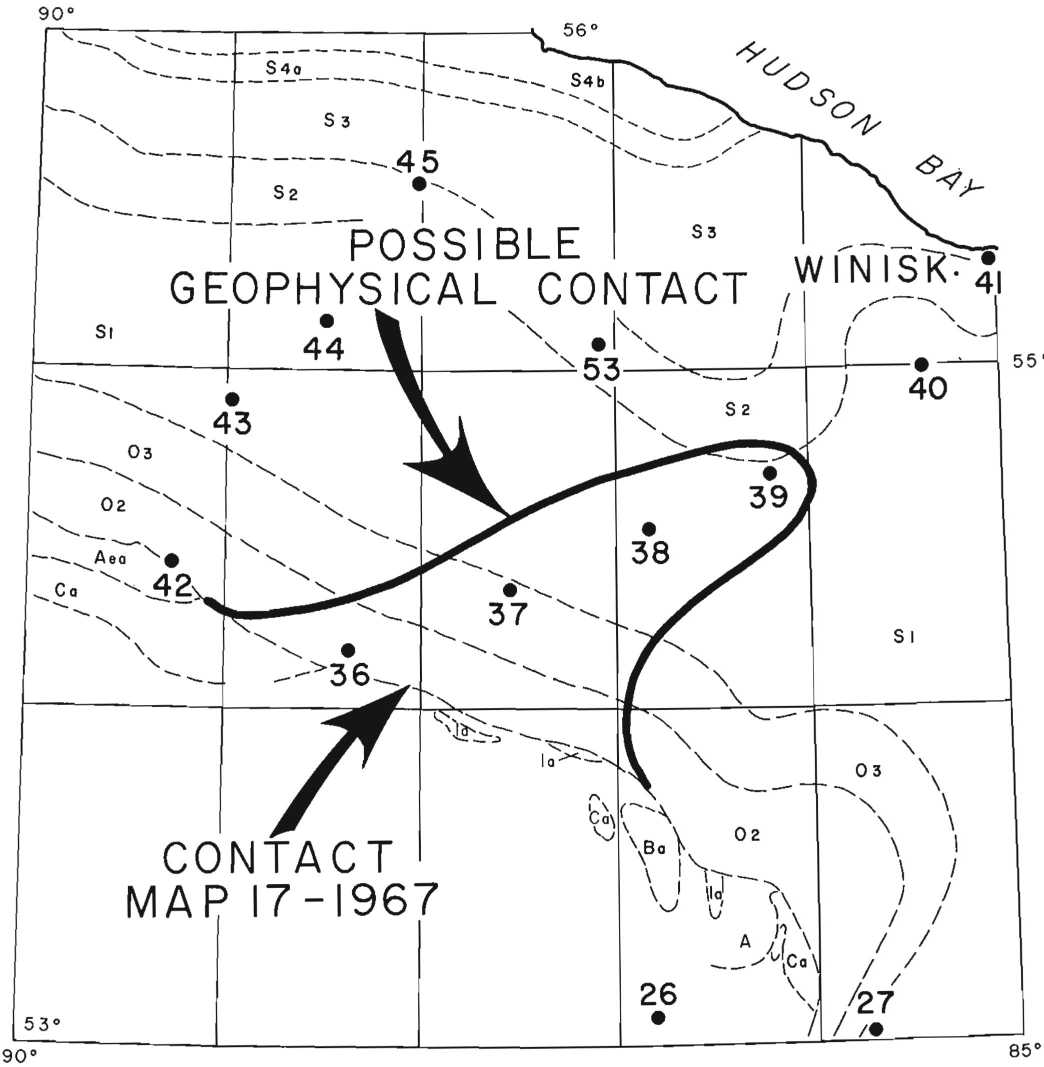


Figure 11. Alternative interpretations of the Paleozoic edge from geology and from geophysics.

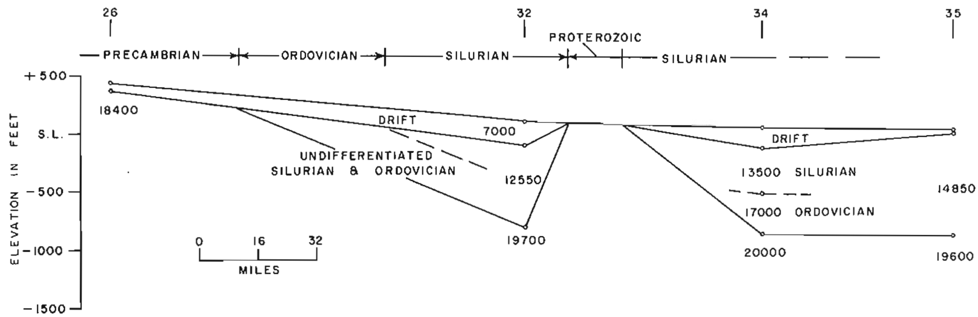


Figure 12. Section, southwest from Cape Henrietta-Maria across the Hawley Lake Proterozoics, Hudson Bay Lowlands, Ontario.

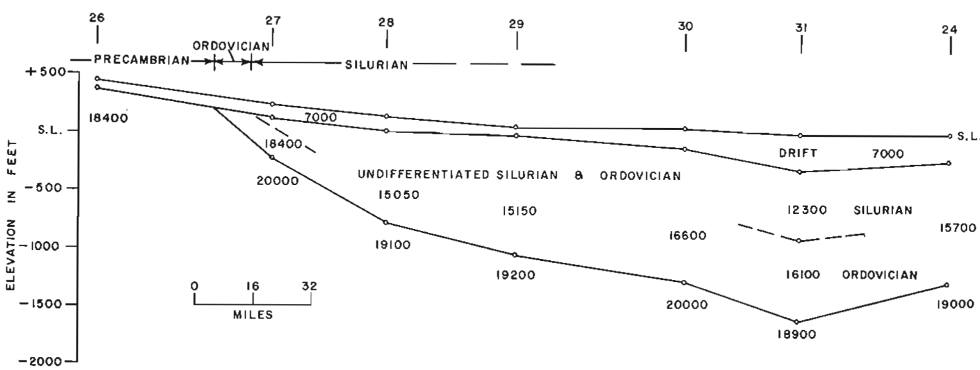


Figure 13. Section, west from Akimiski Island, Hudson Bay Lowlands, Ontario.

Figure 12 extends southwest from Cape Henrietta-Maria across the Hawley Lake Proterozoics. This profile is probably the most difficult one to reconcile between geologists and geophysicists. The Proterozoic outcrop between seismic locations 32 and 34 might be explained by introducing faults on both sides of this outcrop or suggesting that severe erosion on the Precambrian surface has left this outcrop feature as a remnant of erosion. However, the area to the northeast of the Proterozoic outcrop is an enigma in that some geologists suggest that there is no Ordovician present in this area. The seismic data at locations 34 and 35 are good and it is impossible to suggest another interpretation than that presented in this figure. To eliminate the Ordovician below location 34 would require suggesting that the 17,000 feet per second velocity is Proterozoic. And to suggest that the 14,850 feet per second beneath location 35 is all Proterozoic is almost unimaginable from a seismic point of view. This velocity is just too low for Proterozoic sediments.

Figure 13 is a profile extending westward from Akimiski Island. Here again the Silurian and Ordovician Formations are undifferentiated over the length of the profile except beneath location 31. Also it is worthy of note that the Silurian and Ordovician Formations do tend to thin towards the edge of the basin as shown beneath location 24. It has been suggested that Akimiski Island is the reflection of a Precambrian high and this seems to be evident on this section.

Figure 14 is a section southwest from Fort Albany principally located along the Albany River. Beneath this section the Silurian and Ordovician Formations canbe differentiated locally beneath locations 19, 21 and 23 while the introduction of the Devonian Formations has been recorded where appropriate on the seismic profiles. The data at location 20 are good and the resolution of the seismic velocities into only one velocity, 12, 300 feet per second, overlying Precambrian is not explainable unless hidden layers are utilized. This is highly unlikely since at the locations on both sides of location 21 the Devonian, Silurian and Ordovician have been observed as individual formations and velocities. It has been difficult to label the formations beneath locations 22 and 23, relatively low velocities having been observed at these stations. All data observed on this profile are good to excellent and it is believed the best interpretation has been presented in this section.

Figure 15 extends southwest from Moosonee. This is the only profile upon which drillhole control was available. The fault at the northeast end of this profile between locations 14 and 15 was not detected seismically but it is introduced on the basis of Map 17-1967 as a post Upper Silurian uplift.

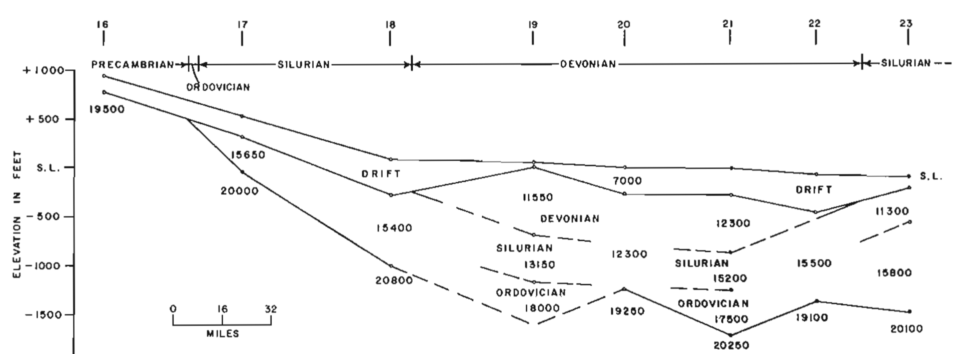


Figure 14. Section, southwest from Fort Albany, Hudson Bay Lowlands, Ontario.

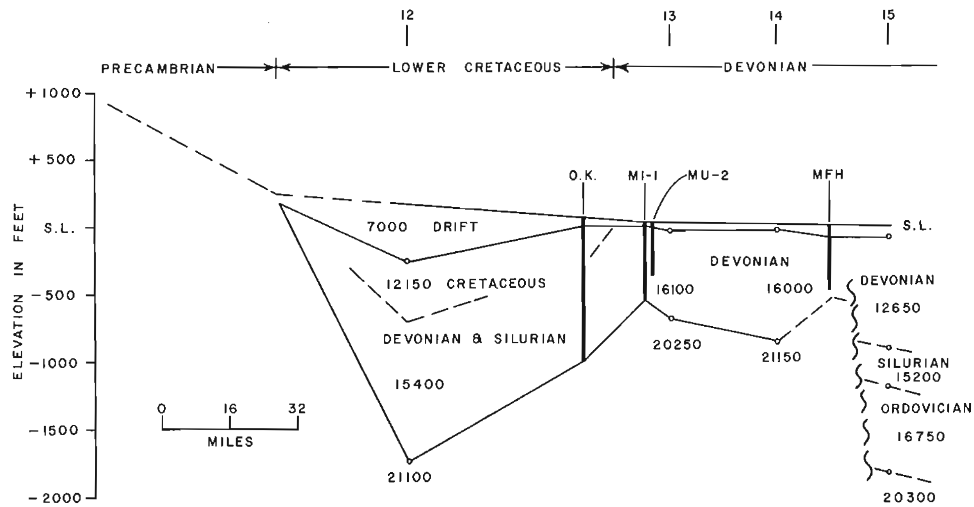


Figure 15. Section, southwest from Moosonee, Hudson Bay Lowlands, Ontario.

Central Shoal

The central shoal, location 47 on the north-south section of Figure 6 is also an enigma. Seismically, it shows as a relatively low velocity layer overlying other strata. By the process of elimination, this shoal must be a young Devonian Formation weathered to a degree that permits the low seismic velocity associated with it. The uppermost beds of the shoal structure cannot be Silurian in age since two definite and thick velocity strata have been recorded below the first bedrock refractor. The nature of a grab sample does not permit a Lower Cretaceous age to be considered. Similar low velocity areas have been revealed seismically to exist in other parts of Hudson Bay and the Ontario Lowlands but not in the Manitoba Lowlands area.

The repetitive spark survey reveals the central shoal to be a broad arch structure with stratification in the upper few hundred feet reflecting the gross structure. Strata are truncated at the sea floor as they are exposed on the flank of the arch. It is worthy of comment that the anticlinal structure of the shoal is not reflected by underlying interfaces at depth.

Relations between Velocity and Geology

The various velocity layers shown in Figures 3 to 15 represent geological strata. The velocity ranges and lithology for both the marine seismic and the onshore programs are presented below. The following tabulation is suggested as a correlation between velocity and lithology for the conventional marine seismic program of 1965:

Velocity Range (feet per second)	Rock
4, 750	Water
6, 800-8, 700	Unconsolidated or semi-consolidated Lower Cretaceous of younger
11, 300-13, 600	Upper Devonian
14, 500-16, 200	Devonian (Middle or Lower)
16, 400-19, 000	Silurian and Ordovician undifferentiated
18, 800-22, 600	Precambrian basement
>20, 900	Proterozoic sediments

The following tabulation is suggested as a correlation between velocity and lithology for the onshore seismic program in the Manitoba and Ontario Lowlands, 1963 and 1964:

Velocity Range (feet per second)	Rock
7, 000 approximate	Drift
12, 150 approximate	Cretaceous
11, 600-16, 100	Devonian
13, 200-15, 900	Silurian
15, 600-18, 400	Ordovician
14, 800-18, 400	Silurian and Ordovician undifferentiated
18, 400-21, 100	Precambrian basement

Both tabulations have been presented for the two different seismic programs and it is obvious that there is a definite similarity between the velocity ranges and the correlation with lithology.

Some General Comments

The velocity strata represented by 11, 300-13, 600 feet per second in the marine seismic program may be Lower Cretaceous in age but this interpretation is not regarded favourably. It is certainly a possibility worthy of mention since such a velocity has been correlated with the Cretaceous onshore but it is not one which is compatible with the samples dredged from the central shoal.

The possibility of a salt section in the geological column under the waters of the bay must also be considered. It is rumored that salt was drilled in the Kaskattama hole and this may be divulged during the symposium. If such a section is present, it will probably be thin and of high velocity and therefore not decrease the thickness of the total column to any great extent. On the other hand, if there are shales in the Ordovician section, they could be of considerable thickness, low in velocity and thereby undetectable by refraction seismic techniques and would increase the total thickness of sediments considerably. The depth to the Precambrian surface as depicted in Figure 2 is therefore minimal.

The question also arises as to whether or not the strata represented by the velocity range of 16, 400-19, 000 feet per second could be the Precambrian Shield. This would immediately decrease the estimated total thickness of sediments in Hudson Bay to about 4, 000 feet and therefore would not be attractive to petroleum prospecting. However, this range of velocities has been directly correlated with the Ordovician and Silurian rocks during the Lowlands onshore investigations and it is considered to be quite legitimate to carry these correlations offshore. On the other hand if some of the strata included in the velocity range of 18, 800 to 22, 600 feet per second were carbonates the geological section could be extended considerably deeper. It is appreciated that velocities of 20, 000 feet per second and greater have been recorded in Western Canada and Arctic carbonate sections. However since this velocity range has been directly correlated with the Shield rocks around the bay it appears to be a logical conclusion to assume that the uniformities extend across the entire basin.

There are a few anomalies with respect to the correlation of velocities with lithology in the Lowland areas that cannot be explained at this time. More seismic control beyond the general reconnaissance surveys of 1963 and 1964 are required for closer correlation between the geology of Map 17-1967 and seismic velocities. It would be most desirable of course to have a few shallow drillholes for control.

Acknowledgments

I sincerely acknowledge the untiring support of the members of the Seismic Section, Geological Survey of Canada who participated in the acquisition of seismic data in the field often under adverse and unpleasant conditions. The captains, officers and crews of the C. S. S. Hudson and the M. V. Theron were most cooperative in all their efforts to assist the scientists in the acquisition of data during the 1965 cruise. B. R. Pelletier, as scientist-in-charge of that cruise, was most understanding and tolerant of the demands of the seismic projects upon total time available to the various disciplines.

REFERENCES

Hobson, George D.

1964a: Nine reversed refraction seismic profiles, Hudson Bay Lowlands, Manitoba; in Summary of Activities; Office and Laboratory 1963, Geol. Surv. Can., Paper 64-2, pp. 33-40.

1964b: Thickness of sedimentary formations, Ontario Hudson Bay Lowlands; Ontario Dept. Mines, Prelim. map. No. P 243.

Hobson, George D. (cont'd)
1965: Seismic refraction survey, Hudson Bay Lowlands; in Report of Activities, 1964, Geol. Surv. Can., Paper 65-1, pp. 104-106.

1967a: A reconnaissance seismic refraction survey in Hudson Bay, Canada; Proc. 7th World Petrol. Congr., Mexico City, vol. 2, pp. 813-826.

1967b: Recent geophysical investigations in the Hudson Bay Basin; Proc. 6th Annual Conf., Ontario Petrol. Inst., London.

Hood, Peter
1964: Sea magnetometer reconnaissance of Hudson Bay; Geophysics, vol. 29, No. 6, pp. 916-921.

Innes, M.J.S., and Weston, A. Argun
1965: Crustal uplift of the Canadian Shield and its relation to the gravity field; Ann. Acad. Sci. Fennicae, ser. A 111, No. 90; reprinted as Contrib. Dominion Obs., vol. 7, No. 5, pp. 1-8.

Martison, N.W.
1953: Petroleum possibilities of the James Bay Lowland area; Ontario Dept. Mines, 61st annual report, vol. 61, Pt. 6.

Norris, A.W., Sanford, B.V., and Bostock, H.H.
1967: Geology, Hudson Bay Lowlands, Manitoba, Ontario, Quebec and District of Keewatin; Geol. Surv. Can., Map 17-1967.

Addendum

The papers presented by Johnson and Nelson and by Hodgkinson at this symposium revealed velocity data unknown during the preparation of this paper. The correlation of seismic refractors with top Upper Silurian, top Middle Silurian and top Ordovician in the Kaskattama hole is most interesting. And the disclosure of a velocity of 22,500 or 23,000 feet per second for the Ordovician carbonates certainly increases the thickness of the geologic section where these carbonates are present. This author would believe however that such velocities may be associated with Precambrian and Proterozoic rocks in some parts of the basin.

RECONNAISSANCE SEISMIC AND MAGNETOMETER SURVEYS IN HUDSON BAY, CANADA

J. Hodgkinson
Atlantic Richfield Company
Calgary, Alberta

Abstract

The results of a reconnaissance refraction survey over a portion of Hudson Bay are presented in the form of a structure map on a deep refractor. This structure map is compared with a map of depth-to-basement estimates derived from an aerial magnetometer survey over the same area. The magnetic basement is shown to be 1,500 to 3,000 feet deeper than the deep refractor, although the general form of both maps is similar, and structural features show fair correlation.

The velocity of the deep refractor averages 20,200 feet per second over the area surveyed in the Bay, and a refractor of such a high velocity is considered to be more typical of a carbonate than it is of basement. The accuracy of the deep-refractor map is discussed in some detail, and problems encountered in reflection shooting are reviewed with some examples.

The refraction results in the Bay are correlated with those of a refraction survey shot across the Sogepet-Aquitaine Kaskattama Province No. 1 well on the coast, where a deep refractor of similar velocity was mapped. The results of the coastal refraction survey are correlated with those of a velocity survey in the Kaskattama well, and it is concluded that the deep refractor of the coastal survey is an Ordovician limestone. By extension it is concluded that the deep refractor mapped in the deepest part of the sedimentary basin is probably also an Ordovician limestone. This refractor is believed to be the same as that mapped and identified by G. D. Hobson (1967) as Precambrian.

It is believed that the interpretation of the results of the seismic refraction survey and the aerial magnetometer survey indicate the presence of over 8,000 feet of sedimentary section beneath Hudson Bay.

INTRODUCTION

In Hudson Bay during the summer of 1965, Richfield Oil Corporation conducted a program of geophysical surveys designed to provide a reconnaissance evaluation of 50 million acres of Richfield Permits and 1.5 million acres of offshore Sogepet Permits, as shown in Figure 1. The surveys were planned and directed by Richfield's geophysical staff prior to the merger of Richfield Oil Corporation with the Atlantic Refining Company.

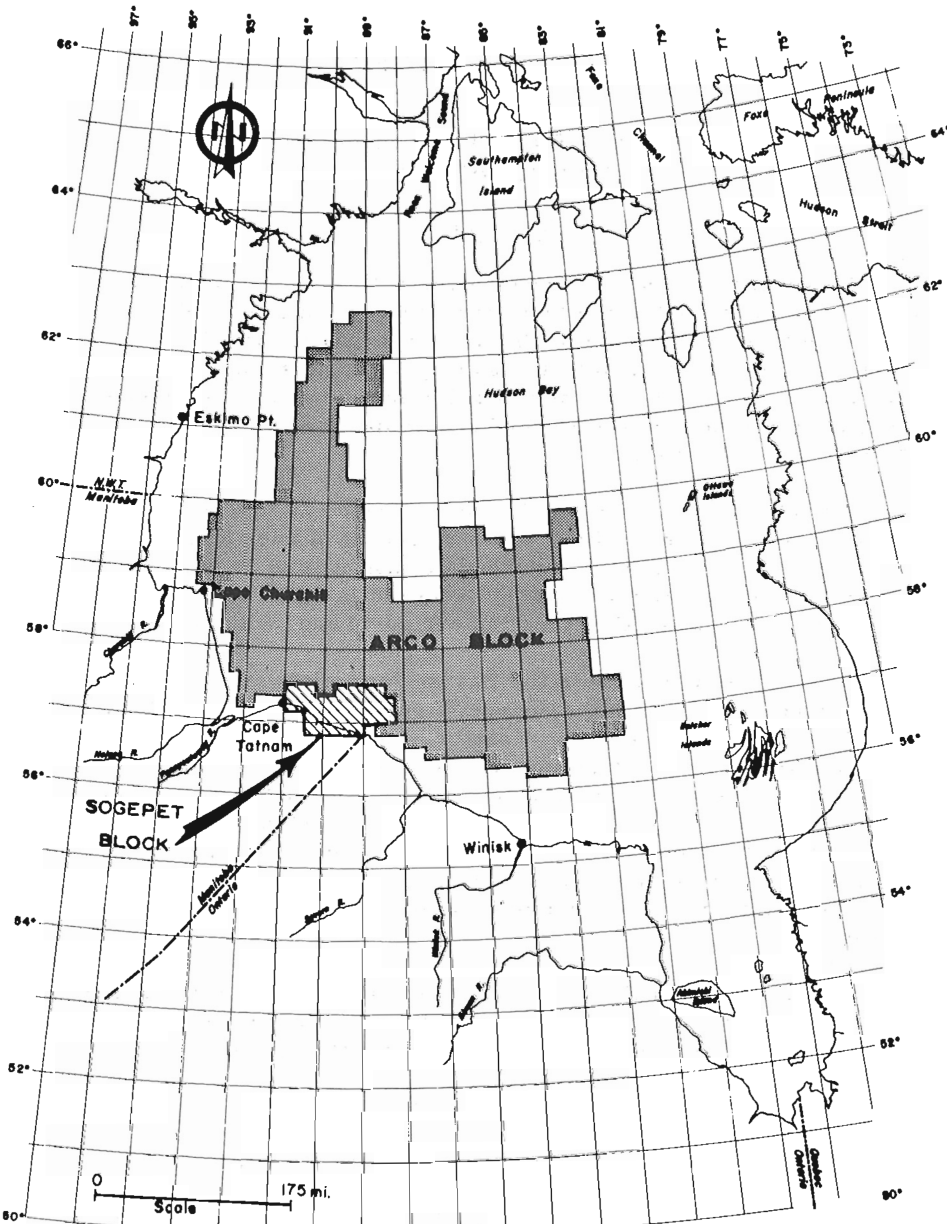


Figure 1. Index map showing the Atlantic Richfield and Sogepet acreage blocks over which the reconnaissance surveys were conducted.

The geophysical program comprised the following surveys:

1. An aerial magnetometer survey conducted by Canadian Aero Service Limited of Ottawa, Ontario.

2. A gas-exploder seismic reflection survey conducted by Marine Geophysical International, Inc., of Houston, Texas.

3. Seismic reflection and refraction surveys conducted by Geophysical Service Incorporated of Dallas, Texas.

Navigation control for all these surveys was provided by a Decca Lambda network, owned by the Department of Mines and Technical Surveys (now the Department of Energy, Mines and Resources) and operated by Computing Devices of Canada Limited. Transmitter sites were located at Cape Churchill, Cape Tatnam and Eskimo Point, providing a lattice of two intersecting sets of hyperbolic radio lanes. The network features a lane-identification system, and maximum range was expected to be about 400 miles from the farthest slave station. In practice a greater range than this was achieved fairly consistently, regular magnetometer flights being made out of Winisk, which is over 500 miles from the slave station at Eskimo Point.

G. D. Hobson (1967) has reviewed the geology surrounding Hudson Bay, the bathymetry of the Bay itself, and the ice conditions encountered during the summer of 1965. His paper also provides a comprehensive review of earlier geophysical surveys conducted over the Bay and in the Hudson Bay Lowland areas of Ontario and Manitoba.

The 1965 Federal Government surveys reported by Hobson and the Richfield surveys described herein were all conducted concurrently, continuous liaison being maintained with the several Government Agencies involved.

Magnetometer Survey

The magnetometer survey, flown by Canadian Aero Service Ltd., utilized Gulf Mark III airborne magnetometers with the flight altitude being maintained at 1,000 feet above sea level. Approximately 45,000 line-miles were flown in a 2-mile by 10-mile grid covering the Richfield and Sogepet acreage blocks which are shown in Figure 1. This survey grid was flown in two stages, the first stage being a 10-mile by 10-mile reconnaissance grid with lines north/south and east/west. After preliminary interpretation in the field, the 10-mile by 10-mile loops were filled in by either north/south or east/west lines spaced two miles apart, the direction of these lines being determined by the lineations of the anomalies revealed by the preliminary interpretation. The aeromagnetic survey began on July 7, 1965, and was completed on October 4, 1965.

The magnetic data were compiled by Canadian Aero Service Limited, the first stage of the compilation being to recover the flight paths. Considerable difficulty was experienced in positioning the flight lines along the coast in the southwest portion of the surveyed area. This is close to the base line extension through the Cape Tatnam transmitter, where poor accuracy of Decca positioning was to be expected. Positions over the coast were checked by means of a 35 mm film strip exposed in flight, and comparison of the visual and Decca plots showed discrepancies of one-quarter mile on the west side of the Cape Tatnam transmitter, and of nearly two miles on the east side of the transmitter. These discrepancies resulted in positioning problems within a ten-mile radius of the transmitter. Since this is the only portion of the survey area over which a visual check of the Decca coordinates was possible, the accuracy of navigation in the rest of the survey area remains in question even though the coastal area was forecast to be most subject to error. This problem will be mentioned again in connection with the results of the seismic refraction survey.

The interpretation of the magnetic data was carried out by M. S. Reford, and was based upon a detailed review of the magnetometer records. A preliminary interpretation was made using the well-known "straight-slope" graphical method applied to anomalies which showed consistently uniform gradients along their flanks. Depth to basement estimates were obtained by multiplying these straight-slope lengths by a factor of 1.5. The next stage of interpretation involved curve-matching techniques applied to the second horizontal derivatives of selected features, the derivatives being calculated numerically. After considerable curve matching it became apparent that a factor of 2.0 resulted in more consistent agreement between depth estimates from analytical methods and those from the "straight-slope" method. Accordingly the factor 2.0 was applied to the straight-slope lengths over the majority of the survey. The factor 1.5 gave better agreement with analytical methods in the northern portion of the survey, and 2.5 in the southeast corner of the survey.

Depth contours were drawn combining depth data from all methods, including straight-slope estimates, curve-matching estimates, and estimates from narrow symmetrical anomalies assumed to be caused by dyke-shaped bodies with width equal to depth.

Generalized contours showing total magnetic intensity over the entire area surveyed have been released to the Geological Survey of Canada for compilation with similar data from other sources. Since a composite map combining all such data will be published in due course by the G. S. C., no detailed discussion of the regional aspects of the Richfield survey is presented here.

Reford's interpretation, showing sub-sea contours on the magnetic basement, is presented in Figure 2. The map shows the average dip on the basement surface to be about 1° towards the centre of the basin, with local

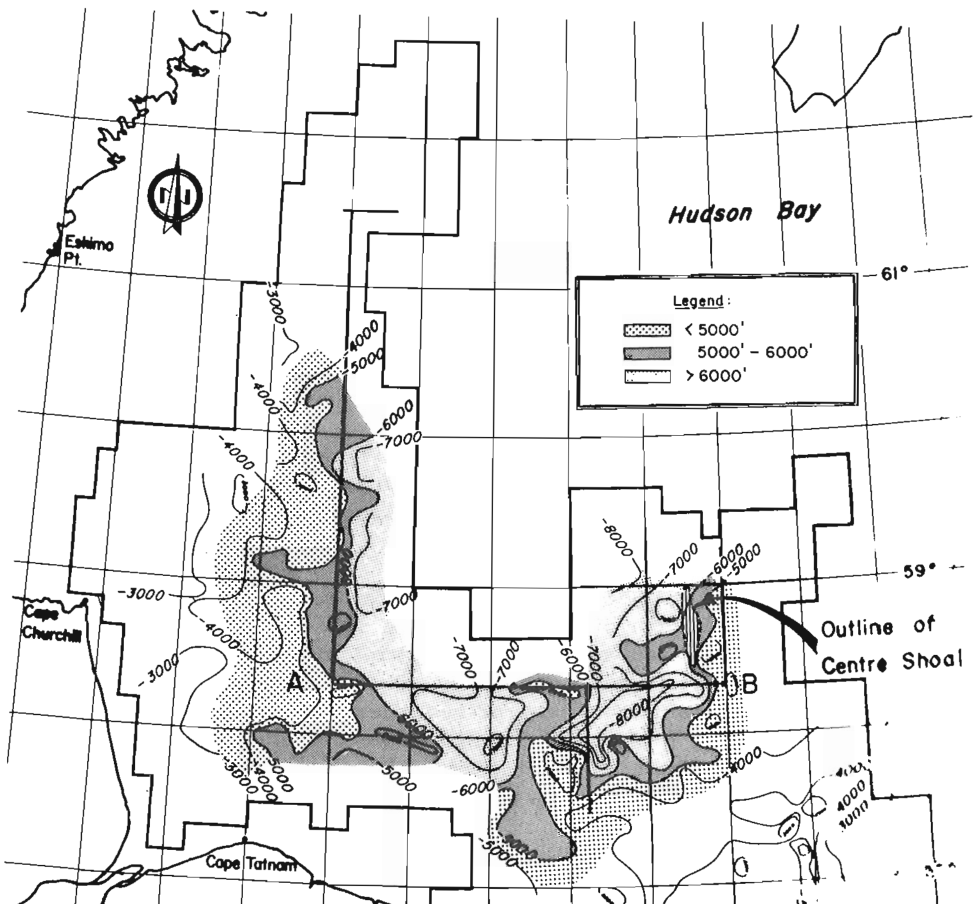


Figure 2. Subsea structure map on the magnetic basement. Contour interval: 1,000 feet.

dips up to a maximum of about 5°, or about 500 feet per mile. The depth to basement in the centre of the Bay is in excess of 8,000 feet on the Atlantic Richfield acreage, and is indicated to be increasing off the acreage block in the north-central area. Some of the deepest portions of the basin underlie the Centre Shoal, the 25-fathom contour of which is indicated in Figure 2. It is apparent that bathymetry in the vicinity of the Centre Shoal does not conform to the magnetic basement.

Gas-exploder Survey

The gas-exploder reflection seismic survey was conducted by Marine Geophysical International, Inc., using a single chartered vessel, M/V Brandal. The energy source comprised four gas-exploder guns fueled by propane and oxygen and fired simultaneously 30 feet astern of the ship. The power output of each gun was roughly equivalent to that of a 20,000-Joule sparker. Two hydrophones, each made up of twenty crystal detectors spaced five feet apart on a one-hundred-foot stringer, were towed in parallel 250 feet astern of the ship. The shots were fired 40 feet apart, data from each shot being recorded by microheads on Techno magnetic tape in analog format. On playback, groups of three microtraces were composited, resulting in one effective shot point every 120 feet along the line, and providing single-fold continuous profile reflection coverage.

The gas-exploder survey began on August 9, 1965 and 1,300 miles of line had been shot by September 8, 1965. The coverage is shown in Figure 3, and a typical example of the data obtained from this survey is shown in Figure 4.

This section has not been corrected for normal moveout, since the constant 300-foot shot-detector distance results in near-vertical incidence. The wave-train of the repeated water-bottom multiple occupies almost the entire time interval between repetitions, thereby effectively masking any primary energy. Attempts to attenuate the reverberations and repeated water-bottom multiples by processing techniques were unsuccessful, and the survey was suspended on September 8th in order to allow M/V Brandal to participate in a two-ship refraction survey.

Marine Reflection Survey

A conventional marine reflection survey was conducted by Geophysical Service Incorporated using a single charter vessel, M/V Polarhav. Twenty-four groups of detectors were spaced 100 feet apart on a 2,400-foot streamer which was towed behind the ship by a 600-foot lead-in cable. Each group of detectors comprised twenty pressure-sensitive phones at five-foot intervals. Single dynamite charges were fired automatically from the ship when they reached the end of a 1,800-foot firing line. The shots were fired at the centre of the detector spread, providing single-fold split-profile continuous subsurface coverage. The reflection data were recorded in digital format on magnetic tape using a Texas Instruments Series-9000 recording system.

The seismic survey began on July 27th and was suspended on September 12th, due to problems of reverberations and repeated water-bottom multiples similar to those observed in the gas-exploder survey. 1,800 miles of line were shot, and the coverage obtained is shown in Figure 3. Figure 5

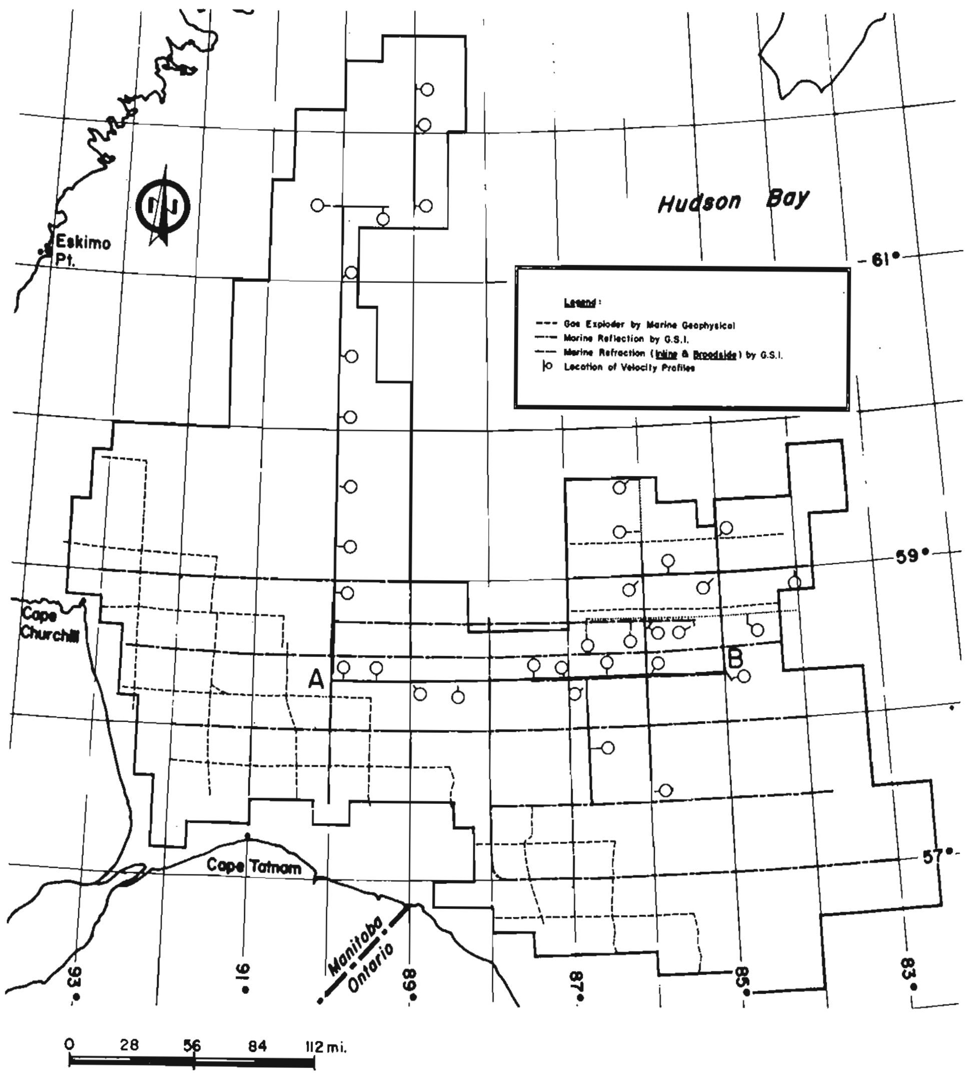


Figure 3. Location map showing reflection lines shot by Marine Geophysical and G. S. I., refraction lines shot by G. S. I., and location of Velocity Profiles.

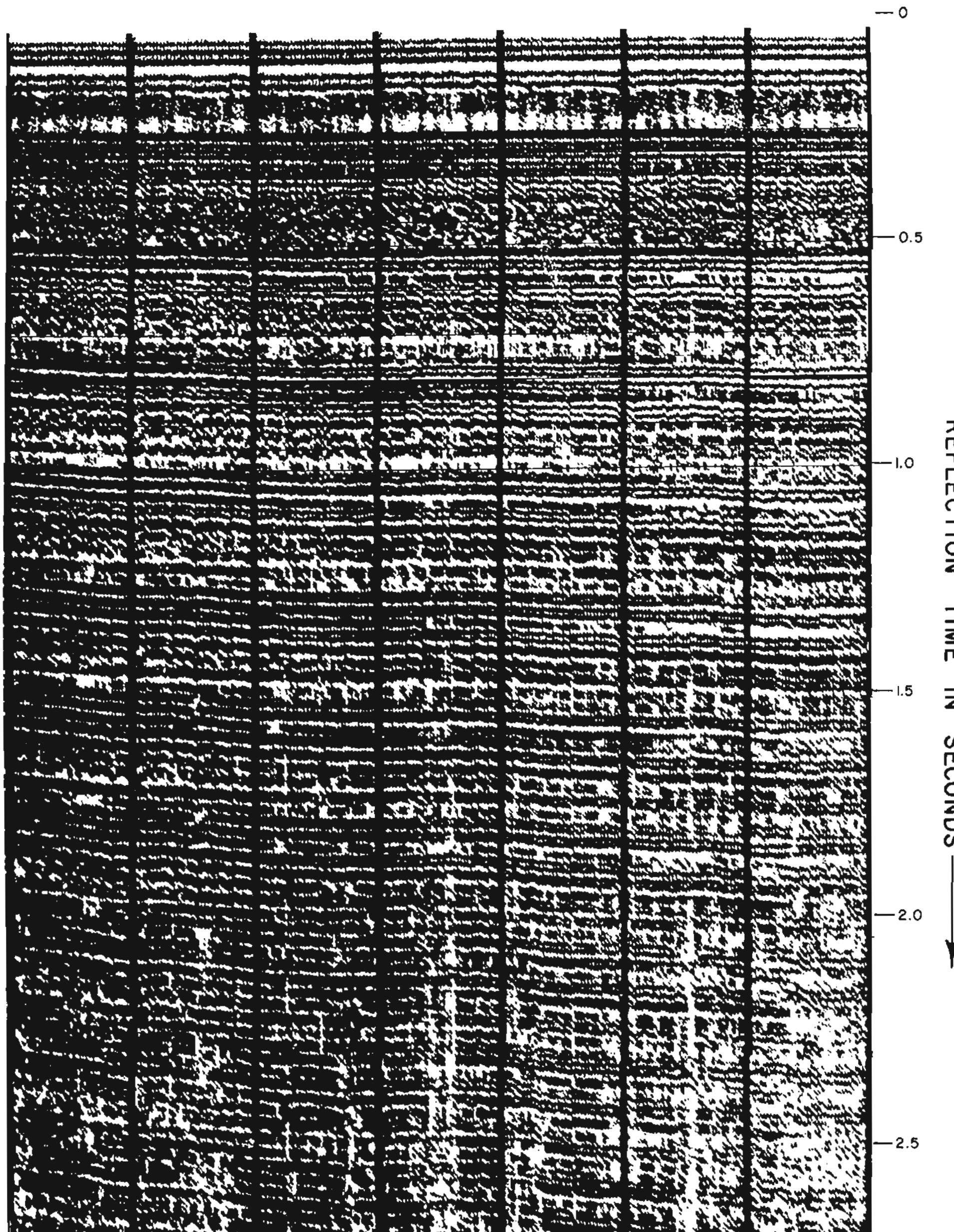


Figure 4. Example of a typical unprocessed gas-exploder reflection section, showing the repeated wave-train of the water-bottom multiple.

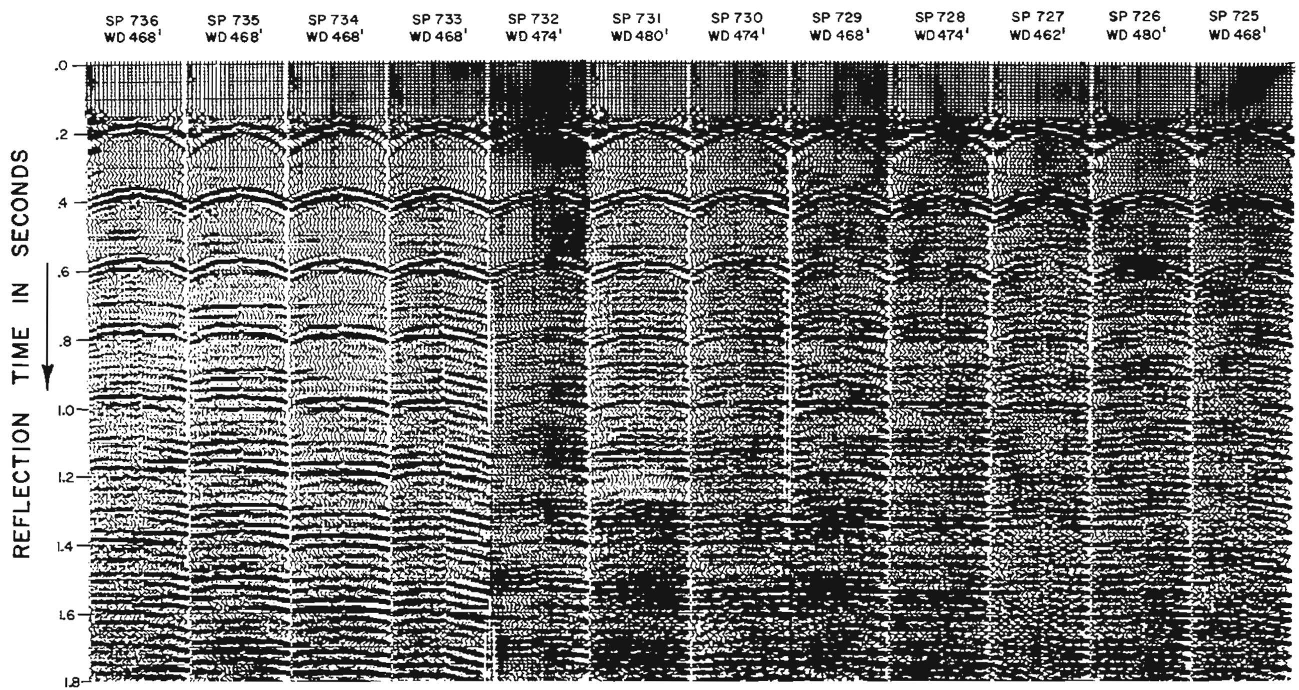


Figure 5. Example of a typical cross-section from the conventional marine reflection survey, showing the repeated water-bottom multiple. (Unprocessed except for NMO removal).

shows an example of a typical section which has had normal move-out (NMO) removed, but which has not been subjected to digital processing for removal of reverberations and repeated water-bottom multiples.

By September 12, 1965, more than half the time available for marine work in Hudson Bay had elapsed. All the reflection data were plagued by reverberations and multiples which were so strong that at the time it was suspected that their attenuation by processing might prove to be impractical. Some of the digitally-recorded G. S. I. data had already been processed using TIAC's dereverberation programs, but with very limited success. Rather than risk spending the entire two-month survey on acquiring unuseable data, it was decided to suspend both reflection surveys and conduct a two-boat refraction survey, using the vessels M/V Brandal and M/V Polarhav, and G. S. I.'s seismic recording equipment.

Marine Refraction Survey

Of necessity the refraction survey was conducted with equipment designed for use in reflection work. Economic retrieval of bidirectional sub-surface refraction coverage called for the use of three boats, but only two were available. Further, although the amplifiers and recording equipment had a frequency response and dynamic range sufficient to handle any data, the detectors were of slightly too high a frequency response to be suitable for low-frequency refracted energy, and the cable length was somewhat shorter than the optimum required for effective or economic in-line refraction coverage.

From September 12th to October 6th, 1965, 100 miles of broadside refraction control and 900 miles of in-line refraction control were obtained, the coverage being shown in Figure 3. All data were recorded digitally.

The broadside refraction lines utilized a shot-to-detector offset of approximately 6, 000 feet. The only significant event noted was the water-bottom refraction arrival, the offset distance being too short to record deeper refractions as first arrivals, and any wide-angle reflections being completely masked by reverberations. The broadside method of shooting was, therefore, discontinued, and the balance of the survey was shot using in-line refraction techniques.

The spread geometry and plotting procedure for the in-line refraction survey are illustrated in Figure 6. A 4, 700-foot streamer was towed behind the recording boat by an 800-foot lead-in cable. The streamer contained 24 groups of detectors at 200-foot intervals, each group comprising 20 detectors spaced five feet apart. For short-offset refraction shots, charges were fired from the recording boat, with the shot point 150 feet from the end of the recording cable. Long-offset refraction shots were fired from the shooting boat, with the shot point approximately 20, 000 feet from the end of the recording cable.

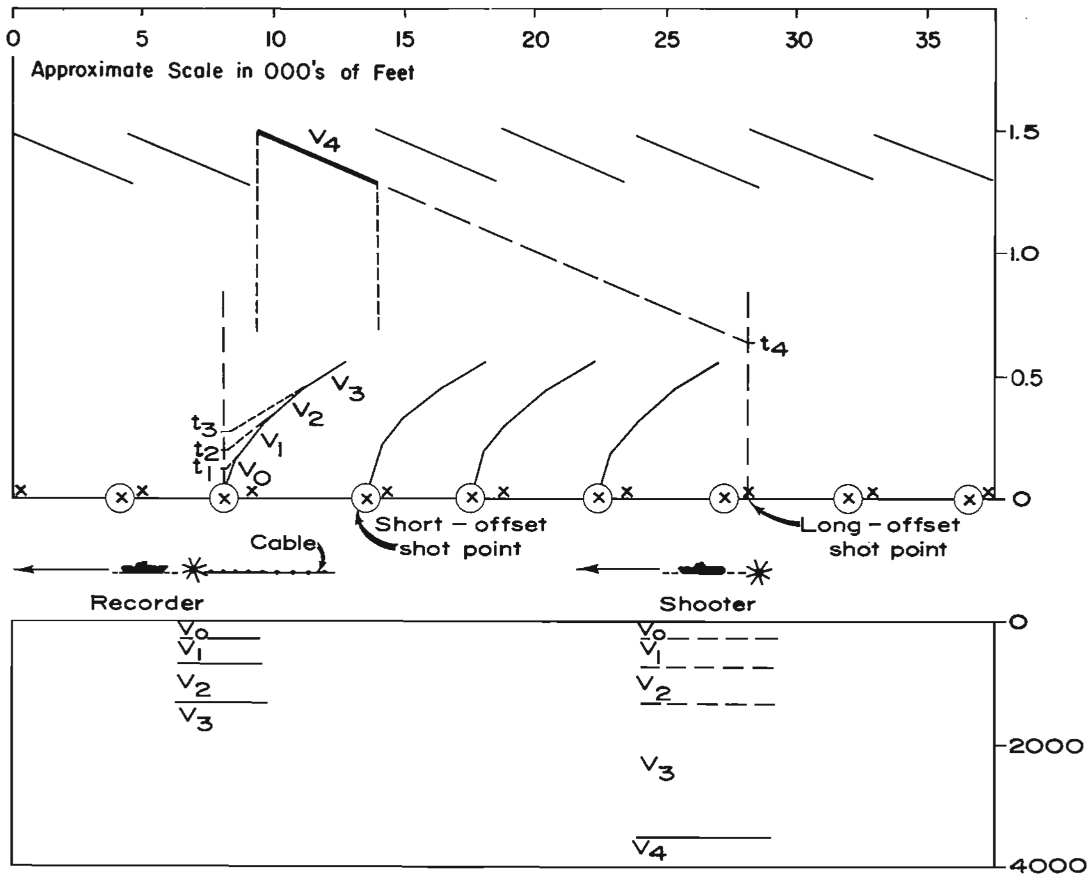


Figure 6. Diagrammatic representation of the spread geometry and plotting procedure used for the in-line refraction survey.

Short and long-offset refraction shots were taken for each cable position and water depths were recorded at all cable positions. Shots were recorded in the same or in opposite shooting directions, depending upon whether the shooting boat was ahead of or behind the recorder. Due to the motion of the recording boat between shots, the cable was not in precisely the same location for the long and short-offset shots.

The location of the recording cable for each shot was obtained from Decca Lambda coordinates, which are theoretically accurate to within about 1, 500 feet at the extreme range of the navigation system, and progressively more accurate at shorter ranges. As will be seen later, this accuracy was probably not consistently achieved. However, the relative distances between shot point and detector spread were obtained by timing water-break arrivals from every shot, and thus measurements of spread geometry are subject only to errors in timing and variations in water velocity.

Over virtually the entire prospect, refracted events were recorded in only one direction from each refractor, and thus only the apparent velocities of the refractors are known. Also, for long-offset shots, no continuous control was obtained between the shot and the closest geophone on the spread.

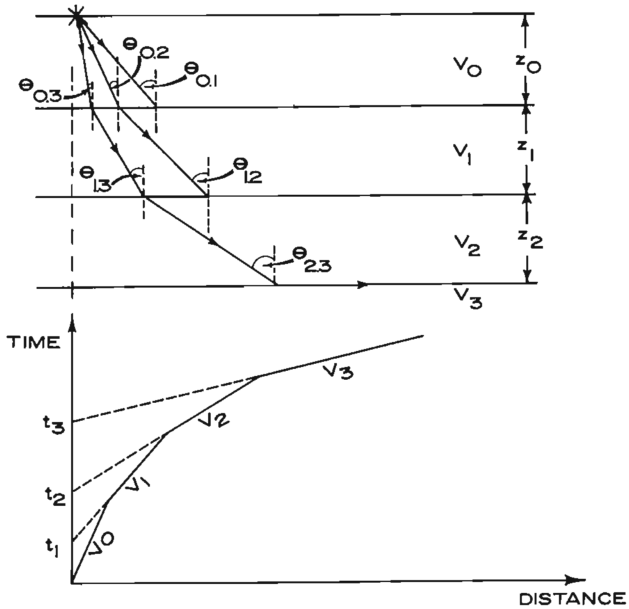
Refraction data recorded with such spread geometry does not lend itself to a unique interpretation, since many assumptions must be made regarding the velocities, thicknesses and attitudes of the refractors from which no first arrivals were recorded due to the lack of continuous coverage between shot and detectors. However, the necessity to obtain broad reconnaissance coverage with the two ships available in the time remaining before winter made it impractical to use techniques which would provide reversed profiles or continuous detector coverage out to the longest offset distances.

Velocity profiles were shot at 35 locations as shown by the small circles in Figure 3. The shooting procedure generally resulted in overlapping subsurface coverage, and first-arrival refracted events were recorded at shooting distances ranging from zero to 30, 000 feet. However, since neither the detector spread nor the shot point remained stationary, the time-distance plots are not continuous lines, but have the form of separate, non-continuous segments.

In-line Refraction Interpretation

Due to the merger between Atlantic and Richfield, which took place in January, 1966, completion of the interpretation of the refraction data was delayed until May, 1966, at which time Keith Moyse of Independent Exploration Company (Canada) Ltd. was retained to review and complete the project. The sections and maps discussed herein are based on his work.

Time-distance plots were made for all events recorded as first arrivals, from both the short and long-offset shots. Refraction arrival-times



$$Z_n = \frac{V_n}{2\cos\theta_{n.n+1}}\left[t_{n+1} - 2\sum_{l=0}^{n-1}\frac{Z_l\cos\theta_{l.n+1}}{V_l}\right]$$

Figure 7. Schematic diagram illustrating the refraction computation procedure.

were plotted at detector locations as determined by their Decca Lambda coordinates, so that the relative positions of all detector locations were correct to within the accuracy provided by the navigation control. The shot points were then plotted in the correct positions relative to the detector spreads, the appropriate distances having been determined from water-break arrival times.

The time-distance plots for each apparent velocity recorded on the short shots were projected back to the time axes at zero distance, and the intercepts used to compute the thicknesses of the refractors from the generalized formula given with the schematic diagram shown in Figure 7. It should be noted that this formula for the thickness of the nth layer (Z_n) assumes that the refractors are horizontal and, by extension, that the velocities used are true velocities. The computed depths were used to construct cross-sectional profiles of the shallow refractors.

The following refractor velocities are typical of those plotted from short-spread data:

V_0 = 4,725 feet per second (water velocity)
V_1 = 9,000 feet per second
V_2 = 13,500 feet per second
V_3 = 15,500 feet per second

The layer immediately below the water-bottom (9,000 feet per second) was not always evident on the first-arrival plots, but was not required since Z_0 (water depth) was taken from fathometer measurements at each spread and shot-point location for the short-offset shots. When the 13,500 feet per second velocity was not evident due to the thinness of the layer (hidden-layer problem) the velocity V_2 was projected through the V_1V_3 knee of the first-arrival plot, resulting in a maximum thickness of the 13,500 feet per second refractor. The 15,500 feet per second refractor was at some locations too deep for penetration using the short spreads, and in such cases the velocity V_3 was projected through the most-distant point of the first-arrival plot, resulting in a minimum thickness for the 13,500 feet per second layer.

The time-distance plots for the deepest refractor (the only first-arrivals recorded on the long-offset shots) were also projected back to their intercepts (t_4) on the time axes at zero distance. However, in this case, each segment of the projection was drawn parallel to the apparent velocity recorded in that segment from some other shot, it being assumed that the time-distance plot for the long-offset shots represented events returned by the same continuous refractor. The time-distance plots showed no evidence to invalidate this assumption, although very few overlapping spreads were shot. The intercept times thus obtained are believed to be reliable, since virtually continuous subsurface coverage was maintained on the deep refractor.

These t_4 intercepts were substituted in the formula for Z_n, using the values of Z_0, Z_1 and Z_2 appearing on the profile at the appropriate long-offset shot point locations.

The computed depths to the deep refractor were plotted on the cross-sectional profile at the shot location. In order to smooth local errors, three-point averages of the deep-refractor depths were mapped, the depths having been taken from the cross-sections at the appropriate spread locations.

Depths and true refractor velocities were computed at each "velocity profile" location, using the formulae given for Z_n. These values checked fairly well with those computed from the single-direction coverage obtained over the majority of the area surveyed.

Figure 8 presents the cross-section plotted from the east-west line A-B indicated in Figure 3, and shows the attitude of the refractors in relation to the basement profile as determined from magnetic depth estimates.

Refractors with velocities of 13, 500 feet per second, 15, 500 feet per second and 20, 200 feet per second were carried consistently on the sections. A refractor with a velocity of 17, 000 feet per second to 18, 000 feet per second is suspected to exist over at least a portion of the area, but was not consistently recorded, due possibly to the geometry of the spreads or to changes in thickness of the refractor.

The apparent velocity of the deep refractor varies between 20, 000 feet per second and 21, 000 feet per second over most of the surveyed area, decreasing to 19, 000 feet per second in the northwest. Long spreads shot as velocity profiles indicate no higher velocity for at least 1, 000 feet below this refractor. Although the long-offset spreads were shot in only one direction, the averaging effect of shooting up and down dip results in an average velocity of the deep refractor which is a statistical approximation to the true velocity. The average of approximately 900 measured apparent velocities is 20, 200 feet per second.

An alternate interpretation is shown in broken line in the western portion of profile A-B. The interface between the 13, 500 feet per second and 15, 500 feet per second layers may be considerably deeper than is indicated by the solid line, and if the 13, 500 feet per second layer were arbitrarily thickened by about 1, 500 feet, as might seem geologically more reasonable, the computed deep refractor depth would be about 500 feet shallower. This example serves to illustrate the magnitude of error in the depth to the deep refractor introduced by incorrect interpretation of the shallow section.

Although large changes may be made in the interpretation of the shallow refractors without affecting to any significant degree the gross attitude of the deep refractor, such errors may contribute to a problem which so far has eluded a satisfactory solution. The subsea structure on the deep refractor is shown in Figure 9, data within 20 miles of the Permit boundaries having been omitted for reasons of company security. At line intersections there are mis-ties on the deep refractor of as much as 1, 000 feet, and at the same locations the water depths mis-tie by as much as 50 feet, and the t_o values for the deep refractor by as much as 0. 090 seconds.

The possible reasons for these mis-ties are manifold.

Since Decca Lambda locations are known to be in error by as much as two miles on the southwest coast of the Bay, it seems possible that they might be in error by at least one-half mile in the centre of the Bay. If, at the intersection of two lines, there were positioning errors of one-half mile in opposite directions on each line, a 350-foot mis-tie on the deep refractor would result if its dip were 4°.

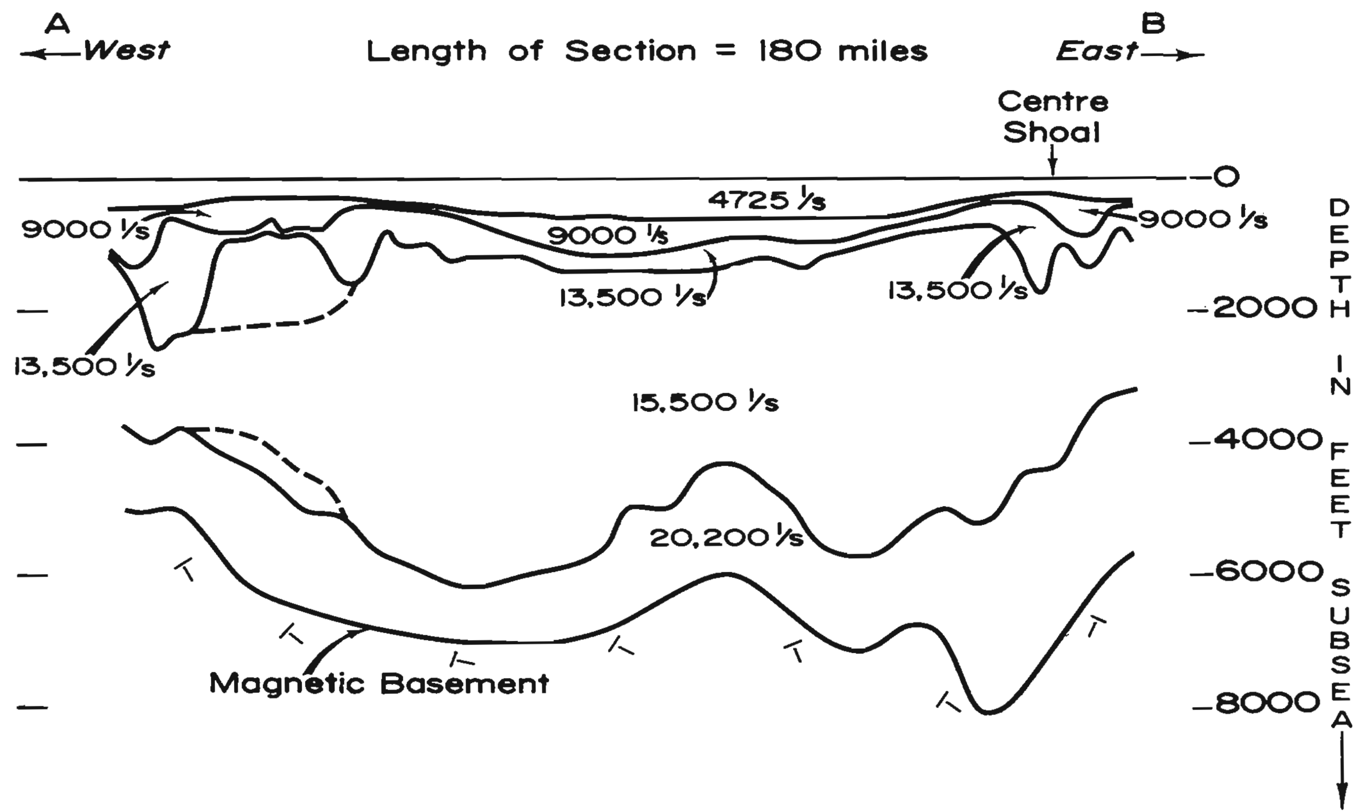


Figure 8. Computed cross-section along refraction line A-B of Figure 2. Alternate interpretation shown in broken line.

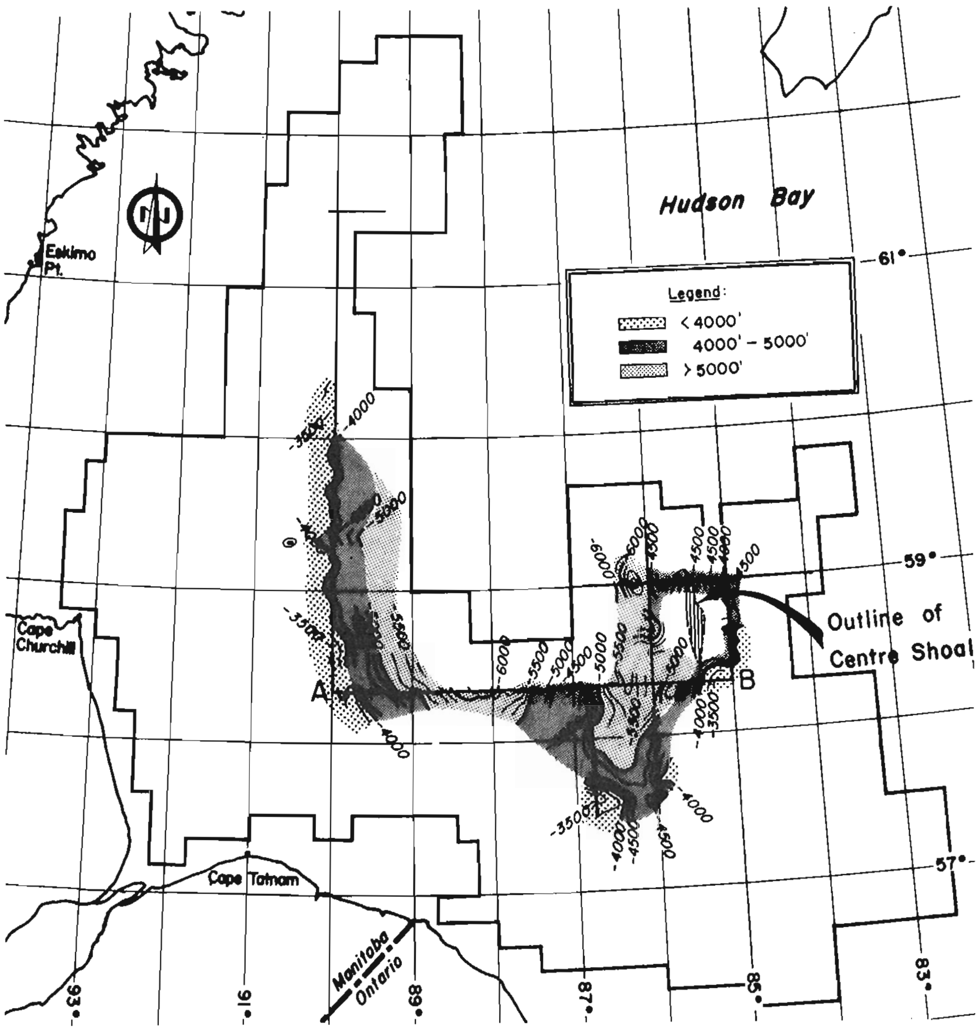


Figure 9. Subsea structure map on the deep refractor. Contour interval: 250 feet.

Another possible source of error arises from the fact that the water depths used for Z_0 in the formula for Z_n were interpolated at the long-offset shot-point locations from data recorded when the detector spread had occupied that position. This was necessary since no fathometer readings were recorded at the long-offset shot point locations.

For such a procedure to be valid, it must be assumed that the line followed by the shooting boat reproduced exactly the line followed by the recording boat. If the boats did not travel in line, but en echelon due to tidal drift, cross-wind, or faulty navigation, the water depths used for Z_0 would not apply at the locations occupied by the shot points. Similarly, the values of Z_1 and Z_2 computed for the short spreads at the detector locations would not apply at the long offset shot locations.

It can be shown that for the velocities encountered, a 100-foot error in Z_0 (water depth), when used with the intercept time for the deep refractor in the formula for Z_n, results in an error of 400 feet in the depth to the deep refractor. Errors of 100 feet in Z_1 and Z_2 result in corresponding errors of 140 feet and 35 feet respectively in the depth to the deep refractor. Thus errors in water depth have a far greater effect on Z_3 than errors in the computed values of Z_1 and Z_2.

If the shooting boat were off-line a sufficient distance to cause an error in water depth of 50 feet in opposite senses on each of two intersecting lines, this would result in a 400-foot mis-tie on the deep refractor.

The lack of control between the shot points and the long-offset spreads, coupled with the hidden layer and minimum thickness problems encountered on the short-offset spreads, could introduce additional errors of unknown amounts, although these would tend to be in the same direction at any one location, and would not normally give rise to mis-ties at line intersections. Early cycles of first-arrival energy could be well developed on one line and poorly developed on an intersecting line, thus causing mistiming on one line with respect to the other, and resulting in mis-ties. Correlation of first-arrival events was carefully checked, but this source of error cannot be overlooked.

In summary, if all the errors discussed above were coincidentally in the same sense, it is possible to account for a 1,000-foot mis-tie on the deep refractor. It must, therefore, be accepted that the overall accuracy of the deep refractor structure map is at best $\pm$ 500 feet.

Notwithstanding these errors and mis-ties, the deep refractor map of Figure 9 shows fair correlation with the magnetic basement map of Figure 2. The same relationship is demonstrated in the profile of Figure 8, with the deep refractor in places as much as 3,000 feet shallower than basement. This difference in depth is believed to be greater than the limit of error indicated for the depth to the deep refractor, and leads to the conclusion that the deep refractor is not basement. Furthermore, it is considered that a velocity of 20, 200 feet per second is more typical of a carbonate than it is of basement.

The deep refractor is believed to be the same as that mapped and identified by G. D. Hobson (1967) as Precambrian, although it is now suggested that it is not Precambrian but an Ordovician limestone. Further evidence in support of this conclusion is provided by the results of the Sogepet-Aquitaine surveys conducted in the Hudson Bay Lowland, Manitoba.

Results of Sogepet-Aquitaine Surveys

During October and December, 1966, the Sogepet-Aquitaine group conducted a seismic refraction program in the vicinity of the Sogepet-Aquitaine Kaskattama Prov. No. 1 well, and a conventional velocity survey was run in the well. The results of these surveys have been reported by R. D. Johnson and S. J. Nelson (1967), and are discussed herein through the courtesy of Sogepet and Aquitaine.

Figure 10 shows the gross lithology encountered in the hole, the interval velocities averaged by the author across the lithologic units indicated, and the cross-sectional profile resulting from the author's interpretation of the refraction data.

The shooting technique used for the refraction profile provided continuous detector coverage between two shot points 13, 000 feet apart, the line being shot in both directions. Difficulty of access did not allow refracted energy to be recorded from common subsurface coverage of the deep refractor in both directions of shooting, so again no true velocity is known for the deep refractor.

The only velocities appearing on the time-distance plot of the land refraction profile are those indicated in the figure, a velocity of 4, 000 feet per second having been assumed for the low-velocity surface layer whose presence was indicated by the time-distance plot.

The 13, 000 feet per second refractor is correlated with a Devonian limestone of velocity 13, 500 feet per second in the well. Since no velocity measurements were made in the surface casing, the interface between the 10, 500 feet per second and the 13, 500 feet per second velocities was computed from travel times, the presence in the well of the 13, 500 feet per second velocity having been established by the upper portion of the sonic log, and the 10, 500 feet per second velocity being inferred from the refraction profile.

The 18, 200 feet per second refractor is correlated with a layer of velocity 18, 500 feet per second which was encountered in the well at the top of the Middle Silurian section.

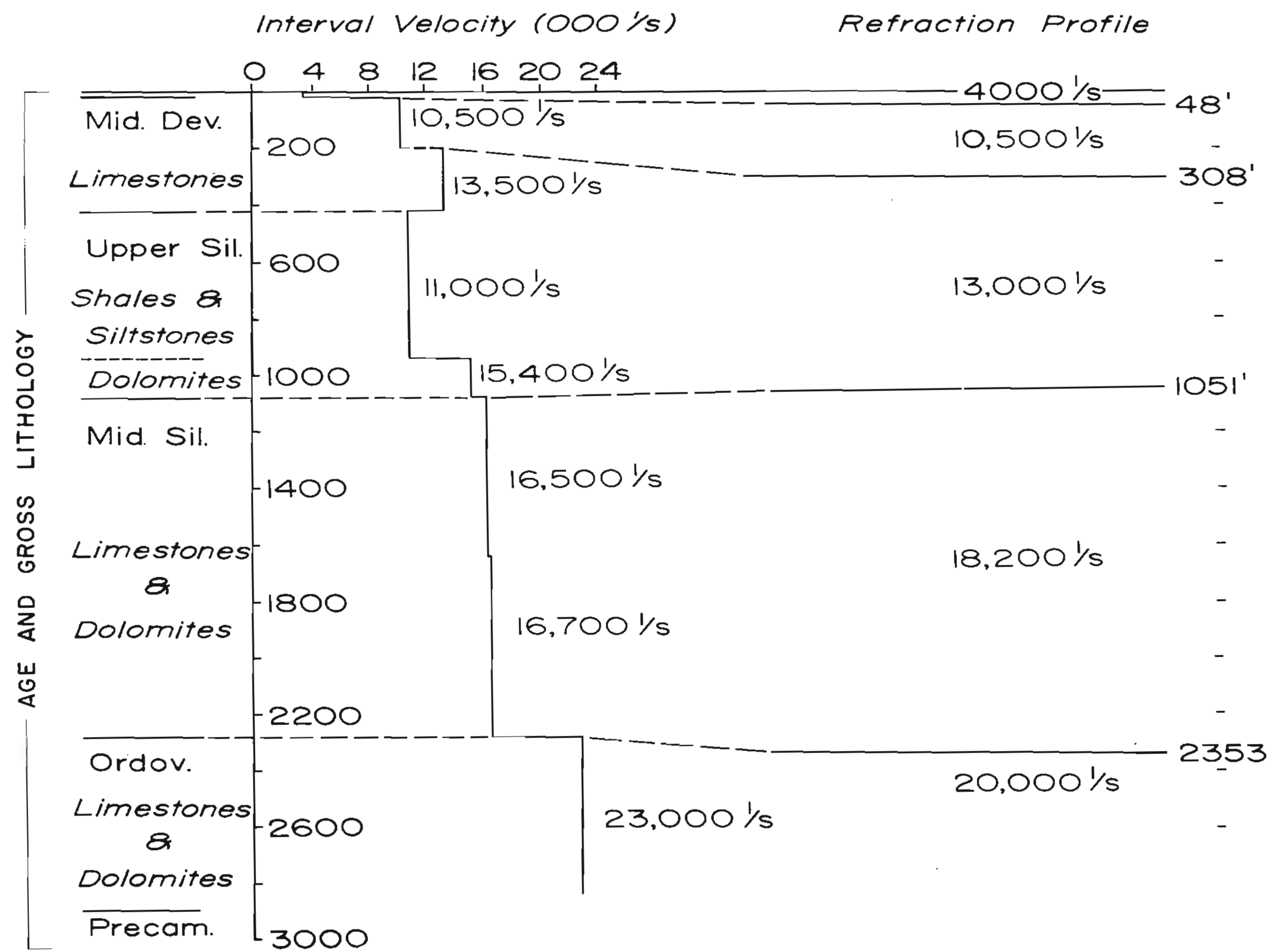


Figure 10. Sogepet-Aquitaine Kaskattama Province No. 1 well – comparison of results of land refraction survey with velocity survey and gross lithology in the well.

The average velocity of the Ordovician section as measured in the well is 23, 000 feet per second. Precambrian basement was encountered in the well some 600 feet deeper than the top of the Ordovician limestone. The velocity survey did not extend to total depth in the well, the bottom 70 feet being unlogged, but core-velocity measurements in this lower interval indicate higher velocities in the limestone than in the underlying basement.

It is inferred from these results that the deep refractor mapped on the coast is not basement, but an Ordovician limestone of higher velocity than basement. If similar geologic conditions can be assumed to exist beneath the bay, it seems probable that the 20, 200 feet per second refractor mapped by Richfield is a limestone, possibly the same or a similar lithologic unit of Ordovician age.

Although no direct correlation is claimed between Kaskattama and Melville Island, it is noteworthy that G. D. Hobson (1967) has stated in "Seismic Refraction Prospecting" that "an extremely high interval velocity averaging 22, 500 feet per second was recorded in the Lower Cape Phillips and/or Cornwallis carbonate formation of Ordovician age at depth in the Winter Harbour hole".

From Figure 10, the Upper Silurian dolomite section of velocity 15, 400 feet per second is indicated to be too thin to register as a first arrival refracted event, and, therefore, the time-distance plot of the land refraction survey shows only velocities of 13, 000 feet per second and 18, 200 feet per second. As shown in Figure 8, a 15, 500 feet per second refractor was mapped over most of the area surveyed in the bay, and only occasionally did a refractor of velocity 17, 000 feet per second to 18, 000 feet per second appear. Thickness and/or facies variations might account for the absence of either the 15, 500 feet per second or the 18, 000 feet per second refractors.

The following identifications are suggested for the refractors mapped beneath the Bay:

9, 000 feet per second	Upper Devonian or Cretaceous
13, 500 feet per second	Middle Devonian
15, 500 feet per second	Base of Upper Silurian
20, 200 feet per second	Top of Ordovician

Over the majority of the Atlantic Richfield acreage, a thick section of undifferentiated material of 15, 500 feet per second velocity is represented as occupying the interval between the Upper Silurian refractor and the underlying Ordovician. The absence of information in this interval results from the lack of control between the short and long offset spreads, and to the probable presence of so-called "hidden layers". The refractors above this interval exhibit distinct unconformity with the Ordovician refractor below it, suggesting the presence of a major unconformity within this interval.

SUMMARY AND CONCLUSIONS

Of all the geophysical surveys conducted by Richfield in Hudson Bay in the summer of 1965, only the aerial magnetometer survey and the in-line refraction survey can be considered to have given conclusive results, and the accuracy of the latter is open to question. The reverberation and repeated water-bottom multiple problems encountered in both reflection surveys have not yet yielded to solution by any type of processing.

The aerial magnetometer survey indicates the presence of a sedimentary basin with depths in excess of 8, 000 feet. The in-line refraction survey indicates the presence of a refractor with a velocity of 20, 200 feet per second, at depths ranging to a maximum of 6, 250 ± 500 feet. In certain locations the basement is indicated to be more than 3, 000 feet deeper than the deep refractor. By correlation with the refraction survey in the vicinity of the Kaskattama well, and with the velocities encountered in the well itself, the deep refractor of the Richfield survey is believed to be an Ordovician limestone.

The absence of information within the thick undifferentiated Middle Silurian section of velocity 15, 500 feet per second probably results from lack of control between the short and long offset spreads, and the unconformable relationship of the refractors above and below this interval suggests the presence of a major unconformity within the interval.

Bedrock samples, collected from the Centre Shoal by Richfield in 1965, contain fauna dated as Late Middle Devonian. Interpretation of the refraction data suggests that the section beneath the Centre Shoal consists of some 4, 500 feet of Devonian and Silurian beds, underlain by some 1, 500 feet of Ordovician beds.

Neither the magnetic basement nor any of the refractors conform with bathymetry, and in fact the Centre Shoal, where water depths average less than 20 fathoms, is located near the axis of a pronounced basement trough.

Refraction surveys using spread configurations designed on the basis of the velocity distribution now indicated to exist beneath the bay, and using reversed-profile shooting techniques to obtain true-velocity information, hold promise of providing a successful reconnaissance of the Hudson Bay sedimentary basin. The next vital step in the evaluation will then be a stratigraphic test of the sedimentary section.

ACKNOWLEDGMENTS

This paper is published through the courtesy of Atlantic Richfield Company, Aquitaine Company of Canada Ltd., and Sogepet Limited. The author wishes to express his appreciation to Messrs. M. S. Reford, R. K. Moyse and R. D. Johnson for their technical contributions and helpful comments.

REFERENCES

Hobson, G. D.

1967: A reconnaissance seismic refraction survey in Hudson Bay, Canada; Panel discussion No. 9, Seventh World Petroleum Congress, Mexico City, vol. 2, pp. 813-826.

1967: A seismic section of the Sverdrup Basin, Canadian Arctic Islands; Soc. Expl. Geophysicists, Seismic Refraction Prospecting, pp. 550-562.

Johnson, R. D., and Nelson, S. J.

1968: Sogepet-Aquitaine Kaskattama Province No. 1 Well, Hudson Bay Lowland, Manitoba (this volume).

AN ANALYSIS OF THE CRUST-MANTLE BOUNDARY IN HUDSON BAY FROM GRAVITY AND SEISMIC OBSERVATIONS[1]

J. R. Weber and A. K. Goodacre
Gravity Division, Dominion Observatory
Ottawa, Ontario

Abstract

A study of the results of the 1965 gravity and seismic surveys in Hudson Bay has shown that the gravitational effect of a two-layer model based on the seismically-determined depths has no correlation with the observed gravity anomalies (Innes *et al.*, 1967). On the profile from Churchill to Povungnituk on the east coast of Hudson Bay the gravity and seismic observations can be reconciled by postulating lateral variations of the compressional-wave velocity within the crust. A crustal model has been calculated using the same time-terms and the same mean crustal seismic velocity whose gravitational effect fits the observed gravity. The velocity varies from 6.15 to 6.56 km/sec and the postulated depths are almost entirely within the confidence limits of the original model.

In order to test the hypothesis, the postulated velocity variations have been compared with the bottom refractor velocities of the shallow seismic survey (Hobson, 1968), based on the assumption that the crustal velocities ought to be systematically higher than the crystalline basement velocities and that there may be a correlation between variations in crustal and basement velocities. The test is inconclusive because bottom refractor velocities are higher than crustal velocities in two areas where volcanic flows and high seismic velocity sediments may be present.

The case of linearly related velocity (V) and density (ρ) variations has been analysed and it is shown that the gravitational effect of the crust-mantle boundary undulations may be completely masked or even overbalanced by density changes in the crust if $\frac{d\rho}{dV} \gtrsim 0.11$ g cm^{-4} sec. The crust can be characterized by having dominant velocity variations (in which case the gravity anomaly reflects the undulations of the crust-mantle boundary) or dominant density variations (in which case the gravity anomaly inversely reflects the crust-mantle boundary undulations) depending on the relationship between average crustal density and average crustal velocity. Some light on this subject may be shed by comparing crystalline basement velocities with calculated crustal velocity variations in a structurally homogeneous area where the crystalline rocks are exposed. However until the relationship between compressional-wave velocities and rock densities is better known, no conclusions on crustal depths can be drawn from gravity information alone.

---

[1] The complete paper is to be published in the Canadian Journal of Earth Sciences, vol. 5, No. 5, pp. 1297-1303, 1968.

REFERENCES

Hobson, G. D.
1968: Sedimentary seismic surveys over the water and lowlands; in Science, History and Hudson Bay, Can. Dept. Energy, Mines Resources, vol. II, Chapt. 10, Pt. I, pp. 615-628.

Innes, M. J. S., Goodacre, A. K., Weber, J. R., and McConnell, R. K.
1967: Structural implications of the gravity field in Hudson Bay and vicinity; Can. J. Earth Sci., vol. 4, pp. 977-993.

MAGNETIC SURVEYS IN HUDSON BAY: 1965 OCEANOGRAPHIC PROJECT

Peter Hood, Margaret Bower, Geological Survey of Canada
and E. A. Godby, National Aeronautical Establishment

Abstract

A low-level Decca-controlled high-resolution aeromagnetic survey of a portion of central Hudson Bay was carried out as a joint Geological Survey-National Aeronautical Establishment project during the 1965 Oceanographic Project in Hudson Bay. Approximately 5, 400 line miles of aeromagnetic data were obtained, and as both the navigational and aeromagnetic data had been digitally recorded it was possible to automate the compilation of the total intensity maps to a considerable extent. Most of the small amplitude anomalies recorded were repeatable and some extend for many miles in directions which are quite different from the main anomalies observed. Depth-to-basement determinations carried out on the main anomalies consistently give values in excess of 8, 000 feet.

The 200-gamma generalized total intensity map of the southwestern part of Hudson Bay and its periphery shows that the northeast-striking Owl River magnetic high continues into Hudson Bay and bends in a southerly direction to become first east-striking and then southeasterly-striking. There is some indication that a branch may continue northeastwards in the general direction of Cape Smith. Sea magnetometer data obtained to date does indicate however that the Cape Smith-Wakeham Bay belt of basic rocks extends into the Ottawa Islands.

It is interesting that the Ordovician and Silurian equators as determined by paleomagnetic measurements on North American samples pass through Hudson Bay. Because the best chance of finding oil in economic quantities in Paleozoic formations seems to be in paleolatitudes of less than 30°, Hudson Bay would appear to be a prime location for oil exploration. This hypothesis would include formations of Devonian age in Hudson Bay also.

1965 AEROMAGNETIC SURVEY OF CENTRAL PORTION OF HUDSON BAY

Survey Procedure

During the 1965 Oceanographic Project in Hudson Bay, an aeromagnetic survey of a portion of central Hudson Bay was carried out as a joint Geological Survey of Canada-National Aeronautical Establishment project. The survey area which is shown on Figure 1 is bounded by the following co-ordinates 58° 20'N., 89° W.; 58° 47'N., 89° W.; 58° 58'N., 86° W.; and 59° 45'N., 86° W. The primary navigational aid used was the 6F Lambda Decca chain on loan from the Polar Continental Shelf Project which was

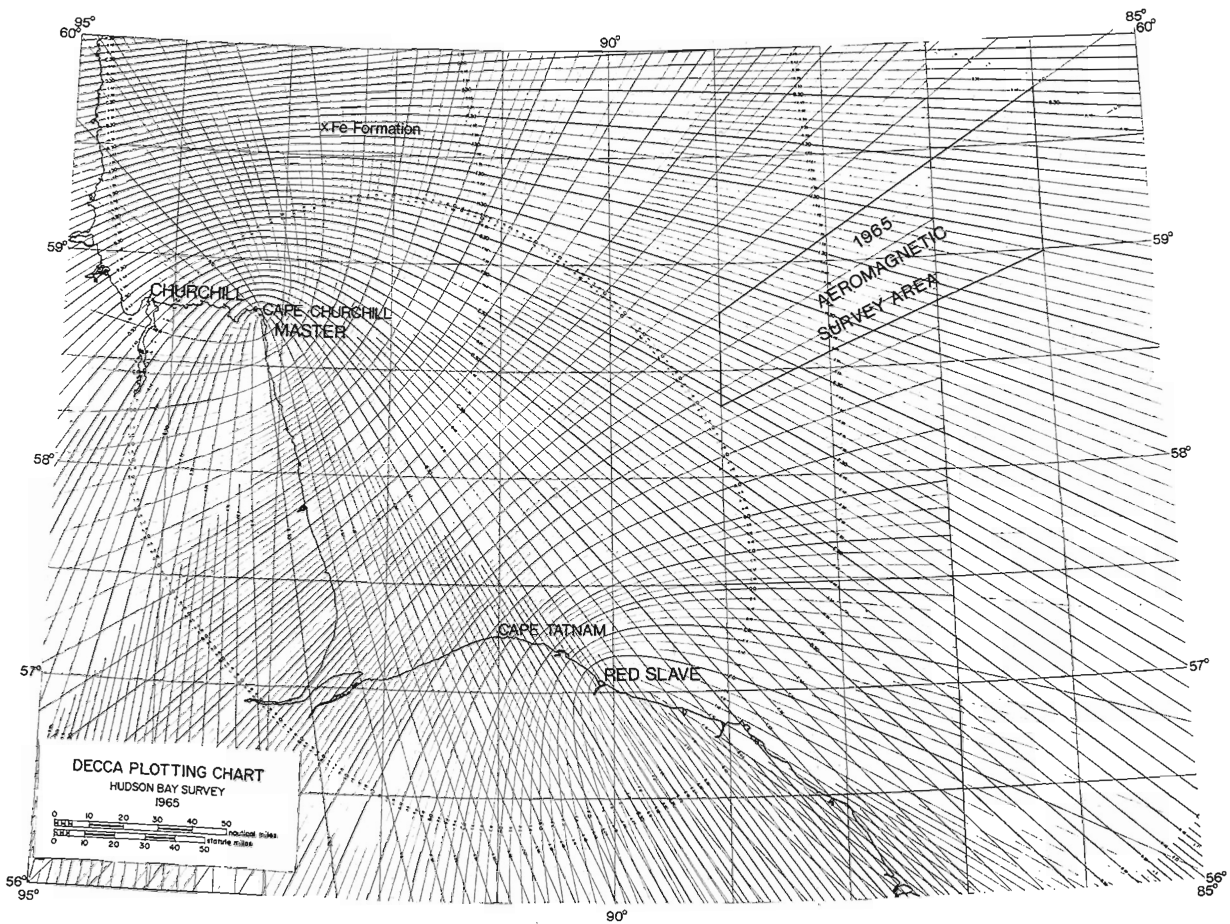


Figure 1. Decca plotting chart for 1965 Oceanographic Project showing aeromagnetic survey area.

installed in the southwest part of the Bay for the Hudson Bay Oceanographic Project. The survey lines flown were integral red Decca Lines, which can be seen in Figure 1 striking northeast in the survey area and whose distance apart varied from about 2, 400 feet in the southwest to 3, 800 feet in the north-east end of the survey area. The flight elevation of the North Star aircraft (see Fig. 2) used in the survey, was closely maintained at 500 feet above sea level. A rubidium-vapour magnetometer system modified by the National Aeronautical Establishment was used to digitally record on magnetic tape the total intensity of the earth's magnetic field at two heights. This was accomplished using a tail 'stinger' installation together with a 'bird' which was towed below the North Star aircraft (Fig. 2), and thus was an attempt to measure the first vertical derivative of the earth's magnetic field directly. Approximately 5, 400 line miles of aeromagnetic data with values every half second (approximately 150 feet) were obtained in the survey area and the Decca co-ordinates were also recorded at 10 second intervals (3, 000 feet) on the same magnetic tape.

Figure 3 shows part of one of the eight-channel Offner analog charts used to monitor the survey data in Hudson Bay. At the top of the figure is the total field trace whose full scale deflection is a hundred gammas. The double trace is due to the fact that values from both the stinger and bird magnetometers were being multiplexed. The two traces therefore show the slight difference in the total field between the two rubidium magnetometers. Note that the gradient almost falls to zero on the steepest part of the anomaly. Below the total field trace is the time code obtained from a digital clock. Because the particular Decca receiver used in the North Star aircraft did not have a lane identification system, the outputs from the red and green deccometers were continuously monitored on the Offner chart. This permitted any lane jumping to be quickly observed, and also made a 'post-mortem' examination of the deccometer readings possible. Because the aircraft actually flew the red Decca lanes, the red deccometer trace appears as a straight line. The green deccometer trace is actually folded in order to accommodate range changes. The fourth trace from the top recorded the yaw of the aircraft, and it was also possible to substitute pitch and roll on this same trace in order to monitor aircraft motion. The sixth trace from the top is a filtered magnetometer trace. The last two traces show the bird altitude as determined by a pressure altimeter installed in the bird, and the bottom trace shows the aircraft altitude measured by a radar altimeter in the aircraft itself. It can be seen that there was very good correspondence between the two altitude profiles. This means that the bird followed the small manoeuvres of the aircraft reasonably well. As both the navigational and aeromagnetic data had been digitally recorded it was possible to automate the compilation of the total intensity maps to a considerable extent. The compilation of the aeromagnetic data was carried out by H. N. C. Lyster of the National Aeronautical Establishment and Margaret Bower of the Geological Survey of Canada.

Figure 2. North Star aircraft of the National Aeronautical Establishment used in the 1965 Hudson Bay aeromagnetic survey. Both the towed bird and tail stinger contain rubidium-vapour magnetometers.

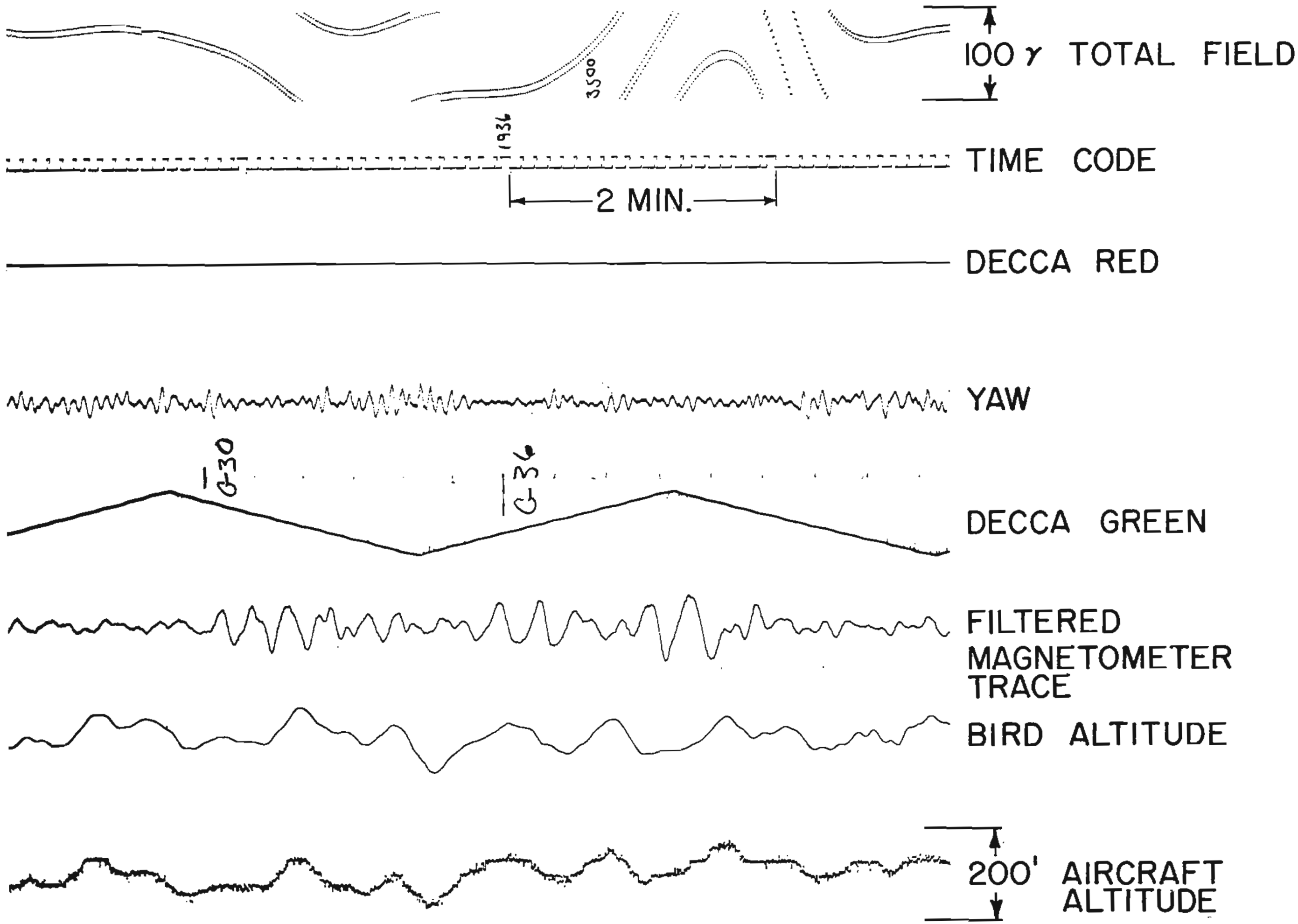


Figure 3. Analog flight record for the aeromagnetic survey showing the various parameters recorded.

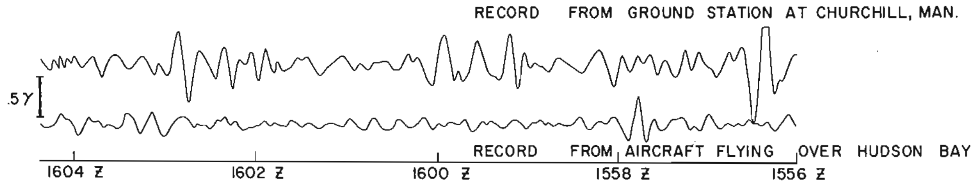
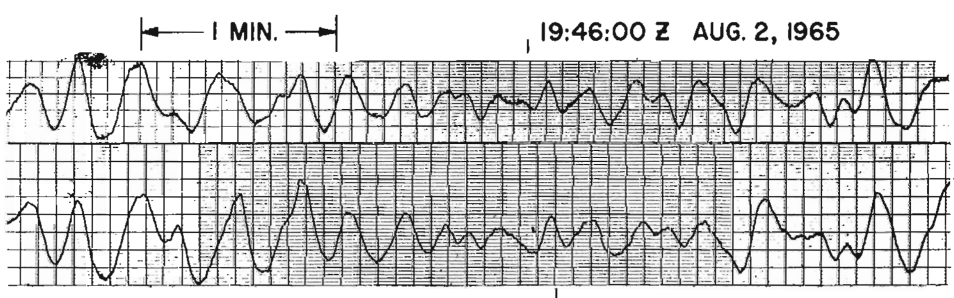


Figure 4. Airborne and ground magnetometer records obtained on August 19th, 1965. The data has been filtered using a bandpass of 0.05 to 1 hertz.

A rubidium vapour magnetometer was set up at Fort Churchill to record the diurnal variation of the earth's magnetic field during the flights. Figure 4 shows part of the airborne and ground magnetometer records obtained on August 19th, 1965, which was a typically quiet day for the magnetic diurnal variations. Both sets of data were recorded using an analog filter having a bandpass of 0.05 to 1 hertz. It is readily apparent that the record from the ground station at Churchill is much more active than that recorded over the waters of Hudson Bay. Thus it would appear that the micropulsations of the earth's magnetic field were somewhat smaller over Hudson Bay than were recorded at Churchill. This was presumably due to the well-known coastline effect (Ponomarev, 1960; Duffus et al., 1962; Roden, 1964; Coode and Tozer, 1965), which causes the variations in the vertical and horizontal fluctuations of the earth's magnetic field to be enhanced in the vicinity of the coast, and to the electromagnetic damping effect of the salt water of Hudson Bay.



TOWED BIRD MAGNETOMETER TRACES
ALTITUDE = 400'.
FILTER CUT OFF = 0.05 c.p.s.
HUDSON BAY.
DECCA LINE, G18 RED.

18:08:00 Z AUG. 3, 1965
CHART SPEED = 1 MM./SEC.

Figure 5. Two aeromagnetic profiles flown along Decca line G18 (red) obtained on succeeding days showing repeatability of fractional gamma anomalies. Profile length is approximately 12 miles.

Quality of the Aeromagnetic Survey Results

Figure 5 shows two towed-bird magnetometer filtered traces which were flown along red decca line G18 on succeeding days, and which thus enables a good comparison to be made of the microanomalies recorded. It is obvious that there is quite good correlation in the extremely small anomalies on the two traces, especially as the aircraft would not be expected to repeat its survey track exactly. This figure therefore shows that the fractional gamma anomalies recorded must be due to magnetization changes in the underlying geology, and are not due to micropulsations of the earth's magnetic field. This proof of the geological origin of these microanomalies is important in the interpretation of two of the later Figures (7 and 9) presented in this paper. It is also a good demonstration of the excellent repeatability of the Decca navigation system.

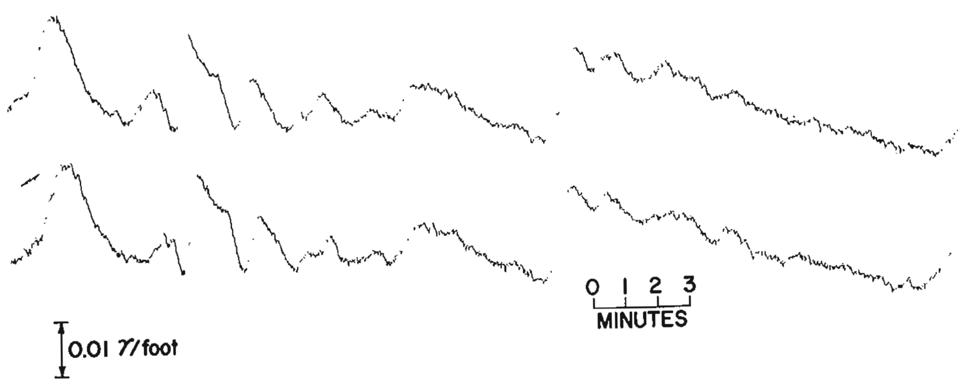


Figure 6. Gradiometer data obtained on two flights over the same path.

Figure 6 shows the gradiometer data obtained on two flights along the same flight line, and it can be seen that again there is excellent correlation between the profiles. A number of the repeatable smaller gradient anomalies have an amplitude less than 1/100th of a gamma per foot, which means that the difference in the total field recorded by the two magnetometers was around one gamma because the vertical separation was approximately 100 feet. Actually these gradiometer profiles are a mixture of the vertical gradient and a small amount of transverse horizontal gradient because there is a horizontal displacement between the heads due to the fact that the bird was towed from a point on the starboard wing.

Analog and digitally filtered aeromagnetic data

Examination of high resolution aeromagnetic data indicates that short wavelength, small amplitude anomalies are often superimposed on the main 'geological' anomalies. The most obvious way to separate out this 'fine structure' is to filter the data either employing analog or digital filters.

Figure 7 shows eleven filtered profiles from the southeastern portion of the area surveyed in 1965 obtained by filtering the analog aeromagnetic data in flight. At the bottom is the total intensity profile from red decca line H4. The line A_1A_2 on Figure 7 is also shown in Figure 8, which is a 10-gamma total intensity map compiled from the survey results. On Figure 7 a number of microanomalies having amplitudes less than 1 gamma can be seen that are sub-parallel to line A_1A_2. The position of these microanomalies has also been indicated on Figure 8 by a thick black line. The line-to-line correlation over 11 lines is, of course, strongly indicative of the fact that these microanomalies are produced by a geological feature. The strike of the two total field anomalies which appear on Figure 8 is almost parallel to the red decca lines. The anomaly to the southwest falls on red Decca line H4 whereas the anomaly to the northeast falls on red Decca line H2. There is thus an offset of two red Decca lanes between the strike directions of the two anomalies, which is a distance of approximately 1 1/4 miles. This offset may be due to faulting, and therefore the microanomalies are possibly due to a transcurrent fault offsetting the two causative bodies producing the main anomalies which would bring rocks with contrasting magnetizations into juxtaposition. However, from the sharpness of the microanomalies their source must be in the sediments themselves, not in the basement rocks which are interpreted as being more than 8,000 feet below sea level in this area. The postulated transcurrent faulting therefore occurred after the sediments had been laid down.

Thus it can be concluded that most of the small amplitude anomalies recorded were repeatable and some extend for many miles in directions which are quite different from the main anomalies observed.

Figure 9 shows seven digitally filtered profiles obtained in the central portion of the 1965 survey area. The digital filter used was a Martin-Graham filter having a bandpass from 0.388 to 1.19 nautical miles (Anders et al., 1964). Unlike the analog filter, this digital filter is a zero phase-shift one so that there is no displacement of the anomaly position and flight

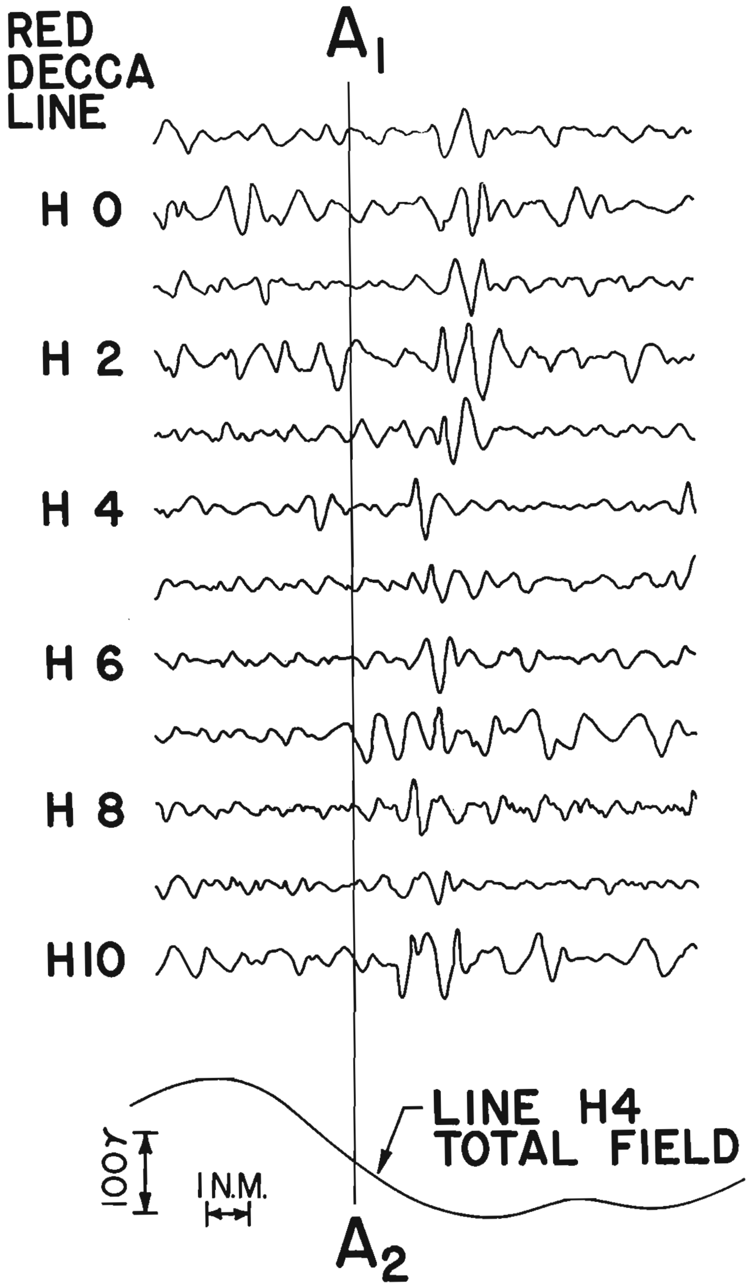


Figure 7. Filtered aeromagnetic profiles obtained by filtering the analog total intensity data in flight. A total intensity profile is also shown for purposes of comparison.

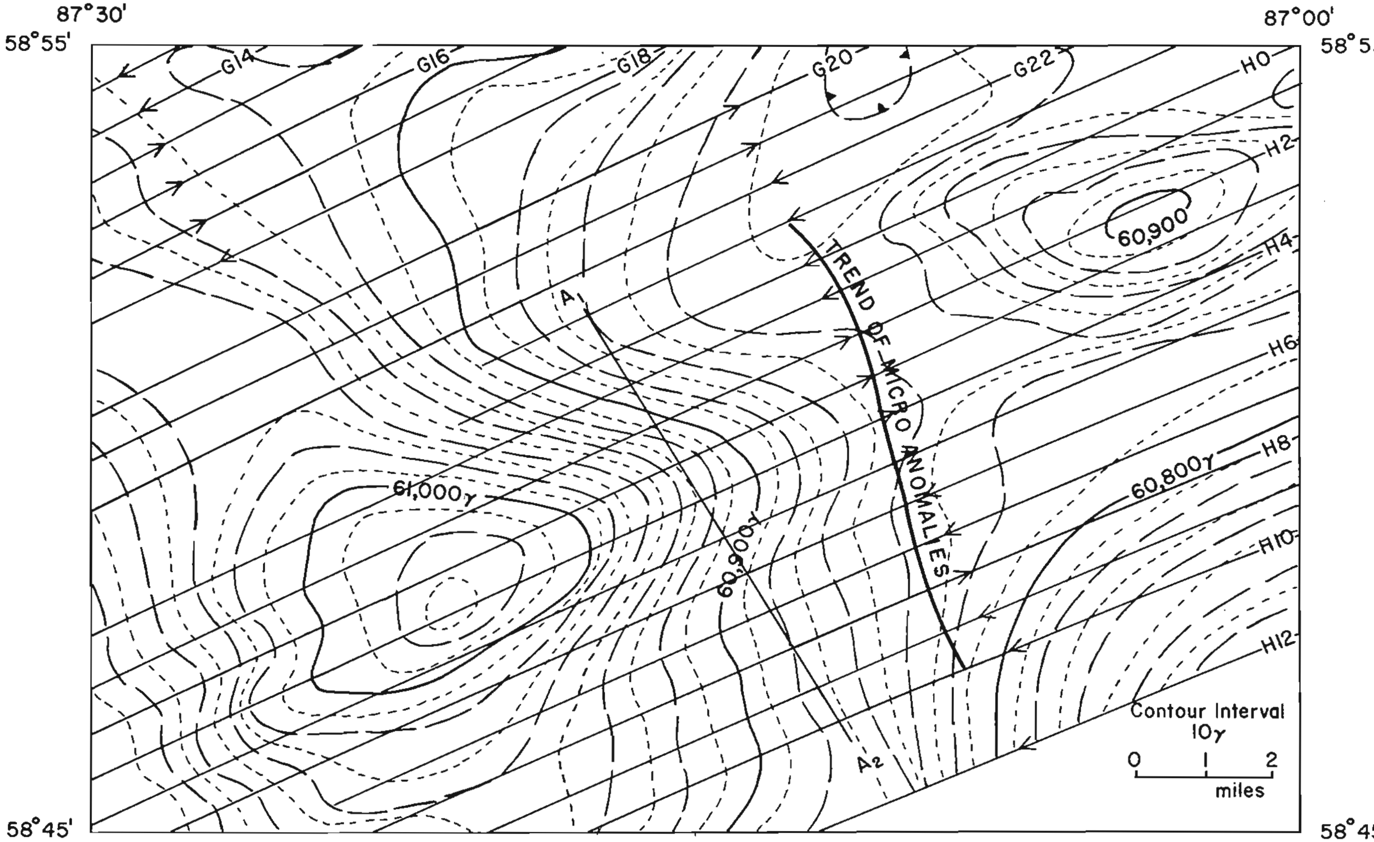


Figure 8. Portion of aeromagnetic map resulting from 1965 survey showing trend of micro-anomalies obtained by filtering analog data.

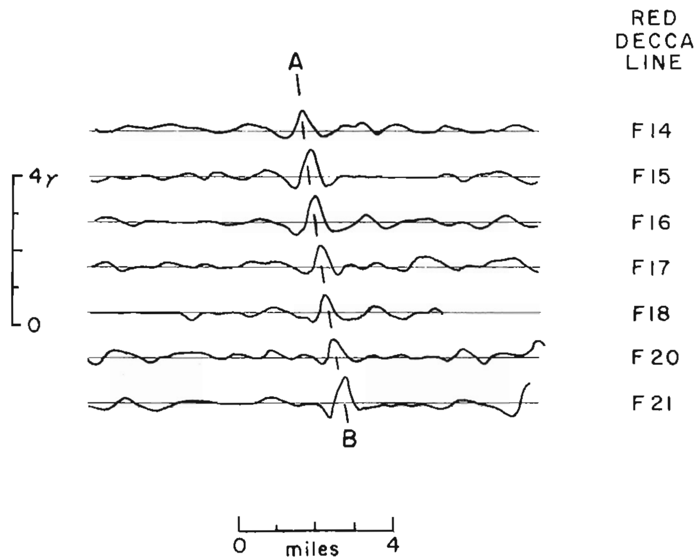


Figure 9. Seven digitally-filtered aeromagnetic profiles obtained using a Martin-Graham filter having a bandpass from 0.388 to 1.19 nautical miles.

line direction is unimportant. The line AB which is drawn through the peaks of the microanomalies on Figure 9, which are all about one gamma peak-to-peak, is also shown on Figure 10, which is a 10-gamma total intensity map of part of the survey area. Again the excellent line-to-line correlation over 7 lines of the microanomalies is strongly indicative of a geological cause which produces a lateral contrast in the magnetization of the underlying rocks. There are many possible geological causes, and some of these are contacts, faults, dykes, eskers, ancient river channels, i.e. any geological feature which has length but not much breadth.

Interpretation of magnetic survey results

Depth determinations were carried out on all the significant anomalies recorded in the survey area. The values thus obtained were consistently in excess of 8,000 feet. The average depth obtained from three anomalies in the southwest portion of the survey area was 10,700 feet (with a range of 9,800 to 11,700 feet) and the average for seven anomalies in the northeast portion of the survey area was 8,500 feet (with a range of 7,900 to 10,500 feet). The results of the 1965 survey seem to be reasonably consistent with those previously published for the 1961 sea magnetometer survey (Hood, 1964; Hood, 1966), and also with those of Hodgkinson (1968) contained in this volume.

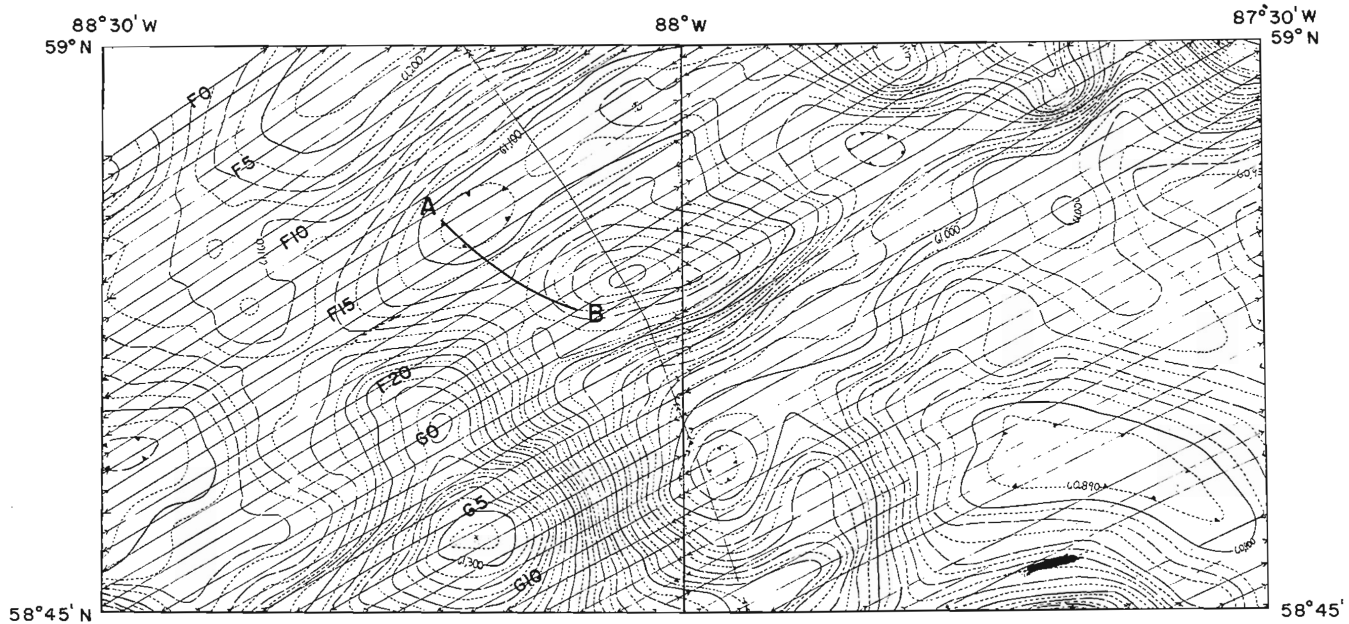


Figure 10. Portion of aeromagnetic map resulting from 1965 survey showing trend of microanomalies (AB) obtained by filtering digital data. Contour interval 10 gammas.

An area of intense magnetic anomalies was observed about 60 miles north-northeast of Cape Churchill where the depth of water is approximately 300 feet. The position of this area is approximately 59° 37 1/2'N., 92° 40'W. and is indicated by the cross in Figure 1. Anomalies in excess of 5,000 gammas were recorded by the survey aircraft and as the minimum depth to the causative bodies is at least 300 feet, there is little doubt that the anomalies are produced by magnetic iron-formation. The magnetic zone appears to cover an area in excess of 100 square miles, which would indicate that a considerable tonnage of iron-formation is located beneath the waters of Hudson Bay in this area.

1965 SEA MAGNETOMETER DATA

Figure 11 shows the sea magnetometer profiles obtained during the 1961 (Hood, 1964; Hood, 1966) and 1965 surveys in northeast Hudson Bay, together with the accompanying geology. Two sea magnetometer profiles were obtained between the Ottawa Islands and Cape Smith. The smaller amplitude of the anomalies on the profiles between the Ottawa Islands and Cape Smith would indicate that the underlying rocks have a much lower magnetic susceptibility than the average for the area. This is supported by susceptibility measurements on rock samples obtained by Dr. I. Stevenson of the Geological Survey of Canada in the Cape Smith area and also in the Ottawa Islands. The inferred magnetic boundaries have been drawn on Figure 11. In general, the trend of the gravity lows in the Cape Smith belt (Tanner and McConnell, 1964) corresponds fairly well with these magnetic boundaries, however near the Ottawa Islands the gravity trends are somewhat different. The sea magnetometer data obtained to date therefore indicates that the Cape Smith-Wakeham Bay belt of basic rocks extends into the Ottawa Islands.

Two large magnetic anomalies lie on the extension of the Manitounuk group of basalt and sedimentary rocks, which occur in the Hopewell Islands. The anomalies are undoubtably due to iron formation, which is known to occur in the Hopewell Islands, which lie in the circular arc of the east coast of Hudson Bay.

REGIONAL AEROMAGNETIC STUDY OF HUDSON BAY

Figure 12 is a 200-gamma generalized total intensity map of the available aeromagnetic data in Hudson Bay and its periphery which has had the regional gradient removed (Morley, MacLaren and Charbonneau, 1968). This composite map brings out the magnetic patterns very well, and there is in general a good correlation with the regional geology. Almost without exception, the regional magnetically-low belts correspond to the areas of folded volcanic and sedimentary rocks, and the magnetically high belts correlate with the granites and granite gneisses. This is a paradox because in general acidic rocks are less magnetic than basic rocks. The magnetic patterns also seem to reflect the grade of metamorphism in many areas.

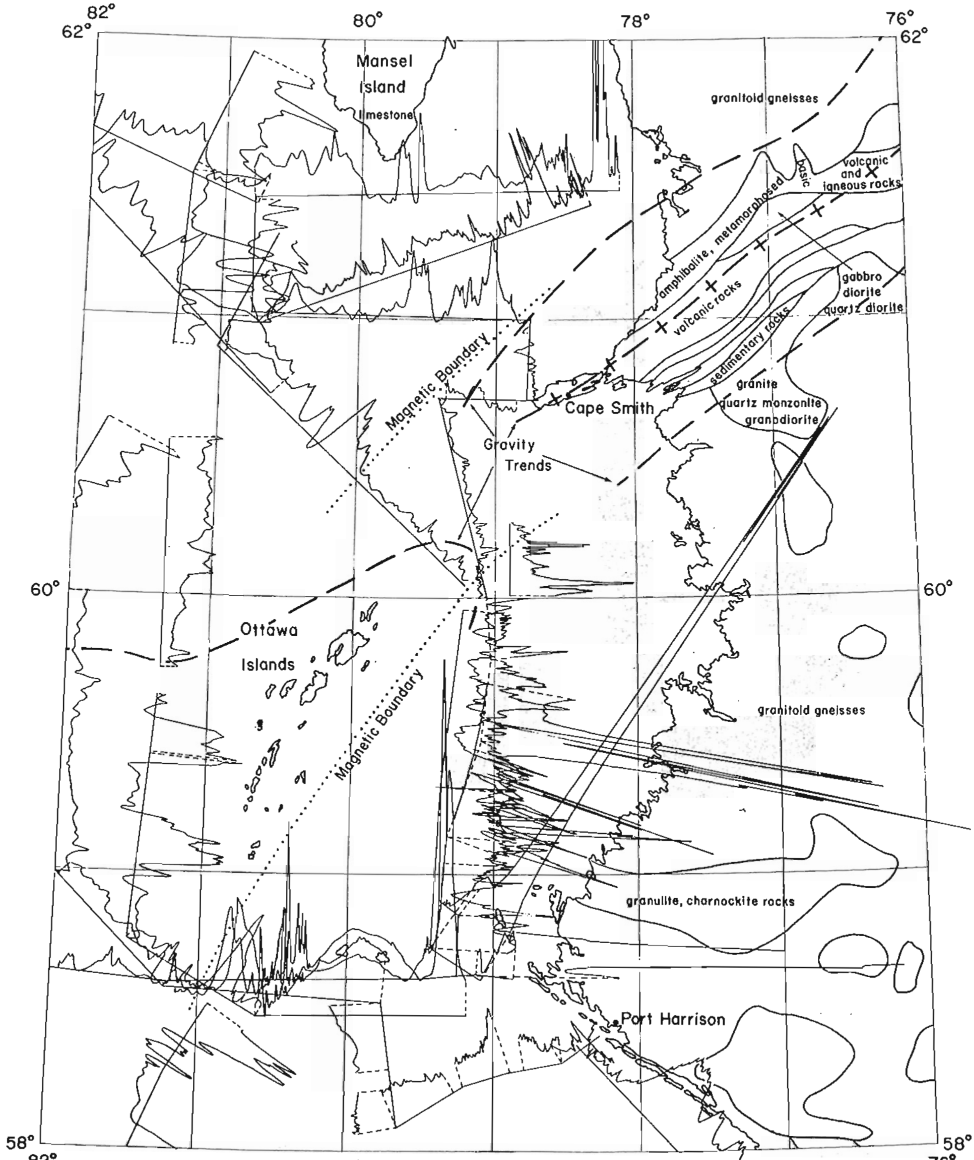


Figure 11. Sea magnetometer profiles obtained in northeastern Hudson Bay during the 1961 and 1965 surveys.

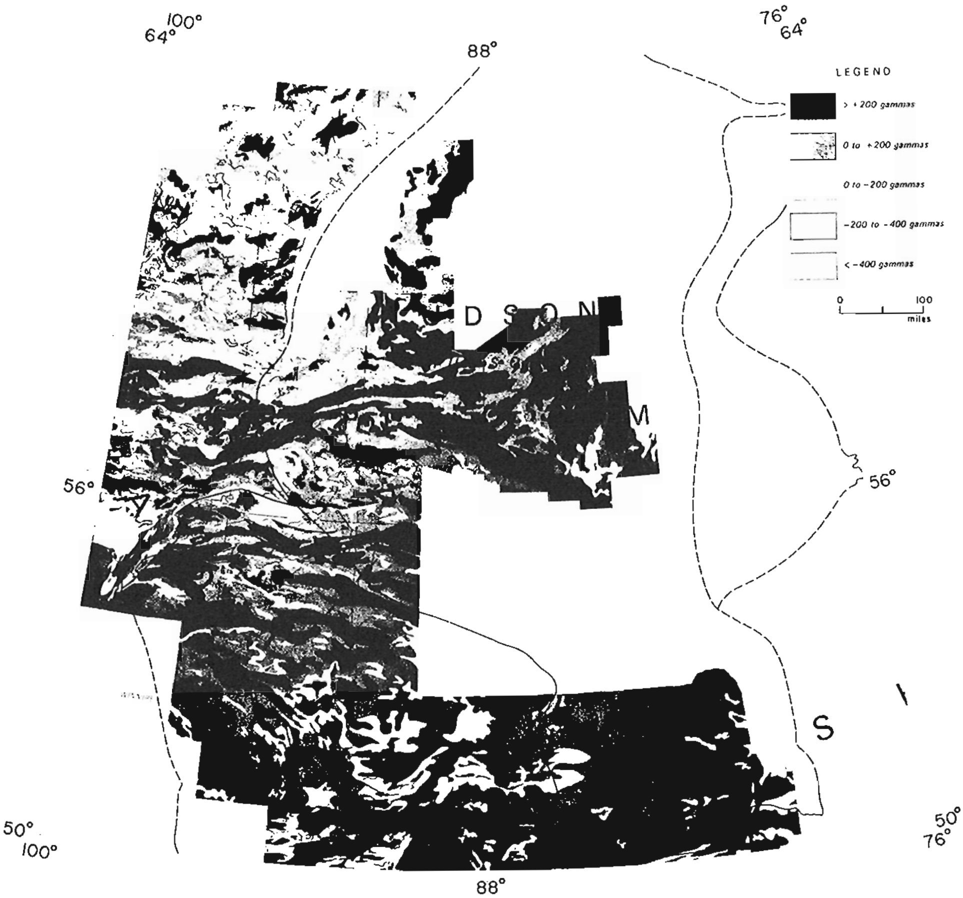


Figure 12. Generalized total intensity aeromagnetic map of the Hudson Bay region (from Morley et al., 1968).

The average value of magnetic field in central Hudson Bay seems to be generally higher than that observed in the peripheral areas. This appears to be true for the gravity data also (see Fig. 3, Innes et al., 1967).

One of the most interesting features on Figure 12 is the Owl River magnetic high which is northeast-striking in Manitoba and crosses the coast at approximately 57°50'N. about 68 miles south of Cape Churchill. The magnetic high continues into Hudson Bay, bends in a southerly direction to become first east-striking, and then southeasterly-striking. It runs approximately parallel to the southwest coast of Hudson Bay on either side of Cape Tatnam for many miles (see also Fig. 13). There is some indication that a branch of the Owl River magnetic high may continue northeastwards in the general direction of Cape Smith.

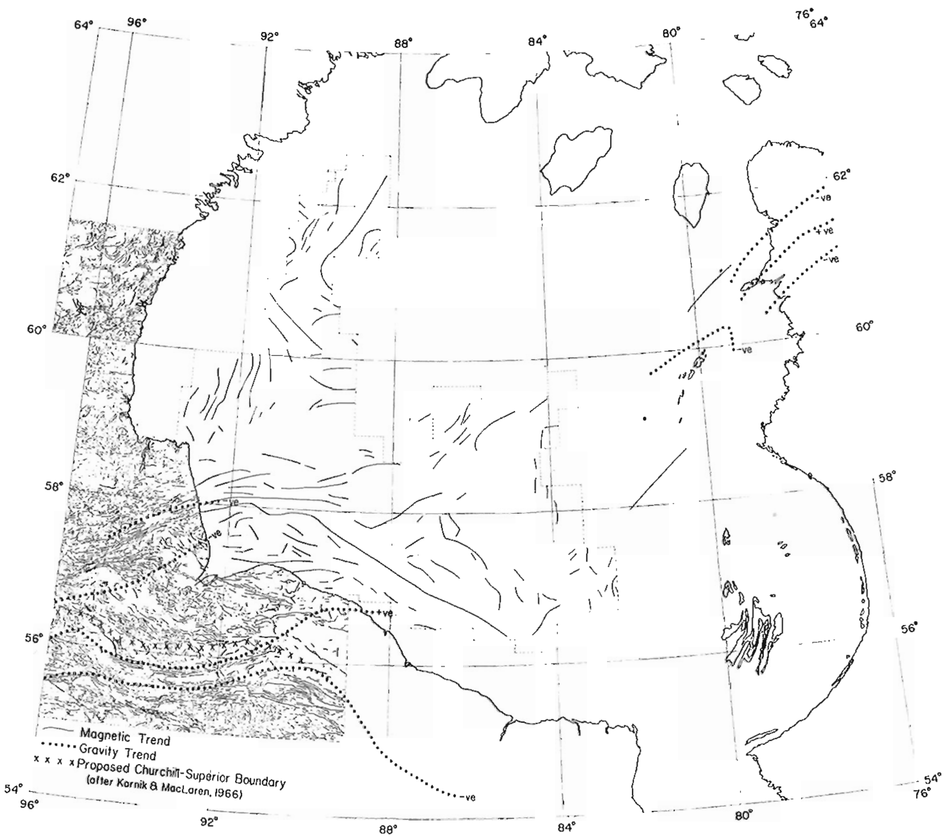


Figure 13. Geophysical trend map of the Hudson Bay region.

The position of the Precambrian-Paleozoic contact has been indicated on Figure 12 by a solid black line onshore and by the dashed line in Hudson Bay to indicate that it is assumed. The position of the Churchill-Superior boundary in Manitoba as deduced by Kornik and MacLaren (1966) is also indicated by a black line (which strikes in a northeasterly direction on the west side of the map). They have inferred that the boundary follows a continuous magnetic low on the published aeromagnetic maps for a distance of over 400 miles. However Bell (1966) has positioned the Churchill-Superior boundary about 38 miles south of that shown in Figure 12 where the boundary runs parallel with 56° N. latitude, and Gibb (1968) in a paper dealing with the Bouguer gravity anomalies in the area, has suggested that the boundary be moved even further south close to the position originally suggested by M. E. Wilson (1941).

The areal extent of the previously-mentioned iron formation may be gauged from Figure 12. The iron formation produces the bat-shaped anomaly which is centred at 59° 37 1/2'N., 92° 40'W.

Figure 13 is a geophysical trend map of the Hudson Bay region. Trend lines for both magnetic and gravity highs and lows have been included. These were obtained by drawing lines through the long dimensions of anomalies, both highs and lows, as far as the anomaly could be seen to extend. Where two anomalies were in line and reasonably close together the trend lines were joined. Thus the resultant map indicates only the predominant geological strikes in the area because the aeromagnetic trend lines will faithfully indicate the geological trends at these high magnetic latitudes. Trend lines were also drawn through anomalies in a number of cases which were undoubtably due to diabase dykes and which cut across the main geological strike. Examples of such trend lines can be seen in the vicinity of 56°N., 92°W. on Figure 13.

The magnetic and gravity trend lines are usually parallel to one another although in some areas this is not the case, for instance the gravity low which crosses the coast north of the Nelson River at approximately 57° 30'N. This indicates that the continuity of the gravity low may have been inferred wrongly from the gravity map of Innes et al. (1967). Thus the gravity and magnetic trend lines seem to agree reasonably well in Hudson Bay and its periphery, and this observation may be used to infer the probable position of the Churchill-Superior boundary, especially where it disappears under the Paleozoic cover of the Hudson Bay Lowlands. It should be emphasized that the magnetic trend lines are a more faithful indicator of the strike of the underlying geological formations than the gravity trends because of the much higher density of the magnetic data.

The position of the Churchill-Superior boundary proposed by Kornik and MacLaren (1967) has been indicated on Figure 12 by the crosses. It is reasonable to suppose that the boundary maintains a parallelism with the gravity low and magnetic trend lines in the southeastern part of the Hudson Bay Lowlands and probably emerges from the overlying Paleozoic cover about 80 miles south of Cape Henrietta Maria at the northwest end of James Bay close to 54°N. The boundary crosses James Bay and then appears to run between Long Island at the northeast tip of James Bay and the mainland and follows the circular shoreline of eastern Hudson Bay (Stockwell, 1965).

PALEOMAGNETIC RESULTS AND HUDSON BAY

It is interesting that the Ordovician and Silurian equators as determined by paleomagnetic measurements on oriented samples collected in North America pass through Hudson Bay (Fig. 14). A good paleomagnetic determination of the Devonian pole position does not appear to have been

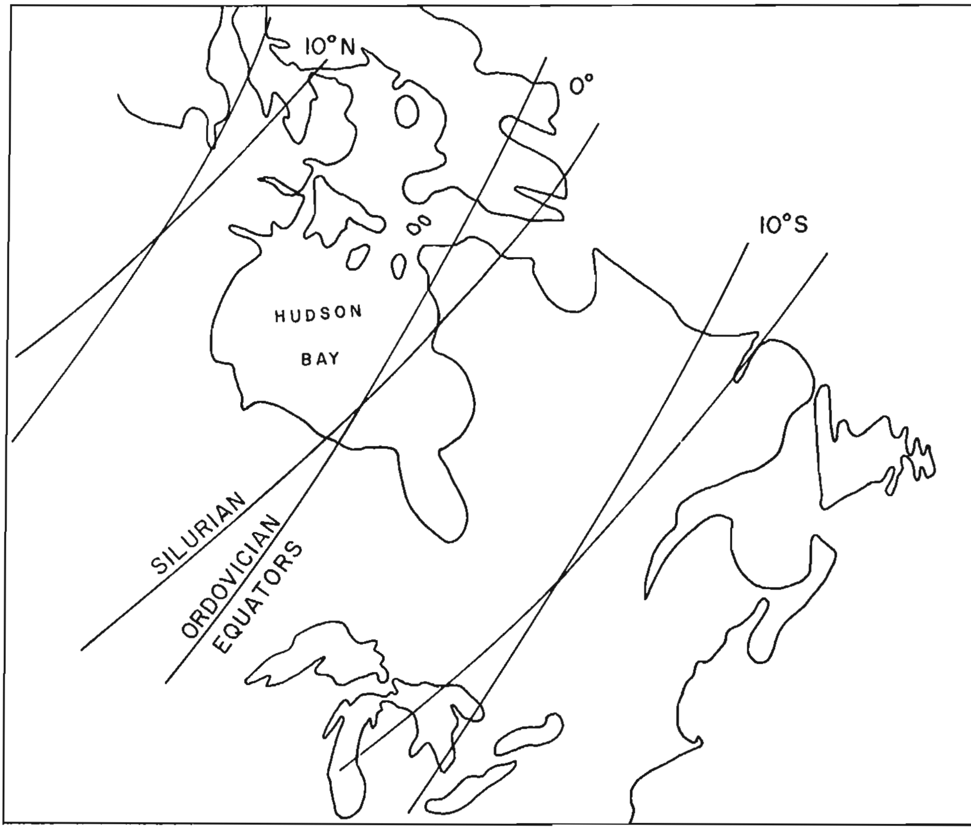


Figure 14. Ordovician and Silurian paleolatitudes as determined from North American paleomagnetic measurements.

obtained yet for North America, so the Devonian equator has not been included on Figure 14. However, a reasonable estimate can be made from the polar wandering curve for North America, and the Devonian equator would pass through James Bay striking in an east-northeast direction. Irving and Gaskell (1962) have studied the paleogeographic latitude of oilfields and have concluded that the best chance of finding oil in economic quantities in Paleozoic formations seems to be in paleolatitudes of less than 20°. The Devonian, Silurian, and Ordovician formations of Hudson Bay therefore meet this criterion - as do the Devonian oil and gas-bearing formations of western Canada and southwestern Ontario. The likelihood of finding oil in commercial quantities in Hudson Bay would therefore appear to be enhanced by this hypothesis.

ACKNOWLEDGMENTS

The authors of this paper wish to thank the following for their contributions to the 1965 Aeromagnetic Survey of Hudson Bay: R. C. Baker, H. N. C. Lyster, and J. Waddell of the National Aeronautical Establishment; Captain N. Paul, pilot of the North Star aircraft and his RCAF (now Canadian Armed Forces) crew; and P. Sawatzky, A. Dicaire and H. W. C. Knapp of the Geological Survey of Canada. Dr. B. D. Loncarevic kindly supplied the 1965 sea magnetometer data used in Figure 11 which was obtained by the C. S. S. Hudson, and Atlantic Richfield Company supplied most of the aeromagnetic data shown in offshore Hudson Bay on Figure 12.

REFERENCES

Anders, E. B., Johnson, J. J., Lasaine, A. D., Spikes, P. W., and Taylo, J. T.
1964: Digital filters; NASA Cont. Rept. 136, 132 pp.

Bell, C. K.
1966: Churchill-Superior province boundary in northeastern Manitoba; Geol. Surv. Can., Paper 66-1A, pp. 133-136.

Coode, A. M., and Tozer, D. C.
1965: Low-velocity layer as a source of the anomalous component of the geomagnetic variations near the coast; Nature, vol. 205, pp. 164-165.

Duffus, H. J., Kinnear, J. K., Shand, J. A., and Wright, C. S.
1962: Spatial variations in geomagnetic micropulsations; Can. J. Phys., vol. 40, pp. 1133-1152.

Gibb, R. A.
1968: A geological interpretation of the Bouguer anomalies adjacent to the Churchill-Superior boundary in northern Manitoba; Can. J. Earth Sci., vol. 5, pp. 439-453.

Hodgkinson, J.
1969: Reconnaissance seismic and magnetometer surveys in Hudson Bay, Canada; Earth Science Symposium on Hudson Bay, Geol. Surv. Can., Paper 68-53, pp.

Hood, P.
1964: Sea magnetometer reconnaissance of Hudson Bay; Geophysics, vol. 29, pp. 916-921.

1966: Geophysical reconnaissance of Hudson Bay; Geol. Surv. Can., Paper 65-32, 42 pp.

Innes, M.J.S., Goodacre, A.K., Weber, J.R., and McConnell, R.K.
1967: Structural implications of the gravity field in Hudson Bay and vicinity; Can. J. Earth Sci., vol. 4, pp. 977-993.

Irving, E., and Gaskell, T.F.
1962: The palaeogeographic latitude of oil fields; Geophys. J., vol. 7, pp. 54-64.

Kornik, L.J., and MacLaren, A.S.
1966: Aeromagnetic study of the Churchill-Superior boundary in northern Manitoba; Can. J. Earth Sci., vol. 3, pp. 547-557.

Morley, L.W., MacLaren, A.S., and Charbonneau, B.W.
1968: Magnetic anomaly map of Canada; Geol. Surv. Can., Map 1255A.

Ponomarev, Y.A.
1960: The nature of the (geomagnetic) coast effect; Geomagnetic Disturbances, Acad. Sci. USSR, pp. 35-41.

Roden, R.B.
1964: The effect of an ocean on magnetic diurnal variations; Geophys. J., vol. 8, pp. 375-388.

Stockwell, C.H.
1965: Structural trends in Canadian Shield; Amer. Assoc. Pet. Geol. Bull., vol. 49, pp. 887-893.

Tanner, J.G., and McConnell, R.K.
1964: The gravity anomaly field in the Ungava region of northern Quebec; Dom. Obs. Canada, Gravity Map Series 5 and 6, 21 pp.

Wilson, M.E.
1941: Pre-Cambrian; Geol. Soc. Am., 50th Anniv. Vol., pp. 269-305.

AN ALTERNATIVE INTERPRETATION OF THE 1965 HUDSON BAY CRUSTAL SEISMIC DATA

A. Overton
Geological Survey of Canada
Ottawa, Ontario

Abstract

Results of the three time-term interpretations of the 1965 Hudson Bay crustal seismic data published in the October 1967 issue of Canadian Journal of Earth Sciences are compared and reasons for discrepancies are discussed.

Uncertainties in shot positions due to navigation problems have been described by Ruffman and Keen (1967) as possibly the greatest source of error in these interpretations. An independent determination of relative structure on the upper mantle has been made for that portion of the profile under the shotpoints of the east-west profile between the Ottawa Islands and Churchill. The proposed structure can be influenced only to a small degree by errors in shot positions.

A comparison of the proposed structure with that derived from the time-term solution demonstrates that the relative crustal thinning beneath the eastern end of the profile is due to errors in shot position or to an inconsistency in upper mantle velocity. Derivation of this structure also demonstrates other sources of error.

An objective method for selecting combinations of data which are mutually consistent with a system of unique time-terms and upper mantle velocity is suggested.

INTRODUCTION

There have been at least three independent interpretations of the data obtained by portable seismic stations in the Hudson Bay crustal experiment of 1965. The interpretations have been published by Hobson, Overton, Clay and Thatcher (1967), Hunter and Mereu (1967), and Ruffman and Keen (1967).

Ruffman and Keen describe the problems of navigation and the consequent doubts in shot positions. These problems were anticipated however in the preliminary plans for the 1965 program, and the plans provided for supplementary positioning control which was to consist of four hydrophone stations (Fig. 1), one at Coats Island, one at Gilmour Island, one at Winisk, and one at the centre of the bay. Of these four hydrophone stations, only one was operative – that of Dalhousie University at the centre. The other three remained inoperative due to technical and logistic difficulties. While water arrivals at Dalhousie's station were used to resolve radial distances of shots

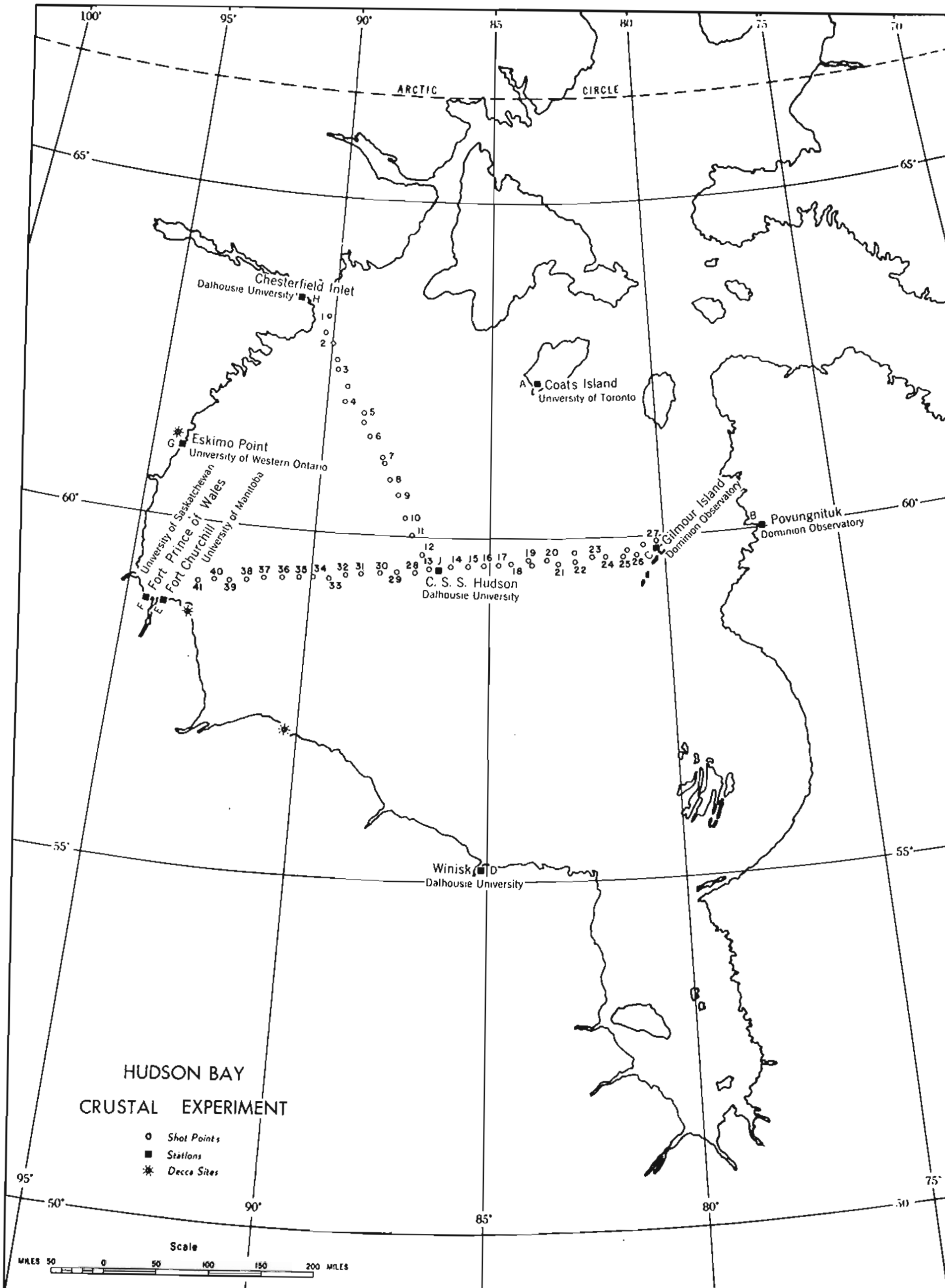


Figure 1. Locations of the shotpoints and receiving stations in Hudson Bay.

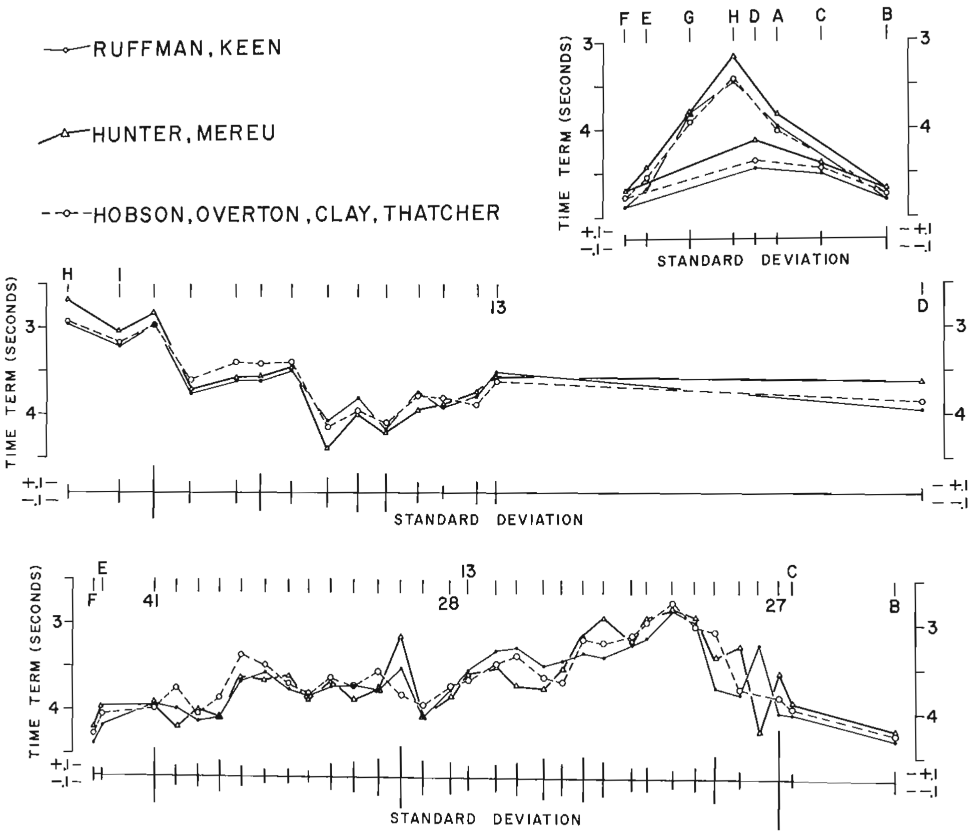


Figure 2. Comparison of time-terms for three published interpretations.

from its central position, the absolute position of this station, the relative position of shots in an azimuthal sense and hence their absolute positions must remain somewhat questionable in terms of the precision required by the seismic interpretation. The expected accuracy of shot positions (Ruffman and Keen, 1967) ranges from ± 2.5 km for shots 1 to 4, ± 2 km for shots 25, 26 and 27, ± 1 km at the centre to ± .1 km at shot 41.

With these possible shot position errors in mind we will look critically at the data in order to estimate the effect of the errors on the resulting interpretation. Stations are lettered A to J and shots are numbered 1 to 41 (Fig. 1). Shots 1 to 13 will be called the north-south profile and 13 to 41 the east-west profile.

Comparison of published results

The published interpretations were all derived using the time-term approach (Scheidegger and Willmore, 1957; Willmore and Bancroft, 1961). Figure 2 shows a superposition of crustal time-terms for the three previously mentioned interpretations, adjusted to the same basis for comparison by equalizing the average time-term for shots 1, 27 and 41 with the average for stations C, E and H. Large scale features are remarkably similar even though values for upper mantle velocity ranged from 8.23 km/sec to 8.27

km/sec. This difference in velocity alone is capable of giving differences in time-terms of up to 0.5 sec for the range of distances at which Pn was observed. A comparison of travel times showed agreement within ± 0.1 sec for 70 per cent of observations which is sufficient to account for most of the small scale differences in the interpretations. Another source of difference is the choice of admissible data. While this disagreement appears to have little effect on the general structure, it undoubtedly contributes further to the smaller scale differences.

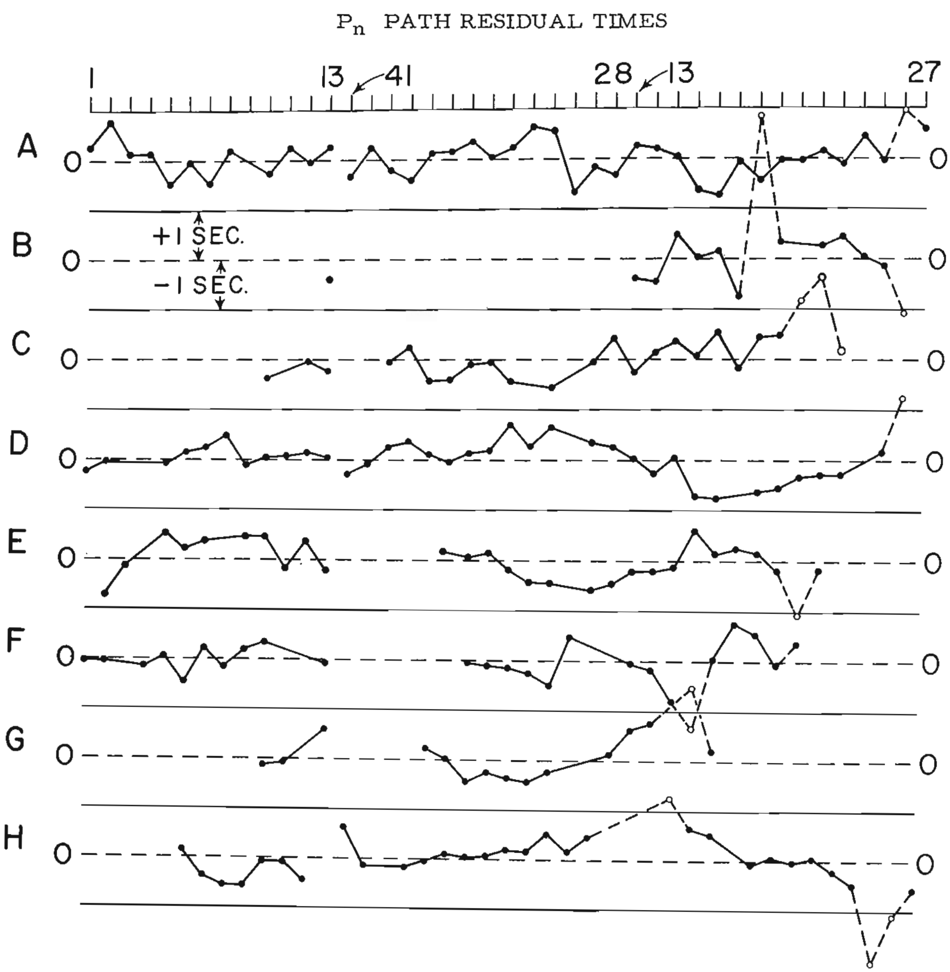


Figure 3. Pn path residual times defined by the time-term solution of Hobson et al. (1967).

The three interpretations support large regional variations in time-terms of up to 1.5 seconds. None of these interpretations has been presented without some reservation concerning large time-term variations.

We shall henceforth refer only to the data and results of Hobson et al. (1967) whose standard deviations are illustrated. These are quite large, being two to three times as great as Berry and West (1966) report for the Lake Superior experiment.

Pn residual times

Figure 3 shows the Pn path residual times of Hobson et al. (1967). They range from zero to well in excess of ± 1 second. Those observations yielding residual times in excess of ± 0.9 sec were excluded from our time-term solution. It is important to note the similarities in pattern for corresponding shots at different stations, i.e. stations A and E shots 1 to 13 oppose, stations D and H shots 5 to 9 oppose, station C and D, D and E shots 34 to 20 oppose, station C, G and H shots 17 to 36 are similar.

Reduced travel time curves

Pn travel times reduced at 8.27 km/sec are illustrated (Fig. 4). Our time-term solution gave a velocity for Pn of 8.25 km/sec, the reason for 8.27 appears later. If these curves truly represent the same refractor of constant propagation velocity, if errors in distance and travel times are negligible, the pattern of variation from one shotpoint to another should be very similar for each recording station and should represent the variation of time-terms along the shot profiles. Figure 4 clearly demonstrates that at least one of our assumptions is grossly wrong, for there are many inconsistencies in pattern. Station A opposes the much smaller time-terms on the north of the north-south profile which stations D, E and F strongly support. Stations A, D and H strongly support considerably smaller time-terms near the east end of the east-west profile while other stations do not. The most striking conflict is seen for stations E and F near Churchill for the east-west profile; these patterns should be identical in spite of errors in shot positions or velocity variation on the upper mantle. The only possible cause for this conflict is faulty travel times, since there is no indication of different refractors being involved which would be revealed by a generally consistent difference in slope on the two curves.

Interpretations independent of navigation

It is possible to do some interpretation which is quite independent of shot positions. The approach (Fig. 5) uses shots on the east-west reversed profile which gave observations at a station on both ends. We allow in-line errors in shot positions in the basic time-distance equations, noting that errors perpendicular to the shot line would have to be very large to produce a significant difference in travel times. Addition of equations for each shot

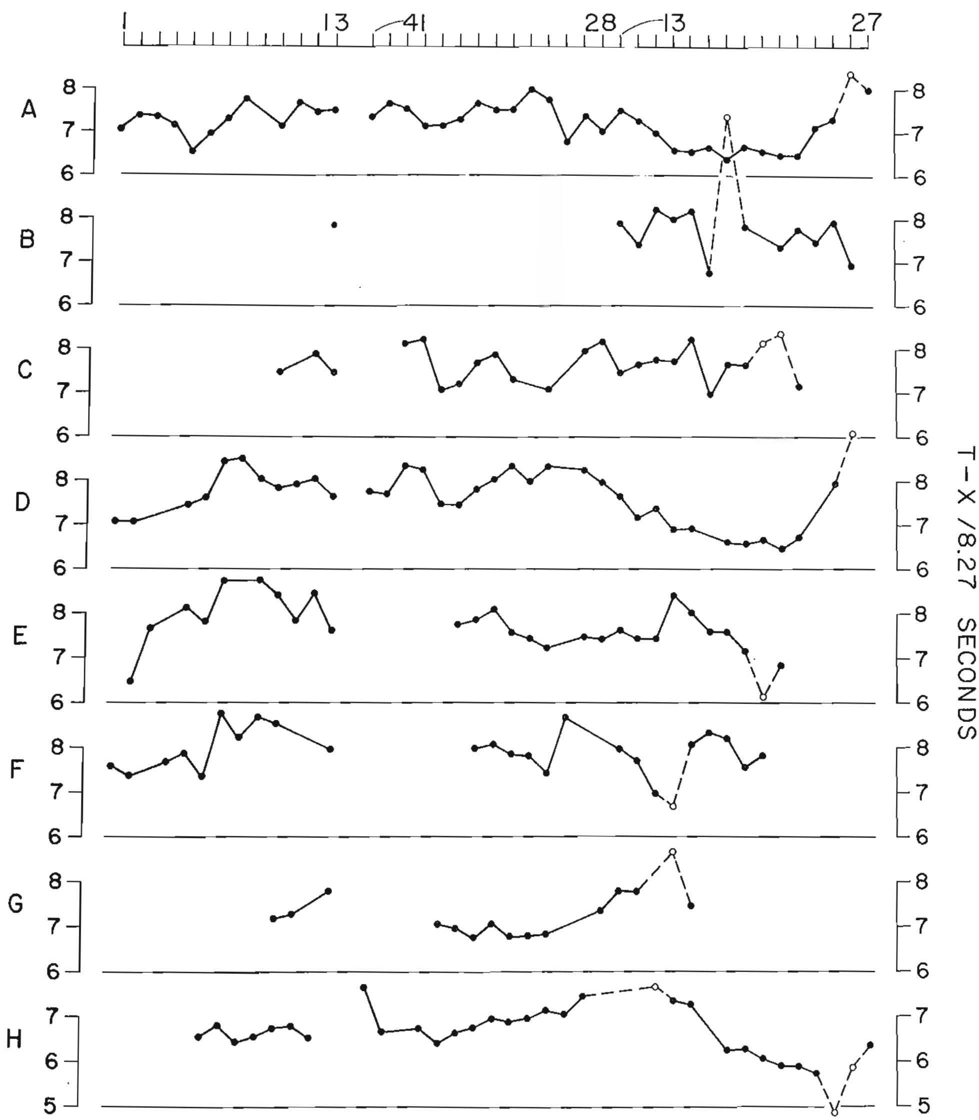


Figure 4. Reduced Pn travel times (after Hobson et al., 1967).

eliminates the error for that shot, and the nominal distances combine to give the distance between the two stations. The difference of these sums for two shots eliminates the distance and velocity and yields twice the difference in shotpoint time-terms as a function only of travel times; so that relative time structure between shotpoints is also independent, to a certain degree, of

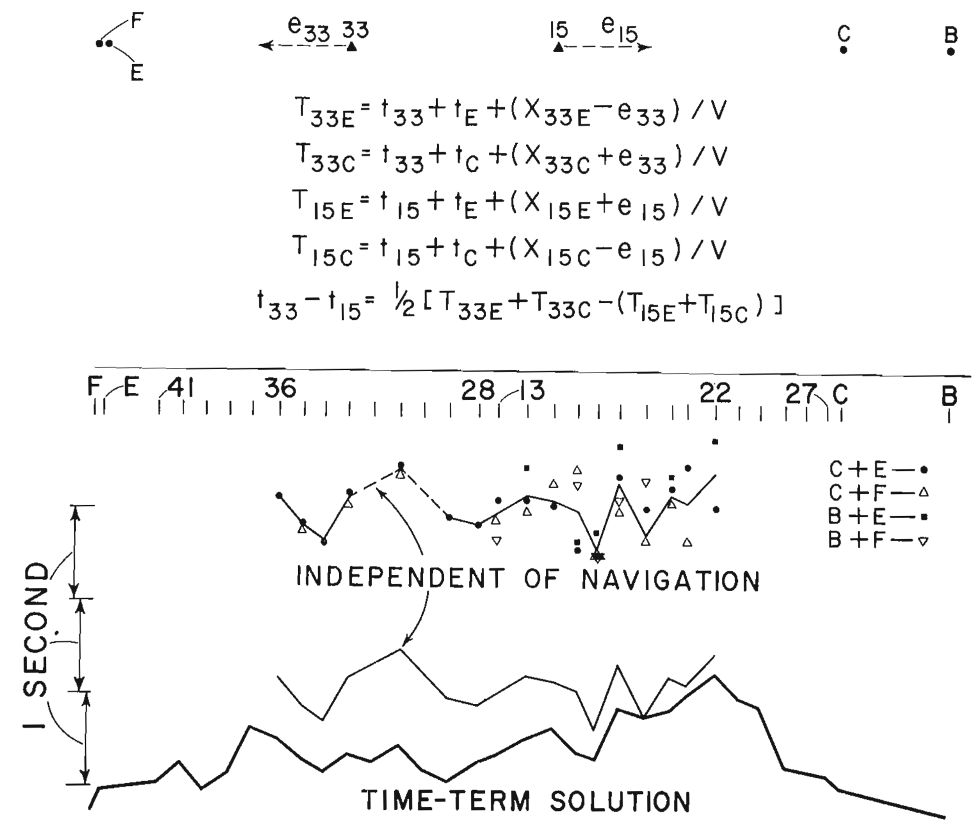


Figure 5. Comparison of relative upper mantle time-term structure as derived from the time-term approach and independently of navigation, east-west profile.

refractor velocity. Figure 5 illustrates the relative time-term structure thus derived for the east-west profile, and shows from 0.5 to 1.0 sec less relative structure between shots 22 and 31 than that obtained using the time-term approach. This conflict can result from the effect of errors in shot positions or refractor velocity variations, or both, on the time-term solution.

The scatter between shots 13 and 22 is due to previously noted inconsistencies in travel times for the different stations.

For the north-south profile (Fig. 6) the treatment was slightly different because the shots were offset appreciably from a straight line joining stations on either end. Here the combined nominal distances exceed that between the stations by an amount which is small enough to yield a reasonable time correction using any reasonable Pn velocity. The resulting relative structure and that of the time-term solution is not greatly different for the north-south profile.

Two possibilities arise from the previous analysis: Firstly, the idea of compensating errors may by some method be extended to observations which do not constitute reversed profiles, and secondly it appears that we may have systematic deviations in our observations which cannot be tolerated in any statistical analysis assuming a Gaussian error distribution.

Authors discussing the time-term approach have clearly stated the assumptions which must be satisfied for a successful solution, but little if anything has been said about the effect of false assumptions.

<u>Time-term solution for an example with systematic deviations</u>

We shall demonstrate the effect of anomalous observations on the results of a time-term solution with an example. Figure 7 shows a system of 9 shots and 3 receiving stations. We assign a marker layer velocity of 8 km/sec and time-terms of 3.5 sec to all positions, but allow observations for shots 4, 5, 6 and 7 into station C to contain an excess time of 1 second. Straightforward application of the time-term approach (Fig. 8) results in a least squares velocity of 7.92 km/sec, and time-terms, by equalizing averages for stations and shots, for the positions fluctuating about the original

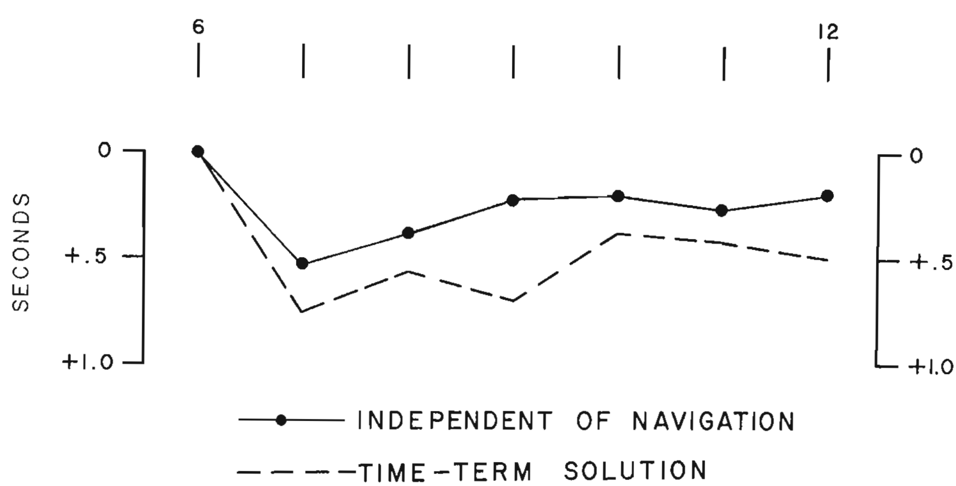


Figure 6. Comparison of relative upper mantle time-term structure as derived from the time-term approach and independently of navigation, north-south profile.

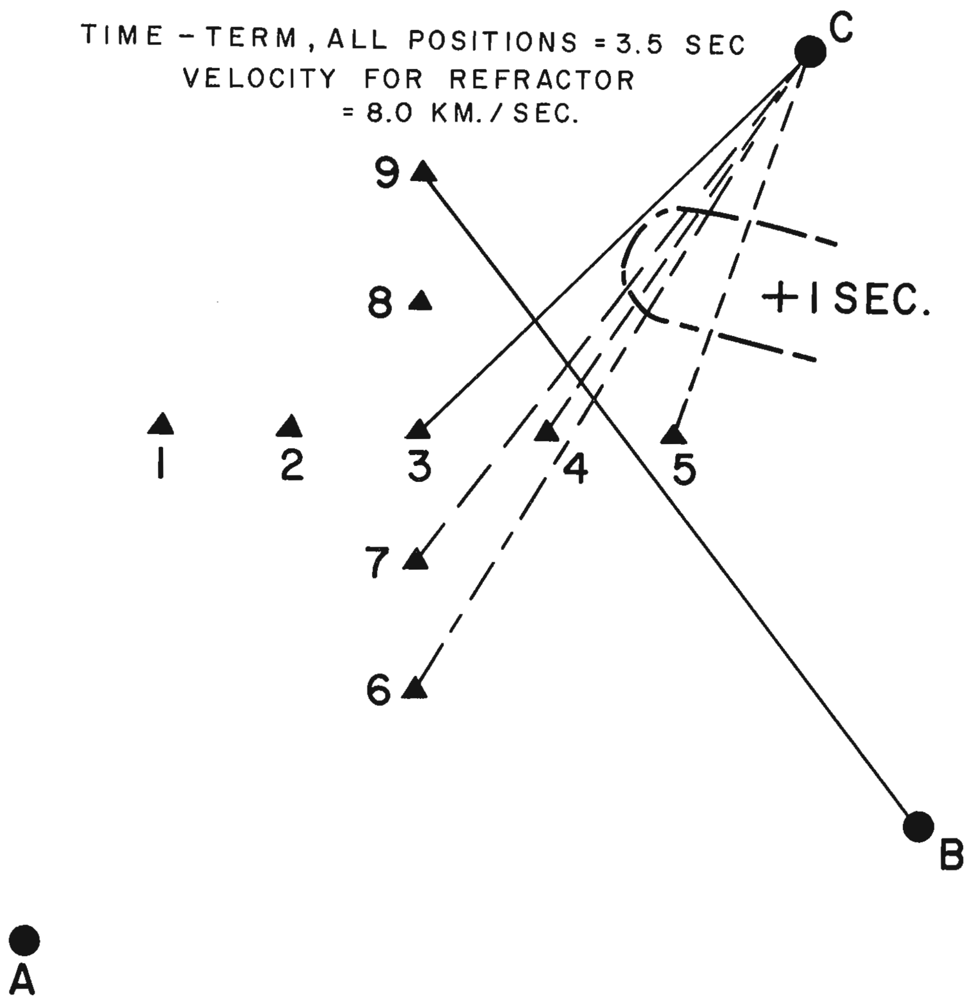


Figure 7. Shotpoint and receiving station plan for an example with systematic discrepancies.

3.5 sec level. Residual times for the stations show pronounced similarities in pattern; plotted against the distance function d (i, j) of the time-term solution the residuals show four distinct lineups at 8 km/sec, none of which have a zero time intercept. The distance function d (i, j) is as defined by equation 8 of Willmore and Bancroft (1961). Now no matter what single marker layer velocity we wish to choose, we cannot eliminate simultaneously the false time-term differences for the shots and for the stations. For more complex cases the distribution of residual times can be such as to completely conceal any indication of the true velocity; the distribution can also be approximately Gaussian which then does not provide a good check on validity of assumptions. Furthermore if we reject observations with large residuals, we stand as great a chance of rejecting normal paths as anomalous. On Figure 8 open circles represent anomalous observations. We now propose a method for separating anomalous and normal paths without distributing discrepancies.

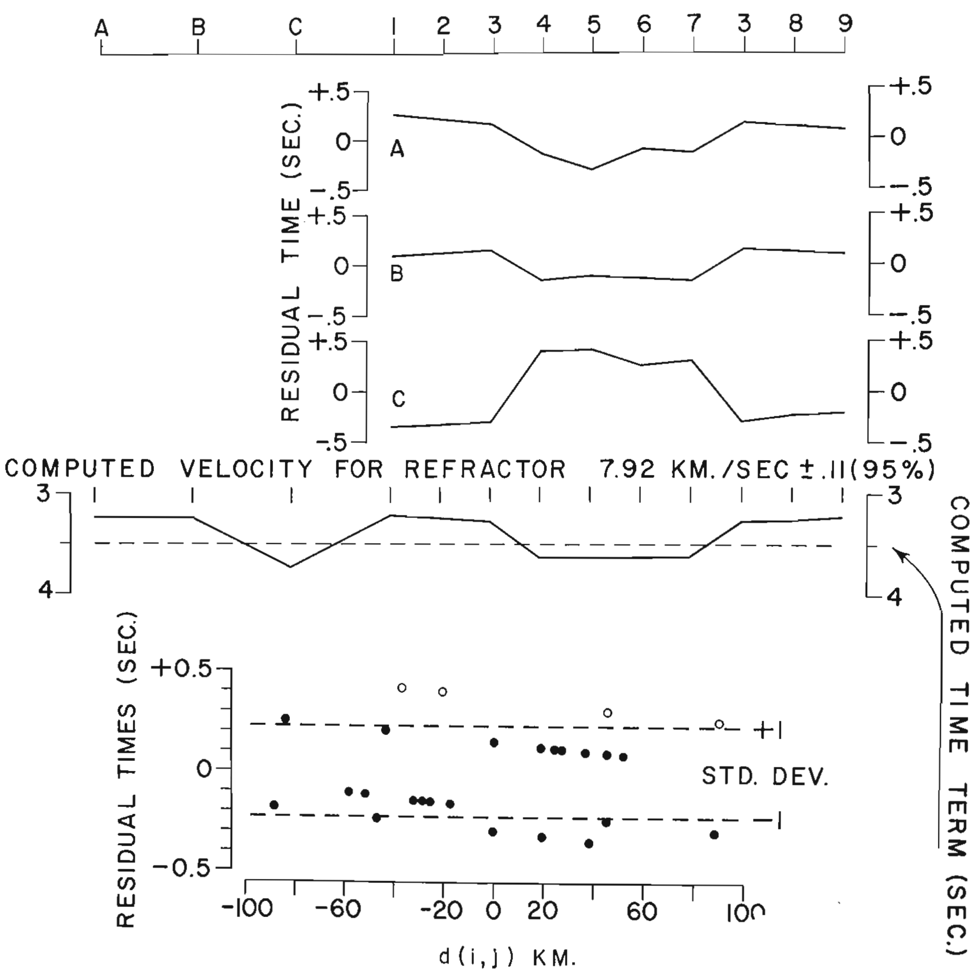


Figure 8. Results of time-term solution for the example with systematic discrepancies.

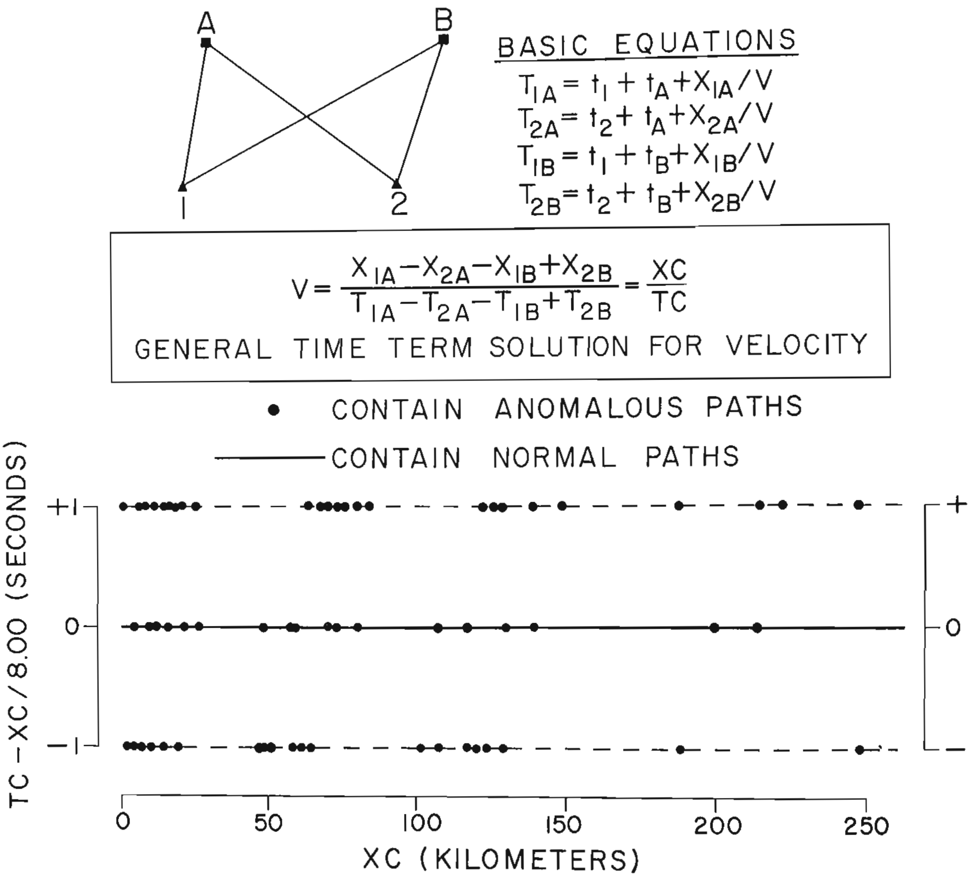


Figure 9. Alternative approach for detection of systematic discrepancies.

Alternative approach for detection of systematic deviations

The method is illustrated on Figure 9, whereby we consider separately each pair of shots and each pair of stations. This is the most elementary configuration amenable to solution with respect to a single velocity and conditionally dependent time-terms. The general time-term solution for velocity is shown in terms of travel times and distances of the observation equations. This expression is also obvious from the basic equations. We call the distance function and time function XC and TC respectively and compute the least-squares velocity represented by all TC and XC. For the example the resulting velocity is 7.92 km/s. The plot of TC – XC/8 versus XC shows three well defined alignments at 8 km/s, one having a zero time intercept and the other two having ± 1 sec intercepts. The significance of the three lines is that those aligning with zero time intercept contain either four paths which are normal or two which contain compensating discrepancies. Those points aligning at ± 1 sec intercept contain a single anomalous path. Three other cases can arise which are not demonstrated and will not be considered here. This sort of plot can be used in a number of ways. If a great proportion of points lie on the line of zero time intercept, representing a well-defined normal condition, the plot provides an objective method for rejecting those paths giving rise to points plotting with large residual times which do not fit into the normal scheme. Another use arises if the normal line is not as well defined by noting that if a point lies on the normal line, the paths contained in the combination can be used to estimate time-term differences between the shot points of the combination. This latter use raises hopes for refining the interpretation of the Hudson Bay data. It should be noted, however, that if distorting effects completely conceal any evidence of a generally normal velocity condition, the method fails, and so does every other method which cannot account for the distortions.

TC, XC analysis of Hudson Bay data

The previous method demonstrates the complexity of the Hudson Bay data (Fig. 10). Indeed we would be most happy to find some conclusive indication of a normal velocity condition. The least squares velocity is 8.27 km/s compared with 8.25 km/s from our time-term solution. The only significant trend away from the random distribution is shown by points lying beyond 700 km. These points indicate a preference for a Pn velocity of 8.34 km/s and are due solely to shots on the east-west profile this could indicate that shot point intervals are 1 per cent too great in an east-west sense. The inconsistency of the data is exemplified by considering that out of 4596 TC, XC determinations, only 188 fall within Vn = 8.27 ± .02 km/s, and only 177 fall within Vn = 8.34 ± .02 km/s. The inserted equation shows the danger in this complex case of computing time-term differences from data whose combinations plot within a limited velocity range. The discrepancies in parentheses can have any value and still compensate within the given range, but upon separating the four equations into pairs as for time-term differences the discrepancies reappear in these differences.

A large proportion of points show combined discrepancies of about ± 2 seconds. If this discrepancy is divided four ways in the most optimistic sense, individual discrepancies amount to ± 0.5 second, representing about ± 4 km in distance. It is interesting to speculate that if the majority of shots were actually 4 km further north than positions suggest, this error would account for the one second difference in time-term between the Winisk and Chesterfield Inlet stations.

Station time-term differences

Figure 11 illustrates the contribution of each shot to the time-term differences between stations at Coats Island, Eskimo Point and Chesterfield

Inlet on the north portion of the bay compared with the station at Winisk on the south. The method of computation is shown by the equation, and differences implied by the time-term solution are represented by dashed lines. If the assumptions of the time-term approach were valid and random errors were small for the Hudson Bay data, the plotted points would lie very close to the dashed lines, whose time intercepts would represent time-term differences for each of the station pairs. But the analysis of Figure 11 shows large deviations which are both systematic and irregular, and time-term differences between stations are not at all well defined.

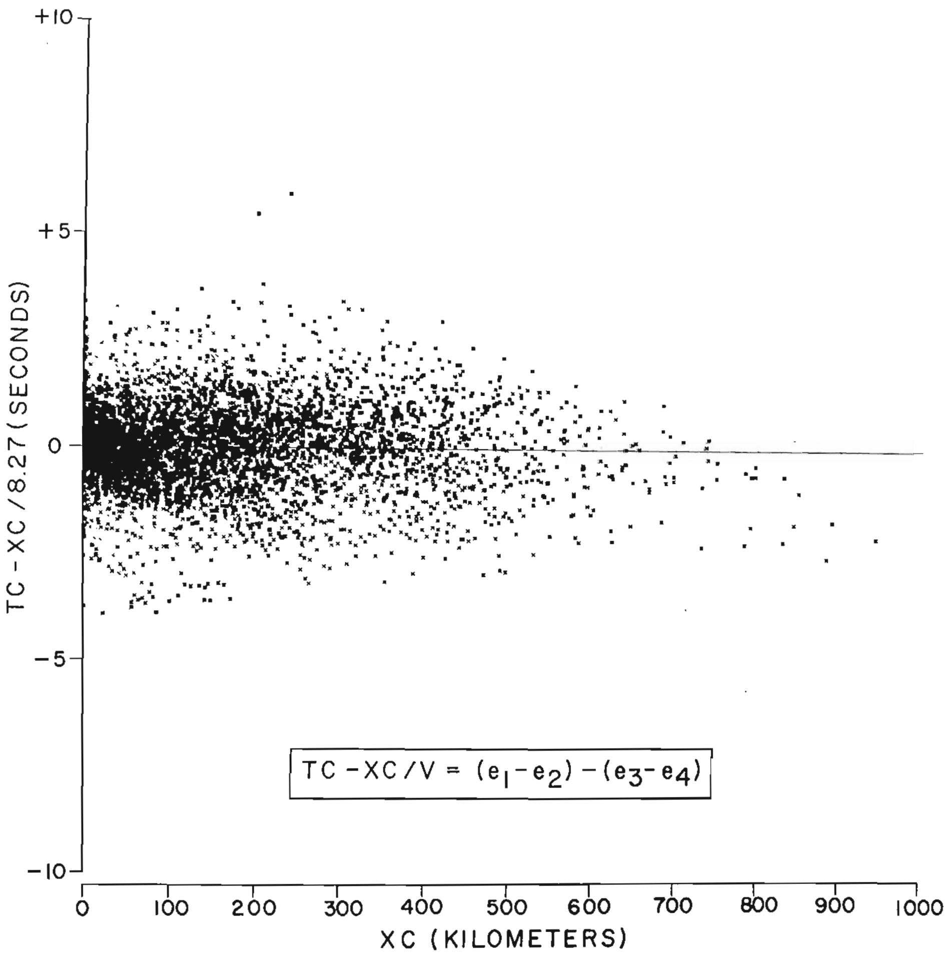


Figure 10. TC, XC analysis of Hudson Bay Pn data.

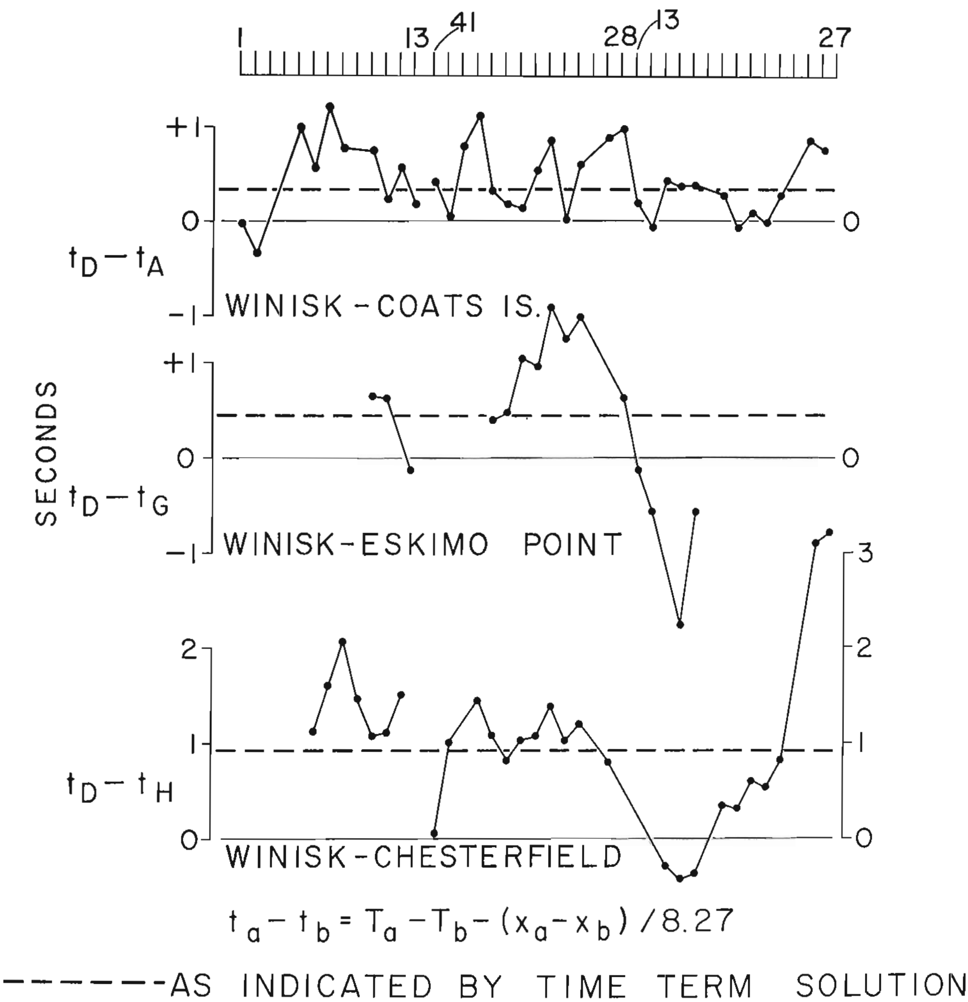


Figure 11. Time-term differences for the Winisk station (D) compared with the Coats Island (A), Eskimo Point (G), and Chesterfield Inlet (H) stations.

CONCLUSIONS

The time-term approach cannot yield, for the Hudson Bay data in its present form, time-terms which are significant in terms of variations in crustal thickness. Nor is it apparent that any analytical procedure can. Reliable definition of crustal time-term variations for Hudson Bay still awaits some means of accounting for conflicts in the data. Many attempts to do this with P_1 and Pn observations alone and in combination have failed. All that can be said with reasonable certainty about the crust under Hudson Bay considering P and Pn alone is that the upper mantle velocity probably lies between 8.1 and 8.3 km/s and may not be constant, the average crustal time-term is close to 3.6 seconds, and the average crustal thickness is close to 35 kilometres. We should continue to view our published time-term variations with doubt.

REFERENCES

Berry, M.J., and West, G.F.
1966: An interpretation of the first-arrival data of the Lake Superior experiment by the time-term method; Bull. Seismol. Soc. Am., vol. 56, pp. 141-171.

Hobson, G., Overton, A., Clay, D.N., and Thatcher, W.
1967: Crustal structure under Hudson Bay; Can. J. Earth Sci., vol. 4, pp. 929-947.

Hunter, J.A., and Mereu, R.F.
1967: The crust of the earth under Hudson Bay; Can. J. Earth Sci., vol. 4, pp. 949-960.

Ruffman, A., and Keen, M.J.
1967: A time-term analysis of the first arrival data from the seismic experiment in Hudson Bay; Can. J. Earth Sci., vol. 4, pp. 901-928.

Scheidegger, A.E., and Willmore, P.L.
1957: The use of a least squares method for the interpretation of data from seismic surveys; Geophysics, vol. 22, pp. 9-22.

Willmore, P.L., and Bancroft, A.M.
1961: The time-term approach to refraction seismology; Geophys. J., vol. 4, pp. 419-432.

SEISMIC INVESTIGATIONS OF THE CRUST IN THE HUDSON BAY REGION

Alan Ruffman
Institute of Oceanography
Dalhousie University
Halifax, Nova Scotia

The 1965 Hudson Bay crustal seismic experiment has been previously reported upon by the Geological Survey of Canada (Hobson, 1967b; Hobson et al., 1967), the Dominion Observatory (Barr, 1967), the University of Saskatchewan (Stuart, 1967), Dalhousie University (Ruffman, 1966; Ruffman and Keen, 1967) and the University of Western Ontario (Hunter, 1967; Hunter and Mereu, 1967). This paper reviews Dalhousie's interpretation of the crustal structure beneath Hudson Bay using mainly the seismic data available.

The crustal seismic experiment in Hudson Bay consisted of 41 shots of 1800 or 3600 lbs. of explosive detonated along an east-west line between Churchill, Manitoba and the Ottawa Islands and a north line from the centre of Hudson Bay to Chesterfield Inlet. Nine recording stations were operated by the above mentioned universities and government agencies as well as the Universities of Toronto and Manitoba. Eight were located around the periphery of Hudson Bay at Eskimo Point, Chesterfield Inlet, Coats Island, Povungnituk, Gilmour Island, Winisk, Cape Churchill, and Fort Churchill, with one hydrophone station in the centre of Hudson Bay. The navigation used in the Hudson Bay experiment was a combination of a Decca chain located on the west side of the Bay and of ranging using the hydrophone station on C.S.S. HUDSON in the centre of the Bay. The navigation method used and the problems encountered are adequately explained in Ruffman and Keen (1967). Two recent adjustments to the navigation are noted in Appendix 1.

The actual seismic experiment was carried out over a Precambrian crystalline basement almost entirely masked in Hudson Bay by a thin veneer of Palaeozoic and younger sediments 7000 to 10,000 feet thick (Hood, 1964; Hobson, 1967a; Hodgkinson, 1968). The Precambrian Shield in the survey area may be divided on the basis of structure, lithology and isotopic dating into two geological provinces: the Churchill Province to the northwest which is approximately 1700 million years old and the Superior Province to the southeast which is approximately 2500 million years old. The boundary between the two provinces as delineated in Manitoba by magnetic and geological trends (Bell, 1966; Kornik and MacLaren, 1966; MacLaren and Charbonneau, 1968) is confirmed in general by the isotopic dates available (Wanless et al., 1967). The boundary in northern Manitoba is now generally projected east beneath the Paleozoic cover, although earlier papers suggested that it continued northeast beneath Hudson Bay (Innes, 1960; Wilson and Brisbin, 1961). A basement age from the Sogepet-Aquitaine Kaskattama Province No. 1 well would clarify the argument. In northern Quebec, the boundary is placed at the southern edge of the Cape Smith-Wakeham Bay belt of highly folded and metamorphosed volcanics and may be correlated with a steep gradient of the Bouguer gravity field along this contact (Tanner and McConnell, 1964). At present, between Cape Smith and northeastern Manitoba the Churchill-Superior boundary is generally considered to be located along the eastern periphery of the Belcher Basin and westward under the Palaeozoic veneer into Manitoba (Wanless et al., 1967).

The Hudson Bay crustal seismic experiment was originally designed as three reversed refraction profiles. However, all regional interpretations attempted to date by all authors have applied the more versatile time-term method. In our interpretation we followed the time-term method as outlined by Berry and West (1966) and used only the first arrival data from the Hudson Bay experiment.

In using the time-term method one makes the assumptions that (a) P wave velocities in both the crust and the mantle are constant and (b) that for all azimuths the travel-time down to or up from the base refractor (mantle in this case) is a constant. Barr (1968) and Overton (1968) have challenged the first assumption (a) by suggesting that azimuthal variations in velocity may exist in the mantle beneath Hudson Bay. The second assumption (b) is challenged if one realizes that by assuming equal travel-time to the Mohorovičić discontinuity in all azimuths, one is assuming that the Mohorovičić discontinuity is horizontal around the circumference of a circle of radius (h tan i_c) where i_c is the critical angle of refraction and h is the depth to the base refractor. In Hudson Bay for depths of 30 km. to 40 km. the radius of this circle must be 35.7 km. and 47.5 km. respectively. These radii are in general greater than the shot spacing of 33 km. on the east-west line and 45 km. on the north line. From the profiles obtained by the time-term method alone we see that the differences in depth between adjacent shots in Hudson Bay indicate that assumption (b) may not always be warranted.

A further criticism has been made by Hajnal (1968). A single-layer crust was interpreted in earlier articles (Ruffman and Keen, 1967; Hobson et al., 1967; Hunter and Mereu, 1967) and Hajnal has challenged these interpretations by introducing a two-layer crustal model along the east-west line.

In Hudson Bay the travel-time plots and G.S.C. work yielded an average basement velocity of 6.33 km./sec. and the least squares velocity for the upper mantle was calculated to be 8.27 km./sec. This high mantle velocity, even with the curvature correction suggested by Mereu (1968), is entirely consistent with the low heat flow value found on Neilsen Island in the Nastapoka Islands (Jessop 1968) and those lower values generally found on shields. The notable features of the Mohorovičić discontinuity in Hudson Bay are the somewhat irregular topography, the somewhat irregular rise of the crust-mantle interface to shallow depths under Chesterfield Inlet, the persistent rise of the interface from Churchill to shot 22 (at approximately 670 km.) and its sudden drop to greater depths east of shot 22 (Fig. 1).

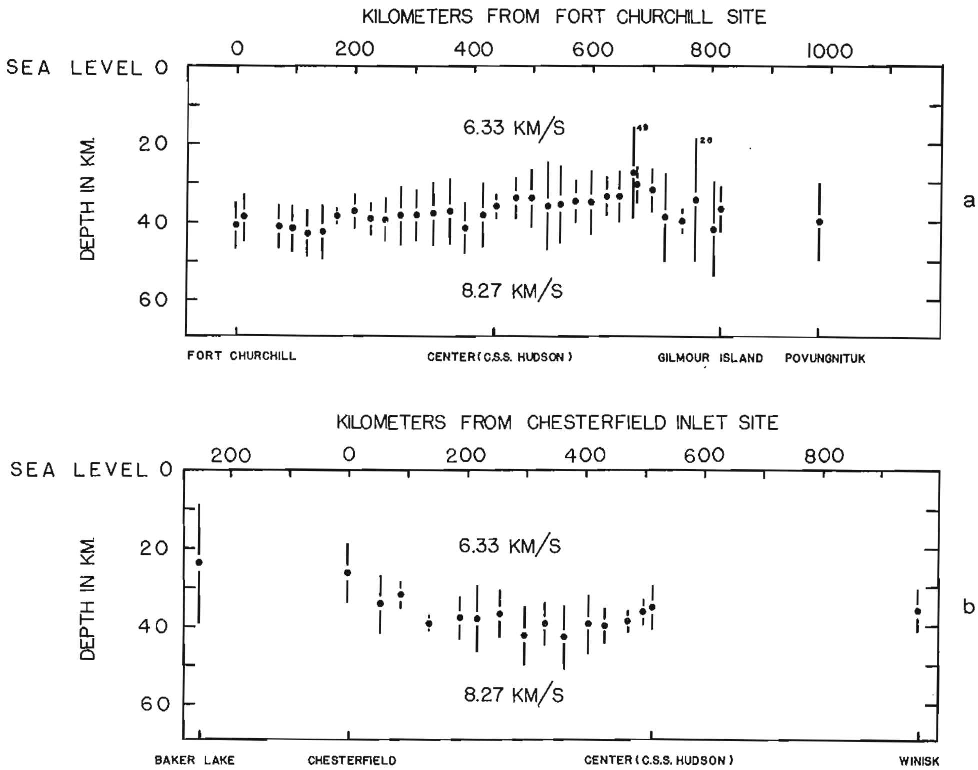


Figure 1. Dalhousie Solution M49, BM57 and M146: Profiles of the Mohorovičić discontinuity in Hudson Bay beneath (a) the east-west line and (b) the north line. The error bars indicate two standard deviations above and below the calculated depths. Shot 49, an extra shot with poor navigation, and shot 26, which depended on a 20 mile radar sight, both had very doubtful coordinates and hence large errors.

These time-term profiles (Fig. 1) are very similar to those from other authors who used slightly different data (Hobson et al., 1967; Hunter and Mereu, 1967). The shallow Mohorovičić discontinuity in the northwest of Hudson Bay and drop from 30 to 42 km. west of Gilmour Island are seen in all time-term publications concerning Hudson Bay. Hajnal's (1968) interpretation shows much the same structure west of Gilmour Island; however Overton (1968) suggests a different structure for the same area. The depths to the Mohorovičić discontinuity obtained by Mereu and Hunter (1967) just west of Churchill using the Early Rise shot point agree with the Hudson Bay time-term depths obtained near Churchill. The very shallow mantle depth to the northwest of the Bay is completely incompatible with the gravity data and in fact the gravity for the whole of the seismic survey area is at odds with the seismic findings and suggests lateral density variations within the crust or mantle (Innes et al., 1967).

If one assumes a crustal structure along the east-west line as seen in Figure 1, then the following interpretations can be made. The Bouguer map of Hudson Bay (Innes et al., 1967) clearly shows the westward continuation of the gravity gradient flanking the southern edge of the Cape Smith-Wakeham Bay belt. This seaward extension is recognizable for about 80 miles and passes northwest of the Ottawa Islands to approximately 59°40'N, 82°00'W. This point coincides with the 12 km. change of depth to the mantle recorded in the time-term interpretations, and it is reasonable to suggest that the change from positive Bouguer anomalies over the Cape Smith-Wakeham Bay belt of volcanic rocks to negative values of up to -70 mgal. south of the belt may be caused in part by the change from a shallow Moho under the belt to a deep Moho on the southern edge. It is also reasonable to suggest that this feature on the Mohorovičić discontinuity and the associated gravity anomalies are directly related to the Churchill-Superior boundary at depth in the crust.

Sea magnetometer data suggest that the Cape Smith-Wakeham Bay rocks continue into the Ottawa Islands (Hood, 1966; Hood et al., 1968). The southern edge of this belt has been traced, using the magnetometer data, to the southeast of the Ottawa Islands thus suggesting that the Churchill-Superior boundary on the earth's surface crosses northern Quebec and then arcs southward as it goes seaward from Cape Smith. A study of detailed bathymetric charts, seismic sparker profiles, and the few magnetic tracks available between the Ottawa Islands and the northern Belcher Islands may show the direct relationship between the rocks of these two areas.

Thus in the northeast portion of the Bay there is an apparent divergence between the surface and subsurface trace of the Churchill-Superior boundary as traced by the magnetic and gravity data respectively. The same divergence occurs in the southwest portion of the Bay where in Manitoba the gravity and magnetic delineation of the boundary seldom coincide and at approximately 56°30'N, 96°00'W the two diverge entirely; the magnetic trends turn east and the gravity trends continue northeast for another 60 miles. However, in this area the Owl River magnetic anomalies are found and Hood et al. (1968) find that these anomalies continue at least as far as 59°N, 88°W where they strike east-west. The authors also state that one branch of the anomaly may strike northeast toward Cape Smith. Thus there is some indication in Manitoba, in the approximate centre of the Bay and to the northwest of the Ottawa Islands, of structures continuing right across the Bay from Manitoba to Cape Smith.

The above data lead one to the conclusion that the location of the Churchill-Superior boundary at depth may be different from the boundary location at the surface. One should consider the boundary as a three-dimensional plane dipping at fairly low angles northwest under the Ottawa Islands and under the deposits of the Belcher Basin and dipping north under Proterozoic deposits southeast of Winisk. Thus the Proterozoic rocks of the Ottawa Islands, Hopewell and Nastapoka Islands, and Winisk area may be considered a moderately thin plate with a shallow northwest dip overlying a crystalline basement of Churchill age.

Apparently the dip of the boundary eventually becomes approximately vertical and it is along this line of vertical dip that one expects the major gravity anomalies to appear as well as possible deep-seated magnetic effects. It is also at the base of this boundary between two different crustal blocks representing two different orogenies that one would expect the greatest topography on the Mohorovičić discontinuity. Just such a feature is seen northwest of the Ottawa Islands coinciding with the gravity anomaly.

In other experiments crustal seismic profiles over boundaries between geological provinces have also shown discontinuities in depth. Mereu and Hunter (1967) found such a feature beneath the Churchill-Superior boundary when they recorded the Early Rise Experiment along a line NNW from the shot point in Lake Superior to a point west of Churchill. Ewing et al. (1966) found a step in the Mohorovičić discontinuity beneath the eastward extension of Logan's Line in the Gulf of St. Lawrence. In Manitoba, Mereu (1968) reports that the crust under the Churchill Province is 5-10 km. thicker than the Superior Province and Ewing found a 10 km. increase in thickness of the Appalachian Province over the Grenville. It is becoming apparent that the linear gravity and magnetic anomalies found along Logan's Line and its Gulf of St. Lawrence extension, along the Grenville Front, along the Churchill-Superior boundary and along the Thelon Front should be interpreted partly in terms of deep crustal structure and at times in terms of a provincial boundary that may be a three-dimensional feature.

At present work is being done at Dalhousie University on the second arrivals on the Chesterfield Inlet and Coats Island records in an effort to verify the structure originally found in the northwest portion of the Bay. The University of Saskatchewan (Saskatoon) also has a study in progress on second arrivals from their records at the Fort Churchill station (David Simpson, personal communication). Dalhousie is also considering deep-seated effects in the magnetic anomalies in the vicinity of the Churchill-Superior boundary in Manitoba.

I would like to thank the many people who cooperated to make the 1965 Hudson Bay Experiment a success and especially George Hobson who coordinated the crustal seismic program. I would also like to thank M. J. Keen who directed me in my M. Sc. work and the National Research Council which supported me.

APPENDIX 1

In Ruffman and Keen (1967) three possible series of navigation were put forward with series 1 by far the most acceptable. It is now clear that an incorrect position of Fairway Buoy off Churchill Harbour was used in our paper (Alan Goodacre, personal communication, 1968). The correct position is 58° 49'38.8"N, 94°06'16.8"W (Milton Hemphill, personal communication, 1968). Using the correct position series 2 becomes the same as series 1 and is therefore eliminated. Goodacre also suggests a different interpretation of M.V. THERON's log to give a revised position for shot 27 (shot 14-3), the easternmost shot. The new position is 59°50'10"N, 80°21'W. This position appears to be more accurate than that originally published by Hobson (1967b). The navigation for the three shots near Gilmour Island may still have large errors (Ruffman and Keen, 1967) because it depends on radar fixes only.

REFERENCES

Barr, K. G.

1967: Upper mantle structure in Canada from seismic observations using chemical explosions; Can. J. Earth Sci., vol. 4, No. 5, pp. 961-975.

1968: Evidence for variations in upper mantle velocity in the Hudson Bay area; this volume.

Bell, C. K.

1966: Churchill-Superior Province boundary in northeastern Manitoba; in Rept. of Activities, May to October, 1965, Geol. Surv. Can., Paper 66-1, pp. 133-136.

Berry, M. J. and West, G. F.

1966: An interpretation of the first-arrival data of the Lake Superior Experiment by the time-term method; Bull. Seismological Soc. Am., vol. 56, No. 1, pp. 141-171.

Ewing, G. N., Dainty, A. M., Blanchard, J. E. and Keen, M. J.

1966: Seismic studies on the eastern seaboard of Canada: The Appalachian System, 1; Can. J. Earth Sci., vol. 3, No. 1, pp. 89-109.

Hajnal, Z.

1968: A two-layer model for the earth's crust under Hudson Bay; this volume.

Hobson, G. D.

1967a: A reconnaissance seismic refraction survey in Hudson Bay, Canada; Panel discussion no. 9, Seventh World Petrol. Congr., Mexico City, April 1967, vol. 2, pp. 813-826.

Hobson, G. D. (con't)
1967b: Hudson Bay crustal seismic experiment: Time and distance data; Can. J. Earth Sci., vol. 4, No. 5, pp. 879-899.

Hobson, G. D., Overton, A., Clay, D. N. and Thatcher, W.
1967: Crustal structure under Hudson Bay; Can. J. Earth Sci., vol. 4, No. 5, pp. 929-947.

Hodgkinson, J.
1968: Reconnaissance seismic and magnetometer surveys in Hudson Bay, Canada; this volume.

Hood, P. J.
1964: Sea magnetometer reconnaissance of Hudson Bay; Geophysics, vol. 29, No. 6, pp. 916-921.

1966: Geophysical reconnaissance of Hudson Bay. Part 1. Sea magnetometer survey; Geol. Surv. Can., Paper 65-32, 42 p.

Hood, P., Bower, M. E. and Godby, E. A.
1968: Magnetic surveys in Hudson Bay; 1965 Oceanographic Project; this volume.

Hunter, J. A.
1967: The crust of the earth under Hudson Bay from seismic refraction studies; Unpubl. M. Sc. thesis, Univ. Western Ontario.

Hunter, J. A. and Mereu, R. F.
1967: The crust of the earth under Hudson Bay; Can. J. Earth Sci., vol. 4, No. 5, pp. 949-960.

Innes, M. J. S.
1960: Gravity and isostasy in northern Ontario and Manitoba; Publ. Dominion Obs., Ottawa, vol. 21, No. 6, pp. 263-338.

Innes, M. J. S., Goodacre, A. K., Weber, J. R. and McConnell, R. K.
1967: Structural implications of the gravity field in Hudson Bay and vicinity; Can. J. Earth Sci., vol. 4, No. 5, pp. 977-993.

Jessop, A. M.
1968: Three measurements of heat flow in Eastern Canada; Can. J. Earth Sci., vol. 5, No. 1, pp. 61-68.

Kornik, L. J. and MacLaren, A. S.
1966: Aeromagnetic study of the Churchill-Superior boundary in northern Manitoba; Can. J. Earth Sci., vol. 3, No. 4, pp. 547-557.

MacLaren, A. S. and Charbonneau, B. W.
1968: Characteristics of magnetic data over major sub-divisions of the Canadian Shield; Proc. Geol. Assoc. Can., vol. 19, pp. 57-65.

Mereu, R. F.
1968: Curvature effects on Hudson Bay and Project Early Rise seismic refraction results; this volume.

Mereu, R. F. and Hunter, J. A.
1967: The structure of the crust and upper mantle across the Superior-Churchill boundary from "Early Rise" data; Can. Assoc. Physicists Meetings, June 22-23, 1967, Toronto.

Overton, A.
1968: An alternative interpretation of the 1965 Hudson Bay crustal seismic data; this volume.

Ruffman, A.
1966: Crustal seismic studies in Hudson Bay, Canada; Unpubl. M. Sc. thesis, Instit. of Oceanogr., Dalhousie Univ., 127 p.

Ruffman, A. and Keen, M. J.
1967: A time-term analysis of the first arrival data from the seismic experiment in Hudson Bay, 1965; Can. J. Earth Sci., vol. 4, No. 5, pp. 901-928.

Stuart, J. A.
1967: Preliminary interpretation of the seismic crustal survey of Hudson Bay; Unpubl. B. Sc. thesis, Univ. of Saskatchewan.

Tanner, J. G. and McConnell, R. K.
1964: The gravity anomaly field in the Ungava region of northern Quebec with maps; Dominion Obs., Ottawa, Gravity Map Series, No. 5 and 6, 21 p.

Wanless, R. K., Stevens, R. D., Lachance, G. R. and Edmonds, C. M.
1967: Age determinations and geological studies, K-Ar isotopic ages (Report 7); Geol. Surv. Can., Paper 66-17, 120 p.

Wilson, H. D. B. and Brisbin, W. C.
1961: Regional structure of the Thompson-Moak Lake nickel belt; Can. Min. Met. Bull., vol. 54, No. 595, pp. 815-822.

CURVATURE EFFECTS ON HUDSON BAY AND PROJECT EARLY RISE SEISMIC REFRACTION RESULTS

R. F. Mereu
University of Western Ontario
London, Ontario

Abstract

The effect of the earth's curvature on crustal and upper mantle seismic refraction investigations was examined to determine under what conditions flat earth assumptions are valid. The results show that:

(i) When refractor depths are greater than 10 km, seismic velocities should be corrected for curvature using the formula $v = v' (R-H) / R$ where v is the true velocity, v' the apparent velocity, H the refractor depth and R the radius of the earth;

(ii) Refractor depths which are greater than 60 km should be calculated from time-terms using a more precise curvature- corrected time-term depth relation;

(iii) In surveys where refractor topography is irregular, curvature-corrections may be incorporated into the time-term method by an iterative procedure in which refractor distances are used in place of surface distances.

When curvature corrections were applied to the Hudson Bay, Early Rise and 1963 Lake Superior experiments, it was found that:

(a) the P_n velocities were reduced by 0.05 Km/sec to 8.20 ± 0.03 km/sec (Hudson Bay) and 8.05 ± 0.02 km/sec (Lake Superior);

(b) a high velocity layer (8.43 km/sec) was found at a depth of 84 km in the upper mantle under the Canadian Shield;

(c) other parameters such as time-terms, refractor depths, and error calculations were not affected significantly.

A comparison is made between the Mohorovičić discontinuity depth profile from the Hudson Bay experiment with that of the Project Early Rise Superior-Churchill line. The latter line shows that the boundary between the Superior and Churchill geological provinces is deep-seated. The earth's crust under the Churchill province is found to be 5 to 10 km thicker than under the Superior province which is relatively flat at 30-35 km. The results from the Hudson Bay experiment show that the boundary, which is not well defined under Hudson Bay near the surface, may still be well marked at depth.

INTRODUCTION

During the summers of 1965 and 1966 two major seismic experiments were undertaken to study the crust and upper mantle structure under the Canadian Shield. In the first experiment, 41 shots were set off by the Geological Survey of Canada along two lines in Hudson Bay. The University of Western Ontario recorded these shots at Eskimo Point which lies approximately 160 miles north of Churchill. Details of this experiment are given by Hobson (1967). In the second experiment known as Project Early Rise, 39 large shots were set off at one location in Lake Superior by the United States Geological Survey. These shots were recorded by a number of Canadian and U.S. universities and research institutions along a series of long profiles radiating from Lake Superior across the North American continent like the spokes of a wheel. Details of this experiment are given by Warren et al. (1967). The University of Western Ontario recorded the Project Early Rise shots at 61 stations. Thirty-nine of these stations (3-component) were placed along a 1500 km line running NNW from Lake Superior, across the Superior-Churchill geological boundary to the Baralzon Lake area of northern Manitoba near the 60° parallel (Fig. 1). One station was placed at Fort Churchill, Manitoba so that the experiment could be tied to the Hudson Bay experiment. In addition to the stations along this line, 21 additional stations were set up on roads in the region north and north-east of Lake Superior, to investigate whether or not the thick crust under Lake Superior extends northwards.

Details of the analysis of the Hudson Bay experiment were published in a collection of papers in the October 1967 issue of the Canadian Journal of Earth Science (Hunter and Mereu, 1967; Ruffman and Keen, 1967; Hobson et al., 1967; and Innes et al., 1967). Details and methods used in the analysis of data from the Project Early Rise Superior-Churchill line are given by Mereu and Hunter (1969). The results showed that at a depth of 84 km, the P wave velocity increases rapidly to 8.43 km/sec from 8.05 km/sec. A comparison of the results of the two experiments is shown in Figure 2. The time-term profile from the Superior-Churchill line was cut off at Churchill and placed end to end with the time-term profile obtained from the Hudson Bay experiment. These time-term profiles will illustrate the shape of the Mohorovičić discontinuity very well provided large changes in mean crustal velocities do not occur over short distances. If the mean crustal velocity is assumed to be 6.3 km/sec, approximate crustal thicknesses may be obtained from corresponding Moho time-terms simply by multiplying the latter by a factor of 10. Thus, for example, a time-term of 3.6 sec corresponds to a thickness of 36 km.

From Figure 2, it is seen that the thick crust (45 km) under Lake Superior rapidly returns to more normal values of 30 to 35 km at a point 300 km from the shot and then remains relatively horizontal to a distance of 900 km. Just south of the Nelson River which marks the boundary zone between the Superior and Churchill geological provinces, it thins to a value less than 30 km. North of the boundary the crust again thickens to values from 40 to

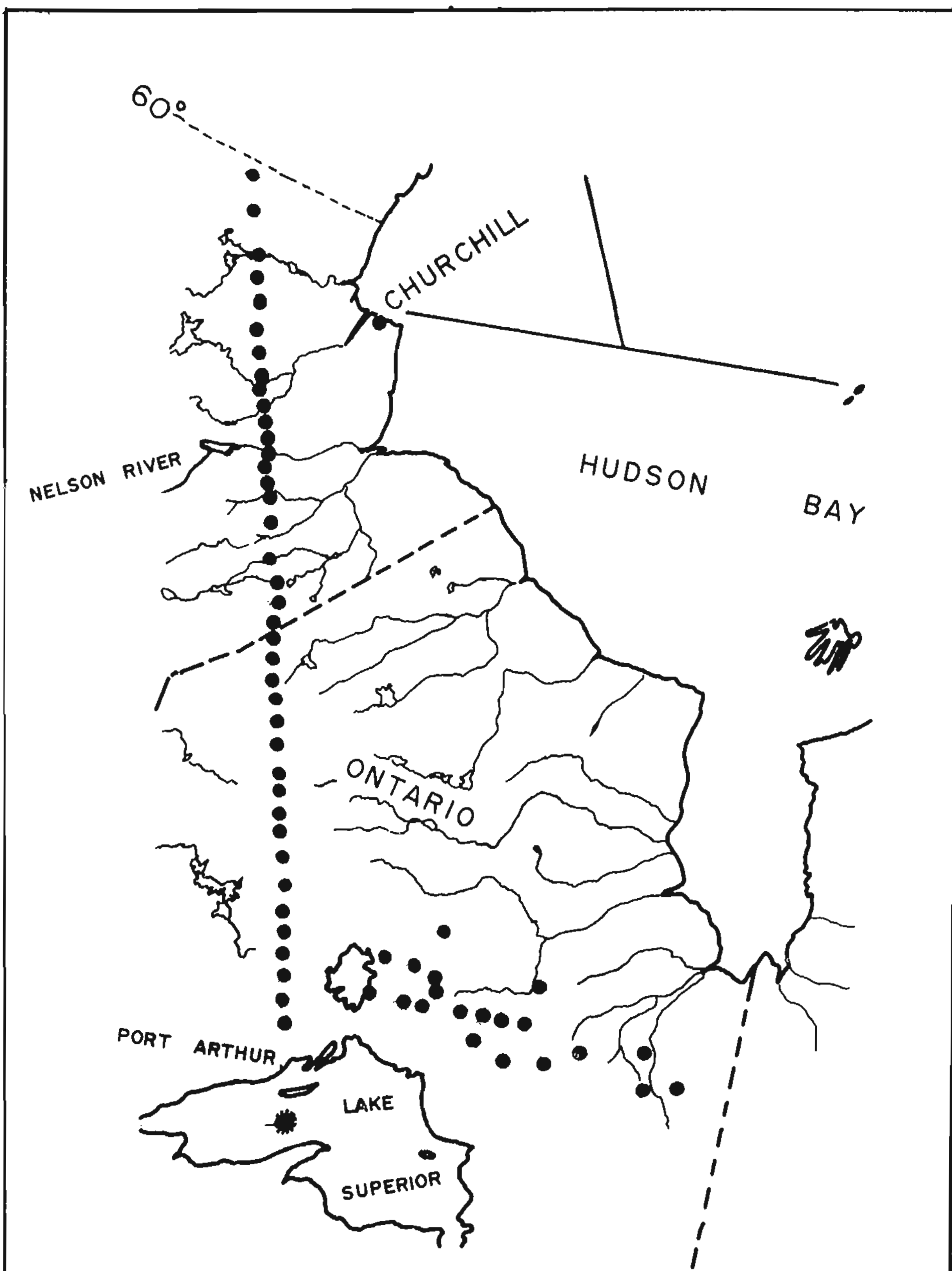


Figure 1. Project Early Rise — University of Western Ontario Stations. Lines drawn in Hudson Bay show 1965 Hudson Bay Experiment lines.

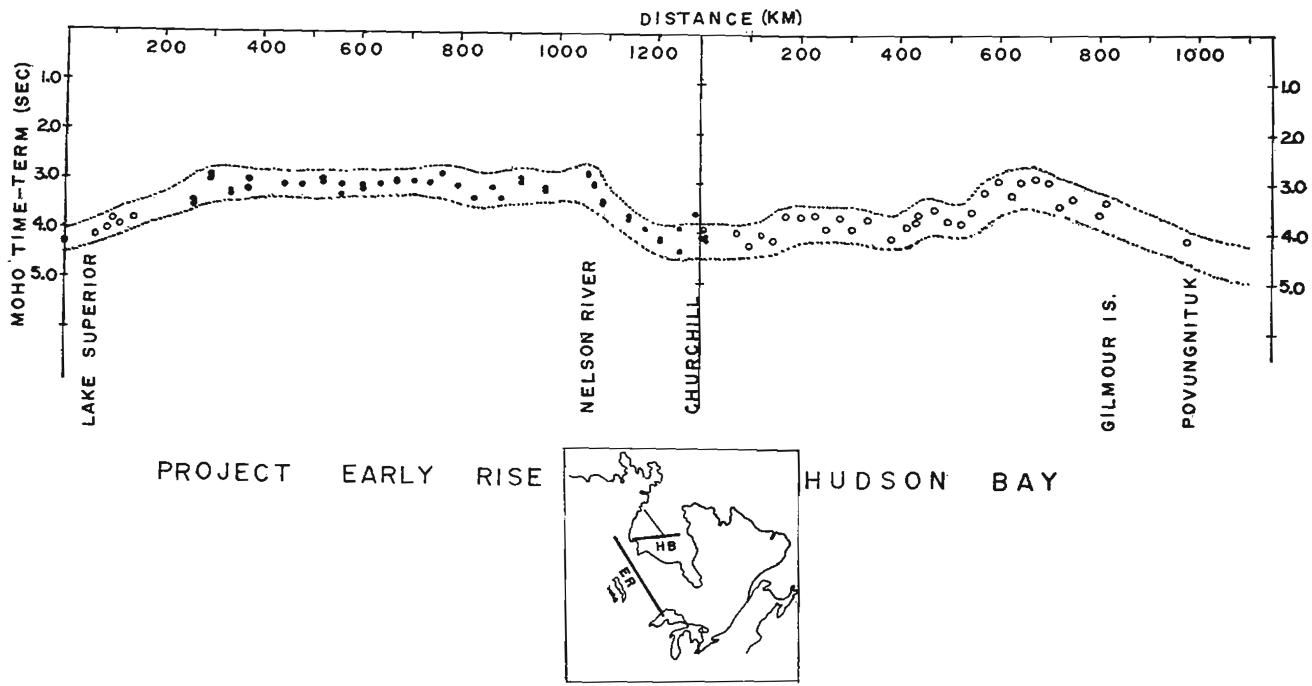


Figure 2. Comparison of Early Rise and Hudson Bay time-term profiles.

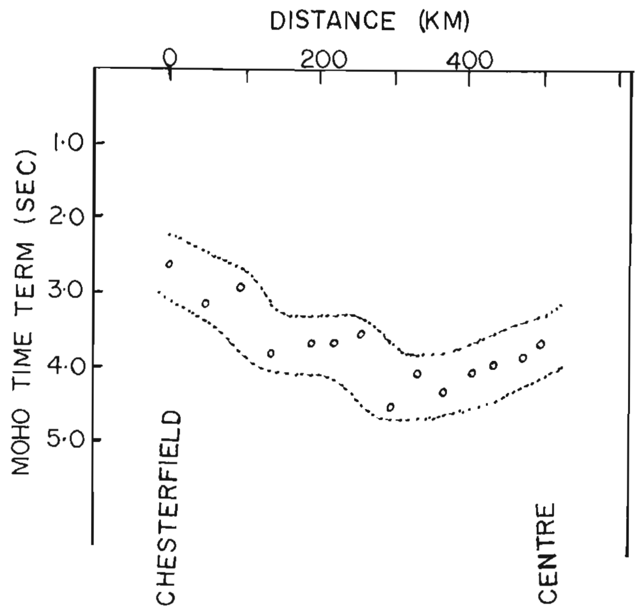


Figure 3. Time-term profile along line from Chesterfield Inlet to centre of Hudson Bay.

50 km thus showing that the contact between the two geological provinces is deep-seated. It is quite probable that during the Hudsonian orogeny mantle material may have extruded at the surface along the contact giving rise to high density rocks and the observed gravity high in the region. The E-W profile across Hudson Bay shows a distinct thinning of the crust over the eastern half of the Bay. If we associate the thinner crust with the Superior province then the boundary between the two geological provinces would occur at a point approximately 600 km east of Churchill. The gravity map by Innes et al. (1967) shows that the Nelson River gravity high does not extend out into Hudson Bay. We may thus conclude that under Hudson Bay, geological time may have erased or made diffuse the contact zone near the surface, while at depth 'finger-prints' of ancient tectonic activity may still be present.

The profile along the line to Chesterfield Inlet (Fig. 3) and time-terms at Eskimo Point (3.26 sec) and Coats Island (3.32 sec) show that the crust thins again over the northern area of Hudson Bay. Similarly the Project Early Rise data and time-term at Winisk (3.56 sec) indicate that the crust under the Superior province is normal and that the deep Mohorovičić discontinuity under Lake Superior is a local anomaly.

The thick crust under Povungnituk on the east coast of Hudson Bay suggests that this area may be associated with the Churchill province at depth.

However, according to geologists, Povungnituk should lie in the Superior province. This apparent disagreement could be removed if one assumes that the contact between the two provinces is not necessarily a vertical one. In other words, one could have Superior crustal material overriding that of the Churchill province. More detailed seismic work would have to be done in that area to test this hypothesis.

Curvature Corrections

Most upper mantle and crustal seismic velocity determinations are obtained by conventional seismic refraction techniques under the assumption that the earth may be considered flat up to distances of about 1500 km. The reason for this assumption stems from the fact that observed travel-time graphs are straight lines and that arc lengths are very nearly equal to their corresponding chord lengths. Over a distance of 500 km, the difference is only 130 meters or 400 feet. Clearly this appears at first to be a secondary effect when one has difficulty positioning a shot to within 0.5 km. However, it is the depth of the refractor rather than the length of the seismic line which determines whether curvature effects should be taken into account or not (Mereu, 1968). This follows from the fact that the travel-time equation for a curved earth is given by

$$a + b = t - \frac{x}{v} \qquad (1)$$

where a and b are station and shot time-terms, t the observed time, v the time refractor velocity, and x the refractor distance (distance measured along the refracting surface between the radii to the station and shot). If surface distances are used in this equation, as has been customary, then the velocity which is obtained is an apparent velocity v' which is related to the true velocity v by the relation

$$v = \frac{(R-H)}{R} v' \qquad (2)$$

where R is the radius of the earth and H the refractor depth. Significant differences between v' and v occur when the refractor depth is greater than 10 km.

Since under Hudson Bay the refractor depth H varies from point to point, equation 2 is not a convenient equation for application of the curvature correction. To get around this problem, an iterative procedure was adopted in which original surface distances were replaced by refractor distances at each step. Approximate refractor distances x_{ij} between shot j and station i were calculated from the relations

$$x_{ij} = \sqrt{r_i^2 + r_j^2 - 2r_i r_j \cos \Delta_{ij}}$$

where $r_i = R_i - H_i$, $r_j = R_j - H_j$,

H_i and H_j are apparent depths to station i and shot j,
R_i and R_j are radii to station i and shot j,
Δ_{ij} = angle subtended at the centre of the earth by the shot and station positions.

It was found that the above curvature analysis had no significant effect on the values of the individual time-terms or their confidence limits. For example the time-term under shot 1 changed only slightly from 3.10 $\pm$ .26 sec to 3.06 $\pm$ .26 sec. This means that time-term profiles are not altered by this correction. To be precise the time-term Moho depth relations for a curved earth given by

$$\alpha = \int_0^H \left[\frac{1}{v^2} - \left(\frac{R-H}{r}\right)^2 \frac{1}{P_n{}^2} \right]^{\frac{1}{2}} dz$$

should be used to determine Moho depths rather than the flat earth expression

$$\alpha = \int_0^H \left[\frac{1}{v^2} - \frac{1}{P_n{}^2} \right]^{\frac{1}{2}} dz$$

It was found however, that there is no significant difference between these two relations for refractor depths less than 60 km and hence need not concern us in this analysis.

The results of this analysis did however show that the value of the P_n velocity which was determined in the flat earth solutions should be reduced by 0.054 km/sec. It should be emphasized that this correction is greater than the standard deviation of the velocity measurement which was 0.03 km/sec and hence is very significant and must not be ignored. If the curvature correction is not made in seismic crustal experiments, "apparent" lateral variations in upper mantle velocities will appear from one region to another which are dependent on crustal thicknesses. The effect of ignoring curvature corrections in an experiment is equivalent to systematic errors in the positioning of the seismometers and shots by amounts up to 5 km.

Discussion

The three time-term solutions for Hudson Bay which were published in the Canadian Journal of Earth Science in October, 1967 were obtained from the same data, and were similar but did differ in fine detail. Because of poor statistical control, these detailed differences are to be expected. The standard error on most of the time-terms is of the order of $\pm$ 0.2 secs. Since many of the time-term values were determined by only 2 or 3 observations, small changes in initial input data resulted in different fine structure detail. This point is further illustrated by Table I where the velocity results and a sample of time-term results for a number of solutions are given. Solution 1 is similar

TABLE I

Selection of time-term solutions to Hudson Bay data

Solution Number	Solution Description	Apparent Velocity P'_n (km/sec)	Curvature Corrected Velocity P_n (km/sec)	Time-terms (sec)				
				Eskimo Point	Gilmour Is.	Shot 1	Shot 13	Shot 23
1.	Mereu	8.25 ± .03	8.20 ± .03	3.26 ± .14	4.05 ± .15	3.26 ± .22	3.72 ± .16	3.09 ± .14
2.	Hobson *et al.*, 1967	8.25 ± .03		3.42 ± .10	3.95 ± .07	3.17 ± .14	3.63 ± .13	3.00 ± .14
3.	Ruffman and Keen, 1967	8.27		3.06	3.74	3.49	3.79	3.25
4.	Hunter and Mereu, 1967	8.23 ± .03	8.17 ± .03	3.26 ± .16	3.85 ± .14	3.10 ± .26	3.62 ± .15	2.98 ± .15
	Omit*							
(a)	Eskimo Point	8.25 ± .03		-	3.98 ± .14	3.16 ± .23	3.51 ± .08	3.01 ± .15
(b)	Chesterfield Inlet	8.20 ± .03		3.09 ± .15	3.64 ± .13	3.04 ± .30	3.63 ± .15	2.99 ± .21
(c)	Coats Island	8.22 ± .04		3.23 ± .16	3.81 ± .14	2.88 ± .31	3.59 ± .18	2.95 ± .18
(d)	Povungnituk	8.22 ± .04		3.21 ± .16	3.78 ± .15	3.06 ± .28	3.68 ± .15	2.84 ± .13
(e)	Gilmour Island	8.25 ± .04		3.37 ± .16		3.16 ± .24	3.65 ± .14	3.02 ± .15
(f)	Winisk	8.22 ± .04		3.20 ± .14	3.75 ± .13	3.33 ± .15	3.61 ± .17	3.00 ± .18
(g)	Cape Churchill	8.23 ± .04		3.29 ± .16	3.91 ± .14	3.07 ± .42	3.67 ± .17	2.92 ± .17
(h)	Fort Churchill	8.23 ± .04		3.25 ± .16	3.85 ± .15	3.09 ± .25	3.67 ± .17	3.09 ± .14

*Note: Solution 4(a) is solution 4 omitting the Eskimo Point data from the analysis etc.

to solution 4 except that all travel-time data in the vicinity of the critical distance were omitted in the former. Solutions 4(a) to (h) were each obtained by omitting the data of one of the stations from the analysis. If the statistics of the problem were not weak, the deletion of one recording station should have only minor effects on the solution. However as is shown in Table I significant differences do occur from one solution to the other. One wonders what the velocity under Hudson Bay would be if there had been even one more station recording data. The only way this statistical problem can be resolved is to have a much larger number of recording stations. Accurate time-term solutions involving only a small number of shots and stations are feasible only in areas where the refractor topography is flat and refractor velocities uniform. It is doubtful that either of these conditions were met under a huge area such as that of Hudson Bay. The errors in the shot-positions only add to the difficulty. It should also be pointed out that because of errors in the arbitrary constant α , which is inherent in the time-term analysis, the level of the whole profile is also uncertain to the same extent as each individual time-term.

CONCLUSIONS

1. A comparison of the Project Early Rise Superior-Churchill line solution with the Hudson Bay experiment solution shows that the contact between the Superior and Churchill structural provinces is deep-seated. The thickness of crust over much of the Superior province is 30 to 35 km. A broad zone 200 to 300 km wide of thick crust (35-50 km) occurs north of the geological contact.

2. When refractor depths are greater than 10 km, seismic velocities should be corrected for curvature. For the Hudson Bay experiment the magnitude of the correction for P_n was found to be 0.054 km/sec.

3. The P_n velocity (corrected for curvature) under Hudson Bay is 8.20 $\pm$ 0.03 km/sec.

4. Because of weak statistical control on the data, and possible errors in shot locations, detailed Moho structure and reliable determinations of regional variations in P_n velocity were not possible.

Acknowledgments

I would like to express my deep appreciation to the following people for the help they gave me in carrying out the Hudson Bay and Project Early Rise experiments:

Mr. G.D. Hobson of the Geological Survey of Canada, Mr. de Le Barre and Mr. G. Thompson from the Arctic Institute of North America, Mr. L. Louttit and Mr. G. Kohls of Austin Airways, and Mr. J.A. Hunter of the University of Western Ontario. I would also like to thank the other participants of the

Hudson Bay and Project Early Rise Experiments for making both experiments a success.

This research was supported by -

(i) Grant A-1793 of the National Research Council of Canada

(ii) Grant AF-AFOSR-1140-66 of the Air Force Office of Scientific Research, The Arctic Institute of North America and the Advanced Research Project Agency of the U.S.A.

Canadian contribution No. 188 to the International Upper Mantle Project.

REFERENCES

Barr, K. G.
1967: Upper mantle structure in Canada from seismic observations using chemical explosions; Can. J. Earth Sci., vol. 4, No. 5, pp. 961-975.

Hobson, G. D.
1967: Hudson Bay crustal seismic experiment: time and distance data; Can. J. Earth Sci., vol. 4, No. 5, pp. 879-899.

Hobson, G. D., Overton, A., Clay, D. N., and Thatcher, W.
1967: Crustal structure under Hudson Bay; Can. J. Earth Sci., vol. 4, No. 5, pp. 929-947.

Hunter, J. A., and Mereu, R. F.
1967: The crust of the earth under Hudson Bay; Can. J. Earth Sci., vol. 4, No. 5, pp. 949-960.

Innes, M. J. S., Goodacre, A. K., Weber, J. R., and McConnell, R. K.
1967: Structural implications of the gravity field in Hudson Bay and vicinity; Can. J. Earth Sci., vol. 4, No. 5, pp. 977-993.

Mereu, R. F.
1968: Curvature corrections to upper mantle seismic refraction surveys; Earth, Planetary Sci. Letters, vol. 3, pp. 469-472.

Mereu, R. F., and Hunter, J, A.
in press: Crustal and upper mantle structure under the Canadian Shield from Project Early Rise data; Bull. Seismol. Soc. Am., vol. 59, No. 1.

Ruffman, A., and Keen, M. J.
1967: A time-term analysis of the first arrival data from the seismic experiment in Hudson Bay, 1965; Can. J. Earth Sci., vol. 4, No. 5, pp. 901-928.

Warren, D. H., Healy, J. H., Hoffman, J. C., Kempe, R., Rauula, S., and Stuart, D. J.
1967: Project Early Rise: travel-times and amplitudes; U.S. Geol. Surv., Tech. Letter No. 6.

A TWO-LAYER MODEL FOR THE EARTH'S CRUST UNDER HUDSON BAY

Z. Hajnal
Department of Geology, Mineralogy and Geophysics
University of Manitoba

Abstract

An interpretation of the primary and some significant correlatable later arrival data from the east-west line of the 1965 Hudson Bay crustal seismic experiment reveals a two-layer crustal model. Two very prominent events are identified as reflection arrivals from the intermediate and the Mohorovičić discontinuities. Head waves are also observable from these interfaces. Both interfaces show significant structural relief. A general gentle decrease in depth to these discontinuities from west to east is interrupted by a significant 'high' immediately west of Gilmour Island.

INTRODUCTION

The Hudson Bay crustal seismic experiment was carried out in 1965. Since then a number of papers have been published describing this survey and the results, Hobson (1967a), Ruffman and Keen (1967), Hobson et al. (1967), Hunter and Mereu (1967), Barr (1967). Because all these papers give an extensive description of the technical aspects and organization of this scientific undertaking, it was felt that no repetition is necessary here.

Although all the above reports give a detailed interpretation of the observed data, they use only the first arrivals of energy and rely mainly upon the time-term analysis technique. Examination of the data recorded by the University of Manitoba seismic crew at Cape Churchill shows that not only the first arrivals but some later events also can be used for interpretation. It is hoped, therefore, that an attempt to correlate both the first and some of the later arrivals with the geological section underlying Hudson Bay might prove to be a useful contribution to the already published results. The records studied are from Stations 13 to 41. These represent 70 per cent of the observed data and were recorded from an approximately east-west line across Hudson Bay (Fig. 1). The later arrivals were recognized as reflections from the intermediate and the Mohorovičić discontinuities.

The present interpretation favours a two-layer crustal model but a one-layer case was also investigated. Neither the one-layer case nor multiple reflections from shallow discontinuities are able to explain the existence of the observed later arrivals. With the exception of the intermediate layer, the velocities applied for depth computations are the same as those values of Hobson et al. (1967).

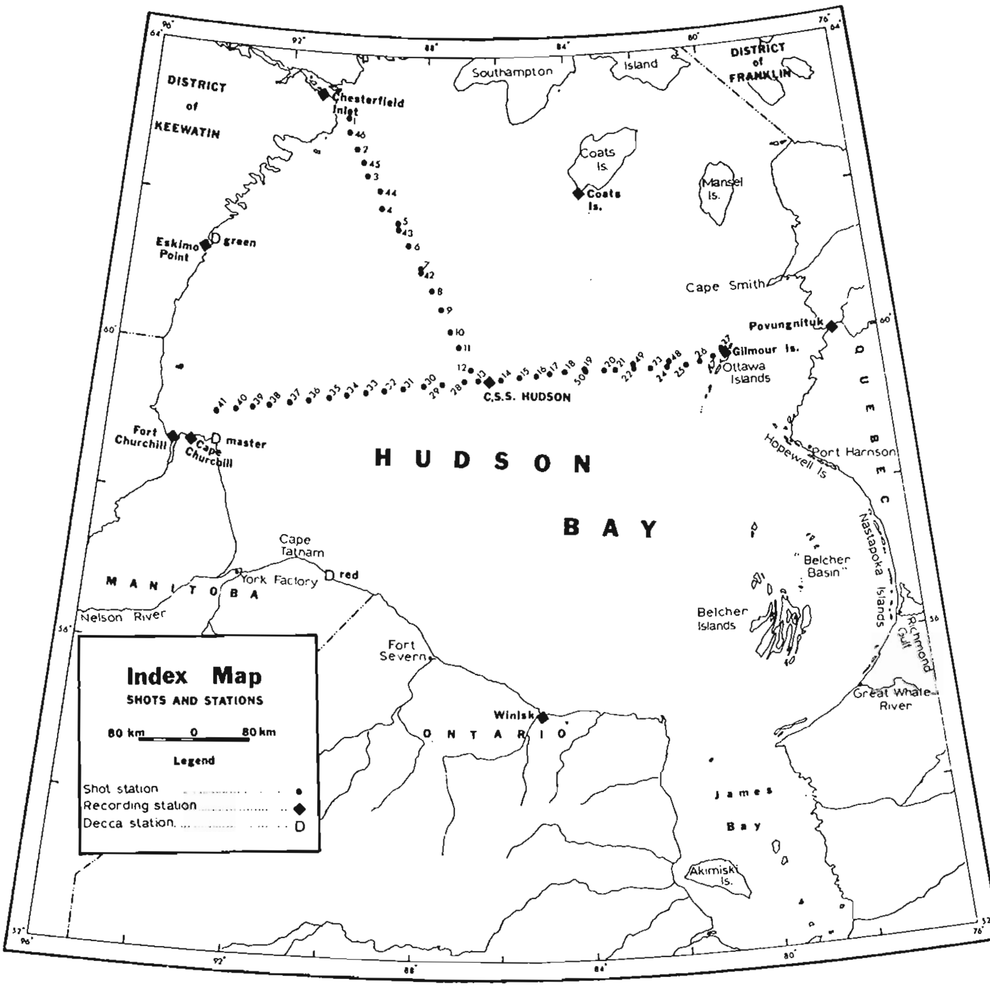


Figure 1. Index map showing shots and recording stations of the 1965 Hudson Bay seismic experiment.

Preparation of Data

The preparation of field data for study of later arrivals requires very extensive playback work. The best results are obtained if the filter and gain settings are changed from one time interval of interest to another on the examined records. In most cases for the Hudson Bay experiment the first arrivals of energy were strong and did not require extra amplification during playback. The later arrivals, especially P*, had to be played back with higher gain than the original recording.

The reflection arrivals are strong; they have large amplitude when the shot and recording sites are separated more than the critical distance. Special attention has to be devoted to records which indicate interference of two or more arrivals. These effects can be seen quite well on the fifth and tenth records on Figure 2. A better separation of events, than those obtained, may be achieved if narrow bandpass frequency filters or correlation techniques are available for playback work.

The frequency spectrum of the studied arrivals can be grouped between 3 to 20 cycles per second. There seems to be a marked change after 200 km. Inside this distance the higher frequencies prevail, whereas beyond this distance the lower frequencies start to dominate.

The observed arrival times were plotted on the standard time-distance graph. The line segments exhibit a distinct layered model crust. The hyperbolic character of the reflection data was also recognizable.

The velocities $V_1 = 5.2$ km/sec. for the sedimentary layer, $V_2 = 6.28$ km/sec. for the granitic layer and $V_4 = 8.25$ km/sec. for the upper mantle were taken from the time-term analysis of Hobson et al. (1967). The velocity of $V_3 = 7.10$ km./sec. was obtained from the previously mentioned time-distance graph. Because no reversed shots were available, this velocity may be considered as an apparent velocity. However the velocities taken from the time-distance curves and the velocities obtained from the time-term analysis deviate only within the experimental error; therefore, the error in V_3 is estimated to be not more than $\pm$ 0.2 km/sec.

Characteristics of the Seismic Profile

As a result of the final playback the records were assembled in section form on Figure 2. With the recognition of the first arrivals, two other dominant later events can be correlated through the whole seismic section. These later arrivals appear to carry a great part of the propagating seismic energy. This phenomenon can especially be observed at larger distances over 300 km. where the separation of the different arrivals is quite distinct.

Some of the marked arrivals on Figure 2 show very small energy. This misleading picture can be explained by the lack of automatic gain control on the playback system. To obtain a clearer view of the extremely strong later events, the gain on the amplifiers had to be decreased to a minimum level. This caused too much suppression for some of the standard events.

Reflection Data

The so-called PP and PPPP arrivals seem to have characteristics similar to those observed by Richards and Walker (1959) and Richards (1960) in the Alberta Foothills, by the German Research Group (1964, 1966), and

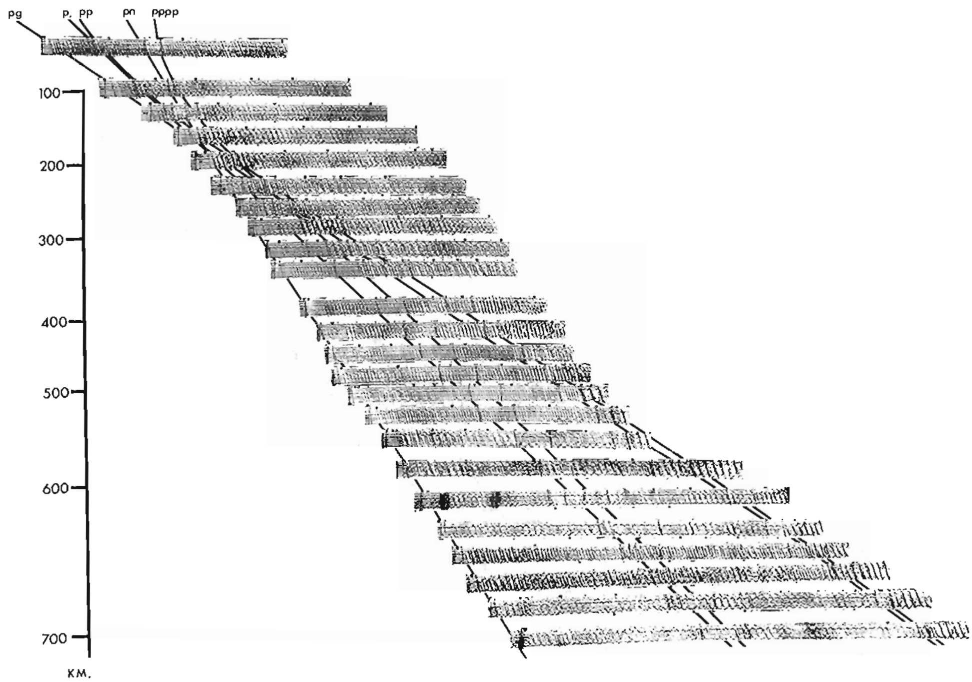


Figure 2. Seismic playback section showing first and later arrivals of energy recorded at Cape Churchill, Hudson Bay (1965) seismic crustal experiment.

by Dohr and Fuchs (1967) during their crustal reflection surveys. There is an observable decrease in the frequency spectrum of these arrivals with increasing distance. The change in amplitude with distance seems to follow the pattern as indicated by Richards.

Figure 3 is the X^2/t^2 plot of the reflection data. Two definite line segments can be observed with average velocity $\bar{V}_1 = 6.15$ km/sec. to the intermediate discontinuity and $\bar{V}_2 = 6.67$ km/sec. to the Mohorovičić discontinuity.

Interpretation Correlation to Geology

The geological setting of the surveyed area is adequately described by Ruffman and Keen (1967). Figure 4 summarises the results obtained from the combined interpretation of the refraction and reflection events. The maximum thickness of the sedimentary strata is attained in the central part of the bay and it is approximately 1.8 km. (Hobson, 1967b).

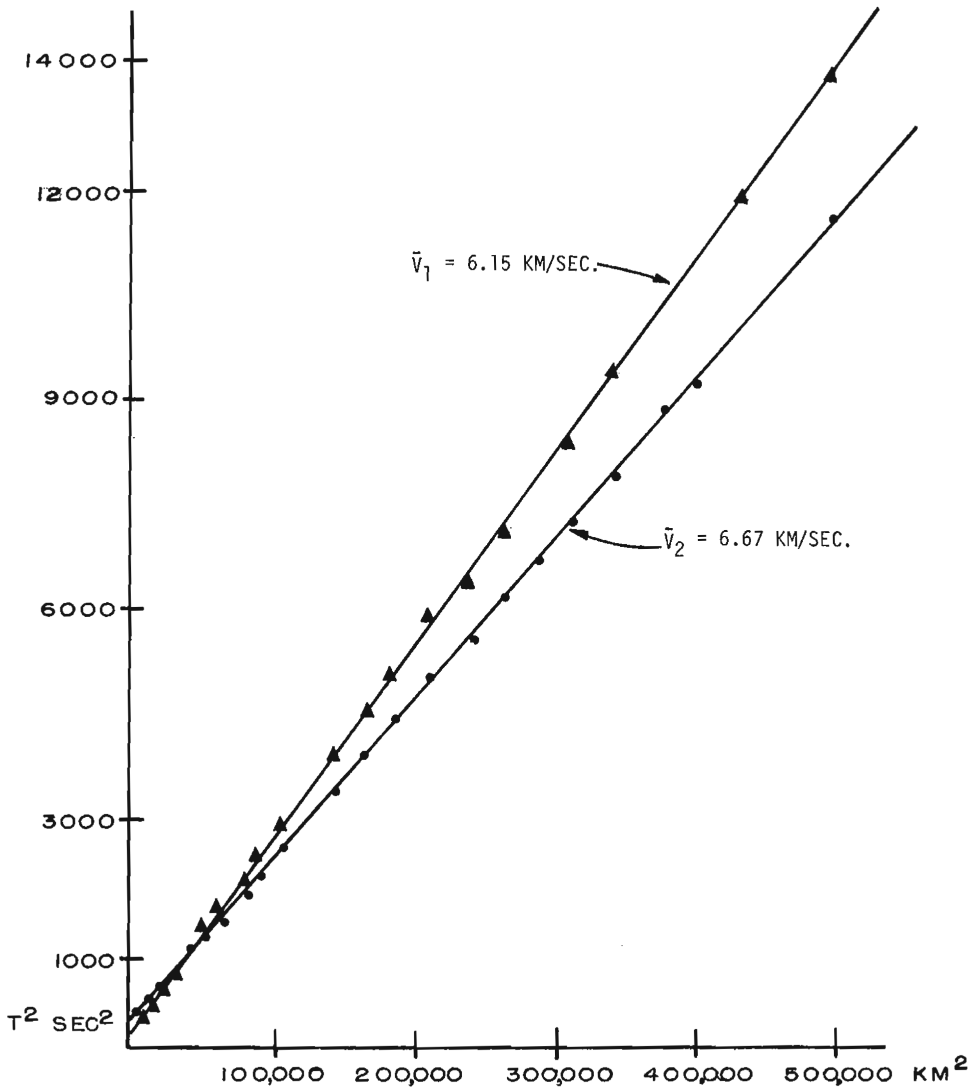


Figure 3. X^2/t^2 plot of reflection arrivals at Cape Churchill from shots 13 to 41, Hudson Bay crustal seismic experiment 1965.

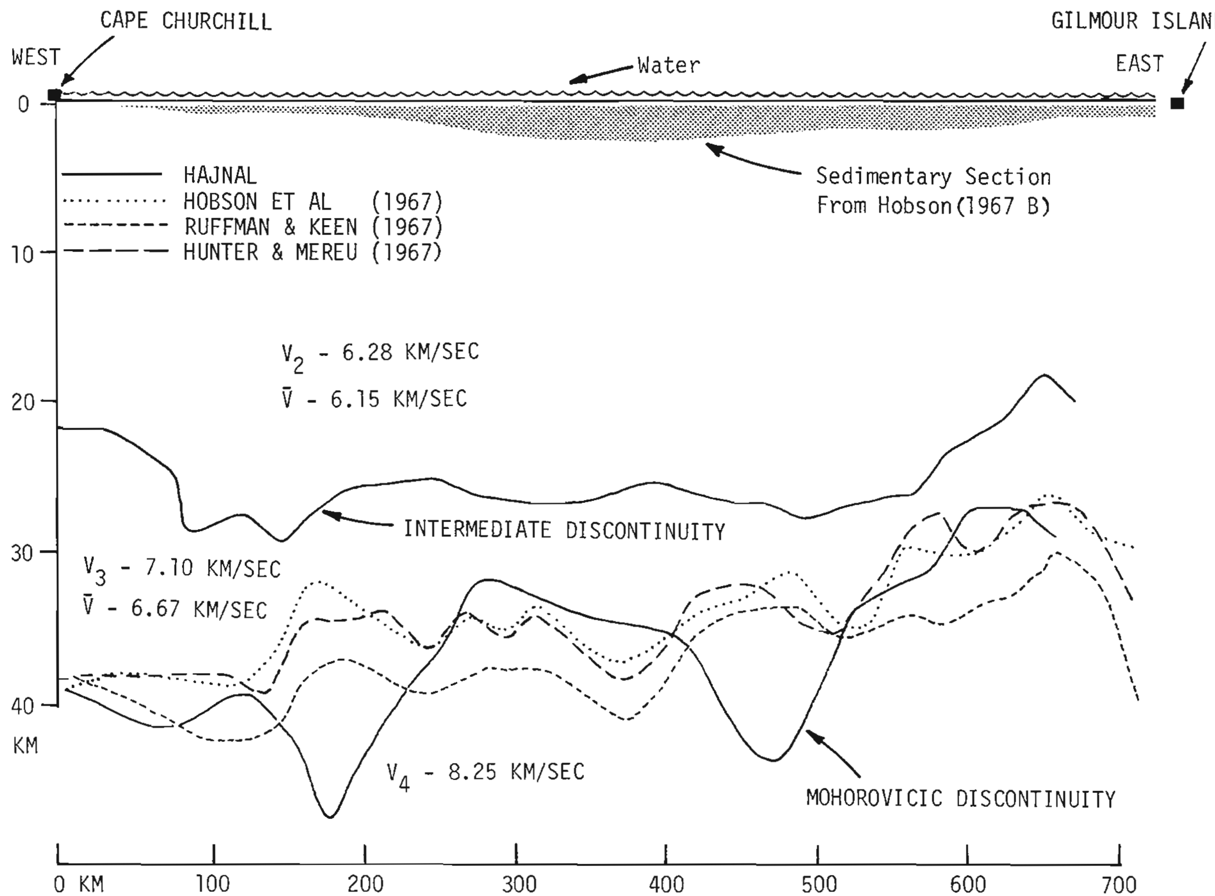


Figure 4. Two-layer model suggested from an interpretation of Hudson Bay 1965 seismic crustal data recorded at Cape Churchill.

Table #1

Sta. #	Distance in km.	Pg	P*	Pn	PP	PPPP	Inter-mediate layer depth km.	Moho depth in km.	Inter-mediate L.offset km.	Moho offset in km.
41	63.18	10.02	12.38	15.30	12.41	16.14	22.00	40.90	39.80	52.80
40	86.16	-	-	-	-	-	-	-	-	-
39	110.90		19.27	21.08	19.53	21.08	24.50	41.80	44.40	52.60
38	134.92	22.27	22.95	24.08	23.31	24.68	28.60	41.00	51.60	49.15
37	160.91	26.01	26.50	27.10	27.22	27.77	27.20	39.50	49.30	47.25
36	189.44	30.05	30.76	30.86	32.04	32.03	29.30	41.00	53.00	50.45
35	215.98	34.80	34.22	34.04	36.52	35.25	26.30	43.70	47.60	56.40
34	239.50	37.20	37.56	37.20	39.84	38.31	25.50	47.70	46.10	63.20
33	265.90		41.05	39.80	44.51	42.28	25.40	39.00	46.00	49.30
32	292.98	47.19	44.95	42.92	48.66	45.97	25.00	36.90	45.50	48.80
31	320.02	51.50	48.80	45.99	52.94	50.11	26.00	31.80	47.00	46.00
30	-	-	-	-	-	-	-	-	-	-
29	373.02	60.00	56.43	52.63	61.58	57.91	26.50	34.00	48.00	46.80
28	404.91	65.20	60.84	56.42	66.41	62.49	26.50	34.70	48.00	41.80
13	425.59	69.30	63.73	59.07	70.44	65.62	25.30	35.10	45.80	49.20
14	458.05	74.00	68.36	62.92	75.84	70.64	25.60	35.20	46.30	43.10
15	485.91	78.20	72.32	66.48	78.35	77.10	26.44	36.74	47.70	36.80
16	512.47	82.45	76.05	70.28	83.45	78.15	26.70	43.90	48.40	56.40
17	532.92	85.70	78.90	72.52		81.25	28.00	43.90	50.60	55.80
18	557.33	80.00	82.73	75.07	90.88	84.72	27.60	36.30	50.00	43.60
19	585.21	97.40	86.12	78.08	96.31	88.33	26.70	31.30	48.50	40.20
20	614.19	99.08	90.27	81.44	100.14	93.39	26.60	31.70	48.20	41.00
21	631.83	101.80	92.48	83.10	102.00	95.53	24.20	27.90	43.60	34.30
22	661.55	106.40	96.67	87.03	107.37	100.00	21.90	27.30	39.70	32.30
23	686.90	110.60	100.40	89.82	111.41		18.50	27.60	33.50	34.65
24	709.63	114.96	103.31	92.66	116.05	106.71	20.10	28.70	36.40	45.55

The two solid lines in the lower section display the present interpretation. The two dashed and one dotted lines are interpretations of Hobson et al. (1967), Hunter and Mereu (1967), and Ruffman and Keen (1967).

The present interpretation reveals a two-layer crust. The intermediate discontinuity has a maximum depth of 28 km. near the west end of the line and shows some rise to the east. A sudden increase in the elevation of the intermediate layer takes place just west of the Gilmour Islands. The minimum depth of 18 km. is close to station No. 23. Table 1 contains all the field and computed data.

The Mohorovičić discontinuity exhibits even more structural disturbance. Its maximum depth of 47 km. is located close to the west end of the profile. This discontinuity also shows a gradual rise towards the east. The unique characteristic of this interface is the separation into three distinct structural blocks. A detailed discussion of this block model for the crust under Hudson Bay is given by Hall (1968).

The easterly low on the Moho seems to fall in the line, which is defined by the free-air anomaly of the Dominion Observatory gravity map (Innes et al., in press). This free-air anomaly, in the Cape Smith region of northern Quebec, follows the boundary between the Superior and Churchill geological provinces. Ruffman and Keen (1967) came to a similar conclusion in consideration of the apparent change in the depth of the Moho west of Gilmour Island.

The broken lines on Figure 4 represent a one-layer crustal model. There are observable similarities between the Moho discontinuities of the one-layer and two-layer models; it is possible to interpret a decrease in depth of the Moho towards the east in both models, while the three blocks in the crust are not as definite in the one-layer crustal models.

The relative obscurity of the local lows in the one-layer models may be explained by the difference in the applied interpretation techniques. The time-term analysis is a least-square best fit method averaging out the recorded data, and it is possible that the local sharp changes are partially filtered by this technique.

The time-term technique also fails to consider the offset distances for the location of the computed depth. This is possibly the reason why there exist different locations of the anomalous zone from the two interpretations. The excellent fit of the location of the anomalies of the present model to the gravity profile over the same area (Hall, 1968), seem to indicate that the offset distances are important factors in the location of the derived depth values.

A further support for the above arguments is given by O'Brien (1968) in his reinterpretation of the Lake Superior seismic experiment. He concludes that the time-term method requires a plane surface beneath the station within the cone of critically-refracted rays. If this is violated the depth computation will supply scattered data which later leads to a distorted structure. He also found a 75 km. displacement of the structure beneath Lake Superior, when the offset distances were neglected.

Theoretical reflection arrivals were computed using a velocity of 6.28 km/sec. for a one-layer crustal model. The resultant values fell between the two observed reflection figures but not significantly close to either one of them.

The possibility of multiple reflections and reverberations were also considered. Several multi-path combinations were computed which included the water-sediment and sedimentary-crystalline rock interfaces. It is possible to find combinations which would give similar results to the observed data. However, all the fitting combinations required many reflections in the shallow zone.

The energy loss in the case of multiple reflections increases with the increasing number of reflections from different interfaces. This fact seems to indicate that multiples with relatively small number of reflections should be observed first and they should be stronger than those generated through multiple-path combinations. This situation does not exist on the Hudson Bay records. Becuase the one-layer model fails to account for the observed later arrivals the two-layer case has to be accepted as the best possible fit to the present set of data. It may be worthy to mention that investigations near Flin Flon, Manitoba, southwest of Hudson Bay also revealed a two-layer crust (Hall and Brisbin, 1965). Explosion studies in southeastern Manitoba and northwestern Ontario (Hall et al., 1968) also indicate a two-layer crustal model.

CONCLUSIONS

The good quality of the recorded data is an indication that the Hudson Bay seismic survey was technically well organized and that it was a successful experiment.

The interpretation utilizing the first arrivals of energy only, and that utilizing the first arrivals plus some of the later events results in two different crustal models. It would be very difficult to eliminate this difference with the present set of data. It may be concluded, however, that the most detailed interpretation should consider all the recorded arrivals. The characteristics of the later arrivals. The characteristics of the later arrivals and the geological section indicate that the observed later arrivals are wide-angle reflections. O'Brien (1968) believes that these wide-angle reflections are almost always present in crustal surveys. Further justification of this observation could open a new field in crustal seismic interpretation.

The sudden downward turn of the Mohorovicic discontinuity after 150 and 400 km. from the University of Manitoba recording site at Cape Churchill seems to reveal major changes in the upper mantle. More data would be required, however, to deduce definite conclusions about these anomalous zones.

ACKNOWLEDGMENTS

It is a great pleasure to express my thanks to G.D. Hobson, Geological Survey of Canada, for his invitation to participate in this project. I also wish to thank Dr. D.H. Hall for his encouragements and critical comments on this paper. This paper is the result of work supported by the Geological Survey of Canada, the University of Manitoba Northern Studies Committee and the National Research Council of Canada.

REFERENCES

Barr, K.G.
1967: Upper mantle structure in Canada from seismic observations using chemical explosions; Can. J. Earth Sci., vol. 4, No. 5, pp. 961-975.

Dohr, G. and Fuchs, K.
1967: Statistical evaluation of deep crustal reflections in Germany; Geophysics, vol. 32, No. 6, pp. 951-967.

Hall, D.H. and Brisbin, W.C.
1965: Crustal structure from converted head waves in central western Manitoba; Geophysics, vol. 30, No. 6, pp. 1053-1067.

Hall, D.H.
1968: A seismic-isostatic analysis of the crustal data from Hudson Bay; this publication, pp. 337-364.

Hall, D.H., Hajnal, Z. and Brisbin, W.C.
1968: Crustal structure of northwestern Ontario: Part II - refraction seismology (in press).

Hobson, G.D.
1967a: Hudson Bay crustal seismic experiment: Time and distance data; Can. J. Earth Sci., vol. 4, No. 5, pp. 879-899.

Hobson, G.D.
1967b: A reconnaissance seismic refraction survey in Hudson Bay, Canada; Panel Discussion No. 9, Seventh World Petroleum Congress, Mexico City, vol. 2, pp. 813-826.

Hobson, G.D., Overton, A., Clay, D.N. and Thatcher, W.
1967: Crustal structure under Hudson Bay; Can. J. Earth Sci., vol. 4, No. 5, pp. 929-947.

Hunter, J.A. and Mereu, R.F.
1967: The crust of the earth under Hudson Bay; Can. J. Earth Sci., vol. 4, No. 5, pp. 949-960.

Innes, M.J.S., Goodacre, A.K., Weston, A. and Weber, J.R.
1968: Gravity and isostasy in the Hudson Bay region; in Science, History and Hudson Bay, Dept. Energy, Mines and Resources, Ottawa, vol. 2, Chapt. 10, Pt. V, pp. 703-728.

O'Brien, P.N.S.
1968: Lake Superior crustal structure - a reinterpretation of the 1963 seismic experiment; J. Geophysics Res., vol. 73, No. 8, pp. 2669-2689.

Richards, T.C.
1960: Wide angle reflections and their application to finding limestone structures in the Foothills of Western Canada; Geophysics, vol. 25, No. 2, pp. 385-407.

Richards, T.C. and Walker, D.J.
1959: Measurement of the thickness of the earth's crust in the Albertan Plains of Western Canada; Geophysics, vol. 24, No. 2, pp. 262-284.

Ruffman, A. and Keen, M.J.
1967: A time-term analysis of the first arrival data from the seismic experiment in Hudson Bay, 1965; Can. J. Earth Sci., vol. 4, No. 5, pp. 901-928.

The German Research Group for Explosion Seismology.
1964: Crustal studies in Western Germany; Ztschr. f. Geophysik, vol. 5, p. 210.

The German Research Group for Explosion Seismology.
1966: Seismic wide angle measurement in the Bavarian Molasse Basin; Geophys. Prosp., vol. 14, No. 1, pp. 1-6.

A SEISMIC-ISOSTATIC ANALYSIS OF CRUSTAL DATA FROM HUDSON BAY

Donald H. Hall
Department of Geology, Mineralogy and Geophysics
University of Manitoba
Winnipeg

Abstract

A set of calculations has been designed to compare crustal seismic sections isostatically without reference to gravity data. These seismic-isostatic methods were applied to various interpretations that have been made for the east-west line (lat. 60°) of the 1965 crustal seismic experiment, and to crustal seismic results in areas surrounding the Bay. The following results were obtained: (1) depth of compensation is probably near 60 km, (2) the crustal section along lat. 60° exhibits a block structure; (3) the blocks may not all be in mutual isostatic equilibrium, although an alternative explanation may be that an inadequate isostatic model has been employed; (4) the west and central portion of the Bay is in isostatic equilibrium with the Precambrian Shield area to the south and the west of the Bay; (5) the extreme western portion of the Bay north of 58° lat. is isostatically 'light' as is a narrow crustal block running north-south at long. 86° W.; (6) a crustal block of about 200 km in width, running southwest from Mansel Island, is isostatically "heavy".

Comparison with gravity results suggests: (1) the isostatically "light" area on the west side of the Bay continues to the west of the Bay between latitudes 57° and 63° N.

INTRODUCTION

A number of interpretations of crustal structure under Hudson Bay have been made from data obtained in the seismic crustal experiment of 1965. Three interpretations of first arrivals using the time-term method have been produced by Hobson et al. (1967), Hunter and Mereu (1967), and Ruffman and Keen (1967). An interpretation using reflections and head waves has also been made by Hajnal (1968). Considering the interest that there has been for many years in the isostasy of the Hudson Bay area as summarized, for example, by Innes and Weston (1966), it is of interest to see how far the seismic crustal data can be used to examine isostasy in the Hudson Bay region. Traditionally, gravity data have been the principal source of information on isostasy, and more recently, with the increase in the amount of seismic crustal data, a combination of the two has been employed. A good summary of such combined interpretations is given by Woollard (1966).

It is an interesting question as to whether seismic data can be used more or less directly to give isostatic information independently of gravity results. If such a procedure were possible, seismic information, since it represents the least ambiguous type of data available on crustal structure could be used to advantage in isostatic studies. The present paper investigates this possibility, applying the results to the Hudson Bay crustal seismic interpretations.

Such studies may be of value in a number of ways. First of all, they might facilitate a comparison of interpretations. The four interpretations that have been made of the Hudson Bay crustal results fall into two distinct groups. The first three suggest a single-layer crust, while the fourth suggests a two-layer crust, with the layers separated by a seismic discontinuity similar to the Conrad discontinuity in Europe, or to the Riel discontinuity in Alberta (Clowes et al., 1958) or to the Intermediate discontinuity in Manitoba (Hall and Brisbin, 1961, 1965; Hall and Hajnal, 1968).

This difference between interpretations is important geologically, and any method whereby interpretations can be tested would be of value. There is the possibility that an examination of the isostatic implications of the interpretations would provide such a test. Some interpretations may, for example, lead to highly improbable values for pressure at the reference level.

Secondly, a number of seismic crustal surveys have been carried out in adjoining regions. From comparison of these results with the Hudson Bay interpretations it may be possible to compare the Bay isostatically with these surrounding regions.

CRUSTAL SEISMIC INFORMATION AND ISOSTASY

Parameters required for isostatic studies

Whether or not crustal units are in isostatic equilibrium is determined by the comparison of the pressures at some suitable "depth of compensation" beneath them (Heiskanen and Vening Meinesz, 1958, p. 124). Thus we shall begin by defining quantities which will enable us to determine pressures at depth from seismic crustal sections.

Pressure in terms of density and depth

Consider material in which density does not vary laterally, but varies in some manner with depth. The pressure p due to the section lying between depths d_o and d_R below sea level is:

$$p = g \int_{d_o}^{d_R} \sigma \, dz = g \, (d_R - d_S) \, \overline{\sigma}. \qquad (1)$$

If the depth d_o is taken as the surface of the earth, p is the pressure at a 'reference level' d_R. In isostatic problems, we will consider that the reference level is at the depth of compensation.

For certain purposes, we require the contributions of the crust to the pressure as a separate quantity. Thus we write:

$$p/g = (d_R - d_M)\,\overline{\sigma}_m + (d_M - d_S)\,\overline{\sigma}_c \tag{2}$$

where d_M is the depth of the Mohorovičić discontinuity below sea level, $\overline{\sigma}_m$ is the average mantle density above d_R and $\overline{\sigma}_c$ is the average density in the crust.

In some cases, it may be advantageous to treat surficial units of the crust, such as sedimentary or oceanic sections, as separate units. For this purpose, let us define a depth d_B (below sea level), which might be referred to as 'depth to basement', above which the surficial units lie. Such units are commonly found to be layered, and we will find it convenient to define layers with tops at d_o, d_1, d_2, ..., d_n, and with densities σ_o, σ_1, σ_2, ..., and σ_n. Letting the symbol $\overline{\sigma}$ represent average crustal density below basement, we may write:

$$\begin{aligned} p/g = {} & (d_R - d_M)\,\overline{\sigma}_m + (d_M - d_B)\,\overline{\sigma} + (d_B - d_n)\,\sigma_n + (d_n - d_{n-1})\,\sigma_{n-1} \\ & + \ldots + (d_2 - d_1)\,\sigma_1 + (d_1 - d_o)\sigma_o \end{aligned} \tag{3}$$

Pressure in terms of seismic velocity and depth

Since most of the quantitative determinations of crustal structure are by means of seismic surveys, it would be advantageous to express pressure in terms of seismic velocities and depths. It is possible to do this if it is assumed that, at the pressures encountered, a simple relationship holds between seismic velocity and density.

There is a considerable amount of evidence to suggest that in a statistically significant proportion of cases such a law does hold within the earth's crust and upper mantle. Graphs of compressional-wave velocity as a function of density are given by a number of authors (Woollard, 1959; Nafe and Drake, 1959). These graphs indicate that for velocities over 6 km/sec, an approximately linear relationship holds. Birch (1961) in a sequence of developments since 1938, has given a theoretical reason for expecting an approximately linear relationship, and has dicussed the relationship when viewed as an equation of state.

As a first-order approximation, then, we may write for density as a function of compressional-wave velocity (V):

$$\sigma = a + b\ V \quad (V > 6 km/sec) \tag{4}$$

where a and b are constants. Values of these constants are assigned by Birch (1961) and implied by the curves of Woollard (1959) and of Nafe and Drake (1959). These values vary somewhat from author to author. Smith, Steinhart and Aldrich (1966) discuss these values and examine their suitability in relating crustal gravity and seismic surveys in Lake Superior. The possibility is indicated in that paper of variations in a and b from area to area in the Lake Superior region. These authors use this form of the density-velocity equation to relate gravity and seismic surveys.

Let us substitute from (4) into (3), taking d_B as the shallowest depth at which (4) holds. Following this substitution, we find that:

$$p/g = d_R \overline{\sigma}_m - b\ [d_m \overline{V}_m - (d_M - d_B)\ \overline{V} - d_B V_B + c_1] \tag{5}$$

where $\overline{V}_m$ is the velocity in the mantle averaged from the reference level to the base of the crust, and $\overline{V}$ is the average crustal velocity from the base of the crust to the top of the basement. Let the crustal density and velocity immediately below the top of the basement be σ_B and V_B respectively. The quantity c_1 may be viewed as a near-surface correction in many problems, and is given by:

$$\begin{aligned} c_1 = \frac{1}{b}\ [\ &(\sigma_B - \sigma_n)\, d_B + (\sigma_n - \sigma_{n-1})\, d_n + \ldots + (\sigma_2 - \sigma_1)\, d_2 \\ &+ (\sigma_1 - \sigma_o)\ d_1 + \sigma_o\, d_o] \end{aligned} \tag{6}$$

This term of (5) is best left in terms of density because of the uncertainty of the relationship between density and seismic velocity at shallow depths.

It will be advantageous in our considerations of the earth's crust to define the quantity

$$S = d_M \overline{V}_m - (d_M - d_B)\, \overline{V} - d_B V_B = d_M (\overline{V}_m - \overline{V}) + d_B (\overline{V} - V_B) \tag{7}$$

This quantity is a crustal parameter, which can be determined from seismic sounding, with properties which are of value in seismic-isostatic studies. Then, from (5) and (7) we have:

$$p/g = d_R\bar{\sigma}_m - b(S + c_1) \qquad (8)$$

Since c_1 may be viewed as a correction term for near-surface conditions, we may form the quantity S' where

$$S' = S + c_1 \qquad (9)$$

Then we have:

$$p/g = d_R\bar{\sigma}_m - bS' = ad_R + bd_R\overline{V}_m - bS' \qquad (10)$$

Whenever c_1 is small, S' can be viewed simply as a corrected form of S i.e. as a reasonable approximation to S, which is a quantity which may be derived from seismic studies.

Expression for S for a particular model

In many cases we will assume that velocity is constant between the reference level and the Mohorovičić discontinuity, making $\overline{V}_m = V_R$. With this assumption, we may write (7) as:

$$S = \int_{V_B}^{V_R} z\, dV \qquad (11)$$

Or, if the crust is layered as shown in Figure 1,

$$S = \sum_{i=B}^{M} d_i \Delta V_i \qquad (12)$$

where d_i is the depth to the i^{th} interface, and ΔV_i is the velocity contrast across it. Because of (11) and (12) we will call S the depth-velocity integral or the depth-velocity sum.

APPLICATIONS OF THE DEPTH-VELOCITY INTEGRAL TO ISOSTATIC STUDIES

We will treat one of the simplest possible isostatic models in what follows. We will assume that we are dealing with crustal units which, during the time they were involved in isostatic processes, were able to move so that if they did achieve isostatic equilibrium, the compensation was local. By 'local compensation', we mean the case where the compensating layers are directly under the topography (Heiskanen and Vening Meinesz, 1958, p. 135). The criterion for isostatic equilibrium between two areas will be that of equal pressure at a reference level. With these assumptions, we may consider the following applications of seismic crustal information to isostatic studies.

Contour maps of pressure at reference level

Let us consider a number of areas such that each is capable of achieving local compensation and each possesses its own particular seismic crustal section (and consequently its particular value of S). If we can consider a common reference level for all these areas, and if $\overline{V}_m$ is the same for all, then it is possible to use the values of S to prepare a contour map which in many cases closely approximates a contour map of the pressures at the reference level corresponding to the various areas. If we choose an arbitrary reference value for S (call it S_b), then from (10):

$$p - p_b = gb\,[(S_b - S) + (c_{1b} - c_1)] = gb(S_b' - S') \qquad (13)$$

Thus, $S_b' - S'$ forms contours which parallel those of p. The near-surface correction $c_{1b} - c_1$ is nearly negligible in most cases. In these cases, we may regard the contours so established as having been formed from a purely seismic quantity. Any isostatic information derived from these contours may be regarded as seismic-isostatic information. A contour interval can be established if b is known.

The contour map, even without the contour interval being known, contains a considerable amount of information. An anomaly may be interpreted to mean any of the following: that an anomaly in pressure exists at the reference level; that the effects of unrecognized density anomalies are affecting the degree of compensation; that imperfections are present in the calculation, due to failure of the model assumed (local compensation) to match actual conditions; that the law relating pressure to density is not the same for all cases considered.

If the last three effects are not significant, the pattern of pressure will be an indicator of the degree to which isostatic equilibrium has been attained.

In a case where $\overline{V}_m$ varies from region to region, and d_R is constant and known, a plot of the quantity $(d_R\overline{V}_m - S')$ with an arbitrary base value subtracted will accomplish the same purpose. Letting the base value be $(d_R V_{mb} - S_b)$, we have

$$p - p_b = gb\,[\,d_R\,(\overline{V}_m - \overline{V}_{mb}) + S_b' - S'\,]$$

$$= gb\,[\,d_R\,(V_m - \overline{V}_{mb}) + S_b - S + (c_{1b} - c_1)\,]. \qquad (14)$$

Determination of reference level

Assuming our model as described above, if we let $c_2 = \frac{1}{b}\,(p/g - a d_R)$, and rearrange equation (10), we have

$$S' = d_R V_m - c_2 \qquad (15)$$

If we have a common reference level for a number of areas which are in isostatic equilibrium, c_2 will be a constant if a and b do not vary. Then if V_m varies from area to area, a graph of S' vs. V_m may be used to determine d_R, the reference level or depth of compensation. The plot will indicate a straight line with slope equal to d_R. Any area which is not in isostatic balance with the others will be presented by a point lying to one side of the line, as will one with a different reference level. Thus a plot of S' against V_R may also be used to compare areas, and indicate their isostatic equilibrium.

Thus a considerable amount of information can be obtained directly from seismic crustal surveys without reference to gravity data. All that is assumed is that a simple law relates seismic velocity to density at the pressures considered, and that this law remains the same for all the areas being compared. We have already seen that it is possible to separate areas which are in isostatic equilibrium, from those which are not, on the basis of seismic-isostatic information alone. Perhaps, however, the most interesting is the possibility of determining the reference level (or depth of compensation) from seismic information alone. We have seen that to make the results (other than the calculation of depth to reference level) fully quantitative, values of one or both of a and b, the constants in the depth-velocity relationship must be known. In order to do this, a comparison must be made between the seismic and gravity results.

COMPARISON WITH GRAVITY RESULTS

For a crust and mantle in which density varies with depth only, we may write for the contribution of material between d_s and d_R to free-air gravitational acceleration as:

$$g_F = 2\pi G \int_{d_S}^{d_R} \sigma \, dz + c_3 \tag{16}$$

where g_F is the free-air gravitational acceleration at the surface, and the integral is the contribution of the material lying above depth d_R (reference level), and c_3 (generally unknown) is the contribution of material below d_R. g_F has a close relationship to the pressure. Substituting from (1) into (16):

$$g_F = \frac{2\pi G}{g} p + c_3 \tag{17}$$

Or, if we are dealing with anomalies, Δg_F, the anomaly with respect to a base is given by:

$$\Delta g_F = \frac{2\pi G}{g} \Delta p \tag{18}$$

(assuming that c_3 does not differ across the area concerned) where Δp is the pressure anomaly related to the same base. Or, substituting from (10) into (17) we may write:

$$g_F = 2\pi G [\sigma_m d_R - b S'] + c_3 \tag{19}$$

If there is lateral variation in density as well as variation with depth, g_F wil have a different value from that given by (19). We may account for this by adding a term S_c to correct for the deviation of the actual case from that for no lateral variations. We may now write:

$$g_F = 2\pi G [\sigma_m d_R - b(S' + S_c)] + c_3, \tag{20}$$

where $\bar{\bar{\sigma}}_m d_R = ad_R + bd_R \bar{V}_m$ and S_c is a correction term for deviations from lateral homogeneity. Since c_3 is not known, there is no way of determining $\bar{\sigma}_m d_R$ and hence no way of determining a. We can, however, determine b, and it is sufficient to work with anomalies. For this case we write:

$$\Delta g_F = c_4 - 2\pi Gb\,(S' + S_c) \tag{21}$$

where c_4 is the value of $2\pi Gb\,(S' + S_c)$ at base. Thus, a plot of Δg_F vs. $S' + S_c$ will be a straight line, and b can be determined from its slope.

RELATION OF PRESSURE TO TIME-TERM

Perhaps one of the most definite quantities that can be calculated from a seismic refraction survey of the crust is the time-term. Berry and West (1966) and Smith, Steinhart and Aldrich (1966) discuss time-term solutions for crustal refraction surveys, and the first three crustal seismic interpretations of the Hudson Bay experiment that were mentioned in the Introduction above, express their results primarily as time-terms. It is of interest to investigate the relationship between this quantity and the parameters developed in the present paper for seismic-isostatic studies.

If we consider velocity, V varying with depth in the crust to depth d_M, and then a constant velocity V_R below the crust, then the expression for the time-term from basement (d_R) to the base of the crust is:

$$\alpha = \int_{d_B}^{d_M} \sqrt{\frac{1 - V^2/V_R^2}{V}}\; dz \tag{22}$$

where $V_R > V$.

If, as we have in the crustal case $(V_R - V) < V_R$, the integrand of (22) may be expanded:

$$\frac{1}{V}\,[1 - V^2/V_R^2]^{1/2} \simeq \frac{9}{4V_R} - \frac{15}{8V_R^2}\,V \tag{23}$$

$$\text{Then } \alpha \simeq \frac{9}{4V_R}\,(d_M - d_B) - \frac{15}{8V_R^2}\int_{d_B}^{d_M} V dz \tag{24}$$

Using definition (7) for S, we find that

$$S \simeq \frac{V_R}{5}\left[\frac{8}{3} V_R \alpha - d_m + \left(6 - \frac{5V_B}{V_R}\right) d_B\right] \qquad (25)$$

These equations have some bearing on whether different interpretations of the same crustal seismic data will lead to different estimations of the pressure at the reference level. Since time-terms can be calculated without assuming any particular vertical distribution of velocity in the crust, these should be the same for all interpretations of the same data. But the value of d_M from a given interpretation does depend on the velocity distribution adopted for the crust. Thus the value of pressure calculated will vary with adopted velocity distributions as follows: From equations (8) and (25), for the case where $\overline{V}_m = V_R$, a constant, the change Δp in p caused by a change Δd_M in d_M (for the same values of c_1, d_R, $\propto$ and d_B) will be given by:

$$\Delta p = \frac{-b}{5} g V_R \Delta d_M \qquad (26)$$

For typical values, such as b = 1/4 of a unit, V_R = 8 km/sec, we find that $\Delta p = 0.04 \Delta d_M$ kilobars. Δd_M rarely represents more than 5 km difference between widely different interpretations. The difference in calculated pressure would be 0.2 kilobars - negligible in isostatic studies.

Thus the theory indicates that the pressure at a reference level as calculated from differing interpretations of the same data will be virtually identical, as long as the different interpretations possess the same time-term. In such a case, an examination of the pressure at reference level gives little hope of choosing the correct interpretation among the various possibilities. On the other hand, the theory indicates that seismic crustal results can be used for calculations of pressure without concern as to the particular velocity distribution adopted within the crust, as long as the time-terms given by the solution for the crust as a whole are correct. This fact should be borne in mind when selecting crustal seismic results for use in isostatic studies.

SEISMIC-ISOSTATIC STUDY OF HUDSON BAY

Depth of compensation in surrounding areas

Values of S' were calculated from crustal seismic surveys in the Canadian Shield, platform areas. the Arctic Islands, the Gulf of St. Lawrence, and New England - within an 1800-mile radius of the Bay. The sources of

Table 1

Data from Canada and the United States before 1963, used in Figure 1

Solution numbers (McConnel and McTaggart-Cowan, 1963):

897, 903, 905, 906
907, 909, 910, 912
913, 914, 915, 918
919, 930, 932, 933

(shown in triangles)

Table 2

Data from Canada after 1963, used in Figure 1

Taken from:

(i) Barrett *et al.* (1964)
(ii) Hall and Brisbin (1965)
(iii) Sander and Overton (1965)
(iv) Ewing *et al.* (1966)
(v) Hall, Hajnal and Brisbin (1968)

(shown in squares)

Table 3

Composite crustal sections used in Figure 1

Solution numbers (McConnell and McTaggart-Cowan, 1963):

1.100, 1.200,
1.300, 1.400,
1.500

(shown in circles)

information are listed in Tables 1, 2, and 3. It is assumed that seismic velocity does not vary with depth in the upper mantle above the reference level. Then, if we let V_R represent the velocity in this portion of the mantle, $\overline{V}_m = V_R$. This quantity may differ from area to area. The calculated values of S' were then plotted against V_R, and are shown in Figure 1. Also included are values from three surveys which cover fairly large areas: that for the English River-Kenora area, the Lake Superior experiment of 1963 and the Hudson Bay experiment of 1965. The ranges covered by these values are shown as lines on the figure. The Lake Superior and Hudson Bay results show special features and will be discussed separately. Considering the remainder of the figure, we may note the following. First of all, in spite of the scatter, it is fair to say that the great bulk of values represents a spread along a line rising to the right. Thus we can say that in this figure, seismic information indicates that there is a tendency towards isostatic equilibrium in the earth's crust. There is no reference to gravity information, beyond the assumption that an equation of state links seismic velocity with density. This is then, an example of a seismic-isostatic study. The method at its present stage is not one with high resolution. The large scatter makes it difficult to decide on a definite slope for a best-fit line through the plot. This situation is the result of the rather low precision to be found in most seismic crustal data. We are, however, entering a period of greatly extended coverage and precision in seismic crustal surveys. It should be possible to produce much more precise seismic-isostatic conclusions from future data. In Figure 1, the English River-Kenora data probably represent a reliable group of values. The survey is over a stable shield area, which, on detailed study (Brown, 1968) appears to consist of crustal blocks nearly in isostatic equilibrium. The precision of the survey is good (Hall and Hajnal, 1968). If we constrain our best-fit line to pass through these data, a slope of anywhere from 50 to 100 km would be reasonable. If we consider only points from the nearest areas to the Bay (the Canadian data, shown as squares), a line with slope well below 75 km makes a good fit. Thus for the eastern half of Canada (the area considered) there is a tendency towards isostatic equilibrium, with compensation taking place at the base of the crust or just below it. This makes 60 km a reasonable value for the reference level – close to the value of 57.6 km for the eastern half of the United States, given in 1917 by Bowie as the depth of compensation for minimum isostatic gravitational anomaly (Bowie, 1917; Woollard, 1966, p. 561). A depth of compensation of 60 km was used by Smith, Steinhart and Aldrich (1966) in comparisons of gravity and seismic data over Lake Superior.

It is of interest that the composite averages for various classifications of continental crust given by McConnell and McTaggart-Cowan (1963) (shown as dots) in the Figure 1, all fall close to this range.

A PROPOSED BLOCK MODEL FOR THE CRUST IN HUDSON BAY

The crustal thicknesses given by Ruffman and Keen (1967), Hunter and Mereu (1967), or Hobson et al. (1967) suggest – although not definitely –

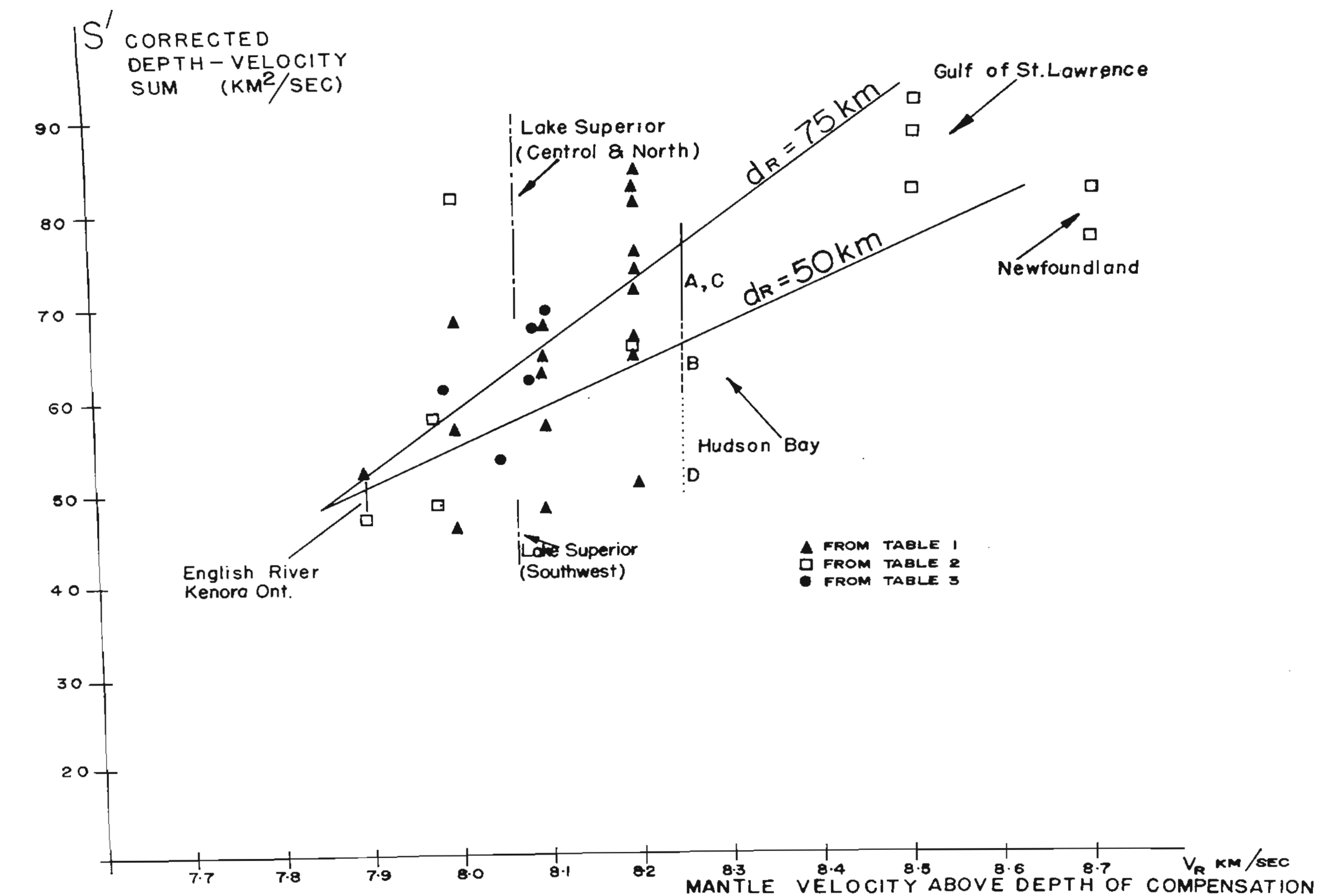


Figure 1. Plot of corrected depth velocity sum against velocity beneath the crust for determination of depth of compensation.

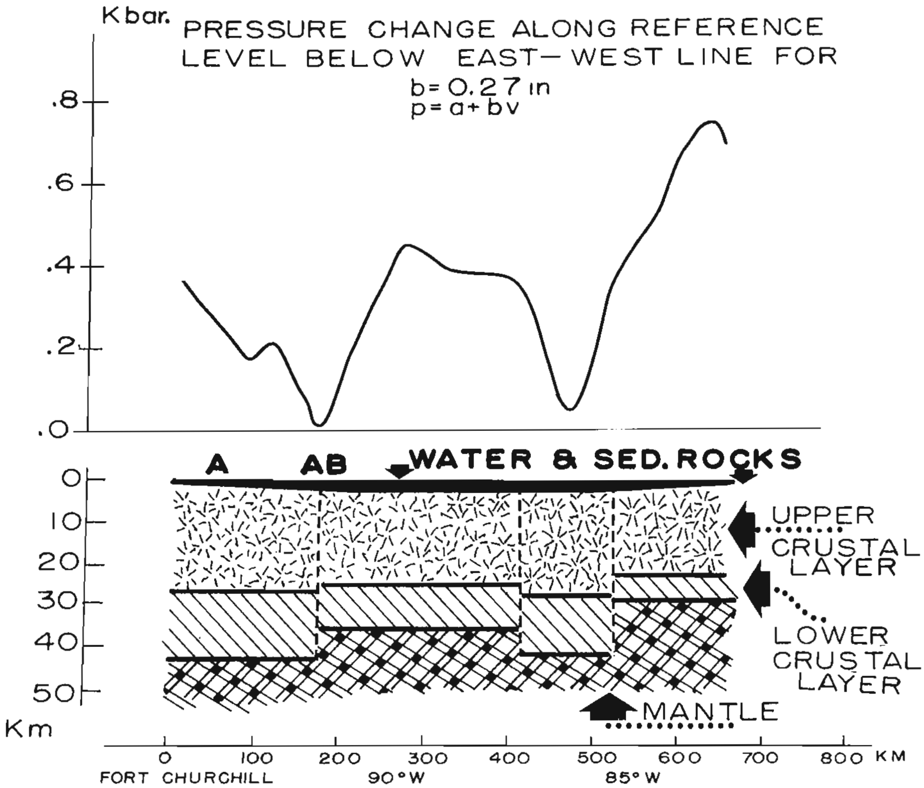


Figure 2. Pressure profile and proposed block model along the east-west line (latitude 60° N.) of the 1965 crustal experiment.

an arrangement of blocks with varying thicknesses. Both the crustal thickness and depth to the Intermediate discontinuity given by Hajnal (1968) suggest this same block structure much more strongly. As a final indication, a block structure is perhaps most strongly suggested by Figure 2. The figure was constructed by assuming a layered model, with the following densities: σ_R in mantle above reference level; σ_M in lower crustal layer; σ_I in upper crustal layer; σ_S in the sedimentary section above d_B (equal to σ_n in equation (3)); and water, density 1 gm/cm^3, overlying the sediments. In equation (3) let us put depth of water $d_W = d_1$, depth to basement d_B, depth to Intermediate discontinuity d_I, and depth to Mohorovičić discontinuity d_M. In this model $d_S = 0$. Then for the corrected depth-velocity sum (equations (7) and (9)),

$$S' = d_M (V_R - V_M) + d_I (V_M - V_I) + c_1, \tag{27}$$

where $$c_1 = \frac{1}{b}\left[(\sigma_I - \sigma_S) d_B + (\sigma_B - 1) d_W\right]$$

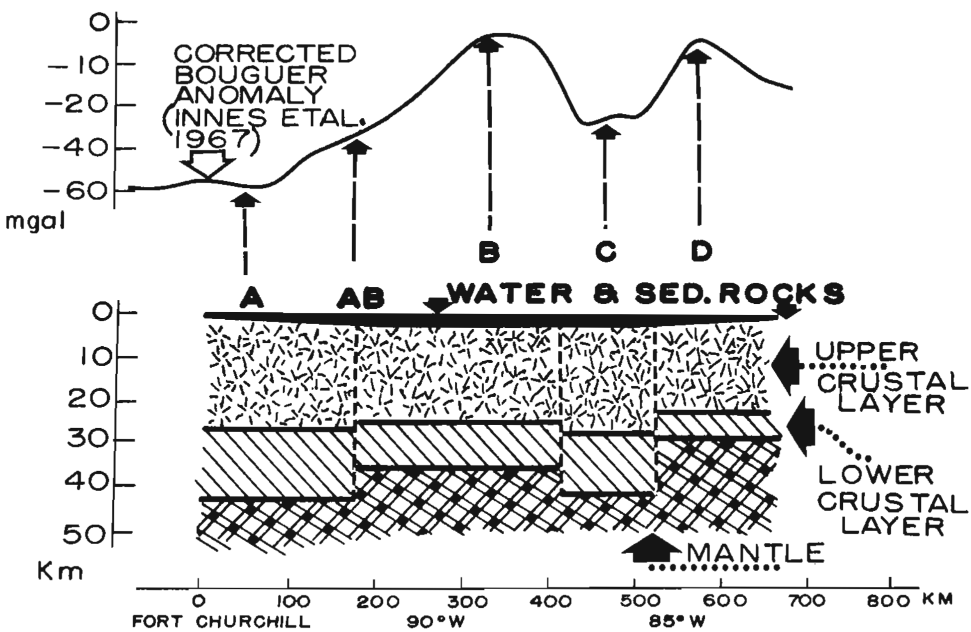


Figure 3. Bouguer gravity anomaly profile and block model for same line.

For calculations of S′, Hajnal's (1968) values of velocity and depth were used. For the correction term, b was taken as 0.27 units (the same value used by Smith, Steinhart and Aldrich (1966)), and the density values used by Innes et al. (1967) were taken. These values are: $\sigma_I = 2.7$ gm/cm^3 and $\sigma_S = 2.6$ gm/cm^3.

Figure 3 consists of a plot of $S_b' - S'$ multiplied by 0.0264 (equation (13)) to give $p - p_b$ in kilobars for S' in km^2/sec. This assumes again that b = 0.27 units. This value will be shown later to be a reasonable one for Hudson Bay. It should be emphasized that the shape of the pressure profile is independent of the multiplier, and that any information gained from the shape independently of the scale on the vertical axis is purely seismic-isostatic information. Points were plotted, on the average, at 25 km intervals. The shape of the graph is strongly suggestive of four crustal blocks, each of which is locally compensated, with blocks A and C in equilibrium with each other but not with B or D. The crustal interfaces for each block were obtained by averaging Hajnal's (1968) depth values across each block. The term "block" will be used to refer to a portion of the crust which acts as a unit during the process of isostatic adjustment, so that when masses are considered as averages over the lateral extent of the block, the blocks exhibit local compensation. Nothing is implied in the term as used in this paper as to the shape or nature of the boundaries between blocks. The block structure is proposed as an isostatic model at this point.

It should be pointed out that the two-layer interpretation would portray any block structure that might be present more clearly than the single-layer time-term interpretations, primarily because the time-term method, using many well-scattered observational connections, leads to considerable averaging or smoothing of the derived crustal profiles. This tends to obscure the transition between blocks. Thus the fact that the one-layer interpretations show the block structure to some degree, while the two-layer interpretation shows it clearly, can be taken as a proof of the validity of the two-layer interpretation.

A gravitational test of the block model

It is to be expected from equations (17) and (19) that there is a broad similarity between the pressure profile of Figure 2 and a free-air gravity profile along the same line. Figure 3 shows the Bouguer gravity profile of Innes et al. (1967), corrected for the water and the sedimentary layers. This is then close to being the free-air gravity profile for the crust from basement down. There is considerable similarity between the profiles. Both drop to a low over blocks A and C, and peak over blocks B and D. The model possesses lateral inhomogeneity in density; thus S_c is not zero and equation (20) applies rather than (19). Thus the shapes of the pressure and gravity profiles cannot be expected to coincide in detail.

For blocks with vertical sides, extending to infinity on each side of the profile, an expression for S_c can be derived by expanding equation (7-42a) of Heiland (1940, p. 151) and taking the second-order term. From this we find that S_c for a point over the centre of a block of width w is given by (assuming the sedimentary and water layers to be removed, to match the profile of Innes *et al.* (1967)):

$$S_c = - \sum_{i=M}^{I} \frac{2}{\pi w} (d_i^2 - \bar{d}_i^2) \Delta V_i \qquad (28)$$

where d_i is depths to interface for the block in question, and the $\overline{d_i}$ is the average of the depths to the i^{th} interface for the immediately adjoining blocks on each side.

For a density distribution with depth, considering z a function of depth this expression becomes:

$$S_c = - \int_{V_S}^{V_R} \frac{2}{\pi w} (z^2 - \bar{z}^2) \, dV \tag{29}$$

The corresponding integral for V as a function of z may be obtained by integration of (29) by parts.

For a point at the junction of two blocks numbered 1 and 2 we have (assuming the sedimentary and water layers to be removed):

$$S = S' = \sum_{i=M}^{I} \frac{d_{i1} + d_{i2}}{2} \tag{30}$$

$$S_c = + \sum_{i=M}^{I} \frac{1}{2\pi} \left(\frac{d_{i0}^2}{w_1} + \frac{d_{i3}^2}{w_2} \right) - \frac{1}{\pi} \left(\frac{d_{i1}^2}{w_1} + \frac{d_{i2}^2}{w_2} \right) \Delta V_i \tag{31}$$

For a density distribution, this can be generalized,

$$S_c = + \int_{V_B}^{V_R} \left[\frac{1}{2\pi} \left(\frac{z_0^2}{w_1} + \frac{z_3^2}{w_2} \right) - \frac{1}{\pi} \left(\frac{z_1^2}{w_1} + \frac{z_2^2}{w_2} \right) \right] dV \tag{32}$$

Blocks numbered 0, 1, 2 and 3 lie in sequence, with blocks 1 and 2 of width w_1 and w_2 respectively.

Brown (1968) has, in companion research, extended the derivations of the present paper to higher order terms.

In Figure 4, the gravity anomalies are plotted against $S' + S_c$. The fact that they fall on a straight line is at least a preliminary indication that the block structure as delineated by the seismic information also explains the gravity profile. Thus it would appear that there are no major undiscovered

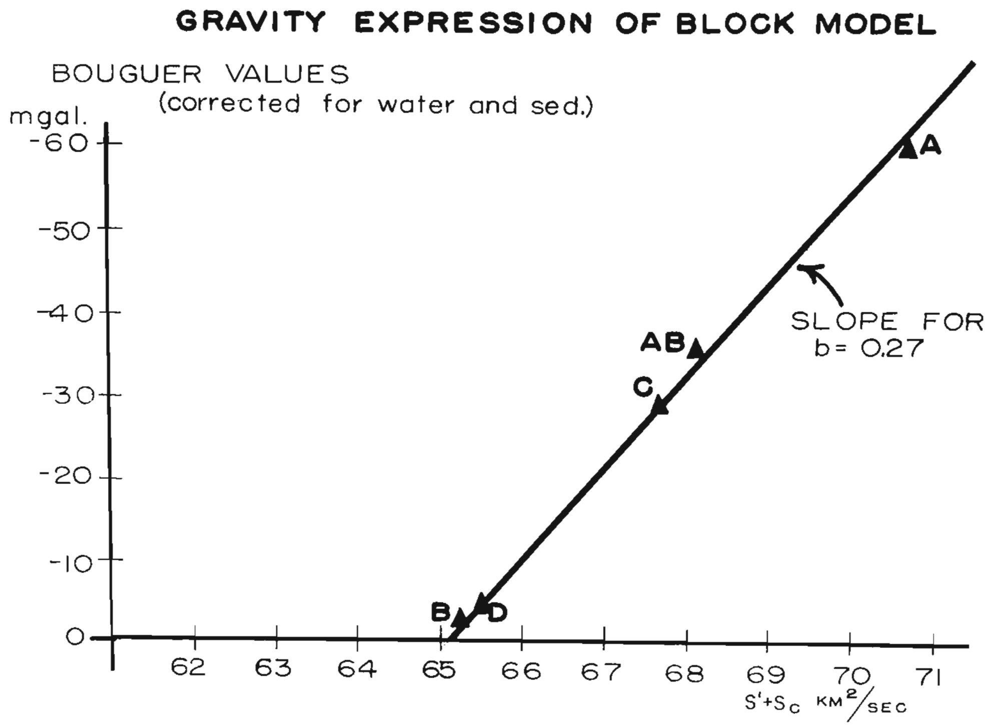


Figure 4. Comparison of the block model with the gravity profile.

density anomalies affecting the system. Figure 4 can also be taken as an indication of the validity of the two-layer interpretation of the crustal structure below Hudson Bay. The fact that the time-term interpretations cannot be reconciled with the gravity survey (Innes et al., 1967) appears to be due largely to the fact that the time-term method fails to offset structures properly, as does a delay-time method with applied offset such as was used for the two-layer interpretation. This may be seen in Figure 3, where the gravity low lies directly over the crustal thickening of block C. In the single-layer (time-term) interpretations, a similar thickening of the crust is shown, but it is displaced from the gravity low. This tendency towards averaging and displacement of structures in the time-term method is pointed out by O'Brien (1968) in a recent re-interpretation of data from the Lake Superior seismic experiment of 1963.

The slope of the line in the Figure 4 gives a value of 0.27 units for b in the equation $\sigma = a + bV$ for all blocks. Smith, Steinhart and Aldrich (1966) obtained this same value by another method for the Lake Superior region.

It should be emphasized that the conclusions that the two-layer block model satisfies the gravity data and that b is constant from block to block are tentative. They are based on calculations at five points only. It is recommended for future work that calculations of S_c' be made continuously along the profile, directly from the results of the two-layer interpretation.

Some features of the blocks

For our crustal model for Hudson Bay,. we may write the following equation, substituting from equation (27) into equation (10) (letting $\overline{V}_m = V_R$):

$$d_M = c_4 - d_I' \frac{\Delta V_I}{\Delta V_M}$$

$$\text{where } d_I' = d_I + \frac{c_1}{\Delta V_I} \text{ and} \qquad (33)$$

$$c_4 = \frac{1}{b\,\Delta V_M} [a d_R + b d_R V_R - p/g]$$

The quantity d_I' can be looked upon as depth to the intermediate discontinuity with a (usually small) near-surface correction applied. If we have a region in which a, b, d_R, and V_R are constant, and if the region is subdivided into blocks of different crustal thickness and average density but all in isostatic equilibrium (p is therefore also constant), then if the values of d_M and d_I' for each block are plotted, they will fall into a straight line of slope $-\frac{\Delta V_I}{\Delta V_M}$

Plots of d_I' vs. d_M were made, taking values approximately every 25 km or so along the two-layer crustal section (Hajnal, 1968). As might be expected, the points for the different blocks lie in different parts of the d_M - d_I' diagram. This occurs because the value of p in equation (33) varies from block to block. The points for blocks A and B form consistent patterns, as may be seen in Figures 5 and 6. This result may be taken as an indication that these blocks each consist of at least two sub-blocks in isostatic equilibrium with one another. Isostatic studies in the Kenora-English River area have indicated blocks of width 100 km or less acting as units in the isostatic process. Thus sub-blocks in A and B would not be unreasonably narrow. The lines in Figures 5 and 6 both have the same slope, about - 0.50. The value expected from the two-layer interpretation is - 0.75. This difference may occur because the actual velocity distribution within the crust is more complex

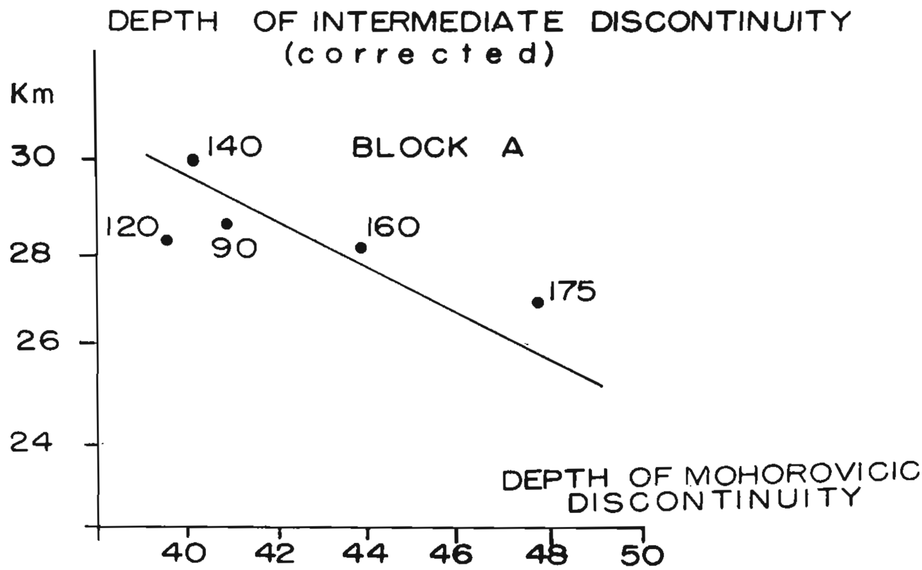


Figure 5. Test for isostatic equilibrium within block A. Distances in kilometres from Fort Churchill of points used are shown.

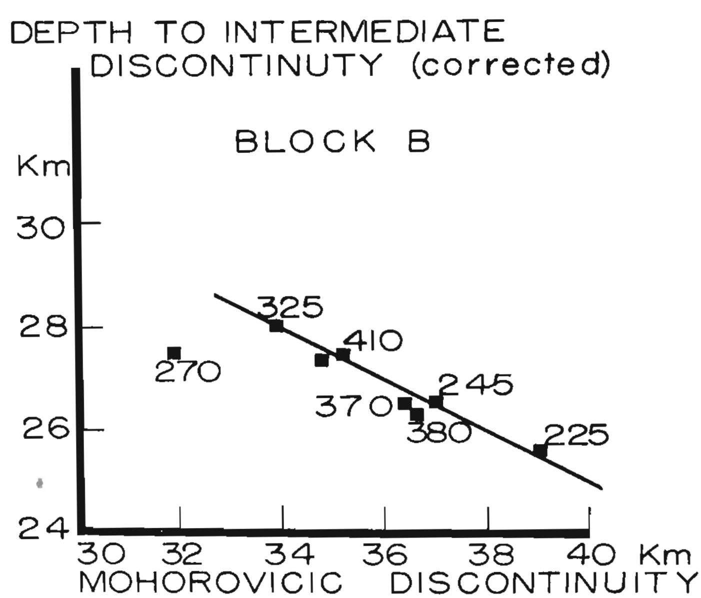


Figure 6. Test for isostatic equilibrium within block B. Distances in kilometres from Fort Churchill of points used are shown.

than was taken for the two-layer interpretation. The fact, however, that the general features of the plots match that expected from theory can be taken as a further indication that the crust does indeed have (at least) two layers.

COMPARISON OF SURROUNDING AREAS WITH HUDSON BAY

Relationship to English River-Kenora area

Returning to Figure 1, we are now in a position to compare the Hudson Bay values with the rest of the data.

We will assume a reference level of 60 km, and first compare the Hudson Bay crustal section with that of the English River-Kenora area to the south. A line with a slope of 60 km joins the English River values with a point representing the lower ranges of pressure beneath block B as may be seen on Figure 1. Thus if we assume that compensation takes place close to the top of the mantle, we imply that block B is in isostatic balance with the shield area to the south. In this case, blocks A and C would represent isostatically "lighter" blocks, while D would be isostatically 'heavier'. This interpretation is taken here as the most likely.

It is of interest to note that a greater depth of compensation would bring blocks A and C into isostatic balance with the shield to the south, while then both blocks B and D would be isostatically 'heavy'. Since crustal thickness places a lower limit on possible depth of compensation, block D (as may be seen on Fig. 1) can never be in isostatic equilibrium with the English River-Kenora area, no matter what is assumed regarding the reference level. Figure 2, and the derived block structure, does not overlap very far on block D, because it is based on the University of Manitoba's recordings at Fort Churchill. Record quality for that station was poor for the most distant shots to the east. The single-layer time-term interpretations also have the results from the Dominion Observatory station at Povungnituk (on the extension of the east-west line, on the east shore of the Bay). Those sections indicate that block D is 200 km wide, and that to the east of it, the crust thickens again.

Comparison with the gravity map of the Bay

The results of Figure 4 show that the gravity field largely reflects crustal structure. Furthermore, the gravity field over block D reaches about the same level as that over block B: the fact that block D is 'heavier' is offset in the gravity effect by the fact that it is narrower than B. Comparing our Figure 3 with Figure 3 of Innes et al. (1967), we can conclude that a crustal section comparable to block B covers that portion of the Bay above about -30 mgal. Thus most of the western half of the Bay is probably in isostatic equilibrium with the English River-Kenora area. Block D lies above the -20 mgal contour in the eastern part of the area – in a strip 200 km wide running southwest from Mansel Island. It may not continue farther south than latitude 60° N. This may be an isostatically 'heavy' block. Block C lies below the -20 mgal contour in the centre of the Bay. Thus there may be a narrow, isostatically 'light' block running north-south in the Bay at longitude 86° W. Block A, also isostatically 'light' lies below the -20 mgal contour in the western portion of the Bay. As shown in Figure 4 of Innes et al. (1967), this area of gravity low extends and increases in intensity to the west of the Bay from lat. 58° N. to 63° N. If our crustal-gravity model continues to apply in that locality, crustal thickening continues to the west, constituting an isostatically 'light' area. We have noted the crustal thickening shown by the time-term interpretations at Povungnituk. This may match the gravity low shown by Innes et al. (1967), in their Figure 4, and indicate a similarly 'light' area isostatically. A lower value of Bouguer gravity (as compared with block B of the Bay) which occurs over the English River-Kenora area would be expected even though the two sections are isostatically balanced because of the greater elevation of this area. This Bouguer gravity low is seen in Figures 3 and 4 of Innes et al. (1967).

An alternative method of comparison

Again, considering our crustal model for Hudson Bay, a substitution of equation (27) into equation (10) followed by a different arrangement of terms than was used to derive equation (33) leads to the following:

$$d_I' \Delta V_I = c_5 + (d_R V_R - d_M \Delta V_M)$$

$$\text{where } c_5 = \frac{1}{b} (a d_R - p/g) \qquad (34)$$

A plot of these quantities has a number of advantages. If a, b and d_R are constant over an area containing a number of crustal blocks, and if $d_I' \Delta V_I$ is plotted against $d_R V_R - d_M \Delta V_M$ for each block, all blocks with the same pressure at reference level will lie on a line with unit slope. Thus areas with different mantle velocities can be examined for isostatic equilibrium with other areas, without knowing anything but the results of seismic surveys. This is an extremely valuable form of seismic-isostatic information. Furthermore, as a result of defining the abscissa and ordinate as we do, the positions of points on the diagram are themselves significant. The crustal velocity distribution derived from an interpretation controls vertical position on the graph, while the interpreted conditions at the base of the crust control horizontal position.

Figure 7 shows such a diagram for Hudson Bay and regions around it, for a reference level of 60 km. Thus the figure indicates the same isostatic relationship between the Bay and the shield area to the south, described in the preceding section. Other crustal seismic sections on each side of the

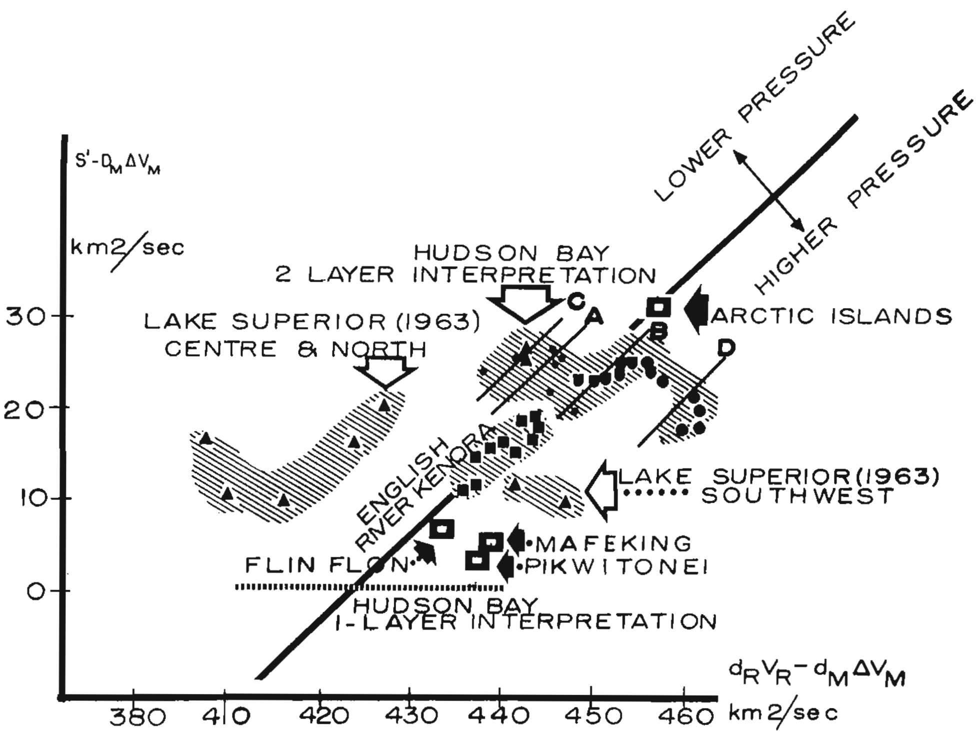


Figure 7. Seismic-isostatic comparison of the crust under Hudson Bay with other areas.

Bay lie near to the same iso-pressure line at the English River-Kenora values. The alignment of the English River-Kenora values is of interest – a more detailed analysis of this area has been made (Brown, 1968).

The relationship between the one-layer and the two-layer interpretations of the Hudson Bay data is also of interest, and illustrates the usefulness of this type of diagram. It has been shown in a previous section that interpretations using different crustal velocities and thicknesses and the same time-terms will yield close to the same values for pressure at the reference level. This fact is shown in Figure 7, with the one-layer and the two-layer interpretations from Hudson Bay. Both span about the same range of pressures. The two plots are in different portions of the diagram, however. The two-layer interpretation has a smaller velocity contrast across the Mohorovičić discontinuity, while depths are comparable, hence has a larger $d_M \Delta V_M$ product. Thus this interpretation is to the right and higher.

THE LAKE SUPERIOR EXPERIMENT

In Figure 1 and Figure 7, the results from the 1963 Lake Superior crustal seismic experiment are in anomalous positions. The results from the southwest portion of the lake form a group of points well separated in the diagrams from those for the central and northern part of the lake.

Smith, Steinhart and Aldrich (1966), in relating the crustal seismic results to gravity results found that a satisfactory agreement could be obtained for these two types of data for the whole lake only if a difference in the constant b ($\partial\sigma/\partial V$) between the two parts of the lake were assumed. They required b to be 0.03 units (about 10%) lower in the northern part of the lake. We may estimate the effect of this difference on Figure 1. From equation (15), the change in S' corresponding to a change Δb in b is given by: $S' = \frac{-\Delta b}{b} c_2$. From Figure 1, we see that c_2 is about -430 units for $d_s = 60$ km. For $\Delta b/b = -1/10$, $\Delta S' \doteq 40$. This is about the separation involved in the figure.

Thus we may have in this example the expression of variation in the parameter b. Since this quantity may be related to composition, it is evident that there is the possibility that seismic-isostatic studies can also provide information on composition.

This effect might, in fact, cause differences in our calculated pressures under various blocks. Therefore this effect should be regarded as a possible alternative to isostatic unbalance as an explanation of pressure profiles such as in Figure 2. In the present case, however, our interpretation of Figure 4 is that b is the same for all blocks. This leaves isostatic unbalance, or an inadequate choice of isostatic model, as the explanation of Figure 2. Thus a more detailed calculation to fill in intermediate points in Figure 4 is recommended for future work, to check the constancy of b from block to block.

MAFEKING AND PIKWETONEI VALUES

Returning to Figure 7, shown are values derived from crustal seismic results at Mafeking and Pikwetonei, Manitoba. Both are points which lie close to the Churchill-Superior boundary, on the Superior side. It so happens that they lie on the same line of unit slope as the Lake Superior southwest values, and block D in Hudson Bay. The connection is pointed out here, but no definite interpretation is offered - and perhaps none should be - at this stage. It has been suggested that block D lies along an extension of the Churchill-Superior boundary, on the Superior side (Ruffman and Keen, 1967). However, this block may rather be related to an extension of the 'Kapuskasing high' (Innes et al., 1967).

CONCLUSIONS

1. If it is assumed that an equation of state links seismic velocity and density, a number of means are available for examining seismic crustal sections directly to yield isostatic information. Thus seismic-isostatic information is a possibility. A quantity called the 'depth-velocity ingegral' is important in these seismic-isostatic studies.

2. If a number of different interpretations have been made of the same seismic refraction data, each having a different velocity distribution through the crust, but all yielding the same time-term, then the pressure at a reference level (and the depth-velocity integral) calculated for each will not differ by more than a few per cent.

3. Seismic-isostatic studies for the eastern portion of Canada suggest a depth of compensation near the top of the mantle. A value of 60 km is adopted for this depth.

4. All interpretations of crustal thickness suggest that the crust below the east-west line from Churchill can be divided into blocks. The two-layer interpretation indicates the block structure more clearly (it is not based on the time-term method, and the averaging inherent in that method has not obscured the transition from one block to the next), particularly in a profile of pressure at a reference level.

5. The block model derived from the two-layer interpretation is consistent with the gravity results of Innes et al. (1967). This agreement suggests that the two-layer interpretation is correct, and that there are no major undiscovered density anomalies affecting the system. Further detailed calculations to check this conclusion are recommended.

6. The pressure profile at a reference level of 60 km does not indicate isostatic equilibrium among the blocks. The pressures below A and C are comparable, but not those for B and D. Assuming that simple local compensation holds, these pressure differences may be due to: (i) failure to achieve isostatic equilibrium, or (ii) an inadequate choice of isostatic model.

7. Blocks A and B may consist of at least two sub-blocks in isostatic equilibrium, when analyzed in terms of the two-layer interpretation. This result, along with the seismic-gravity comparison points to the two-layer interpretation as preferable over the one-layer interpretations.

8. By comparison of seismic and gravity information, a value of $b = 0.27$ units (suitable for σ in gm/cm^3 and V in km/sec) in the equation $\sigma = a + bV$ is derived for the area, being constant from block to block. This conclusion is an important one, because it eliminates another alternative to isostatic unbalance as the cause of the particular form of the pressure profile that is observed (Fig. 2). This alternative that is eliminated is that if b

varies from block to block, the pressure calculation would be affected accordingly. In this case, a balanced set of blocks of widely differing composition could be present. In view of the small number of points used for the calculation of b for each block, more detailed calculations are recommended as a further check on this conclusion.

9. In view of the conclusions above, the following is regarded as being most likely: (a) that most of the western portion of the Bay is in isostatic balance with the shield area to the south and the west; (b) as compared to these areas, (i) that an isostatically 'light' portion of the crust occurs on the western shore of the Bay between latitudes 58° and 63° N.; (ii) a similarly 'light', narrow crustal block runs north-south in the Bay at longitude 86° W.; (iii) an isostatically 'heavy' crustal block 200 km wide runs southwest from Mansel Island. Further crustal seismic work to the west of the Bay would appear to be important.

ACKNOWLEDGMENTS

This paper was the result of work supported by the Geological Survey of Canada, the National Research Council of Canada, and the University of Manitoba Northern Studies Committee.

REFERENCES

Barrett, D. L., Berry, M., Blanchard, J. E., Keen, M. J., and McAllister, R. E.
1964: Seismic studies on the eastern seaboard of Canada: the Atlantic coast of Nova Scotia; Canadian Journal of Earth Sciences, vol. 1, No. 1, pp. 10-22.

Berry, M. J., and West, G. F.
1966: An interpretation of the first-arrival data of the Lake Superior experiment by the time-term method; Bull. Seismol Soc. Amer., vol. 56, pp. 141-171.

Birch, F.
1961: Composition of the earth's mantle; Geophysical Journal, vol. 4, pp. 295-311.

Bowie, W.
1917: Investigations of gravity and isostasy; U. S. Coast and Geodetic Surv., Spec. Publ. 40, 195p.

Brown, R. J.
1968: Isostasy and crustal structure in the English River gneissic belt; unpublished M. Sc. thesis, University of Manitoba.

Clowes, R.M., Kanasewich, E.R., and Cumming, G.L.
1968: Deep crustal seismic reflections at near-vertical incidence; Geophysics, vol. 33, No. 3, pp. 441-451.

Ewing, G.N., Dainty, A.M., Blanchard, J.E., and Keen, M.J.
1966: Seismic studies on the eastern seaboard of Canada: the Appalachian system I; Canadian Jour. Earth Sci., vol. 3, No. 1, pp. 89-109.

Hajnal, Z.
1968: A two-layer model for the earth's crust under Hudson Bay; this vol., pp. 326-336.

Hall, D.H., and Brisbin, W.C.
1961: A study of the Mohorovicic discontinuity near Flin Flon, Manitoba; U.S. Dept. of Commerce, Office of Technical Services, Washington, D.C.

1965: Crustal structure from converted head waves in central western Manitoba; Geophysics, vol. 30, No. 6, pp. 1053-1067.

Hall, D.H., and Hajnal, Z.
1968: Crustal structure of northwestern Ontario: Part II - Refraction seismology; Can. Jour. Earth Sci. (in press).

Heiland, C.A.
1940: Geophysical exploration; Prentice-Hall Inc., New York, 1013p.

Heiskanen, W.A., and Vening Meinesz, F.A.
1958: The earth and its gravity field; McGraw-Hill, New York, 470p.

Hobson, G.D., Overton, A., Clay, D.N., and Thatcher, W.
1967: Crustal structure under Hudson Bay; Can. Jour. Earth Sci., vol. 4, No. 5, pp. 929-947.

Hunter, J.A., and Mereu, R.F.
1967: The crust of the earth under Hudson Bay; Can. Jour. Earth Sci., vol. 4, No. 5, pp. 949-960.

Innes, M.J.S., and Weston, A. Argun.
1966: Crustal uplift of the Canadian Shield and its relation to the gravity field; Annals Academiae Scientarium Fennicae, vol. No. A. III. 90, pp. 169-176. Also contributions from the Dominion Observatory, vol. 7, No. 5, pp. 1-8.

Innes, M.J.S., Goodacre, A.K., Weber, J.R., and McConnell, R.K.
1967: Structural implications of the gravity field in Hudson Bay and vicinity; Can. Jour. Earth Sc., vol. 4, No. 5, pp. 977-993.

McConnell, R.K., and McTaggart-Cowan, G.H.
1963: Crustal seismic refraction profiles, a compilation; University of Toronto, Institute of Earth Sciences; Scientific Report No. 8.

Nafe, J.E., and Drake, C.L.
1959: in Talwani, M., Sutton, G.H., and Worzel, J.L.; A crustal section across the Puerto Rico Trench; Jour. Geophys. Research, vol. 64, No. 10, pp. 1545-1555.

O'Brien, P.N.S.
1968: Lake Superior crustal structure - A reinterpretation of the 1963 crustal experiment; Jour. Geophys. Res., vol. 73, No. 8, pp. 2669-2689.

Ruffman, A., and Keen, M.J.
1967: A time-term analysis of the first arrival data from the seismic experiment in Hudson Bay, 1965; Can. Jour. Earth Sci., vol. 4, No. 5, pp. 901-928.

Sander, G.W., and Overton, A.
1965: Deep seismic refraction investigation in the Canadian Arctic Archipelago; Geophysics, vol. 30, No. 1, pp. 87-96.

Smith, T.J., Steinhart, J.S., and Aldrich, L.T.
1966: Lake Superior crustal structure; Jour. of Geophys. Res., vol. 71, No. 4, pp. 1141-1172.

Woollard, G.P.
1959: Crustal structure from gravity and seismic measurements; Jour. Geophys. Research, vol. 64, No. 10, pp. 1521-1544.

1966: Regional isostatic relations in the United States; Amer. Geophys. Union, Geophysical Monograph No. 10, pp. 557-594.

EVIDENCE FOR VARIATIONS IN UPPER MANTLE VELOCITY IN THE HUDSON BAY AREA

K. G. Barr
Division of Seismology
Dominion Observatory
Ottawa

Abstract

Arrivals at the three permanent seismograph stations nearest to Hudson Bay are used to test the consistency of the time-term solutions that have been presented. It is shown that the residuals from these solutions show a strong dependence on ray path, which could not have been deduced from the temporary station data used to derive them because of the shot-station geometry.

The first arrival data have been examined from the opposite point of view to the time-term approach, i.e., with the initial hypothesis that all of the residuals from a linear travel-time distance relation can be attributed to upper mantle velocity variations. This extreme hypothesis is surprisingly successful in explaining much of the data. The northern part of the Bay appears to have an upper mantle velocity (8.4 - 8.5 km/s) which is significantly higher than that of the remainder of the survey area (8.1 - 8.3 km/s). The time-term models published have ignored this effect and are probably seriously in error at the northern end of the Bay.

INTRODUCTION

The larger shots of the Hudson Bay series were recorded by the permanent seismograph stations maintained by the Dominion Observatory as far away from the centre of the Bay as Alert (2600 km), and these more distant recordings have been used (Barr, 1967) to derive P-wave velocities deep in the upper mantle under the Canadian Shield. The present purpose is to examine the recordings at the closer permanent stations and to see how these relate to the crustal structures that have been derived for the Hudson Bay area by Hobson et al. (1967), Hunter and Mereu (1967) and Ruffman and Keen (1967).

In the analysis of the long range permanent station data cited above, first arrivals out to 1200 km were interpreted as body waves from a layer whose upper surface was the Mohorovičić discontinuity. Only three permanent stations, Baker Lake (BLC), Flin Flon (FFC), and Frobisher Bay (FBC), provide data in this distance range, and only these three stations will be used in the present investigation. Temporary station data have been taken from Hobson (1967).

Figure 1 shows the location of the three permanent stations, the

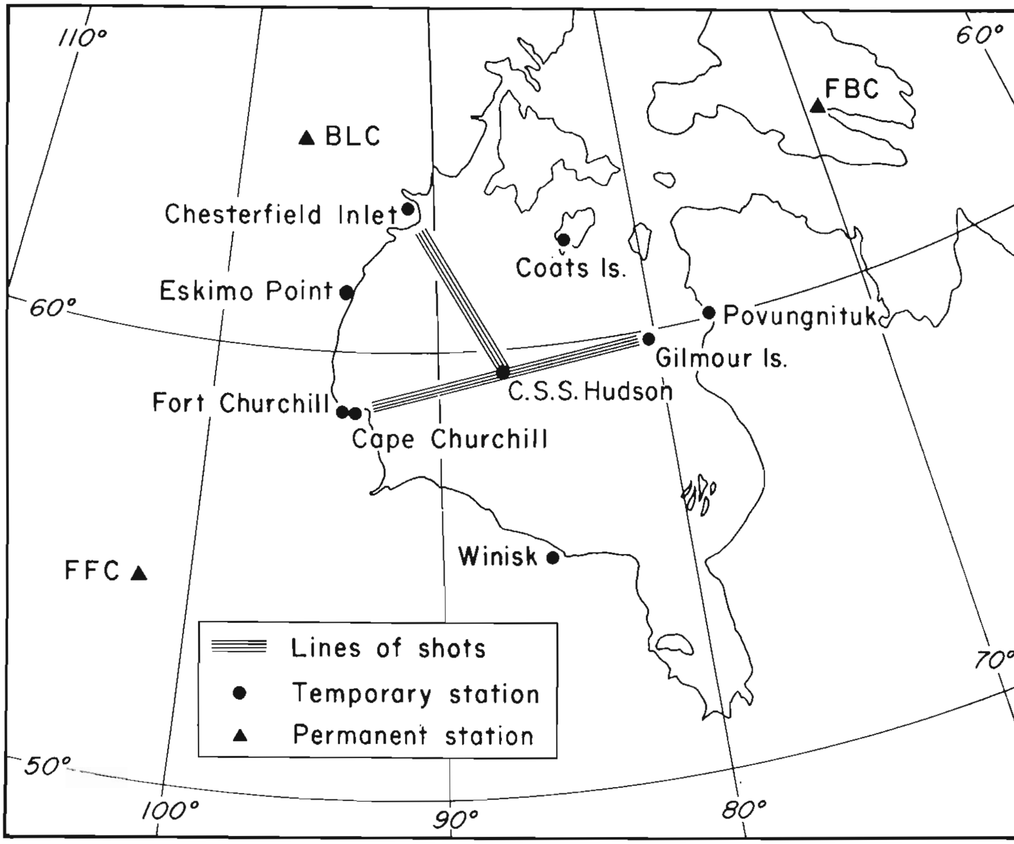


Figure 1. Shows the positions of the permanent and temporary stations, and the lines of shots.

temporary stations and the Hudson Bay shots. The lines of shots going north, east and west from the centre of the Bay will be referred to as the N line, E line and W line, respectively.

The three permanent stations add more information than their number indicates. The temporary stations were roughly equidistant from the centre of the Bay, and the poor shot-station geometry prevented the authors of the time-term solutions cited above from effectively checking whether the postulates of the time-term method were satisfied.

Description of travel-time data

Since the arrival times at the permanent stations were read from standard seismograms, recorded at 60 mm/min, the accuracy of these readings is not as good as that considered normal in crustal work. As the records were read, subjective estimates were made of the accuracy of each reading, taking into account the character of the arrival, the background noise and the quality of radio time signals. Out of a total of 118 readings, 33 were considered better than ± 0.2 sec, 64 were considered better than ± 0.4 sec and 21 were considered better than ± 1 sec. Readings considered less accurate than these were rejected.

Figure 2 and 3 show the reduced travel times of P_n observed at Baker Lake and Chesterfield Inlet for shots on the north and east lines. In Figure 2 these reduced travel times have been plotted against the shot-station distances, whereas in Figure 3 they have been plotted against the distance of the shot from Chesterfield Inlet. It is clear from Figure 3 that the travel time to Baker Lake from a particular shot is strongly correlated with the travel time to Chesterfield Inlet from the same short, whereas Figure 2 shows that there is little correlation between the arrival time at Baker Lake at a particular shot-station distance and the arrival time at Chesterfield Inlet at the same shot-station distance. In particular, the break to a higher apparent velocity that is obvious in the arrivals at Baker Lake at about 700 km appears at Chesterfield Inlet at about 500 km, corresponding in both cases to shots near the centre of the Bay.

If the same marker velocity were everywhere present over the survey area, it should be possible to remove this type of location-dependent scatter by subtracting shot time terms from the data, and this has been done in Figure 4, using the time terms derived from the temporary station data by Hobson _et al_. (1967). A comparison of Figures 3 and 4 shows that subtracting the shot-time terms has not lessened the common shot-location dependence of the data, and, in fact, appears to have increased it slightly.

Figure 5 shows the reduced travel times to Povungnituk and Gilmour Island from the E-W line of shots with the shot time terms subtracted, plotted against the distance of the shots from Gilmour Island. Although the common dependence upon shot location is not so clear as for Baker Lake and Chesterfield Inlet, it is still apparent that the time terms derived by Hobson et al, using all available data, have not removed all of the shot-location dependence common to two stations where these stations lie on a particular azimuth from a line of shots.

The temporary stations at Coats Island and near Churchill, and the permanent stations at Flin Flon and Frobisher Bay lie approximately on the same normal to the N line of shots. With this geometry, variations in the shot-time term will appear as a variation of arrival time with shot common to all stations, whereas variations in marker velocity between the shots and stations will cause variations in the travel times to each station independently. Figure 6 shows the reduced travel times plotted against the distance of the shot from Chesterfield Inlet. The temporary stations at Fort Churchill and Cape Churchill were very close together and are both plotted. Once again we see a correlation between the travel times to the broadside stations for particular shots. However, when we compare the arrival times for shots at

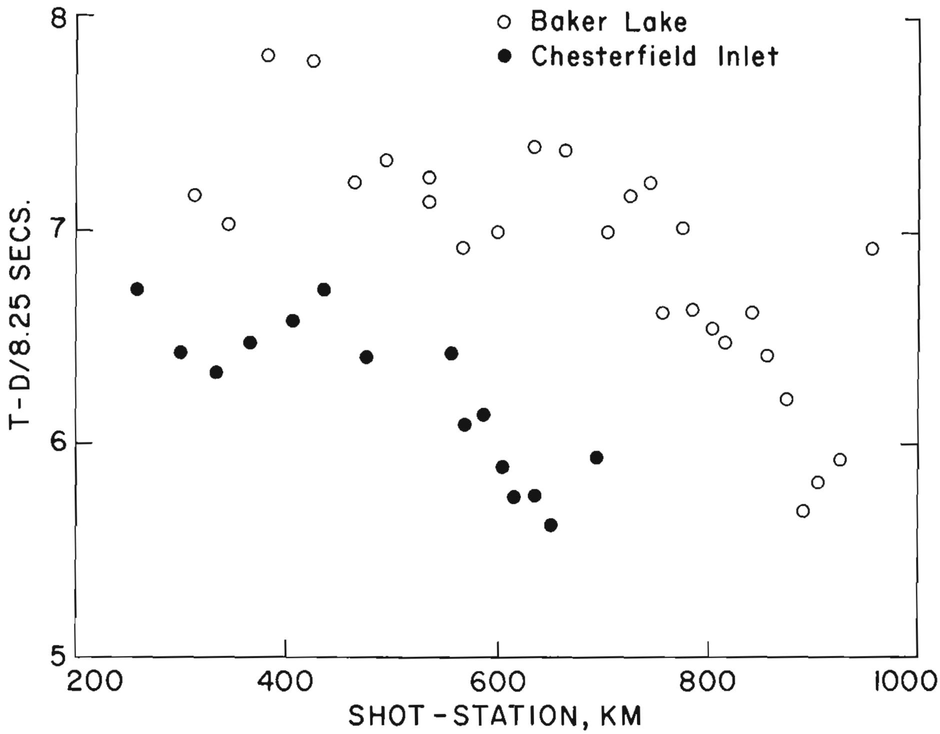


Figure 2. Reduced travel times to Baker Lake and Chesterfield Inlet from the N and E lines of shots, plotted against shot-station distance.

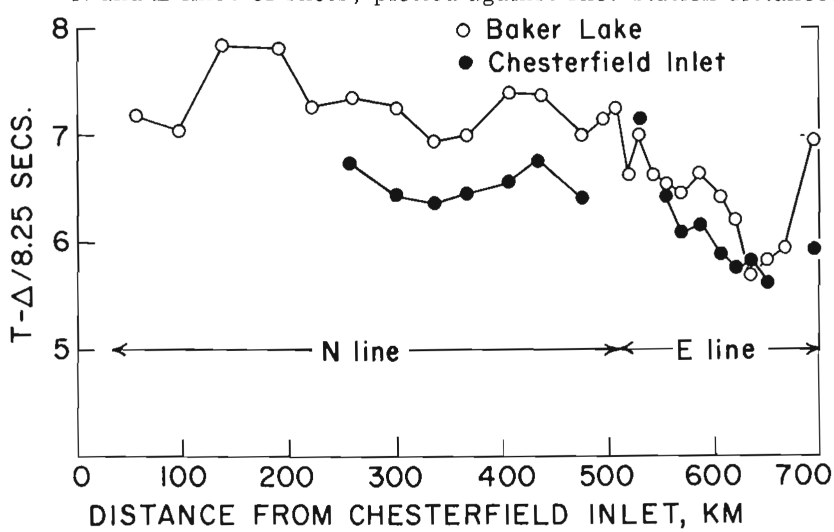


Figure 3. Reduced travel times to Baker Lake and Chesterfield Inlet from the N and E lines of shots, plotted against the distance of the shot from Chesterfield Inlet.

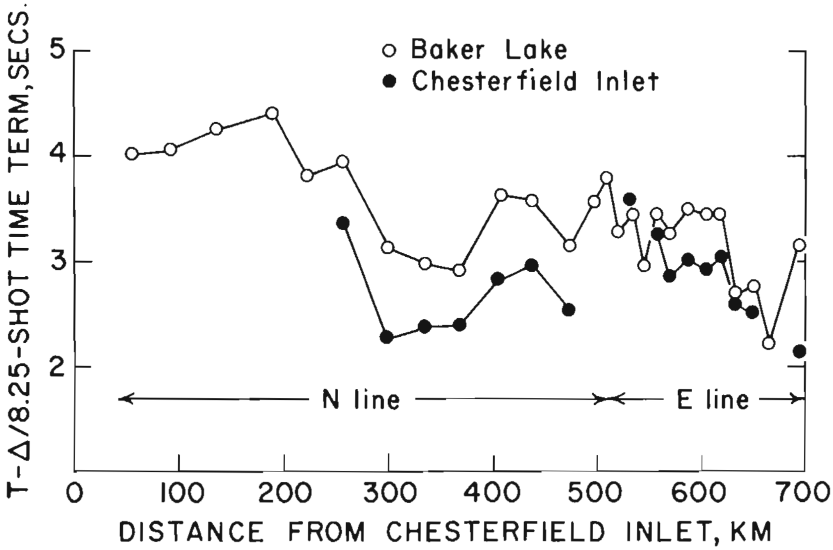


Figure 4. Reduced travel times less the shot time term for Baker Lake and Chesterfield Inlet, from the N and E lines of shots, plotted against the distance of the shot from Chesterfield Inlet.

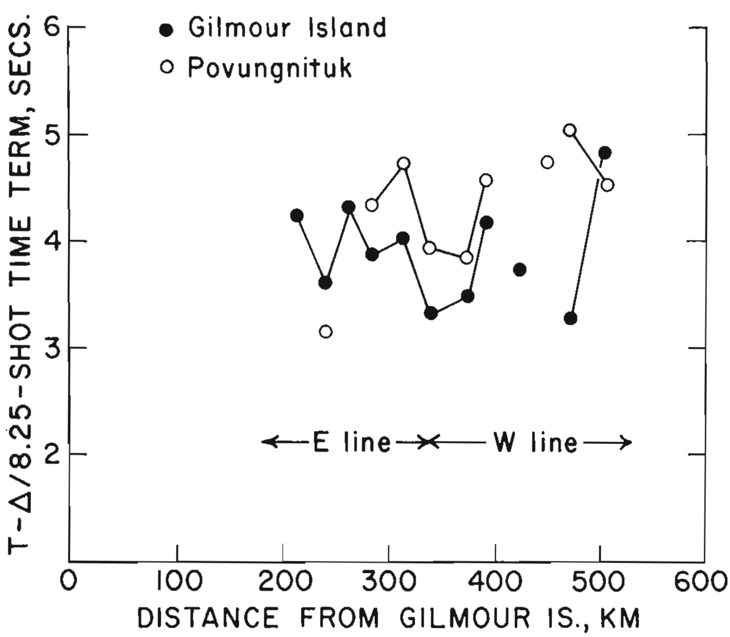


Figure 5. Reduced travel times less the shot time term for Gilmour Island and Povungnituk, from the E and W lines of shots, plotted against the distance of the shot from Gilmour Island.

Baker Lake and Chesterfield Inlet with the arrival times of the same shots at the broadside stations (Figure 6), there is, if anything, a negative correlation. Shots that arrive early at the on-line stations (Baker Lake and Chesterfield Inlet) tend to arrive late at the broadside stations, and the large jump in the broadside travel times to the broadside stations at 280 km does not appear at all in the travel-times to the on-line stations.

We first conclude that the data cannot possibly be satisfied by any set of shot time terms, since subtracting time-terms can only remove shot-location dependence that is common to all stations, both broadside and on-line.

Another possibility that must be considered is that the scatter in travel-times has been caused by navigational errors. There is a clear and positive correlation between the arrivals from the N line of shots at broadside stations on either side of the line. Thus navigational errors would have to be parallel to the line, and would cause a much larger scatter at the on-line stations than at the broadside stations. Figure 6 shows that the reverse is the case, and we conclude that navigational errors are not responsible for the scatter in arrival times from the N line of shots.

Another possible explanation is that the marker velocity varies over the survey area. Hobson et al. (1967) have made time-term analyses of the Hudson Bay data for various groups of data, and have found least, square marker velocities varying from 7.38 $\pm$ .12 to 8.45 $\pm$ .04 km/s. This lends support to this explanation, and it will now be considered in more detail.

Horizontal variations in marker velocity

Location-dependent scatter can only be reduced by time terms if the travel times from any pair of locations to all other locations are positively correlated. In these circumstances, it is most natural to assume a varying marker depth and a constant marker velocity. If the horizontal changes in marker depth required to satisfy the travel-times are very rapid, the simple time-term formulation will break down, and the time terms derived will be azimuth dependent, but this can be avoided by plotting marker depths at off-set positions. In our case, there is, if anything, a negative correlation between the arrivals at on-line and off-line stations for a particular group of shots, and it is natural to try the opposite assumption -- to assume a constant marker depth and a variable marker velocity.

The distribution of shots and stations around Hudson Bay obviously makes it impossible to determine the areal distribution of marker velocity with any precision, so that a fairly crude approach is appropriate. A computer program was written which accepted as input the coordinates of the shots and stations, the travel-time data, and the position and radius of a number of circular zones. For each observation, the program determined the zones intersected by the shot-station path, and assumed the travel time to be an estimate of a true travel time

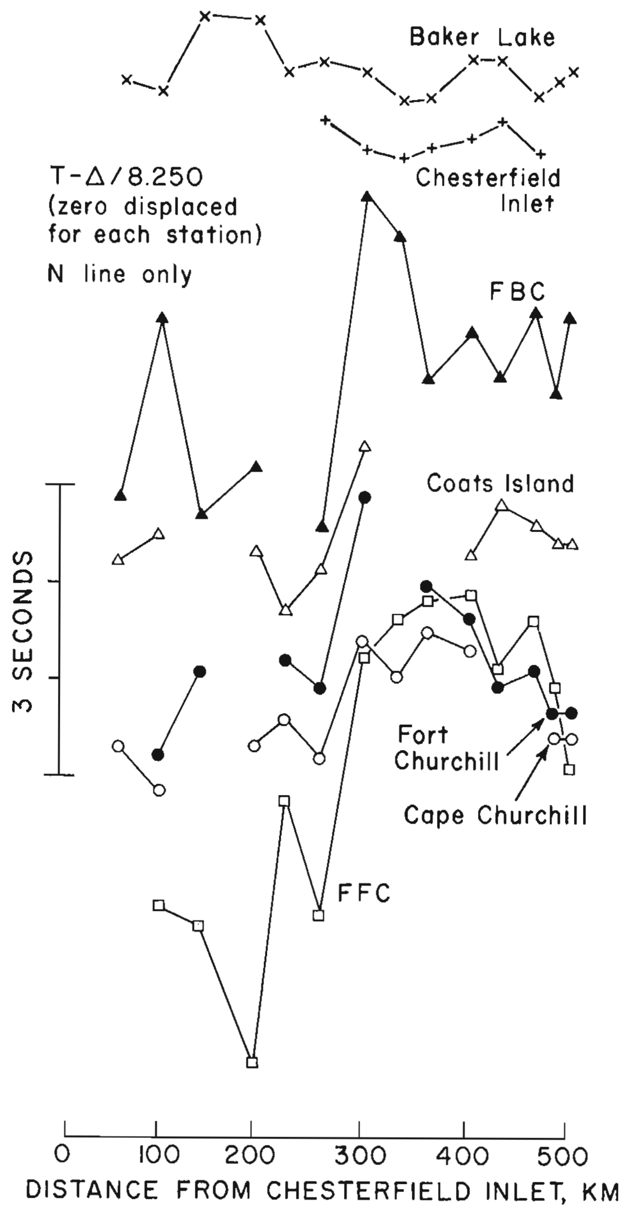


Figure 6. Reduced travel times from the N line of shots at the in-line stations (BLC and Chesterfield Inlet), and at the broadside stations (FFC, FBC, Coats Island, Cape Churchill and Fort Churchill), plotted against the distance of the shot from Chesterfield Inlet. Note that each trace has been displaced vertically.

$$T = a + \sum_{k=1}^{n} (\Delta/n)\, S_k \qquad :$$

In this relation a is a time intercept assumed to be the same for all observations, Δ is the shot-station distance, n is the number of zones intersected by the particular observation, and S_k is a slowness (reciprocal velocity) associated with a particular zone.

This formulation ignores horizontal refraction and the effect of marker velocity on intercept time. The latter assumption is justified, since the intercept time is usually a small fraction of the total travel time. The shot-station distance has been equally partitioned between all of the zones intersected by the ray.

With these limitations we can only derive time-distance curves consisting of connected segments of straight lines, and will be unable to interpret discontinuous jumps in travel time as are observed at FFC (Flin Flon) and FBC (Frobisher Bay) at a shot-Chesterfield Inlet distance of 280 km. It was felt, however, that the method was adequate as a first check of the hypothesis.

The program determined the values for the intercept time and the zone slownesses that gave a least-square fit to the observations, and also the standard error of the solution

$$E = \sqrt{\frac{\sum R^2}{N - F}}$$

where R is the time residual of an observation and the summation is over all observations, N is the number of observations, and F is the number of degrees of freedom fitted (i.e., one plus the total number of zones assigned).

The travel-time curves presented by Hobson et al., and similar curves for the standard stations were used to define areas where it was thought that the upper mantle velocity might be reasonably homogeneous. These areas are represented by the circular zones in Figure 7.

First of all, the temporary data used by Hobson et al. in their time-term solution was fitted to a straight line by least squares. The lines obtained was

$$T = 7.39 + \Delta/8.28 \text{ sec}$$

and the standard error of this solution (N = 190, F = 2) was 0.71 sec. The same data were then fitted by the zones 1 - 6 shown in Figure 7. The intercept and zone slownesses obtained were

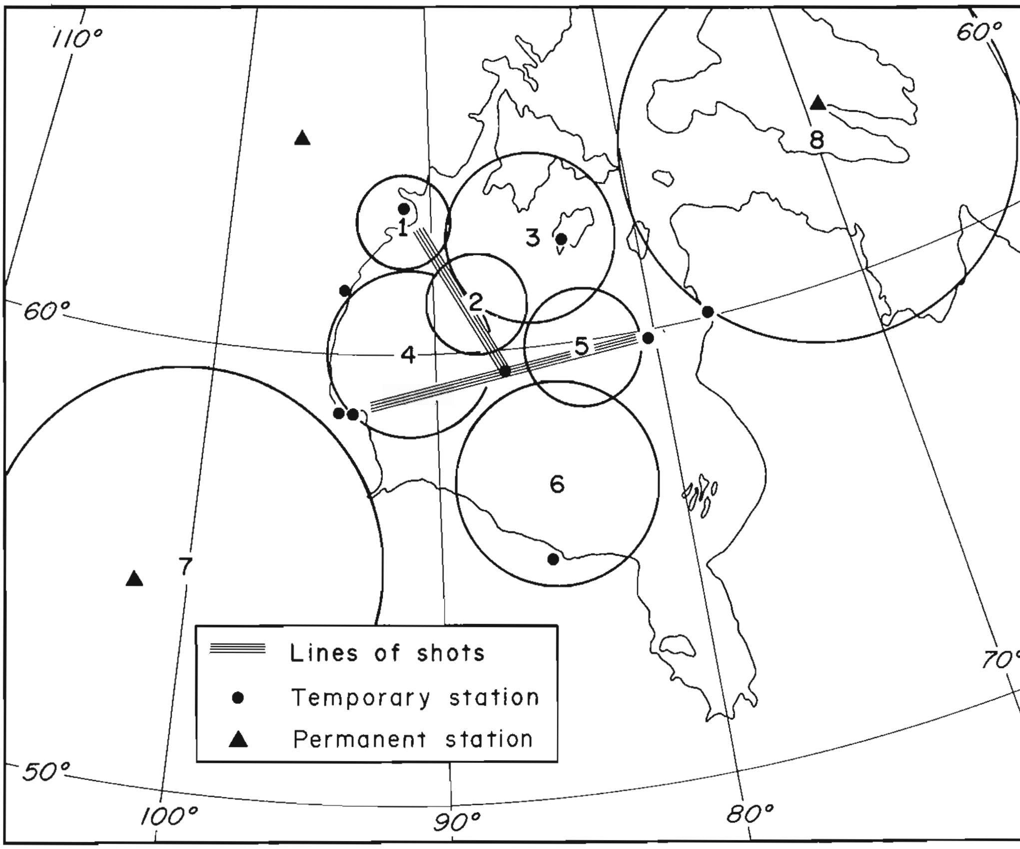


Figure 7. The circles define the zones (1-8) of constant velocity referred to in the text.

$$a = 7.44 \text{ sec}$$

$$1/S_1 = 8.54 \text{ km/s}$$

$$1/S_2 = 8.16 \text{ km/s}$$

$$1/S_3 = 8.41 \text{ km/s}$$

$$1/S_4 = 8.22 \text{ km/s}$$

$$1/S_5 = 8.33 \text{ km/s}$$

$$1/S_6 = 8.25 \text{ km/s}$$

and the standard error of the solution (F = 7) was 0.59 sec. The maximum standard error for any of the zone velocities quoted (as determined from the diagonal elements of the inverse coefficient matrix) was 0.04 km/s, so that zones 1 and 3 jointly define an area at the north of the Bay where the marker velocity is significantly higher than elsewhere. A time-term solution for the same data, fitting 48 time terms ($F = 49$) gave a standard error of 0.52 sec.

The data for the three standard stations was then added to the temporary station data, and the above procedures repeated. The best-fitting straight line was then

$$T = 6.44 + \Delta/8.16 \text{ sec}$$

with a standard error of 1.18 sec. Two additional zones, zone 7 and 8, were added to take into account the possibility that the marker velocities east and/or west of the Bay were different. The new zoned velocity solution gave

$$a = 7.53 \text{ sec}$$

$$1/S_1 = 8.51 \text{ km/s}$$

$$1/S_2 = 8.16 \text{ km/s}$$

$$1/S_3 = 8.43 \text{ km/s}$$

$$1/S_4 = 8.25 \text{ km/s}$$

$$1/S_5 = 8.34 \text{ km/s}$$

$$1/S_6 = 8.26 \text{ km/s}$$

$$1/S_7 = 8.16 \text{ km/s}$$

$$1/S_8 = 8.23 \text{ km/s}$$

with a standard error of 0.61 sec. The total number of observations has been increased from 190 to 311, yet the intercept time and the velocities associated with zones 1 - 6 are essentially the same as before, demonstrating the stability of this type of solution. The velocities associated with zones 7 and 8 are not markedly different from those of zones 2, 4, 5 and 6.

CONCLUSIONS

Table I gives a summary of the various standard errors.

TABLE I

Type of Solution	Standard Error of Solution (sec)	
	Without Standard Stations	With Standard Stations
Straight line	0.71	1.18
Zoned velocity	0.59	0.61
Time term	0.52	0.53

If we accept that the aim of a solution should be to find a model with the least number of parameters that will reduce the residuals to values acceptable as experimental errors, we must conclude that the model for Hudson Bay will include areas of different upper mantle velocity. From the results quoted above, it appears likely that the introduction of a single area in the north of the Bay with a velocity higher than elsewhere would reduce the residuals almost as much as a complete time-term analysis.

The technique that has been used in this paper is, of course, totally inadequate as an interpretive tool. The residuals have been assumed to be entirely due to variations in upper mantle velocity, and the method used to describe even this over-simplified model has been inexact. The results can best be described as indicating guidelines for a more satisfactory approach.

A satisfactory model for Hudson Bay must include time terms and a variable marker velocity. If the variation in marker velocity is described by defining zones of constant velocity, these zones must be large enough to include ray paths in many different azimuths so that a different marker velocity can be distinguished from a dipping marker observed only in one direction.

It is highly probable that the result of fitting such a model would be to assign a marker velocity to the northern end of the Bay of 8.4 - 8.5 km/s, and to assign a fairly constant marker velocity of 8.1 - 8.3 km/s elsewhere. The effect of this on the time-term profiles would be to increase the time terms (thicken the crust) at the northern end of the N line.

The author is grateful to Drs. M. J. Berry and K. Whitham for helpful suggestions and critical reading of this manuscript.

REFERENCES

Barr, K. G.
1967: Upper mantle structure in Canada from seismic observations using chemical explosions; Can. J. Earth Sci., vol. 4, No. 5, pp. 961-975.

Hobson, G. D.
1967: Hudson Bay crustal seismic experiment: time and distance data; Can. J. Earth Sci., vol. 4, No. 5, pp. 879-899.

Hobson, G. D., Overton, A., Clay, D. N., and Thatcher, W.
1967: Crustal structure under Hudson Bay; Can. J. Earth Sci., vol. 4, No. 5, pp. 929-948.

Hunter, J. A., and Mereu, R. F.
1967: The crust of the earth under Hudson Bay; Can. J. Earth Sci., vol. 4, No. 5, pp. 949-960.

Ruffman, A., and Keen, M. J.
1967: A time term analysis of the first arrival data from the seismic experiment in Hudson Bay, 1965; Can. J. Earth Sci., vol. 4, No. 5, pp. 901-928.

SYSTEMATIC ERRORS IN THE DECCA NAVIGATION SYSTEM* USED IN HUDSON BAY FOR THE 1965 OCEANOGRAPHIC PROJECT*

A.K. Goodacre
Dominion Observatory
Ottawa

ABSTRACT

Results from radar, astronavigation and aerial photography indicate that fixed errors, generally of the order of 1 to 3 km, are present in Decca positions obtained in 1965 in the central and eastern parts of Hudson Bay. A plot of these fixed errors versus total number of lanes from the master transmitter indicates that a systematic error, common to the red and green slave lattices and having a maximum value of about 0.3%, was present in the electronic navigation system. Most of the distortion in the Decca lattice is probably due to variations throughout Hudson Bay in the speed of propagation of the radio waves.

INTRODUCTION

A Decca electronic navigation system was used during the summer of 1965 to determine the positions of geophysical and oceanographic measurements made in Hudson Bay by the Department of Mines and Technical Surveys (now Department of Energy, Mines and Resources), Canadian universities, and a petroleum exploration company. Useful signals were obtained throughout Hudson Bay and the repeatability of the measurements was excellent. However, results from radar, astronavigation and aerial photography indicate that systematic or fixed errors, generally of the order of 1 to 3 km, were present in Decca positions obtained in the central eastern parts of Hudson Bay.

The Hudson Bay navigation system

A Master and two Slave transmitting stations, located on the western side of Hudson Bay (Fig. 1), broadcast continuous wave (CW) signals that were on different frequencies but locked together in phase. Decca receivers, installed on the ships and aircraft involved in the survey, measured the differences in phase between the signals from the Master-Red Slave and Master-Green Slave station pairs. The resulting readings, which were

*Although this paper was not actually presented at the Symposium, there was considerable discussion of navigational accuracies during the question periods. Because the Decca Navigation System was used for all the geophysical surveys carried out during the 1965 Oceanographic Project in Hudson Bay, it was thought appropriate to include this dissertation in the Symposium volume.

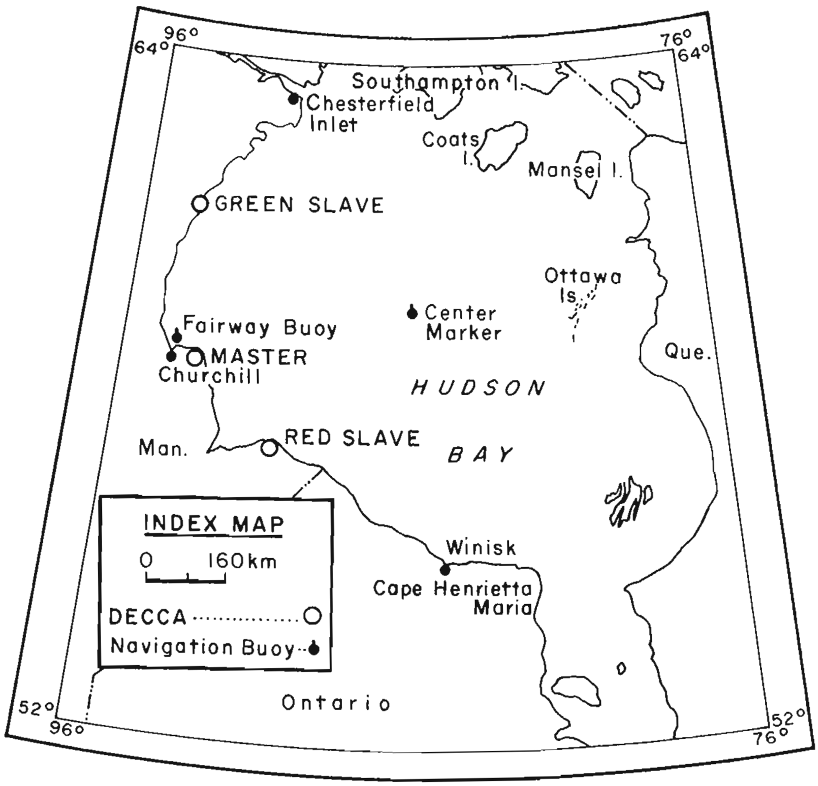


Figure 1. Index map showing the positions of the Decca transmitters, and two of the navigation buoys used for the 1965 Hudson Bay survey.

in units of lanes (one lane is equal to a phase difference of 360°) defined two position lines of constant phase difference; the intersection of the two position lines defined a geographical position. Details of the Decca system of navigation may be found in the publication "Radio aids to maritime navigation and hydrography" (1956).

The main problem in using the Decca 6F system of navigation in Hudson Bay was that sky-wave interference at night could cause a Decca receiver to become unlocked from the ground-wave transmissions, particularly if the receiver was more than 200 km from the shore stations. When the interference ceased and the receiver was again locked onto the ground-wave signals, the Decca readings were often shifted by an integral number of lanes and the geographical positions were in error by an amount dependent upon the location of the receiver in the Decca pattern. This problem was minimized by traversing during daylight hours between temporary marker buoys. The technique, described in detail by Ruffman (1966), provided consistent results throughout the season and enabled most of the positions to be referred to Decca co-ordinates for landmarks at Churchill.

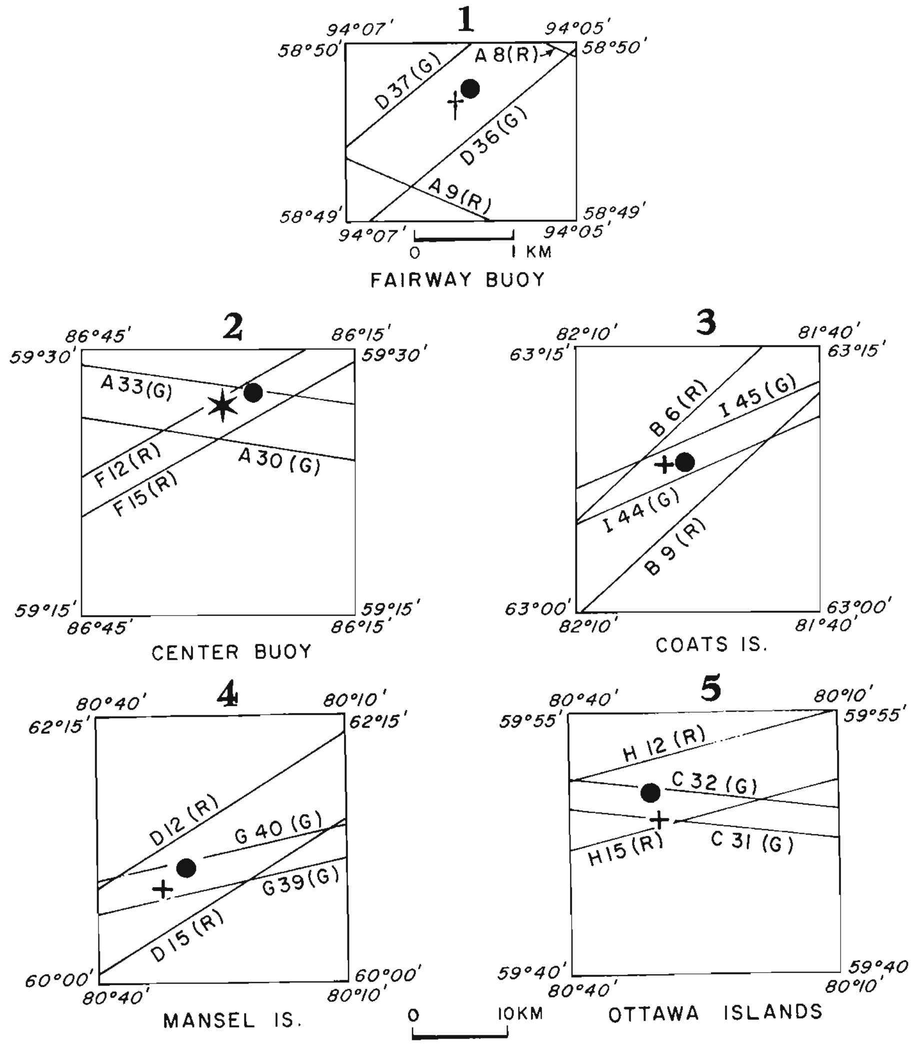


Figure 2. Fixed errors in the Hudson Bay Decca system. Solid dots indicate Decca positions determined by land-count procedure; crosses indicate radar positions; a sword marks the position of Fairway Buoy; and a star indicates the position of Center Buoy.

Evidence for fixed errors in the Decca pattern

The evidence for fixed errors in the Hudson Bay Decca navigation system is divided into two groups; Decca readings that can be expressed relative to Churchill by means of a lane-count procedure and those that can not. In the second group, integral Decca lane values are chosen by the author to minimize the distance between the Decca and reference positions. Most of the reference positions for the two groups are obtained with radar and have uncertainties of the order of 1 km due to errors in ranges and bearings and to inaccuracies in the nautical charts. The remaining reference positions have smaller uncertainties. In all cases, the precision of the Decca readings is better than 0.1 lane.

The data for the first group are presented in Figure 2. Latitudes, longitudes, and samples of Decca position lines are given in each diagram. Diagram 1 in Figure 2 shows the Decca position (solid circle) for Fairway Buoy and its geographical position (sword) at the entrance to Churchill Harbour. Note that the scale of this diagram is approximately ten times smaller than the scale of the other diagrams. Diagram 2 presents the Decca position of Center Buoy and its geographical location (star) as determined by star shots from the C.S.S. Hudson (M. Hemphill, personal communication). The remaining three diagrams show Decca co-ordinates and radar positions (crosses) obtained aboard the M.V. Theron at Coats Island, Mansel Island and the Ottawa Islands.

Data for the second group, presented in Figure 3, have been obtained by Canadian Aero Services Ltd. at Winisk Airport (M. Reford, personal communication), by the Canadian Hydrographic Service north of Cape Henrietta Maria (M. Hemphill, personal communication) and by the M.V. Theron at Chesterfield Inlet and Southampton Island. Diagram 1 of Figure 3 presents the mean Decca position of Winisk Airport (open circle) and its location (cross) obtained from the Canadian Aerodrome Directory (1967). Diagram 2 gives the Decca position (open circle) and the geographical location of the C.S.S. Hudson (cross) as measured by a radar range and bearing from Cape Henrietta Maria. Diagrams 3 and 4 show Decca positions (open circles) and radar positions (crosses) obtained on the M.V. Theron at Chesterfield Inlet and Southampton Island. Small dots in Figure 3 represent alternate Decca positions obtained by adding to or subtracting from the Decca readings an integral number of lanes.

The following points may be deduced from Figures 2 and 3: (i) Discrepancies between Decca and geographical positions range from 200 metres at Fairway Buoy near Churchill (Diagram 1, Fig. 2) to 12 km at Cape Henrietta Maria (Diagram 2, Fig. 3); (ii) Neither the probable Decca positions (solid or open circles) nor alternate positions (dots) coincide with the reference geographical locations. Because the discrepancies are generally larger than possible uncertainties of up to 1 km in the reference

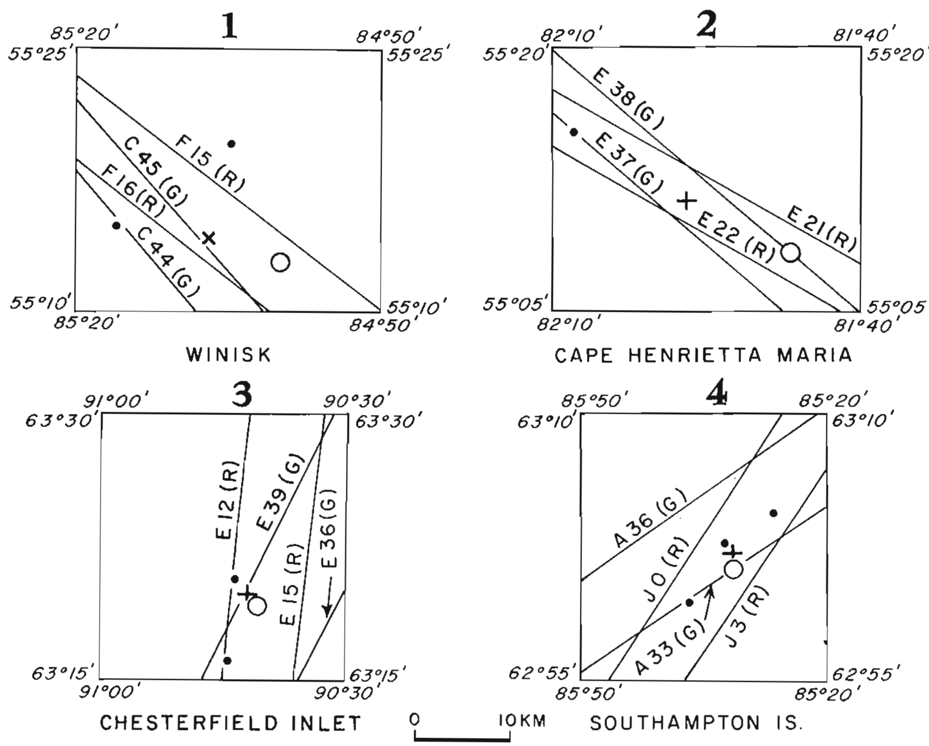


Figure 3. Fixed errors in the Hudson Bay Decca system. Open circles indicate adopted Decca positions; small dots mark alternative positions; crosses indicate radar positions; and the letter x marks the location of Winisk Airport.

positions, it appears that fixed errors of a few kilometres were present in many of the Decca positions obtained in Hudson Bay in 1965.

The spatial distribution of fixed errors in a Decca system may form a complex pattern; for an example see Figure 4. There are insufficient data to describe similarly the distribution of fixed errors over the whole of Hudson Bay since most of the information in Figures 2 and 3 was obtained near the shore at large distances from the transmitters. However, when the discrepancies are plotted with respect to the values of the Decca readings expressed in terms of the total number of lanes from Master (Fig. 5), it can be seen that within about 350 lanes of Master the observed red and green Decca readings are numerically greater than the calculated values whereas at higher lane count values the opposite is true. Therefore, there appears to be a systematic error with a maximum value of about 0.3% in the Decca system that is common to both the red and green patterns.

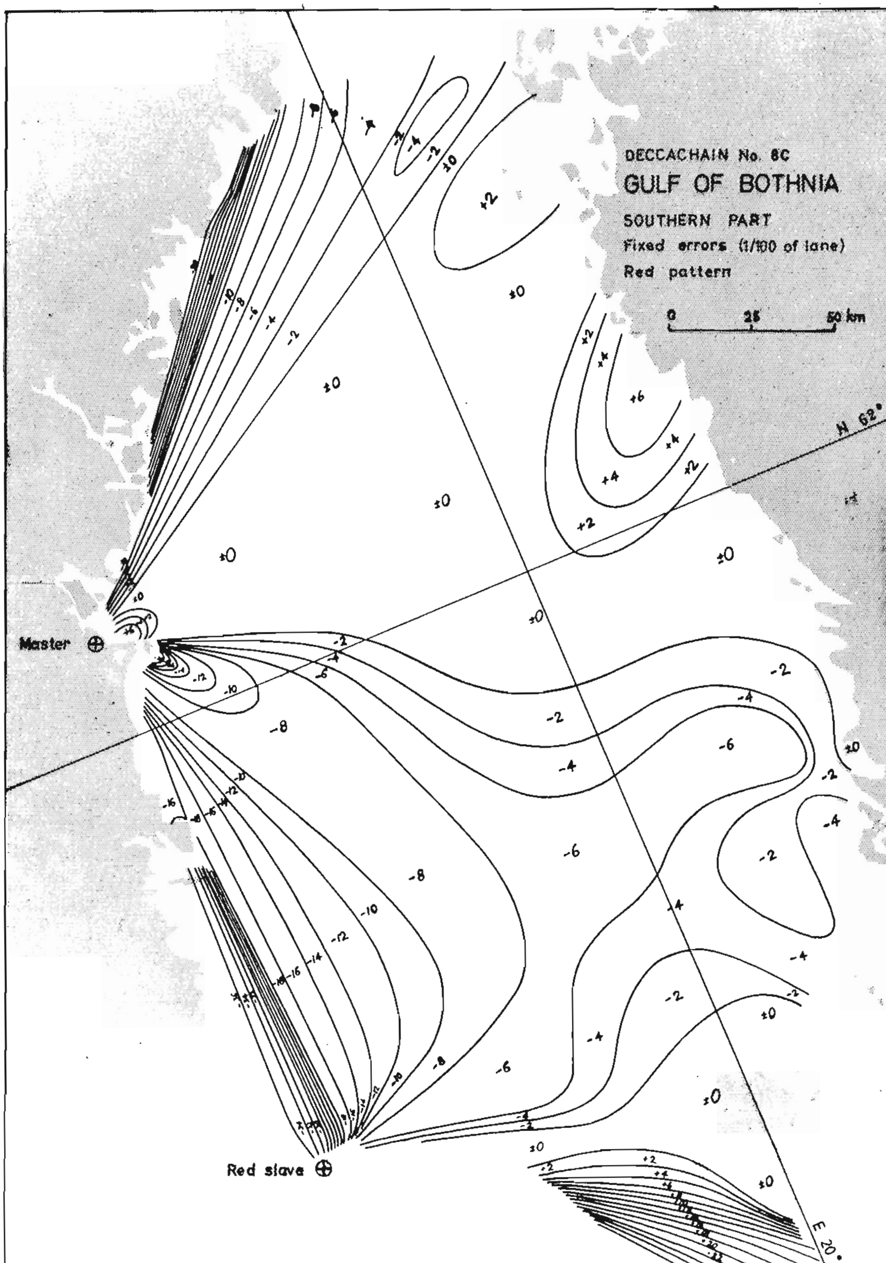


Figure 4. Fixed errors for Decca chain No. 8C, Gulf of Bothnia (figure from Fagerholm and Thunberg, 1964).

Possible Sources of Errors in the Decca System

Discrepancies between the observed and theoretical readings could be due to (i) errors in the lengths and orientations of the baselines between the Master and Slave stations, (ii) an incorrect basic frequency of the system, and (iii) variations in the speed of propagation of the radio waves. Some combination of these factors appear to be necessary, not only to explain the complex form of the error patterns in Figure 5 but also to account for their magnitude (approximately 0.3%) which is too large to attribute to an error in any one of the parameters alone. It is unlikely that significant errors were present in the locations of the transmitting stations and the following speculations are made on the basis of the data in Figure 5; (i) the actual speed of propagation of the radiowaves may have been slightly higher than the assumed value (299,600 km/sec) over most of Hudson Bay and somewhat lower along the southern and western shoreline; (ii) The basic frequency of the system may have been slightly lower than normal. Only a minor systematic error could result from an incorrect basic frequency as the Decca transmitters were crystal controlled. Most of the distortion in the Decca patterns was probably caused by variations in the speed of propagation of the radio waves.

The effect of systematic navigation errors in the measurements made in Hudson Bay

Errors of 2 or 3 km in the geographical positions of the underwater gravity, oceanographic, shallow seismic and magnetic observations made in Hudson Bay can be tolerated in view of the reconnaissance nature of the measurements. However, the accurate location of the work done by the petroleum exploration company is important for legal purposes and the correct positioning of water depths measured by the Canadian Hydrographic Service is necessary for safe navigation. In addition, the quality of an interpretation of crustal seismic data depends upon an accurate knowledge of geographical position. For example, an error of 3 km in the distance between a shotpoint and a receiving station will give an error of about 0.4 sec in the travel-time of an acoustic compressional wave, a value which is about 35% of the range of the time-terms in Hudson Bay (Ruffman and Keen, 1967). An analysis by Overton (1968) of the effect of navigation errors on the Hudson Bay crustal seismic data suggests that systematic errors in shotpoint position may be responsible for some of the variation of time-terms observed in Hudson Bay.

Remarks

It should be pointed out that the Decca system was not intended to give accurate geographical co-ordinates at extreme ranges. Decca is generally meant to be used at distances of 400 km or less from the transmitter sites and the system operated in 1965 probably contained fixed errors of the order of 1 km or less in the western side of Hudson Bay. There is no doubt

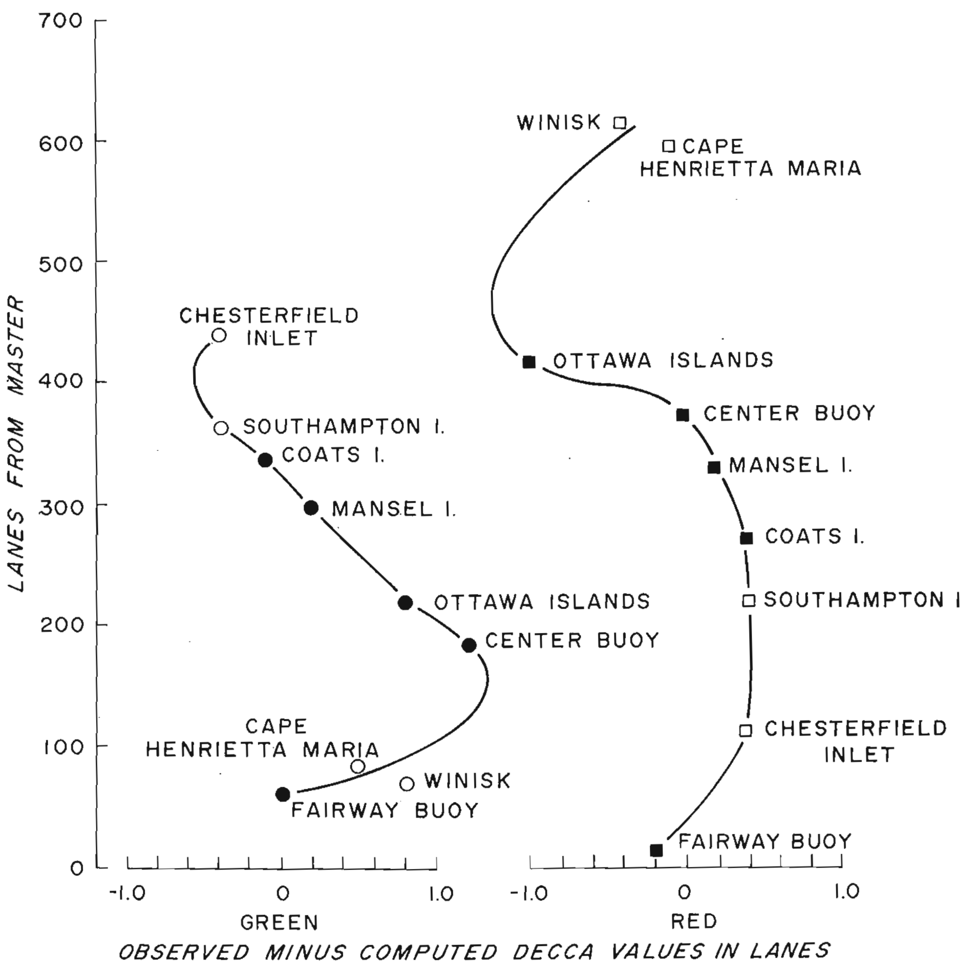


Figure 5. Differences between observed and theoretical Decca co-ordinates for various locations in Hudson Bay plotted against total number of lanes from Master. Solid squares and dots indicate differences determined by lane count procedure. Open squares and dots represent adopted differences.

that the Decca system provided much better control than techniques such as radio direction finding, dead reckoning etc., previously used in this area. However, where reliance is being placed upon the Decca system of navigation at extreme ranges, for example on the Polar Continental Shelf Project and on the east coast of Canada, systematic errors in the system will have to be taken into account if accurate positions are required.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the help of the following people: Captain Maro and First Mate Egset of the M.V. Theron, Messrs. R. Melanson and M. Hemphill of the Canadian Hydrographic Service, Mr. M. Reford, consultant for Canadian Aero Services, Ltd., and Mr. J. Hodgkinson of Atlantic Richfield Company.

REFERENCES

Energy, Mines and Resources
1967: Canadian Aerodrome Directory, Surveys and Mapping Branch, Ottawa.

Fagerholm, P.O., and Thunberg, A.
1964: Determination of fixed errors in navigational (and hydrographic) Decca chains, Supplement to the International Hydrographic Review, vol. 5, pp. 30-44.

International Hydrographic Bureau
1956: Radio aids to maritime navigation and hydrography, Special publication No. 39, Monaco.

Overton, A.
1969: An alternative interpretation of the 1965 Hudson Bay crustal seismic data, this volume, pp.

Ruffman, A.S.
1966: Crustal seismic studies in Hudson Bay, Canada. Unpublished M.Sc. thesis, Dalhousie University, Halifax, Nova Scotia.

Ruffman, A.S., and Keen, M.J.
1967: A time-term analysis of the first arrival data from the seismic experiment in Hudson Bay, 1965. Can. J. Earth Sci., vol. 4, No. 5, pp. 901-928.

Cover design based on
Lakes, Rivers and Glaciers,
National Atlas of Canada
Special Interim Series, 1967.