GEOLOGICAL SURVEY OF CANADA
COMMISSION GÉOLOGIQUE DU CANADA

PAPER 79-9

TERTIARY FLUVIAL SEDIMENTS IN THE LAKE HAZEN INTERMONTANE BASIN, ELLESMERE ISLAND, ARCTIC CANADA

ANDREW D. MIALL

Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

1979

GEOLOGICAL SURVEY
PAPER 79-9

TERTIARY FLUVIAL SEDIMENTS IN THE LAKE HAZEN INTERMONTANE BASIN, ELLESMERE ISLAND, ARCTIC CANADA

ANDREW D. MIALL

1979

Available in Canada through

authorized bookstore agents
and other bookstores

or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Hull, Québec, Canada K1A 0S9

and from

Geological Survey of Canada
601 Booth Street
Ottawa, Canada K1A 0E8

A deposit copy of this publication is also available
for reference in public libraries across Canada

Cat. No. M44-79-9 Canada: $3.00
ISBN – 0-660-10207-2 Other countries: $3.60

Price subject to change without notice

CONTENTS

Illustrations

Critical Readers
R.L. CHRISTIE
A.F. EMBRY

Technical Editor
E.R.W. NEALE

Layout
C.E. FINDLAY

Typed and checked by
H. KING
P.L. GREENER

Artwork by Author

Manuscript Received: November 2, 1978

Author's address: Institute of Sedimentary
and Petroleum Geology
3303 - 33rd Street N.W.
Calgary, Alberta
T2L 2A7

Abstract

Tertiary sediments at Lake Hazen have been divided into two units, a lower sandstone-mudstone member, up to 450 m thick, consisting of very fine to very coarse, weakly consolidated sandstone, siltstone, mudstone, with minor coal and conglomerate, and an upper conglomerate member, 450 m thick, comprising cobble and boulder conglomerate with subordinate sandstone. The name Eureka Sound Formation is retained for the entire succession, which is Eocene to ?Oligocene in age. The contact between the members probably is conformable and gradational, and an earlier assignment of the conglomerate member to the Beaufort Formation (Miocene) is now judged to be incorrect.

Sediments of the sandstone-mudstone member were deposited mainly by small, high sinuosity, single channel ("meandering"), mixed load streams, although coarse deposits within the member may reflect temporary establishment of more competent, multiple channel ("braided") bedload streams as a result of minor climatic fluctuations or tectonic pulses. Sand petrography and paleocurrent evidence indicate derivation from lower Paleozoic rocks of Hazen Plateau, south of the basin.

The conglomerate member was formed as a result of thrust movement and uplift along Hazen Fault Zone. Beds of the sandstone-mudstone member grade up into cobble and boulder conglomerates deposited on an alluvial fan zone bordering the fault. Petrographic and paleocurrent evidence indicates a shift in source area and transport direction, the conglomerates being derived from lower Paleozoic and Carboniferous to Mesozoic sediments and diabase sills of Grantland Uplift, north of Lake Hazen.

Absence of Paleocene strata suggests initiation of basin subsidence as much as 20 Ma later at Lake Hazen than in many other parts of the Arctic Islands. The tentative correlation of the conglomerate beds at Boulder Hills implies that there is now no positive evidence in the report area of the final episode of the Eurekan Orogeny, which involved renewed faulting and sedimentation during the Miocene elsewhere in the Arctic Islands.

Résumé

Les sédiments tertiaires du lac Hazen ont été divisés en deux unités: d'une part, un niveau inférieur, formé de grès et de mudstone, mesurant jusqu'à 450 m d'épaisseur, qui comprend en particulier du grès très fin à très grossier et friable, du siltstone, du mudstone, avec un peu de charbon et de conglomérat; d'autre part un niveau supérieur conglomératique, de 450 m d'épaisseur, qui comprend du conglomérat à blocs et galets avec quelques petites intercalations de grès. On a donné à toute cette succession d'âge éocène à oligocène, le nom de formation d'Eureka Sound. Le contact entre les deux niveaux semble être concordant et progressif et nous pensons maintenant que c'était une erreur d'avoir attribué antérieurement le niveau conglomératique à la formation de Beaufort (Miocène).

Les sédiments qui forment le niveau grès-mudstone ont été surtout déposés par des petites rivières, à chenal unique formant des méandres et à charge composite; mais les dépôts les plus grossiers qu'on rencontre dans ce niveau peuvent correspondre à l'établissement temporaire de cours d'eau plus compétents à chenaux anastomosés résultant de faibles changements climatiques ou d'impulsions tectoniques. La pétrographie des sables et la constatation de paléocourants montrent que ces sédiments proviennent de roches du Paléozoïque inférieur du plateau de Hazen qui se trouve au sud du bassin.

Le niveau conglomératique a été formé à la suite de mouvements tels que poussées et soulèvements le long de la zone faillée de Hazen. Les lits du niveau grès-mudstone passent vers le haut à des conglomérats à galets et blocs qui se sont déposés sur une zone de cône d'alluvions en bordure de la faille. Les indices pétrographiques et la présence d'un paléocourant montrent qu'il y a eu variation du lieu de l'origine et de la direction de transport, les conglomérats provenant des sédiments du Paléozoïque inférieur et du Carbonifère au Mésozoïque, et des sills de diabase du soulèvement de Grantland au nord du lac Hazen.

L'absence de dépôts du Paléocène suggère qu'il y a eu un début de subsidence avec formation d'un bassin au lac Hazen, 20 Ma plus tard que dans les autres parties de l'archipel Arctique. L'essai de corrélation des lits conglomératiques de Boulder Hills implique qu'il n'existe dans la région étudiée aucune évidence positive de la phase finale de l'orogenèse de l'Eureka, qui a donné lieu à un nouvel épisode de fracturation et sédimentation pendant le Miocène ailleurs dans l'archipel Arctique.

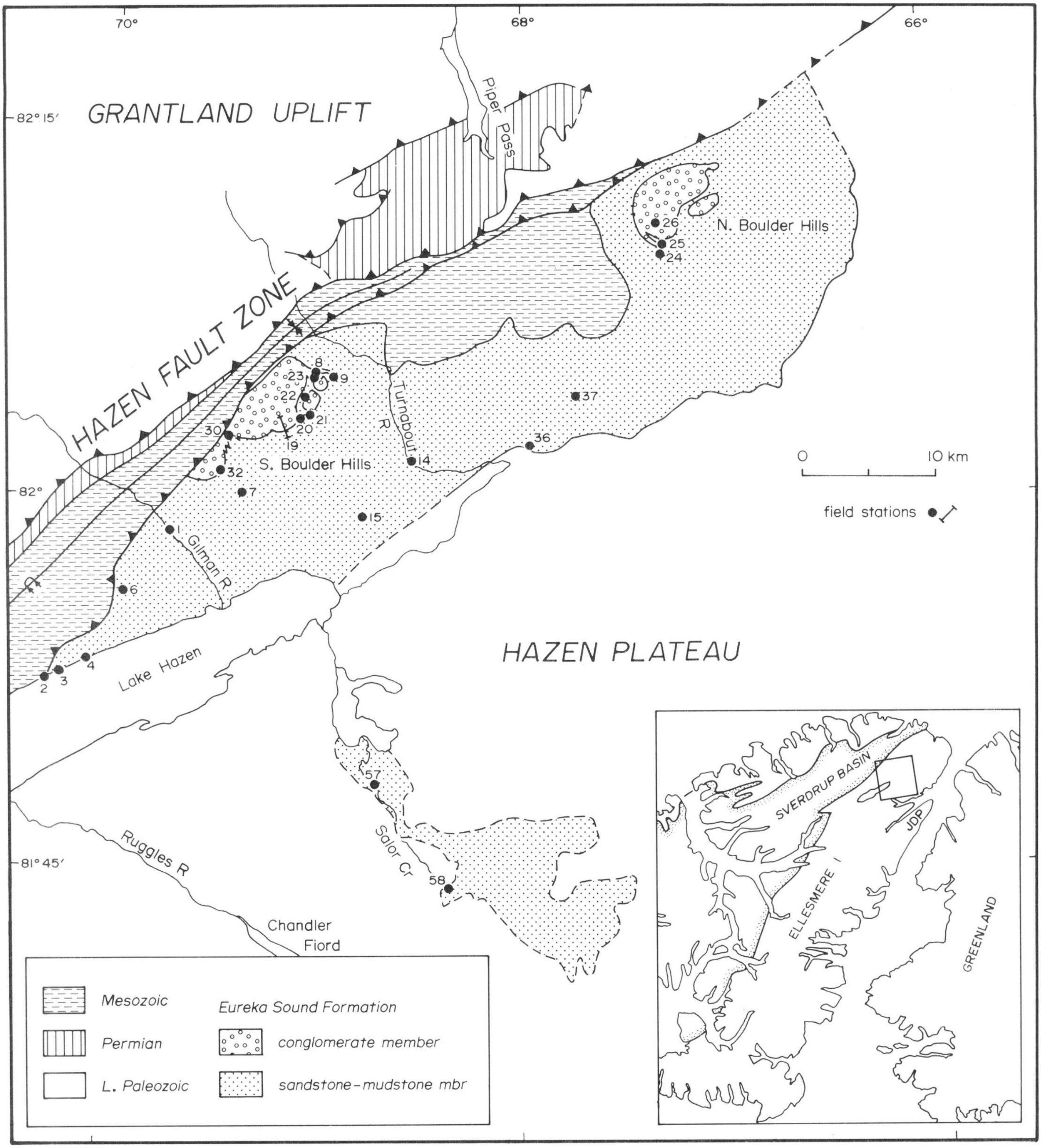


FIGURE 1. Geology of the report area, showing location of field stations. Inset shows location of Lake Hazen in northern Ellesmere Island, on the southern flank of Sverdrup Basin. JDP = Judge Daly Promontory.

TERTIARY FLUVIAL SEDIMENTS IN THE LAKE HAZEN INTERMONTANE BASIN, ELLESMERE ISLAND, ARCTIC CANADA

INTRODUCTION

Scope of study

Paleogene clastic deposits are widespread in the Arctic Islands from Banks Island in the southwest to Bylot Island in the southeast and Ellesmere Island in the northeast. The deposits are fluvial, lacustrine, deltaic and marine in origin; they occur mainly in a series of closed or open-ended intermontane or pericratonic basins bounded by folds or faults generated during the Late Cretaceous to mid-Tertiary Eurekan Orogeny. In several of these basins the total thickness of Tertiary deposits is in the order of 2500 to 3000 m. The predominantly nonmarine to shallow marine depositional environments, the close genetic association with orogenic activity along a major fold belt, and the thickness and areal extent of the sediments are all characteristics that qualify these rocks as a molasse deposit, in the sense described by Van Houten (1969, 1973).

The present report is part of a long term project to study the stratigraphy, sedimentology and tectonic implications of this molasse deposit. The outcrops at Lake Hazen are a minor part of the whole, but they provide the basis for an interesting case study of synorogenic sedimentation in a small, enclosed basin, which is now about 70 km long and in which up to 900 m of sediment are preserved.

Field work for this study was carried out over a period of two weeks in June 1977, during which time the writer made use of the helicopter support and other logistic facilities of a GSC mapping party led by H.P. Trettin. Field assistance was provided by M. Seifert. A.F. Embry and R.L. Christie critically read the manuscript and provided many useful comments.

Previous work

Nonmarine, coal-bearing sediments of Late Cretaceous or Tertiary age outcropping in Ellesmere Island were named the Eureka Sound Group by Troelsen (1950, p. 78). Tozer (1963, p. 92) redefined the Eureka Sound as a formation, as it had not been subdivided into more than one mapping unit. Subsequently the Eureka Sound Formation has been mapped in many parts of the Arctic Islands. It is now known that the formation is predominantly Paleocene to Eocene in age, but that locally it extends into the Maastrichtian (Thorsteinsson and Tozer, 1970; Kerr, 1974; Bustin et al., in press; Miall, in press).

Tertiary strata in the Lake Hazen area were first described in detail by Christie (1964), who mentions the few observations made in the area by earlier workers. Petryk (1969) studied the sections of Mesozoic and Tertiary strata exposed along the shores of Lake Hazen. Both these were essentially stratigraphic reports, although Petryk (1969, p. 12) reported (without documentation) some paleocurrent determinations made on crossbedding in the Tertiary. Further work by Christie (1974, 1976) and Christie and Rouse (1976) included the first section measured through the boulder conglomerate unit that forms the top of the the Tertiary succession. Christie (in Petryk, 1969, p. 16; pers. com., 1977) also recognized that Triassic rocks are thrust over the Tertiary sediments on the shore of Lake Hazen.

Regional setting

Lake Hazen lies within the Northern Ellesmere Fold Belt (Douglas et al., 1963; Trettin et al., 1972). This region is underlain by lower Paleozoic rocks metamorphosed, intruded and deformed during the Ellesmerian Orogeny (Middle Devonian to Early Mississippian), and by a succession of upper Paleozoic and Mesozoic strata which was less intensely deformed during the mid-Tertiary Eurekan Orogeny.

The dominant structural feature in the report area is the Lake Hazen Fault Zone (Fig. 1). The main fault, mapped by Christie (1964) and Trettin (1971), is a steeply northward-dipping structure which juxtaposes Cambrian clastic sediments of the Grant Land Formation against a Permian to Cretaceous sequence. Mapping by A.F. Embry and the writer in 1977 showed that the second thrust fault recognized on the shore of Lake Hazen by Christie can be traced throughout the length of the report area subparallel to the main fault. Between the two faults is an area underlain by Permian to Cretaceous strata which are deformed into a doubly plunging syncline with a steeply dipping to overturned north limb. This sequence is, in turn, thrust over Tertiary sediments along the southernmost fault. South of Piper Pass an inlier of Mesozoic strata containing diabase sills is present on the south side of the southernmost thrust fault. This is the only area where Mesozoic and Tertiary strata appear to be in stratigraphic contact, although there are no good exposures of the contact relationships. The youngest Mesozoic unit recognized in the Lake Hazen area by A.F. Embry (pers. com., 1977) is the Lower and/or Upper Cretaceous Hassel Formation, and so a major disconformity is interpreted to exist at the base of the Tertiary.

The southern limit of the Tertiary outcrop area is marked by the erosional edge of the succession, where it rests on the Ordovician to Silurian greywacke, siltstone and shale of the Imina Formation (Trettin, 1971). The older rocks are tightly folded along northeasterly trends. Trettin (1971, p. 3) suggested that the Tertiary rests on an exhumed mid-Paleozoic plain, which may have been extensively covered by upper Paleozoic and Mesozoic sediments prior to a period of erosion just before Tertiary sedimentation. A downwarp in the plain preserved part of this sedimentary cover in the Lake Hazen-Piper Pass area, whereas it was removed east and northeast of Lake Hazen, so that the Tertiary has overstepped the Mesozoic to rest directly on the Imina Formation.

The same downwarp, continued to the present day, was responsible for preserving the Tertiary strata in a small basin extending northeastward from Lake Hazen, the subject of the present report. Scattered outliers of Tertiary sand and shale are present on the Imina Formation in the Hazen Plateau area south and east of the lake (Christie, 1964, 1976).

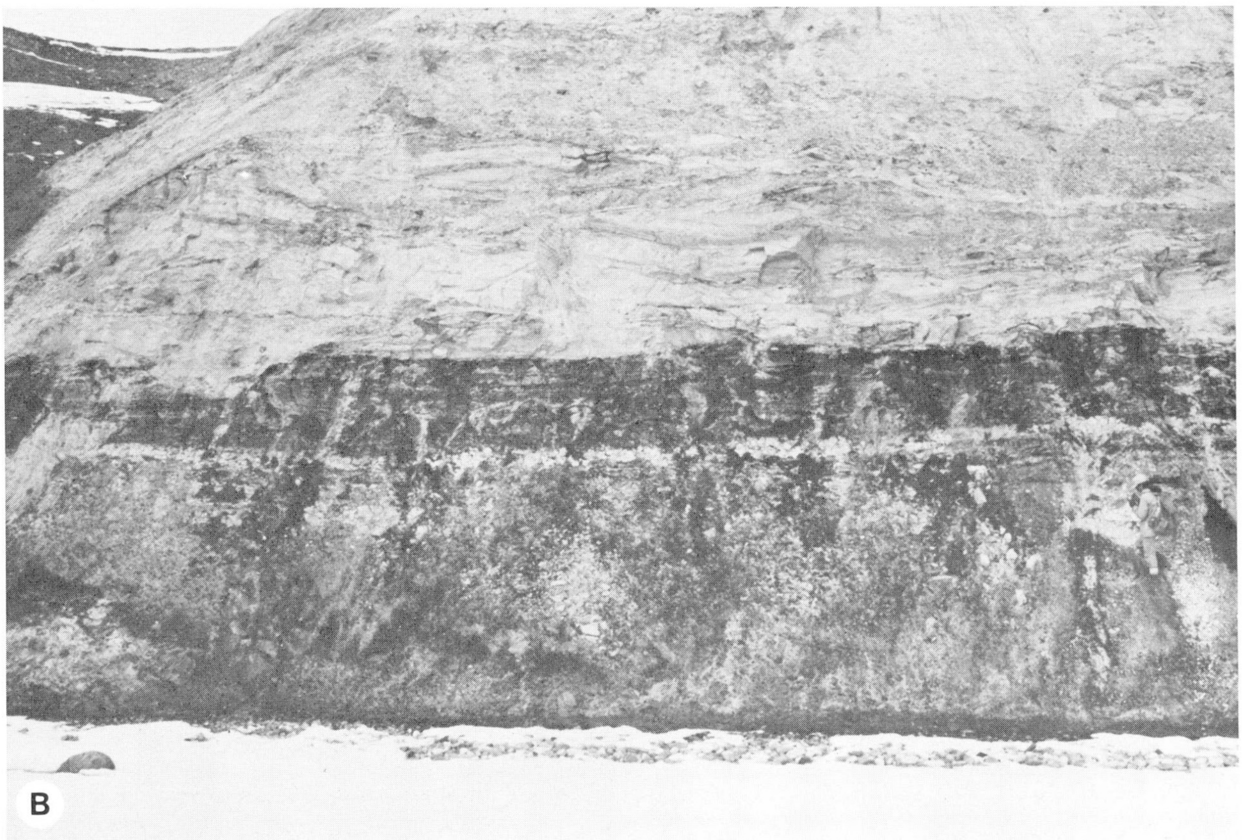


PLATE 1. Sandstone-mudstone member. A. Fine- to very fine grained sand and silty sand with argillaceous coal resting on tightly folded beds of the Imina Formation, station 36, Turnabout River. B. Crossbedded sandstone overlying a coal seam 2 m thick, station 2, Lake Hazen.

Sedimentological evidence presented in this report will show that the downwarp at Lake Hazen was in existence during the Tertiary, and that the Eureka Sound Formation was deposited in an enclosed intermontane basin setting. Subsequent reports will describe a second Tertiary intermontane basin extending northeastward along the east side of Judge Daly Promontory, a basin that probably was entirely separate from that at Lake Hazen.

It should be pointed out that neither of these basins appears to bear any genetic relationship to Hazen Trough, the early Paleozoic depositional feature described by Trettin (1971) and Trettin et al. (1972). The axis of this trough lay approximately 40 km to the southeast of Lake Hazen. Evidence both from the Permian (Miall, 1978a) and the Mesozoic (A.F. Embry, pers. com., 1977) rocks of the report area suggests that the region now occupied by the Hazen Fault Zone lay close to the southern margin of Sverdrup Basin. This was deformed and uplifted as a result of the Eurekan Orogeny, leaving the downwarp in the Lake Hazen area as a marginal remnant.

STRATIGRAPHY

Field work up to 1978 indicates that the Eureka Sound Formation of the Arctic Islands consists of at least ten distinct lithofacies assemblages, three of them marine in origin, the remainder nonmarine. Many of these facies comprise locally mappable stratigraphic units, but it remains to be determined whether any of these units can be traced further than a few tens of kilometres. Until field work is complete, it would be premature to attempt a formal revision of Paleogene stratigraphic nomenclature, and the name Eureka Sound Formation will be retained for the purpose of this report.

In the Lake Hazen area, four lithofacies assemblages can be recognized, and these have been conveniently grouped into two informal members, an older, sandstone-mudstone member and a younger, conglomerate member (Fig. 1). Sedimentological discrimination of the facies types is described in the section on facies analysis.

Sandstone-mudstone member

Definition, distribution and thickness

Most of the Eureka Sound Formation of the Lake Hazen area is assigned to this member, including the outcrops on the shores of Lake Hazen, exposures of the basal Tertiary on Turnabout River, and other exposures on this river, Gilman River and Mesa Creek. Tertiary outliers south and east of Lake Hazen are also assigned to the sandstone-mudstone member. As such this member includes all the Tertiary strata described by Petryk (1969; his "sandstone-shale members" are thin bedding units that can be traced for a few kilometres along the shore of Lake Hazen, near stations 2, 3 and 4 in Fig. 1) and the "lower part of the Tertiary" of Christie (1976) and Christie and Rouse (1976).

Complete exposures of the sandstone-mudstone member are not available and therefore the thickness of the member must be estimated. Based on structural considerations the total thickness is estimated at 450 m, but may thin to less than 150 m near the Boulder Hills.

The lower contact of the sandstone-mudstone member is a disconfomity near Piper Pass, where Tertiary strata rest on the Mesozoic. Rocks of Late Cretaceous age are probably missing, although exposures are inadequate to confirm this assumption. On Turnabout River, at station 36 (Fig. 1), the sandstone-mudstone member rests unconformably on tightly folded clastics of the Imina Formation (Pl. 1A). The upper contact of the sandstone-mudstone member, with the conglomerate member (best exposed at station 19), appears to be conformable and gradational (but see under age of conglomerate member). It is drawn at the horizon above which the section is composed of more than 50 per cent conglomerate. Conglomerate and sandstone are interbedded over an interval of about 40 m.

Lithology

The sandstone-mudstone member consists of very fine to very coarse, weakly consolidated sandstone, siltstone, mudstone, coal and rare pebble or cobble conglomerate. The sandstone is commonly crossbedded and may contain abundant carbonaceous plant debris or lenses of ironstone intraclasts. Logs up to 50 cm in length were observed. Petryk (1969, p. 13) observed pelecypod shells in the fine grained units. Coal seams are common; most are thin and lenticular but seams a few metres thick, up to a maximum of 3 m, are present. Amber is abundant. Conglomerate lenses a few decimetres in thickness are rarely present in this member. Clasts up to 23 cm in diameter were observed (at station 37), consisting of white or grey quartzose sandstone, red sandstone and conglomerate, limestone, diabase and ironstone (clast petrography is discussed further in a later section).

Sandstone and mudstone occur in beds a few decimetres to less than 20 m in thickness. Most beds are lenticular and die out, or are cut out by channels, within a few hundreds of metres, but Petryk (1969) was able to trace his 'sandstone-shale members', each less than 40 m thick, for up to 10 km along the shore of Lake Hazen.

Some typical sections through the sandstone-mudstone member are illustrated in Figure 2 and Plate 1.

Vertical and lateral variations in the proportions of the various lithologies are hard to assess owing to poor exposure. The section at station 7 appears to be most typical of the member; similar rock types were observed at stations 1, 14, 15 and 36. In these sections fine sand and silt are the predominant lithologies. Elsewhere, as at stations 2, 3, 4 and 37, the member is dominated by medium to coarse sand. These coarser intervals are probably localized in distribution and it cannot be determined whether they vary systematically in abundance either areally or stratigraphically. However, the uppermost 150 m of the succession comprise a transition unit with the conglomerate member, and are dominated by medium to coarse and gritty sandstone, as at stations 21, 24 and the lower part of the sections at stations 19 and 30 (Pl. 2A).

Age

Seventeen palynological samples from exposures of the sandstone-mudstone member along the shores of Lake Hazen were examined by G.E. Rouse, who reports (Christie and Rouse, 1976) that they indicate a probable Eocene age although the palynomorph assemblage is skewed to appear Oligocene or Miocene in character, as indicated by a palynofacies dominated by pollen of conifer and deciduous, broadleaf, angiosperm tree genera.

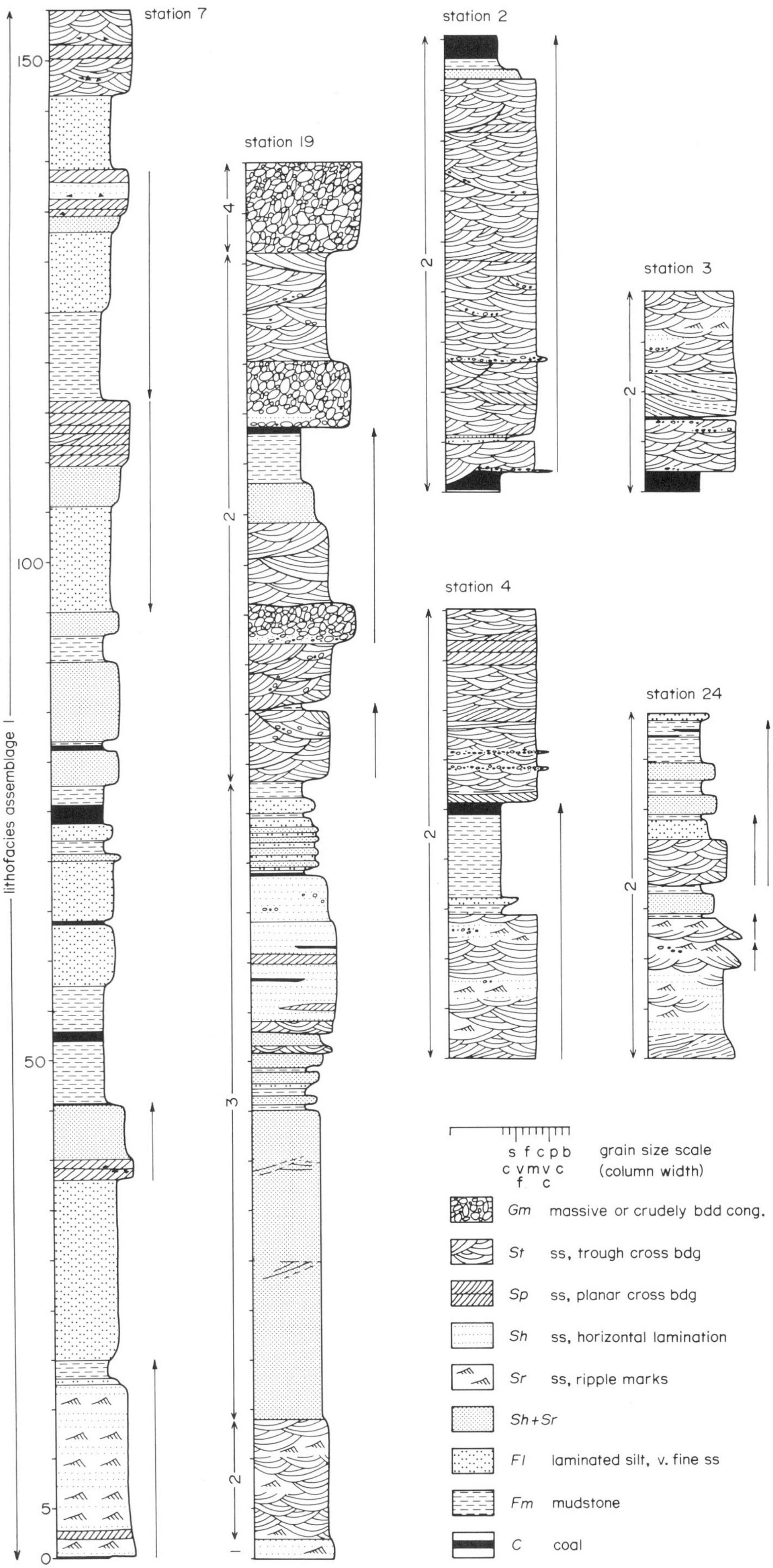


FIGURE 2. *Representative partial stratigraphic sections of the sandstone-mudstone member. The section at station 19 contains the contact with the conglomerate member - the uppermost conglomerate unit is the base of the latter. Scale and lithofacies assemblage classification are given on the left side of each column; each tick = 5 m. Arrows on the right indicate direction of fining in fining-upward and coarsening-upward sequences. Grain size is indicated by width of column; scale abbreviations, from left to right: c = clay, s = silt; sand grades: vf = very fine, f = fine, m = medium, c = coarse, vc = very coarse; p = pebbles, c = cobbles, b = boulders.*

PLATE 2. *Transition beds at the top of the sandstone-mudstone member. A. General view of 50 to 120 m interval of section at station 19, South Boulder Hills. B. Conglomerate with thin sandstone lens, 115 m level, station 19, South Boulder Hills.*

Three samples from the North Boulder Hills area (station 24, GSC locs. C-68650, 1, 2) and two from the Salor Creek area (station 57, GSC loc. C-68706; station 58, GSC loc. C-68707) were collected by the writer and examined by W.S. Hopkins, Jr. He reports (pers. com., 1978) that these samples contain a large and well-preserved microflora but that little of an age-diagnostic character is present. On balance the samples are assigned an Eocene age on the basis of doubtfully identified Eocene forms such as Platycarya sp. and Paraalnipollenites sp.

Five samples from the section at station 19 were also examined by W.S. Hopkins, Jr. (pers. com., 1978). The lower two, at the 45 m and 68.5 m levels (GSC locs. C-68641, 3) are of Paleogene type, but the upper three samples, at 76.5 m, 111 m, and 113 m (GSC locs. C-68644, 6, 7) are dominated by angiosperms and appear more Neogene in character. Hopkins suggests a possible correlation with the Beaufort Formation, of Miocene age, but in view of the absence of any demonstrable unconformity between these collections and those of Eocene age, it is suggested that the upper part of the sandstone-mudstone member at station 19 may be Oligocene.

In summary, the sandstone-shale member is tentatively assigned an Eocene to ?Oligocene age range at Lake Hazen. No beds of Paleocene age have been proven, which suggests that Eureka Sound sedimentation commenced here considerably later than in many other parts of the Arctic.

Conglomerate member

Definition, distribution and thickness

The conglomerate member is preserved in only two small areas in the Lake Hazen Tertiary basin, at Boulder Hills (herein referred to as North Boulder Hills), e.g. at station 26, and in a similar outlier south of Turnabout River (herein referred to informally as South Boulder Hills), e.g. at stations 8, 19, 32. It is probable that originally this member was considerably more extensive. The two outliers no doubt were originally connected, and the member may in fact have occupied much of the Tertiary basin.

The maximum preserved thickness of the conglomerate member is at South Boulder Hills, where about 450 m of section are present. The lower contact of the member is gradational; conglomerate is interbedded with sandstone over an interval of about 40 m and ribs of poorly exposed conglomerate can be traced below the assumed contact on the flanks of both outliers. The upper limit of the conglomerate member is the present day erosion surface.

Lithology

The only good exposures of this member are those of the lowermost beds and their gradational contact with the sandstone-mudstone member, at stations 19, 30 and 32 (Pl. 2). Higher beds, in both Boulder Hills areas, are poorly exposed on bare slopes at or near the angle of repose of the clasts, but these are disturbed exposures, as indicated by the fact that most of the sand matrix has been washed out.

The South Boulder Hills show several sub-horizontal benches suggesting that the lithology of the member is not completely uniform. Sandstone beds are probably present, giving rise to recessive intervals. Such topographic features are not as obvious in the North Boulder Hills.

At station 19, clast size increases up the section from a maximum diameter of 26 cm in the lowermost conglomerate (92-96 m interval) to 1.3 m at the top of the section. At station 26, at the summit of North Boulder Hills, the maximum clast diameter is 1.2 m. Clast types include foliated sandstone, massive white quartzose sandstone, fossiliferous limestone, red sandstone and conglomerate, diabase and black mudstone. All the clasts are well rounded.

Age

No palynological information is available from the conglomerate member. At the South Boulder Hills (station 19), the beds underlying the conglomerate member have been tentatively dated as Oligocene and, on this basis, an Oligocene age is tentatively assigned to the conglomerate member. Other writers (e.g. Balkwill, 1978) have assumed that the Boulder Hills conglomerates are Miocene in age, and have correlated them with the Beaufort Formation, which would imply a major stratigraphic and sedimentological break between the sandstone-mudstone and conglomerate members. The gradational contact between the two members suggests that such a break is not present but, in fact, it might be difficult to detect a disconformity in a fluvial sequence, and a Miocene age for the conglomerate member cannot be discarded as an alternative interpretation. Fry (in Blackadar, 1954, p. 19) identified a cone collected in the northeast corner of the Tertiary outcrop area and assigned it a "Miocene (or) possibly more recent" age. The writer was unable to locate the original outcrop from which this specimen was obtained and its significance remains unclear.

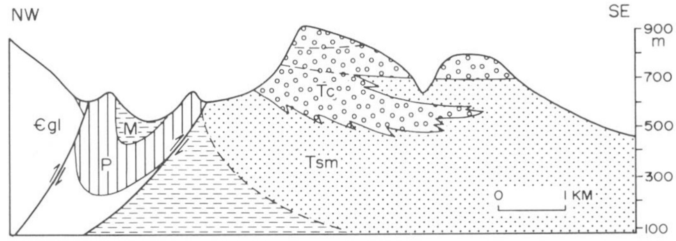
STRUCTURE

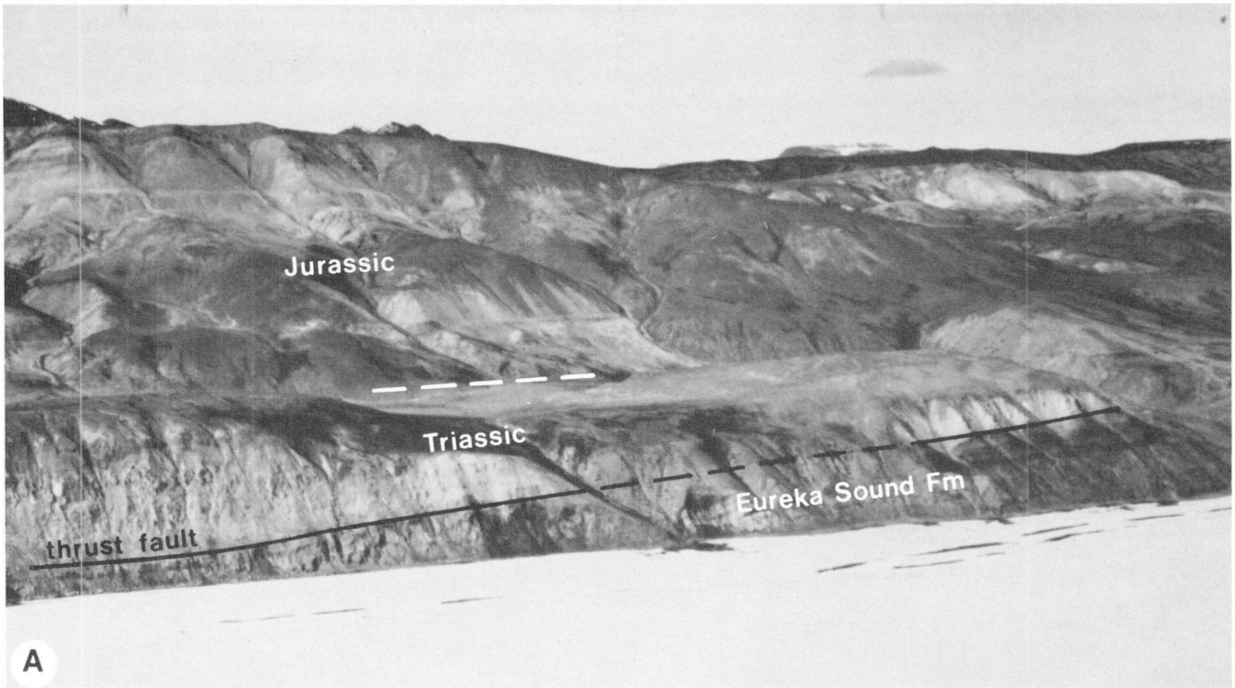
The Tertiary strata rest with a profound unconformity on the Ordovician-Silurian Imina Formation along the southern margin of the basin, and with a disconformity or low angle unconformity on Cretaceous rocks near Piper Pass. Tertiary rocks overstep the Mesozoic in the subsurface toward the south and east.

Throughout most of the Lake Hazen area, dips in the Tertiary are low and undisturbed horizontal stratification is common. Deformation increases toward the northwestern, thrust-faulted boundary of the Tertiary basin, where dips steepen to at least 10°. In places the Tertiary beds dip away from the fault (Fig. 3); elsewhere, as at stations 19, 30 and 32, the dip is toward the fault. In places incompetent beds of the sandstone-shale member have been tilted vertically or deformed into tight folds in the footwall zone, within 2 km of the bounding thrust fault (Pl. 3B). The indicated direction of tectonic transport on these folds is southeastward, the same as on the fault itself.

The main thrust fault of the Hazen Fault Zone is steeply dipping to near vertical, whereas the more sinuous outcrop trace of the other fault, which borders the Tertiary outcrop area, suggests that it dips more gently. Near Lake Hazen it may dip north at an angle approximately that of the bedding in the hanging wall, which is about 20°.

FIGURE 3. *Structural cross-section through South Boulder Hills (station 19) and the Hazen Fault Zone. Ornamentation is as in Figure 1. Єgl = Grant Land Formation, P = Permian, M = Mesozoic, Tsm = Eureka Sound, sandstone-mudstone member, Tc = Eureka Sound, conglomerate member. Elevations at right are in metres above sea-level.*





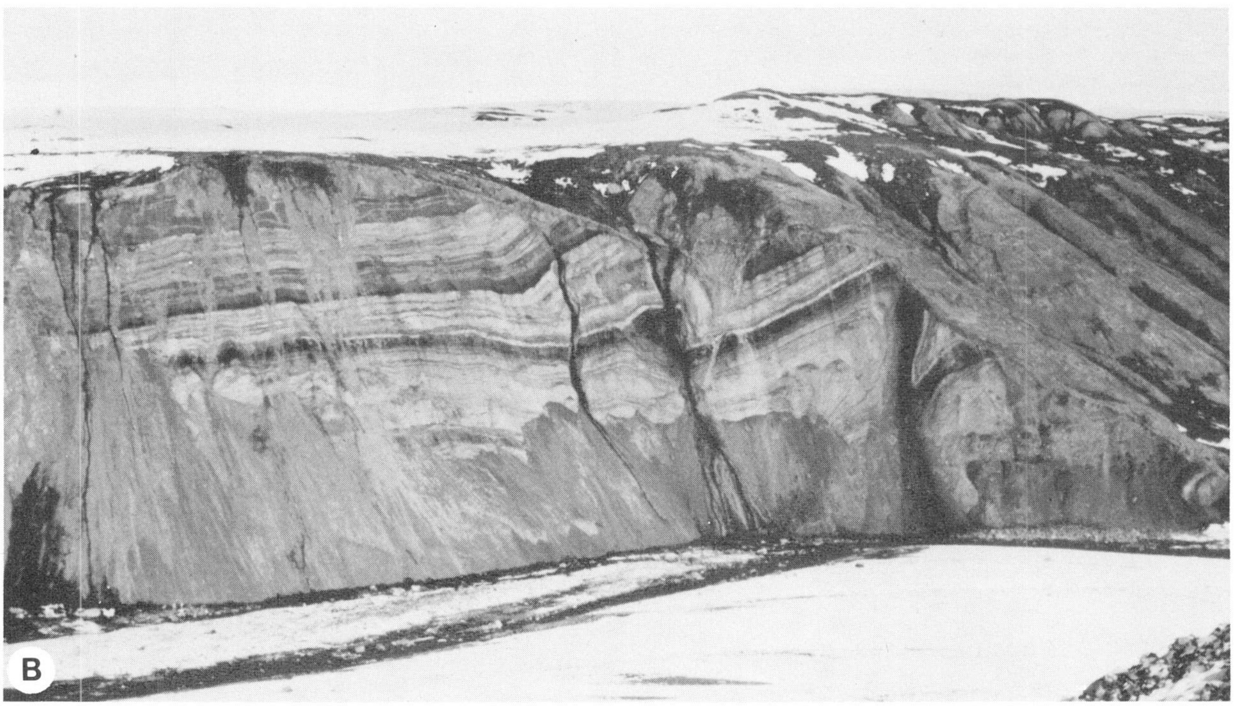


PLATE 3. *Structural features of Lake Hazen Fault Zone. A. Mesozoic strata thrust over the Eureka Sound Formation at Lake Hazen, station 2. B. Folded sandstone and coal beds of the sandstone-mudstone member 2 km south of the thrust fault at station 1, Gilman River.*

FACIES ANALYSIS

Introduction

Alluvial deposits can conveniently be analyzed at three levels of detail:

1. Description and characterization of individual bed types, as defined by grain size, sedimentary structures and biofacies (if any). For braided river deposits, a detailed lithofacies nomenclature and code system was devised by Miall (1977, 1978b). It can probably be used in modified form for most fluvial deposits.

2. Lithofacies assemblages are the key to depositional environments, as formalized by the concept of facies models (Potter, 1959; Walker, 1976). There is, for example, the "meandering river" model, the "river-dominated delta" model, etc. These models tend to emphasize vertical profiles, and generally contain some description of an ordered, cyclic bed-type sequence.

3. Individual assemblages, or a limited number of assemblage types, may form thicknesses of strata tens to thousands of metres in thickness. On a gross scale these appear relatively uniform, and they are the usual basis for stratigraphic subdivision of alluvial sequences into members and formations.

This ranking parallels that of the bedform hierarchy which Allen (1966, 1967) and Miall (1974) used to analyze paleocurrent variability at different levels of observational scale (bed, outcrop, region etc.). Both approaches should parallel nature, in that individual members or formations represent specific alluvial systems, or perhaps a single river; individual cycles represent a single major depositional event of that river, such as a point bar complex representing a few tens to thousands of years; and individual beds represent small scale geomorphic units such as a bar or a floodplain pond. Hierarchical classifications of landforms have been used recently by geomorphologists and ecologists in studies of modern coastal environments (Dolan et al., 1972; Terrell, 1977), but the implications of their work for studies of stratigraphy and sedimentology have not yet been explored.

Recent examples of studies that use a hierarchical facies analysis approach to stratigraphic synthesis include that of the Middle to Upper Devonian clastic wedge of the Arctic Islands, by Embry and Klovan (1976), the Siluro-Devonian clastic wedge of the Boothia Uplift region, by Miall and Gibling (1978), and the Proterozoic Belt Supergroup of Montana and Idaho, by Winston (1978). A rather more complex, statistical approach was used by Friend et al. (1976) in their study of the Devonian sediments of East Greenland.

In this report the lithofacies classification scheme of Miall (1978b) is used for the smallest scale of analysis (Fig. 2), and an attempt is made to recognize various fluvial facies model types based on the work of Miall (1977, 1978b), Jackson (1978), Nijman and Puigdefabregas (1978), Nanson (in press) and others. The facies hierarchy scheme is shown in Figure 4.

Lithofacies types

A list of the lithofacies types recognized in this study is given in Figure 2. Most of these lithofacies were defined and described by Miall (1977, 1978b), and the following brief notes are intended only to document features particularly characteristic of this basin.

Conglomerate units (lithofacies Gm) in the sandstone-mudstone member are commonly moderately well sorted, with a well-developed clast framework (Pl. 4A). Clast imbrication is crude owing to the lack of discoidal clasts. Sorting decreases as grain size increases upward into the conglomerate member.

Lithofacies St and Sp in some places include broad, shallow scours and possible small scale lateral accretion sets, analogous to Allen's (1963) epsilon crossbedding (Pl. 4B). Elsewhere they comprise stacked sequences of trough or planar crossbedding (pi and omikron cross-stratification of Allen, 1963) comparable to those occurring in numerous fluvial deposits, particularly those of low sinuosity, multiple channel ("braided") rivers (Pl. 5A; cf. Miall, 1977, Fig. 7).

Lithofacies Sh is represented mainly by well-sorted, massive weathering sandstone units in which lamination is extremely faint. In a few places, however, bedding is rendered more prominent by the abundance of comminuted carbonaceous detritus (Pl. 5B). Lithofacies Sh and Sr commonly are interbedded on a fine scale and in some cases have been grouped for the purpose of section description.

Lithofacies Fl, consisting of fine to very fine sandstone, siltstone and mudstone, is locally abundant; lithofacies Fm is less common, and most occurrences are markedly silty. Much of the Tertiary outliers along Salor Creek consists of lithofacies Fm, but elsewhere this lithology is a subordinate component of the sandstone-mudstone member.

Lithofacies C, coal, occurs in units up to 3 m thick and is present throughout the sandstone-mudstone member. None of the finer grained lithofacies (Fl, Fm), or coal, has been recorded in the conglomerate member.

Lithofacies assemblages

As shown in Figure 4, four lithofacies assemblages have been defined in the report area. They are described and interpreted in this section.

Assemblage 1

Description

This assemblage is characterized by a wide range in lithofacies types, conglomerate (lithofacies Gm) being the only type not yet observed. The commonest lithofacies are very fine to medium-grained sandstone units (lithofacies Sh, Sr), and silty and muddy lithologies (lithofacies Fl, Fm). Large scale sedimentary structures are not common. Coal is most abundant in this assemblage. The section at station 7 (Fig. 2) is typical of assemblage 1. That at station 14 (Fig. 5) is similar but, because of the wide lateral extent of the outcrop, it provides considerably more data for detailed sedimentological interpretation.

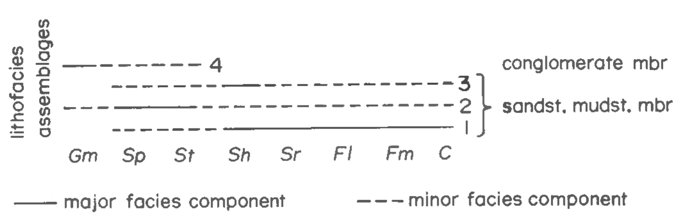


FIGURE 4. The facies hierarchy scheme. Lithofacies codes as in Figure 2.

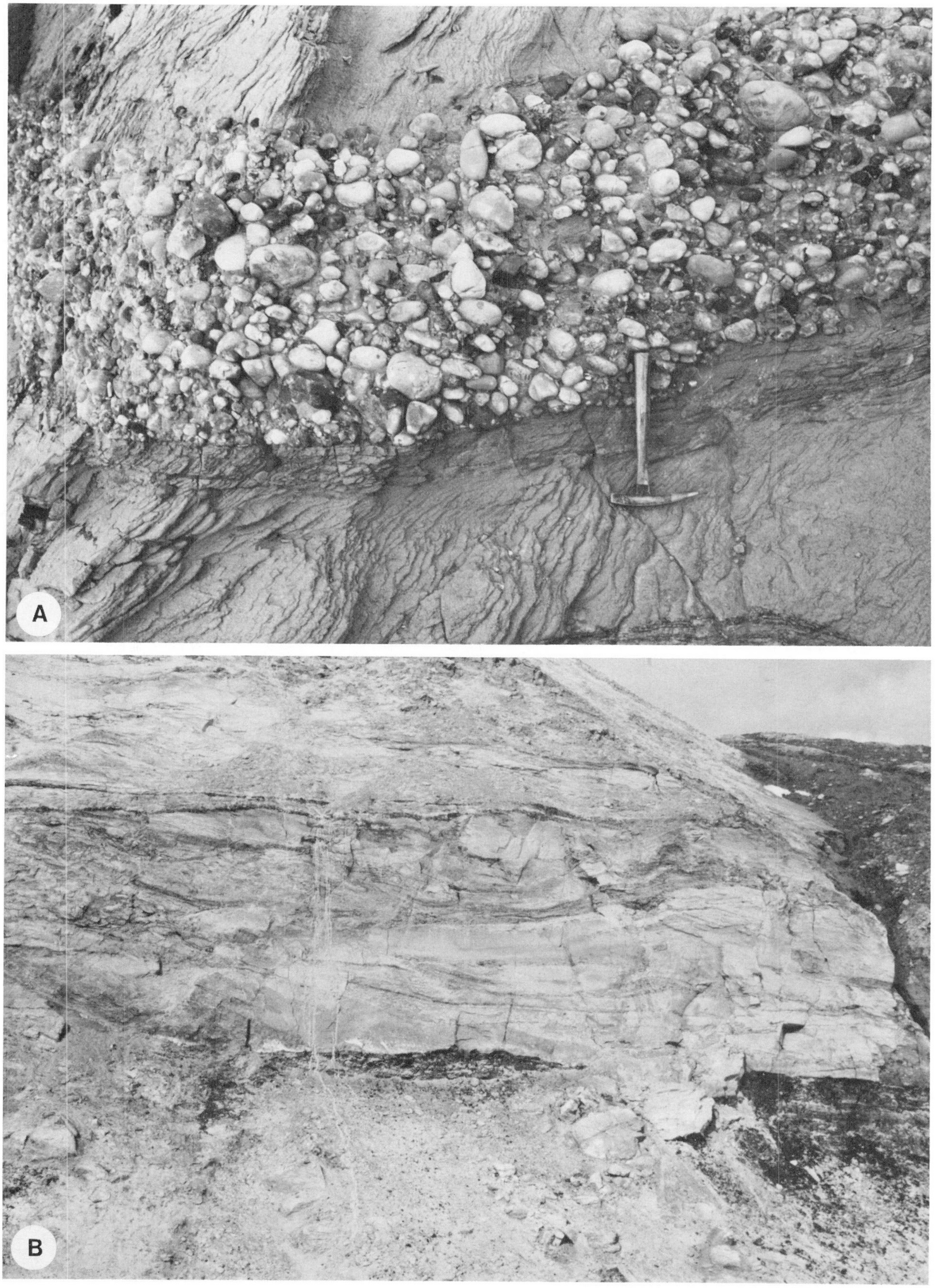


PLATE 4. *Lithofacies types. A. Lithofacies Gm, imbricated conglomerate enclosed in units of crossbedded sandstone, station 30, South Boulder Hills. B. Complex lateral accretion surfaces developed in Lithofacies St, trough crossbedded sandstone, station 2, Lake Hazen.*

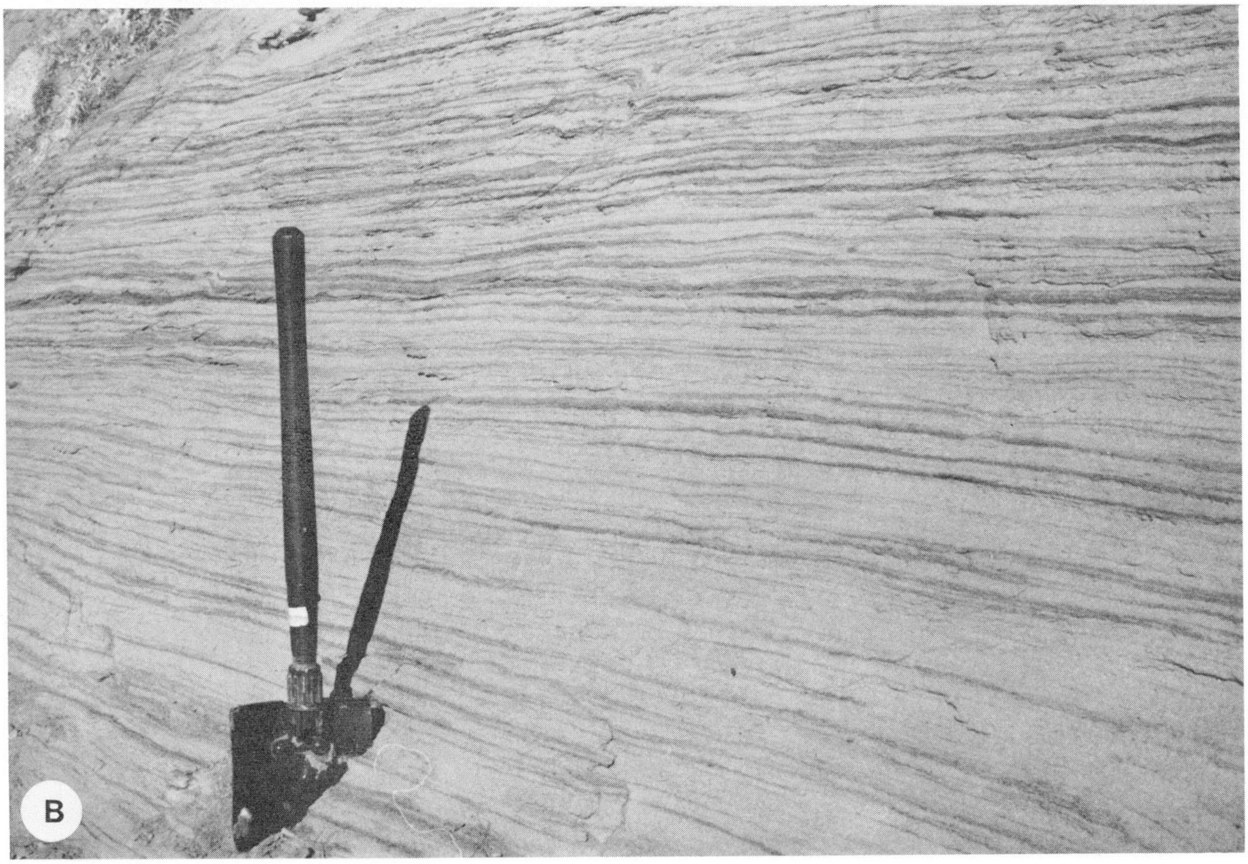


PLATE 5. Lithofacies types (continued). A. Lithofacies Sp, planar crossbedded sandstone, station 37, near Turnabout River. B. Lithofacies Sh, planar laminated sandstone, with dark streaks formed by sand-sized comminuted carbonaceous debris, 50 m interval of section at station 19, South Boulder Hills.

Assemblage 1 is the most widespread of the three that have been defined in the sandstone-mudstone member. All the Tertiary outliers south and east of Lake Hazen are composed of this assemblage. Exposures along Salor Creek (stations 57, 58) indicate that locally up to 300 m of section are preserved, infilling topographic lows in Hazen Plateau, and most of this is fine grained sediment (lithofacies Fl, Fm).

Interpretation

A useful approach for studying fluvial deposits is to analyze vertical bed sequences, perhaps with the use of statistical techniques such as Markov chain analysis (Miall, 1973). The by now classic fining-upward cycle, interpreted to be of meandering river origin, is one of the foremost products of such an approach (Allen, 1970). In the present case, data on vertical lithofacies successions are inadequate to support a statistically rigorous Markov analysis. Subjective analysis of sections such as that at station 7 (Fig. 2) suggests a few repeated lithologic associations, but does not provide a good basis for sedimentological interpretation. Fortunately the section at station 14 on Turnabout River, with its vertical exposure of about 35 m and lateral exposure of over 250 m, provides an excellent basis for interpreting facies asssemblage 1 in the light of our current knowledge of fluvial depositional environments (Fig. 5).

The coarser units at Turnabout River contain clearly defined, large scale, low angle crossbedding surfaces of the type defined by Allen (1963) as epsilon crossbedding, and subsequently interpreted as superimposed lateral accretion surfaces formed by the building of a point bar complex in a high sinuosity ("meandering") river (Allen, 1965). The epsilon foresets consist predominantly of fine sandstone with some very fine sandstone and siltstone laminae. In some places a marked upward decrease in grain size occurs. No minor sedimentary structures were observed within the foresets. Two point bars are visible in the Turnabout River exposure; these are designated as the upper and lower point bar, respectively, in Figure 5. They are each of variable thickness, reaching a maximum of about 4 m, and have a maximum foreset dip of 25°.

Lithofacies Fl is finely laminated and, adjacent to the upper point bar, also contains low angle crossbedding surfaces, dipping away from the point bar. These crossbeds have a maximum amplitude of about 3 m, and are interpreted as levee deposits.

The river flood plain is represented by lithofacies Fm and C.

The exposure has also been interpreted in terms of the fining-upward fluvial model. Three cycles can be recognized, each containing a sand unit at the base and floodplain deposits at the top. The cycles are 9 m, 17 m and >9 m thick, in order from base to top of the section. In places a relatively smooth upward fining within the cycles can be observed, but in most parts of the exposure the cycles are far from simple. The upper point bar dies out to the north (left in Fig. 5) and is replaced by levee deposits. The same point bar scours down into a stray sand which thickens and coarsens to the north; the latter is probably a floodplain sheet deposit formed as a crevasse splay from another channel out of the exposure to the north. The coal in cycle 2 is not at the top of the cycle but is followed by an interval of floodplain mud, suggesting a renewed period of overbank flooding. Toward the south side of the exposure, the lower point bar appears to split into three separate sandy intervals although, unfortunately, critical parts of this exposure are covered by talus. In summary, the exposure at Turnabout River reveals at least three episodes of lateral channel migration, with accompanying point bar, levee and floodplain formation.

Applying the insight gained from this exposure to vertical sections such as that at station 7 (Fig. 2), it becomes obvious why it is difficult to recognize the classic fining-upward cycle in this lithofacies assemblage. Two possible intervals of upward fining are noted by arrows in the lower part of the section, but the only other apparently cyclic units are two coarsening-upward intervals in the upper part of the section. A possible interpretation of these is that the lower part of each cycle represents a period when channels had migrated a long distance from this location, which became part of an extensive floodplain swamp; then, when the area was again influenced by higher energy conditions, the first deposits to reach the area were crevasse splays. These commonly form coarsening-upward intervals in deltaic environments, where a distributary levee flanking a backswamp or interdistributary bay is breached during flooding (Coleman and Gagliano, 1964).

The detailed work of McGowen and Garner (1970), Jackson (1976a, b, 1978), Puigdefabregas (1973), Nijman and Puigdefabregas (1978) and Nanson (in press) on modern and ancient point bars permits a detailed comparison of published features of point bars with those occurring in the sandstone-mudstone member. Those exposed at Turnabout River are most similar to those described by Nanson (in press) and correspond to facies class #1: "muddy fine-grained streams" of Jackson (1978). The fine grain size of the point bar deposits, the steepness of the epsilon crossbed dip, the scarcity of subordinate sedimentary structures, the thickness of associate floodplain deposits (Fl, Fm, C) and the prominence of levees are the principal points of comparison with Jackson's class #1. The point bars described by Nanson (in press) are somewhat coarser in grain size and contain prominent scroll bars, as indicated by undulations in the point bar accretion surface when seen in cross-section. The point bars at Turnabout River, particularly the left-hand exposure of the lower bar (Fig. 5), show prominent benches, indicating the presence of incipient scroll bars or mid-bar benches, such as are characteristic of coarser grained point bars (McGowen and Garner, 1970; Jackson, 1976a; Nijman and Puigdefabregas, 1978).

The paucity of large scale sedimentary structures such as planar and trough crossbedding and the lack of well-developed scroll bars indicate that there were few of the within-channel bedforms which are characteristic of coarser grained, high sinuosity rivers (Jackson, 1978). It is unlikely, therefore, that the rivers were, in any sense of the word, braided, even at low water stages when in many rivers flow is diverted around bar forms, leaving them exposed as temporary islands. The rivers forming the Turnabout River cycles thus are thought to have been "classic" meandering rivers; single-channel streams of high sinuosity. The complete preservation of the point bars and the thickness of overbank sediments suggest relatively rapid aggradation with little reworking. Scours are present at the base of the point bars but they do not show more than a few metres of erosional relief.

In some areas, as in the large outlier along Salor Creek (stations 57, 58), most of the Tertiary section is fine grained sediment (lithofacies Fl, Fm), suggesting the existence of a widespread swamp crossed by few sluggish streams.

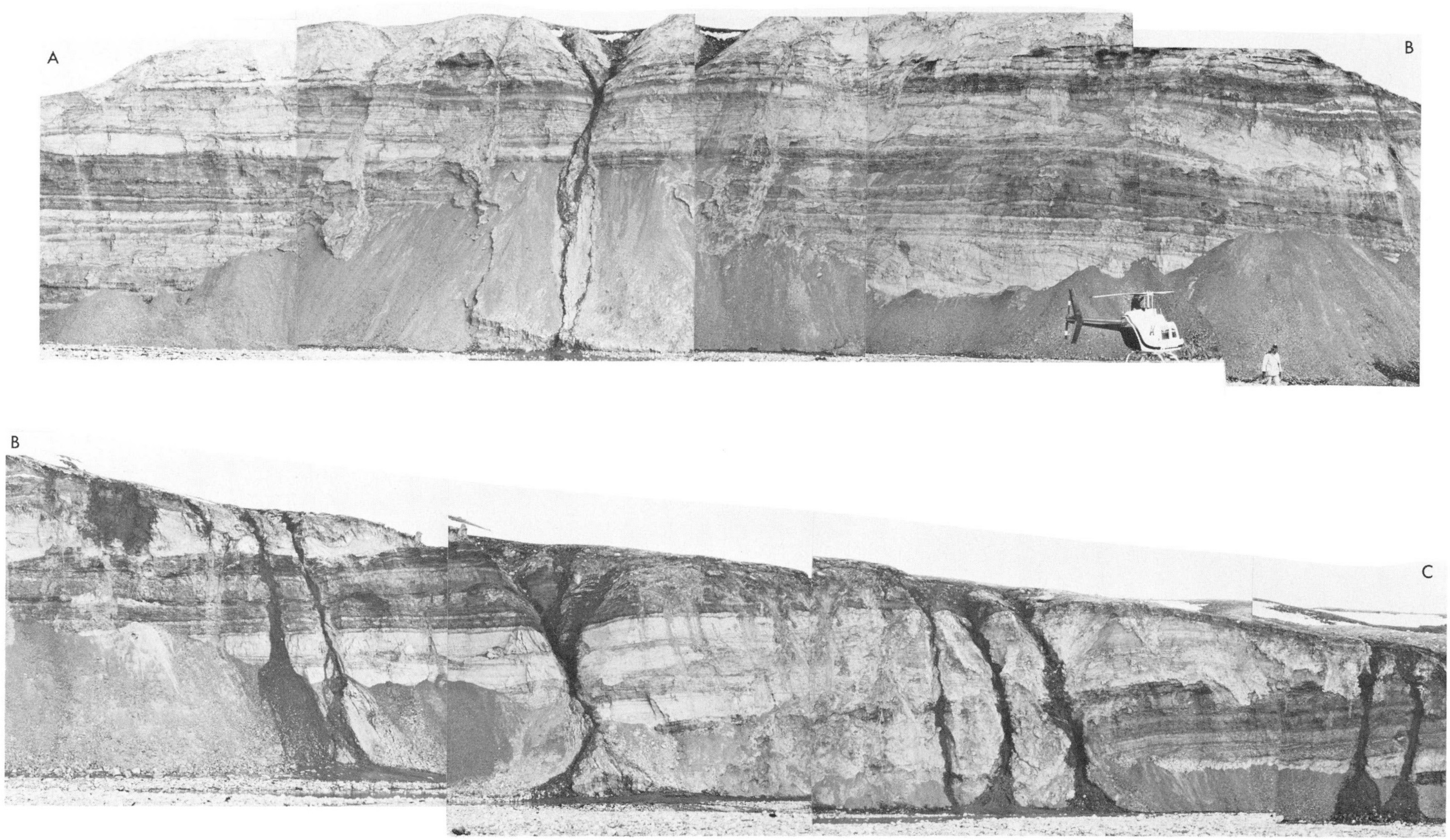


FIGURE 5A. *The sandstone-mudstone member at station 14, Turnabout River; view is toward the northeast; panorama of outcrop.*

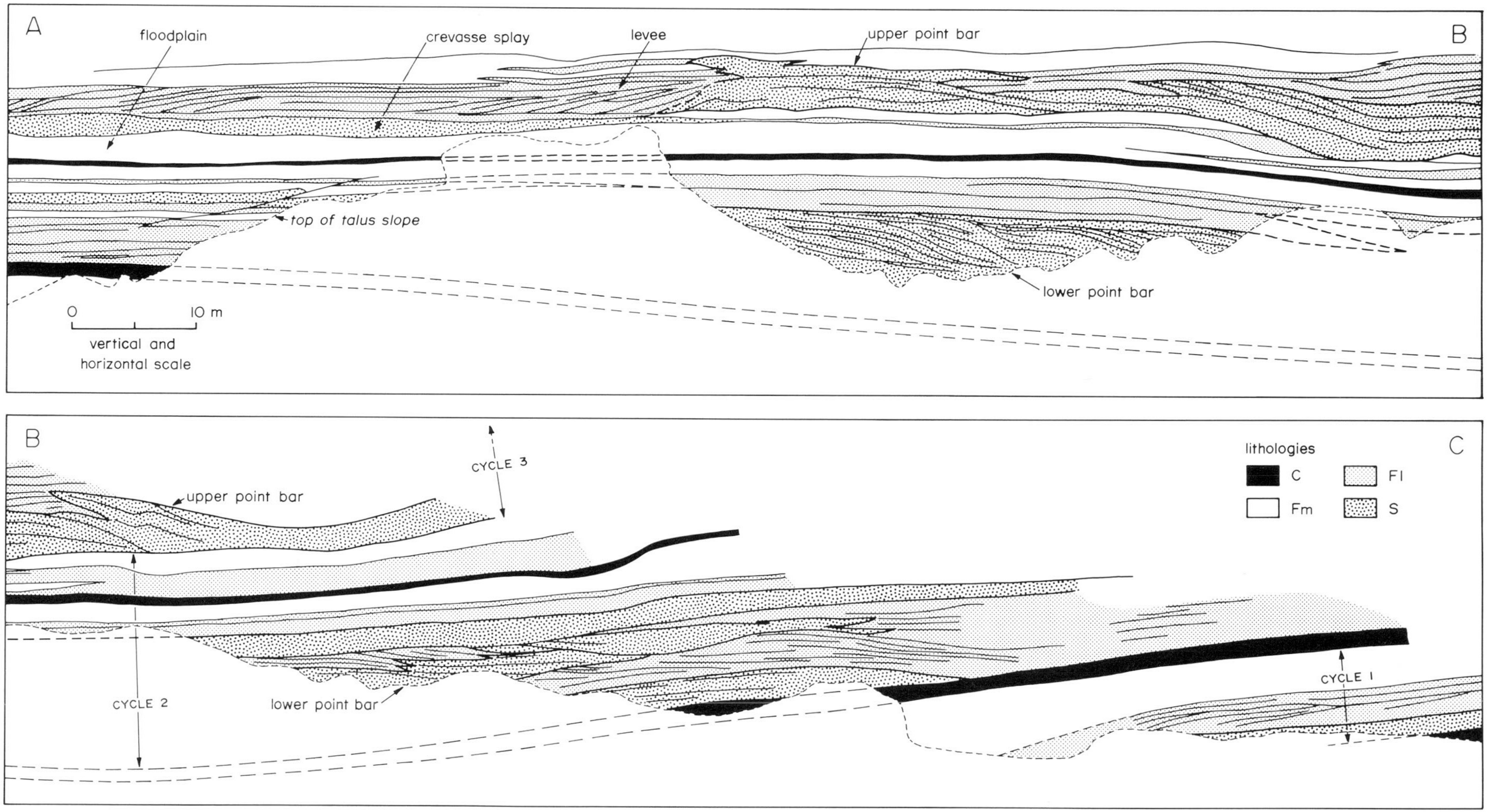


FIGURE 5B. *The sandstone-mudstone member at station 14, Turnabout River; view is toward the northeast; interpretation in terms of three fluvial cycles, with various depositional environments indicated. Lithologies: S = sand, other codes as in Figure 2.*

Assemblage 2

Description

This assemblage is dominated by crossbedded sandstone (lithofacies St, Sp), although all the lithofacies observed in the Lake Hazen Tertiary basin have been recorded. Typical exposures of the assemblage are at stations 2, 3, 4, 24 and 37 (Fig. 2). Part of the section at station 19 is also composed of assemblage 2, interbedded with intervals of assemblage 3. Crude fining-upward cycles are visible in some of the sections, up to 44 m in thickness; most of these consist of a thick, coarse interval comprising stacked units of lithofacies St or Sp with rare Gm interbeds, followed by a thin capping of Fl, Fm and possibly coal. One cycle in the 92-113.5 m interval at station 19 (21.5 m thick) has a 4 m conglomerate unit at the base. Some sections, as at station 37, exhibit no obvious cyclicity. The broad, shallow scours and small scale lateral accretion sets referred to in "Lithofacies types" (Pl. 4B) occur in this assemblage.

Assemblage 2 occurs as lenses within the sandstone-mudstone member; exposures are prominent from the air as whitish areas within an otherwise pervasive, grey ground colouration imparted by the fine grained facies of assemblage 1. Assemblage 2 also forms part of the transition unit immediately underlying the conglomerate member.

Interpretation

The crude cyclic sequences are analogous to those described as braided "South Saskatchewan-type" by Miall (1978b). Sections which lack cyclicity, as at station 37, contain intervals of stacked crossbedding (Pl. 5A) and are reminiscent of the "Platte-type" of vertical profile, as defined by Miall (1977). A complicating factor is the presence of epsilon crossbedding, which has been recorded at stations 2, 24 and 37, within this assemblage, and the assemblage as a whole contains some of the features of Jackson's (1978) classes 2 and 3 "meandering" streams.

Is assemblage 2 the product of braided or sandy meandering rivers, and how can either interpretation be reconciled with the fact that the assemblage is intimately interbedded with assemblage 1, the product of muddy, fine grained meandering rivers? This question focuses attention on our concepts of fluvial facies models, which recent work has shown to be overly simplistic. As Rust (1978) has pointed out, our two common morphological terms, braided and meandering, emphasize two different parameters, channel multiplicity and sinuosity, and the features which they define are not mutually exclusive in nature. High sinuosity sandy and pebbly rivers may have internal braids, and in such cases can equally well be termed braided or meandering. This fact is responsible for much confusion in our interpretation of fluvial sediments. Jackson (1978) states that many deposits which are routinely interpreted as braided stream deposits may in fact be of meandering river origin. Probably both interpretations are correct but both contain only half the truth. Jackson (1978) does not agree with the suggestion by McGowen and Garner (1970) that coarse grained meandering stream deposits are a transitional form between those of braided and meandering streams. However, I feel McGowen and Garner (1970) are probably correct, although there are many complicating factors such as variability in discharge and bank cohesiveness, the morphological implications of which have yet to be fully explored. It is becoming apparent that continued use of the terms "meandering" and "braided" is serving to generate confusion. More precise, though admittedly more cumbersome, morphological descriptions would make use of phrases such as "high-sinuosity, single channel river" and "low-sinuosity, multiple channel river" etc. The sedimentological applicability of such definitions is examined briefly by Rust (1978).

In the case of assemblage 2 the sections contain clear evidence of both "meandering" and "braided" characteristics. Epsilon crossbed sets up to 2.5 m in thickness indicate sedimentation by lateral accretion, which is a feature most typical of bank-attached bars inside high curvature channel bends. Sandy rivers, be they of high or low sinuosity, are characterized by abundant channel-floor bedforms; dunes and linguoid bars are particularly common. If the sand supply is adequate and the rate of aggradation is relatively rapid, these may coalesce into large compound bar forms or sand flats (Cant, 1978). Emergence of such bars during low water or their colonization by vegetation causes flow diversion and the development of multiple channels, i.e. braiding. Such bars are particularly well-known in low sinuosity rivers but are increasingly being reported from high sinuosity rivers as well (McGowen and Garner, 1970; Bluck, 1971; Jackson, 1976a, 1978). The abundance of large scale crossbedding in assemblage 2 is interpreted as indicating an abundance of bars and bedforms, particularly dunes (trough crossbedding) and linguoid or transverse bars (planar crossbedding). Some of the bars are associated with epsilon crossbedding and may therefore be bank-attached, possibly components of small scroll bars; others likely are mid-channel forms. The short cyclic sequences and the longer cruder cycles which are both present in assemblage 2 are similar to many which have been observed in modern low sinuosity multiple-channel ("braided") rivers (Miall, 1977). Their origin is diverse, and may relate to channel aggradation, point bar growth or flood cycles.

The conglomerate-based cycle at station 19 (92-113.5 m interval) may be of different origin. As discussed later, the upward coarsening of the Tertiary into the conglomerate member is attributed to the increase in relief due to uplift on the thrust faults bounding the basin. Fault movement probably occurred in pulses, each of which would result in a sudden increase in river slope and hence competency. This could account for the sudden appearance of conglomerate in the section and the initiation of a new cyclic sequence at the top of the sandstone-mudstone member.

In summary, the rivers which formed lithofacies assemblage 2 are interpreted to have been of multiple-channel type. They may or may not have been of variable sinuosity. The presence of epsilon crossbedding suggests that at least locally there were high sinuosity reaches, but elsewhere they may have been of classic, low sinuosity "braided" type. The relationship of these rivers to those which formed assemblage 1 is discussed in a later section.

Assemblage 3

Description

The dominant lithology is horizontally laminated sandstone, lithofacies Sh. Some units contain interbeds of lithofacies Sr, St or Sp, but thick intervals of monotonously laminated sandstone without obvious sedimentary structures are common. Fine grained lithofacies, Fl, Fm and coal, are minor components. Contorted lamination is locally common.

The best exposure of assemblage 3 is at station 19 (Fig. 2, Pl. 5B), where it makes up more than 60 m of continuous section.

Interpretation

This lithologic assemblage is very characteristic of what Miall (1977) termed the "Bijou Creek-type" of vertical profile. It is interpreted as the product of flash floods in which deposition took place under high flow velocities. Harms et al. (1975) have shown that for sand of fine to very fine grade - the predominant grain size in this assemblage at Lake Hazen - small variations in grain size, flow velocity and depth can cause fluctuations in bedform conditions between ripples, upper flat bed and dunes. The predominance of the flat bed condition indicates that flow velocities must commonly have exceeded 60 cm/sec.

The 14 to 78 m interval at station 19 probably represents a series of stacked flood cycles. A few relatively compete cycles are present, in which grain size shows small scale upward fining, and a gradation up into lithofacies Fl and/or Fm. However, much of the section consists of continuous laminated sand, which probably represents many cycles, each of which partially eroded earlier deposits and removed any fine grained material. Scour surfaces were not observed except at the base of trough crossbed sets, but scours formed under plane bed conditions likely would be flat and difficult to distinguish from bedding.

Assemblage 4

Description

This assemblage consists primarily of clast-supported pebble, cobble and boulder conglomerate, lithofacies Gm. Clast size reaches a maximum of 1.3 m. There is a gross upward coarsening. Exposures of this lithofacies are poor, but the conglomerate is probably interbedded with minor units of crossbedded sandstone (lithofacies St, Sp).

Interpretation

Thick clast-supported conglomerate units with minor sandstone interbeds have been termed the "Scott-type" assemblage by Miall (1977). The conglomerates represent flash-flood deposition on gravelly alluvial fans, and probably comprise multistory longitudinal bar accumulations. Sandstone beds are the product of lower energy fluvial sedimentation, probably during the waning stages of floods.

Variations in fluvial style

The sandstone-mudstone member contains evidence of a variety of fluvial styles: 1. muddy, fine grained, high sinuosity streams; 2. sandy, multiple channel streams of high and possibly also low sinuosity; 3. sandy streams subject to flash flood, possibly with ephemeral runoff. Deposits of the first two classes of stream are interbedded, indicating coexistence of the stream types. This has not commonly been reported in ancient fluvial deposits. Unfortunately, due to paucity of exposure, it is not known whether there is any ordered vertical or lateral sequential relationship between the main lithologic assemblages and so interpretations of the variations in fluvial style can only be generalized.

Fluvial morphology is controlled by a variety of parameters, of which the most important are discharge magnitude and variability, calibre and quantity of sediment load, abundance of vegetation, regional slope and nature of bank materials (Miall, 1977; Schumm, 1977). Local variations in bedrock controls or downstream variations in climate may cause several changes in channel pattern between source and mouth. Adjacent tributaries may have different morphological characteristics and the whole or part of a river system may undergo drastic changes with time as a result of climatic or tectonic modifications. Schumm (1977) refers to this as river metamorphosis, and gives several examples; others are cited by Miall (1977). Amongst these examples are several in the geological record in which coarse sandy or pebbly deposits, the product of low sinuosity, multiple channel streams, pass up into finer grained sediments as the rivers decreased in competency due to erosion and a lowering of slope, and increased in sinuosity. However, few examples have been described in the geological record of fluvial deposits in which contrasting fluvial styles co-existed side by side along depositional strike, or alternated over a short enough interval of time to be represented by only a few tens of metres of sediment. Friend and Moody Stuart (1972) described the sedimentary history of an intermontane basin in which the rivers entering the basin from either side were of contrasting style; Embry and Klovan (1976) documented several cycles of fluvial change occurring over a vertical thickness of more than 5000 m; more complex vertical and lateral changes are described by Alexander-Marrack and Friend (1976) and Nicholson and Friend (1976).

There are at least five possible causes of the pattern seen in the sandstone-mudstone member:

1. Assemblages 1 and 2 may reflect relatively more distal and more proximal parts (respectively) of a river system. In a graded river, grain size decreases downstream, and the morphology commonly changes from low to high sinuosity in the same direction. This explanation would require that the two lithofacies assemblages occur in discrete belts parallel to the depositional strike of the basin but, in fact, distribution of the assemblages appears to be random.

2. The sediments may have been deposited by several rivers which had different source area geology, resulting in variations in sediment calibre and quantity, with its attendant effects on fluvial morphology. However, as determined by paleocurrent analysis (see later section) most of this member was derived from the south (Hazen Plateau), an area of monotonous geology, as it is underlain mainly by the Ordovician-Silurian Imina Formation. Limited petrographic evidence (see later section) indicates no obvious differentiation in mineralogy of sources to the south of Lake Hazen. This explanation therefore seems improbable.

3. The source area to the south of Lake Hazen may have been characterized by local variations in relief, so that the rivers entering the sedimentary basin had marked differences in slope and competency. Differences in drainage area would also cause differences in discharge and capacity. All this would have been reflected in the river morphology and the grain size and sedimentary structures of the resulting deposits. As stated in the previous paragraph, the monotonous geology of Hazen Plateau lends no support to such a speculation.

4. The Lake Hazen basin may have been subject to minor climatic fluctuations. Schumm (1977) cited several examples where subtle changes in mean rainfall or flood frequency and magnitude brought about drastic changes in fluvial style over periods as short as a few tens of years. An example of the geological results of such variation was described by Shepherd (1978). In Tapia Canyon, New Mexico, deposition changed from aggradation of coarse blanket-like deposits during about 2500-1000 yrs. B.P., to the present regime of flash flood conditions, with channel incision and degradation, and the formation of point bars and lateral accretion deposits.

Rivers of a small basin such as that at Lake Hazen are likely to be particularly sensitive to minor climatic changes because they probably fall within a single climatic zone, unlike larger molasse troughs, such as the modern Indo-Gangetic plain, in which the major rivers reflect an averaging of several contrasting climatic regimes over a wide area.

In the present case, the finer grained deposits of lithofacies assemblage 1 may represent wetter periods and those of assemblage 2 drier periods, or times when the flow was more intermittent. That the climatic variations can only have been minor in nature is emphasized by the fact that coal seems relatively abundant in both assemblages, suggesting no major changes in overall vegetation density. An increased frequency in flash flood seems required to deposit lithofacies assemblage 3, at the top of the sandstone-mudstone member, but this may be in part a tectonic effect, as discussed below.

5. Minor tectonic fluctuations in the Lake Hazen basin could have caused local rejuvenation of source areas, an increase in relief, and thus an increase in local slope. This would be reflected in increased stream competence and an increase in grain size of the sediment load. The variations between lithofacies assemblages 1 and 2 in the sandstone-mudstone member could be explained in this way and, assuming that there is no unconformity between them, the upward gradation from the sandstone-mudstone member into the conglomerate member is presumably a reflection of a major tectonic rejuvenation of sediment sources, with an accompanying change to an alluvial fan fluvial style. It is interpreted as the result of a period of fault movement along the Hazen Fault Zone.

The tectonic (and climatic?) variations interpreted at Lake Hazen are small scale examples of what was taking place throughout the Arctic Islands during the Paleogene. The Tertiary molasse basins were created by an early phase of the Eurekan Orogeny and sedimentation was terminated by uplift following the climax of the orogeny. In a few places, as at Lake Hazen, the major period of movement is reflected by an upward increase in grain size into syntectonic conglomerate. The geomorphic changes accompanying the tectonism obviously would have included changes in fluvial style but, in addition, there may have been subtle climatic effects which would also have been reflected in river behaviour. The elevation of mountain ranges may have created rain shadow areas in the basins between them, the climates of which would have then become more continental in character. This may well be the explanation of the increase in flash flood sedimentation, giving rise to lithofacies assemblage 3, the Bijou Creek-type of sequence, at the top of the sandstone-mudstone member.

PALEOCURRENT ANALYSIS

Orientation measurements were made on a total of 98 sedimentary structures, including solitary and grouped sets of planar and trough crossbedding and a few examples of clast imbrication. Most readings were made in the sandstone-mudstone member; readings from the transitional interval into the conglomerate member were grouped with the latter for calculation purposes (stations 19B, 30 and 32). Corrections for structural dip were not required for any of the readings.

Vector orientation statistics were calculated for each outcrop group using the method of Curray (1956). Each reading was weighted according to set thickness (Miall, 1974), and a second set of statistics was derived. Results are given in Table 1 and Figure 6.

The data suggest a system of internal or centripetal drainage. At stations 2, 3, 4, 15 19A and 37 mean flow directions are northerly. At stations 7, 19B, 24, 30 and 32 they are southerly. At station 19 flow directions show a reversal at about the 54 m level. Readings below this point are assigned to substation 19A and those above to station 19B. Most of the sandstone-mudstone member appears to have been deposited by northward flowing currents, although opposite trends are indicated at stations 7 and 24, demonstrating that the northern source area also was uplifted.

Most molasse basins are filled by longitudinal or transverse alluvial systems, i.e. rivers flow parallel or perpendicular to tectonic strike, However, in this case the fill from the south is oblique, in the sense that paleocurrent trends are at an angle of about 45° to the present strike of the basin. This may mean that the shape of the basin has been radically altered by post-Paleogene tectonics and erosion, and the abundance of Tertiary outliers south and east of the basin supports such an interpretation, as they presumably are remnants of this larger basin.

The northern source area became important during deposition of the conglomerate member, obviously reflecting the movement and uplift along the Hazen Fault Zone, and this is documented by the reversal in flow directions during deposition of the transition beds at the top of the sandstone-mudstone member (station 19). It is not known whether or not sediment continued to be fed to the basin from the south during this conglomeratic phase of sedimentation.

TABLE 1. *Paleocurrent data*

Loc.	n	$\bar{\theta}_u$	L_u	p	n	$\bar{\theta}_w$	L_w	p
2, 3	31	028	72	$<10^{-7}$	31	049	95	$<10^{-12}$
7	8	187	77	0.009	8	185	84	0.004
15	6	008	98	0.003	6	005	100	0.003
19A	7	354	82	0.009	7	349	93	0.002
37	25	000	65	$<10^{-4}$	24	359	91	$<10^{-8}$
24	8	227	92	0.001	8	218	97	$<10^{-3}$
19B, 30, 32	13	150	86	$<10^{-4}$	10	152	95	$<10^{-3}$

n = number of readings, $\bar{\theta}$ = vector mean azimuth, L = vector strength, p = probability of randomness, subscript u = unweighted, w = weighted.

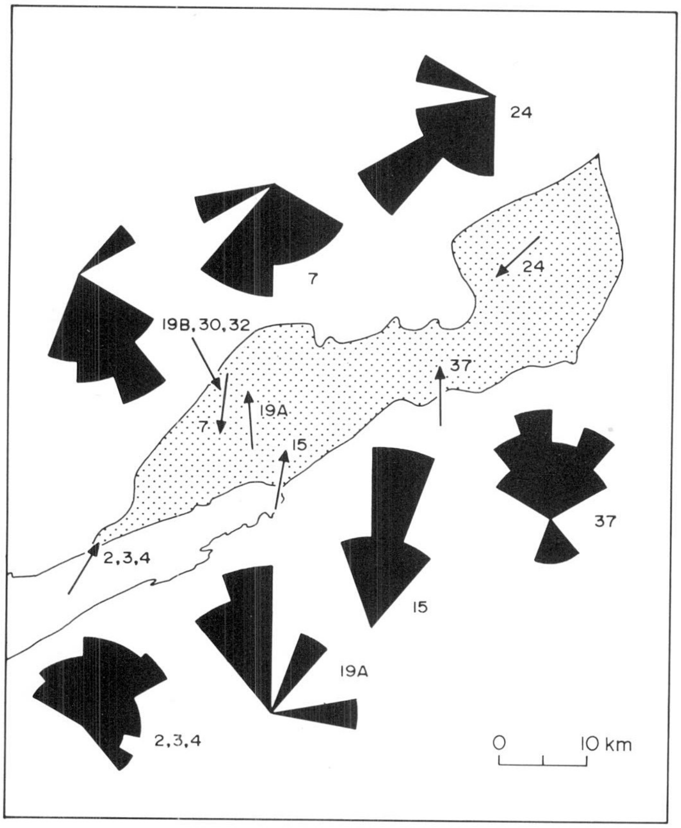


FIGURE 6. Paleocurrent data, showing vector mean azimuth arrows and current rose diagrams (unweighted data) for each of seven locations. Station numbers are indicated. Statistical data are given in Table 1.

The limited evidence available suggests that the basin drainage was entirely internal. No evidence has been found for any outlet, although one might have been located in the Piper Pass area, from which Tertiary rocks have now been largely removed by erosion. Such an outlet would presumably have disappeared during thrust fault movement. It is also possible that the finer grained facies in the sandstone-mudstone member, particularly the large area of mudstone along Salor Creek, represent local base level in the form of a swamp or lake into which the rivers drained.

PETROGRAPHIC ANALYSIS

Fifteen thin sections of sandstone from the report area were examined by optical methods. Two of the sandstone samples are from consolidated units in which matrix and grain relationships are observable; the remainder are from friable units for which the original texture could not be preserved. In these cases sections were made from resin-impregnated samples of the loose sand, and observations are necessarily limited to the detrital grains. All samples were stained with sodium cobaltinitrite for the identification of potassium feldspars. Mineral composition in the sections was determined with the use of a Swift point counter; a minimum of 300 grains were counted per section (Table 2). No separate analysis of heavy minerals was performed. Two typical sandstones are illustrated in Plate 6.

Notable features of these sandstones are the scarcity of feldspar grains (0-2%) and the variety of rock fragments. In addition to the more common species listed in Table 2, these include foliated quartz-mica and quartz-chlorite grains (schist), graphic quartz-feldspar intergrowths, quartzose sandstone with glauconite pellets and a variety of basic igneous rock fragments (pyroxene, amphibole etc.). Opaque grains are interpreted to be weathered fragments of diabase.

Most of the sandstones contain very little detrital matrix, and none contains any chemical cement. In the two lithified samples, C-68619 and C-68648, detrital matrix (predominantly clay) comprises 2 and 8 per cent of total points counted, and porosity measurements are 12 and 26 per cent, respectively. The sandstones may be divided into two groups: quartzose arenites, containing 82 to 89 per cent quartz, and lithic arenites, containing 21 to 51 per cent quartz (classification of Okada, 1971).

Sediment sources

Paleocurrent analysis indicates that sediment was derived from both the north and south sides of the basin, which together include a wide variety of potential source rocks. Amongst the most important probably were upper Paleozoic and Mesozoic sedimentary rocks of Sverdrup Basin. The most abundant clast types in the Tertiary conglomerates are massive white quartzose sandstone, fossiliferous limestone and sandy limestone very similar to Permian rocks mapped at Piper Pass (Miall, 1978a). These rocks probably were a principal source of polycyclic, sand size, monocrystalline quartz, quartzose sandstone and detrital carbonate grains. Rare shell fragments in the Tertiary sandstones probably were also derived from these rocks (e.g. Pl. 6B). Clasts of red sandstone and conglomerate in the Tertiary conglomerates appear to have come from the Carboniferous Borup Fiord Formation. Mesozoic sedimentary rocks, now exposed in the Lake Hazen area, may also have been an important sediment source. The Mesozoic sandstones are mostly mature and would have provided abundant rounded quartz grains. Diabase fragments and grains of plagioclase, amphibole and pyroxene were probably derived from sills that intrude the Permian and Mesozoic rocks.

Remaining grain types were most likely derived from older Paleozoic rocks, including the Grant Land, Imina and Hazen Formations. The Hazen Formation probably was a major source of chert. Rare recrystallized rods and spherules in the chert may represent radiolarians or sponge spicules. Trettin (1971) identified recrystallized radiolarian tests in the Hazen Formation on the coast of Ellesmere Island southeast of the report area. Fine- to very fine grained sandstone, siltstone and mudstone clasts and polycrystalline quartz grains in the Tertiary may have been derived from the Imina Formation, whereas coarser sand grains and some of the minor components in the Tertiary rocks could have originated in the Grant Land Formation. The Grant Land seems to be the most probable source for potassium feldspar grains, as this unit contains up to 27 per cent detrital feldspar, predominantly microcline, microperthite and orthoclase. Grains of mica probably were also derived from the Grant Land or Imina Formation, and the schist grains (foliated quartz-mica or quartz-chlorite) are interpreted as grains of metamorphosed Grant Land sandstone (cf. Trettin, 1971; Fig. 17).

As noted above, the sandstones fall into two groups, quartzose arenites and lithic arenites. The two types are readily distinguished in thin section (Pl. 6) and it can be shown that they were derived at different times from different source areas. In Figure 7, quartz content of the sandstone samples is plotted against total igneous rock fragments (including diabase, pyroxene, amphibole and opaque grains; excluding feldspar). Data points are discriminated

TABLE 2. Petrographic data: optical point count analyses of sandstone thin sections: per cent detrital grains

Station	1	2	3	7	9	14	19	19	19	19	24	30	36	37	37
Sample number	C-68601	C-68607	C-68608	C-68616	C-68619	C-68624	C-68640	C-68642	C-68645	C-68648	C-68649	C-68654	C-68661	C-68662	C-68663
monocrystalline quartz	87	82	84	45	42	89	51	30	88	33	21	22	86	88	82
polycrystalline quartz	3	2	3	2	-	-	1	-	4	2	2	1	3	6	3
chert	-	10	7	6	6	-	5	8	5	8	6	6	2	5	11
quartzose sandstone	1	2	2	12	22	-	31	29	1	18	34	27	1	1	2
mudstone-siltstone	10	4	3	8	11	1	7	9	1	10	10	7	1	r	1
potassium feldspars	-	-	-	-	1	-	r	2	r	-	-	1	1	tr	-
plagioclase	-	tr	-	-	1	-	-	-	-	-	2	r	-	tr	-
detrital carbonate	-	-	-	14	2	-	1	8	-	24	15	17	-	-	-
mica	-	tr	-	-	-	-	-	-	-	-	-	-	tr	-	-
opaque grains	-	-	-	13	7	10	2	5	r	4	5	5	6	-	1
schist	-	tr	-	tr	-	-	-	-	-	-	-	-	-	-	-
pyroxene	-	-	-	-	7	-	1	10	-	1	3	6	-	-	-
amphibole	-	-	-	tr	1	-	-	-	-	-	-	-	-	-	-
diabase	-	-	-	-	-	-	-	-	-	-	3	8	-	-	-

r = rare, t = trace

into: 1. those from the upper, conglomerate member, including the transition beds in the upper part of the sandstone-mudstone member ("younger Tertiary"), and 2. those from the remainder of the sandstone-mudstone member ("older Tertiary"). Beside each point is an arrow indicating local mean direction of sedimentary transport (simplified into north- or south-flowing dispersal systems). It is clear from this diagram that petrographic maturity decreased markedly during depositon of the Tertiary sandstones. Most of the samples from the older Tertiary are quartzose arenites, while those from the younger beds are lithic arenites. This variation appears to be due to a reversal of source directions, the older beds being derived mainly from the south and the younger beds from the north. The one sample in the older Tertiary which had a northerly provenance (as indicated by paleocurrents) is similar in petrographic character to the upper Tertiary sandstones. Sediment sources to the south of Lake Hazen would have been mainly outcrops of the Imina Formation, plus smaller areas of the Hazen Formation. According to A.F. Embry (pers. com., 1978) older Mesozoic strata probably did not extend far to the south over Hazen Plateau, and so were probably not a major source for southerly derived Tertiary sand, whereas Isachsen and younger formations may have been widespread, and could have been a sediment source. Sources in Grantland Uplift to the north of Lake Hazen included all the various upper Paleozoic and Mesozoic sedimentary units of Sverdrup Basin, the diabase sills which intrude them, and the underlying Grant Land Formation - altogether a petrographically more varied assemblage of source rocks.

The marked local variation in sandstone petrography seen at Lake Hazen is characteristic of Tertiary sandstones throughout the Canadian Arctic, and it is typical of molasse deposits in general. Such variation presumably is due both to erosion of young fold belts in which a wide variety of rocks is exposed, and to rapid sedimentation with little or no winnowing or reworking to remove immature components.

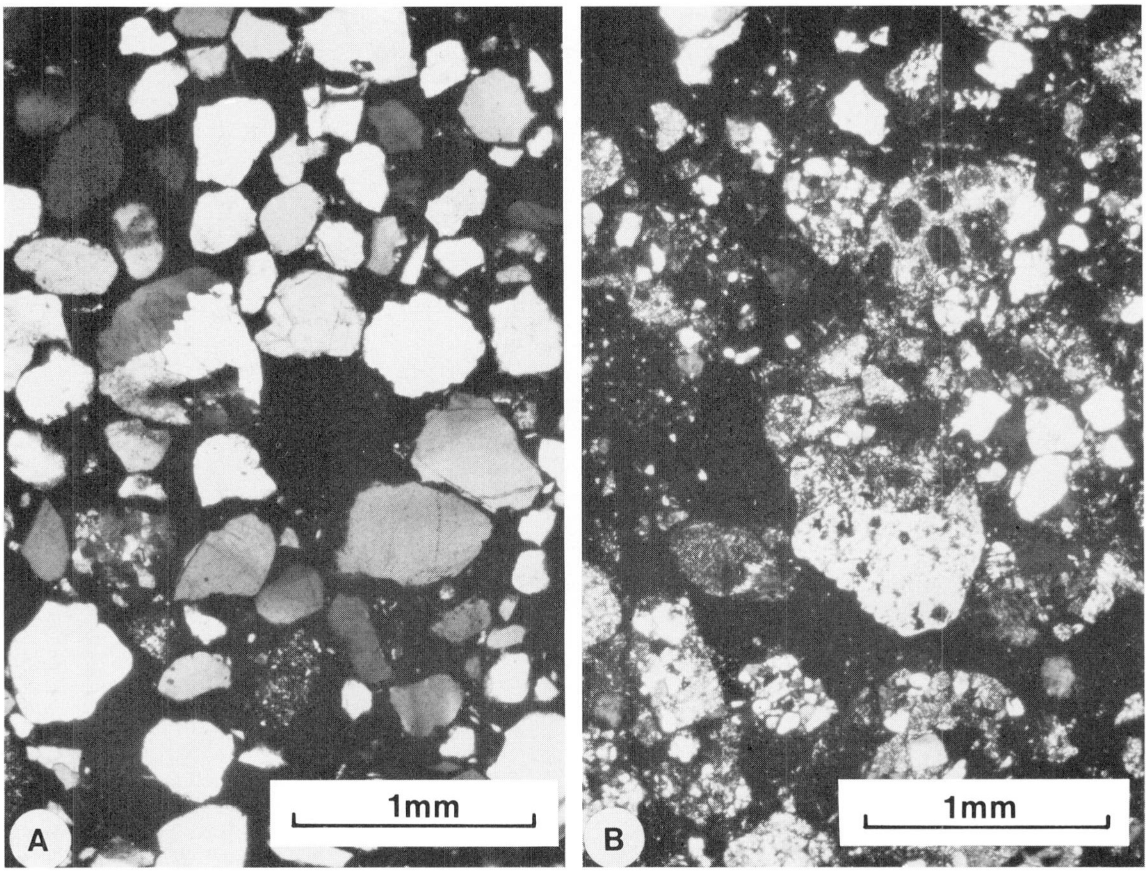


PLATE 6. *Photomocrographs of typical sandstones. A. Sample C-68662, station 37, near Turnabout River; a typical quartzose arenite, consisting predominantly of quartz with occasional chert grains. B. Sample C-68649, station 24, North Boulder Hills; a lithic arenite containing fragments of chert, quartz, glauconitic sandstone, limestone and rare shell fragments.*

PALEOHYDRAULICS

In recent years it has become possible to arrive at estimates of such parameters as sinuosity, meander wavelength, discharge and drainage area of the rivers that formed given fluvial deposits. These estimates are based on geomorphological investigations of modern rivers which have shown that, at least in temperate regions, most of the hydraulic parameters of rivers are statistically related to each other, and that estimates of them can be based on measurements made in outcrops of their deposits. The primary purpose of deriving paleohydraulic estimates in a report such as this is as an aid in paleogeographic reconstruction. The most useful parameters are stream length and drainage area although, unfortunately, the estimation procedure for these two parameters is subject to a particularly wide margin of error. The methodology is described in a recent review article by Ethridge and Schumm (1978) and discussed by Bridge (1978). The various parameters and the symbols and units used in this report are listed in Table 3.

It has been found that the most reliable indicators of river magnitude are point bar deposits, particularly those containing lateral accretion surfaces, termed epsilon crossbedding by Allen (1963). Three parameters can be measured as a basis for hydraulic reconstruction: point bar thickness, dip of epsilon crossbeds, and width of individual foreset beds. Measurements on ten point bar structures in the sandstone-mudstone member are reported in Table 4.

Point bar thickness is known to be approximately equal to channel bankful depth (Allen, 1965; Leeder, 1973; Ethridge and Schumm, 1978). Channel width can be estimated using two different geometric estimates or a statistical relationship:

$W = 1.5h / \tan \beta$ (Leeder, 1973) (1)

$W = W_e \times 1.5$ (Ethridge and Schumm, 1978) (2)

$W = 6.8h^{1.54}$ (Leeder, 1973) (3)

Equations 1 and 3 give results that showed a consistent marked discrepancy (Table 5), probably because in the field β was recorded as the maximum dip angle. As is seen in Figure 5 and as discussed in an earlier section, the point bars all contain incipient scroll bars or mid-bar benches, so that the average point bar dip is always less than β. The higher values, obtained from equation 3, are probably more accurate. The 95 per cent confidence limits on equation 3 (± 2 x standard deviation) are ± 0.7 log units so that, for example, in the case of sample No. 1, for which the width is given as 15.4 m, the limits are 3.1 to 77.1 m.

Columns 5 and 6 in Table 5 give ranges of values for F and P using the highest and lowest estimates of W listed in the table. Sinuosity is calculated as follows:

$P = 3.5F^{-0.27}$ (Ethridge and Schumm, 1978) (4)

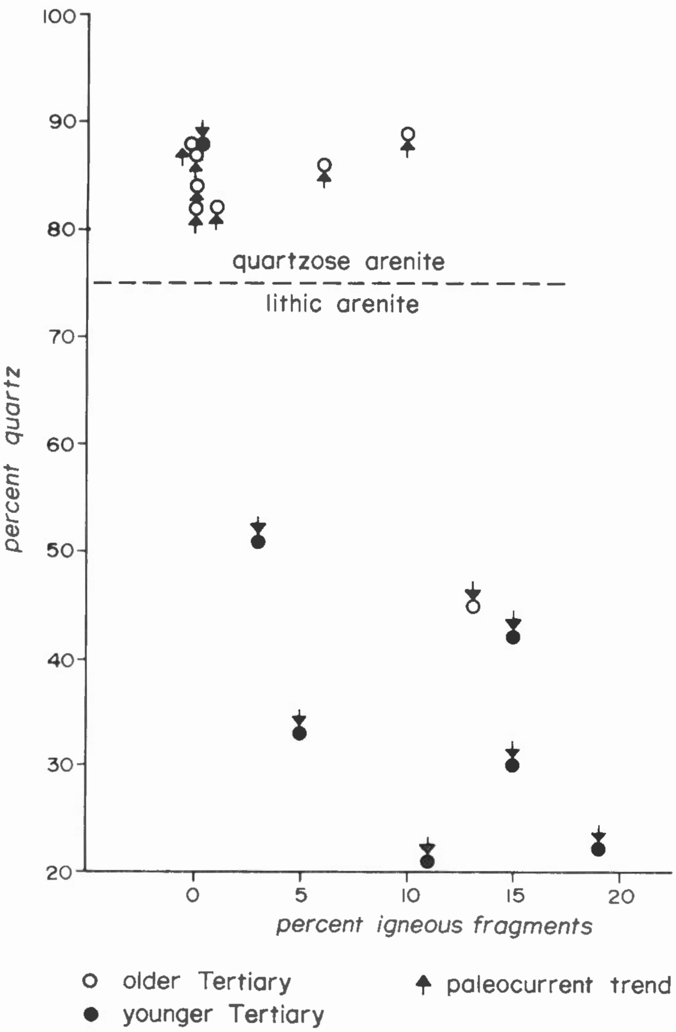


FIGURE 7. Petrography of fifteen sandstone samples showing percentage of quartz (number of grains per cent) plotted against total igneous grains: diabase+pyroxene+amphibole +opaque grains. Paleocurrent directions (generalized to northerly or southerly trends) are shown for each sample location.

TABLE 3. Some fluvial hydraulic parameters and corresponding symbols used in this report

parameter	symbol	units
channel depth	h	m
channel width	W	m
width of epsilon set	W_e	m
epsilon foreset dip	ß	degrees
width/depth ratio	F	-
sinuosity	P	-
meander wavelength	L	m
mean annual discharge	Qm	$m^3.s^{-1}$
drainage area	A	km^2
stream length	l	km

TABLE 4. Field measurements of point bar deposits

Sample No.	loc.	h	W_e	ß
1	2	1.7 m	06.6 m	22°
2	2	2.0	07.0	15
3	14	3.6	12.0	25
4	14	3.6	19.5	25
5	14	2.4	17.4	10
6	14	2.6	14.0	14
7	14	2.6	20.0	14
8	24	2.5	-	15
9	37	1.5	-	14
10	37	2.0	-	15

For explanation of symbols see Table 3

Mean annual discharge can be estimated using equation (5):

$Qm = W^{2.43} / 18F^{-1.13}$ (Ethridge and Schumm, 1978) (5)

This equation uses imperial units, and the result is expressed as cfs. Standard deviation is 0.31 log units. Values of Qm in column 7 of Table 5 have been converted to $m^3.s^{-1}$. The median value for the ten point bars is about $7m^3.s^{-1}$. Extreme estimates of Qm, representing the 95 per cent confidence limits on the highest and lowest values given in Table 5 are 0.3 and 38.6 $m^3.s^{-1}$. These probably were "mixed load" streams, in the terminology of Ethridge and Schumm (1978).

Other estimates that can be based on these results are meander wavelength, stream length and drainage area. Ethridge and Schumm (1978) provide four equations for estimating meander wavelength based on statistical relationships between this parameter and stream width, width/depth ratio and discharge. Using the high, median and low estimates of Qm given above, they suggest meander wavelengths in the order of 30, 300 and 890 m. Dury (1965) showed that drainage area and meander wavelength are related. Use of his data indicates high, median and low values for drainage area of the Lake Hazen rivers of 1, 800 and 5000 km^2. Corresponding estimates of stream length based on Hack's (1957) equation are 1, 70 and 220 km.

The wide range of values reflects the imprecision of the methodology, and it means that by itself the technique is of limited use in paleogeographic reconstruction. However, it is important to note that the median values of stream length and drainage area are about the same as those suggested by conventional geological lines of reasoning. The drainage area for the rivers which formed the sandstone-mudstone member lay to the south of Lake Hazen. A limit on the size of this catchment zone is imposed by the presence of another intermontane Tertiary basin on Judge Daly Promontory, which probably had no connection with the basin at Lake Hazen. The deposits are of different facies (low sinuosity fluvial and ?lacustrine) with different paleocurrent trends (northeast-flowing rivers) and a distinctive petrography dominated by clasts of basic volcanic rocks. The watershed between the two basins presumably lay approximately half way between them, a distance of about 50 km south of Lake Hazen. Similar independent confirmations of paleohydraulic estimates were arrived at by Miall (in press) in a study of Cretaceous streams in Banks Island, N.W.T., and by Padgett

TABLE 5. Hydraulic estimates based on statistical geomorphological relationships

Sample No.	W eq. 1	W eq. 2	W eq. 3	F	P	Qm
1	6.3	9.9	15.4	3.7-09.1	2.5-1.9	0.6-03.5
2	11.2	10.5	19.8	5.6-09.9	2.2-1.9	1.4-03.0
3	11.6	18.0	48.9	3.2-13.6	2.6-1.7	2.9-18.9
4	11.6	29.3	48.9	3.2-13.6	2.6-1.7	2.9-18.9
5	20.4	26.1	26.2	8.5-10.9	2.0-1.8	2.9-05.3
6	15.6	21.0	29.6	6.0-11.4	2.2-1.8	3.0-06.8
7	15.6	30.0	29.6	6.0-11.4	2.2-1.8	3.0-06.8
8	14.0	-	27.9	5.6-18.6	2.2-1.6	2.5-03.4
9	9.0	-	12.7	6.0-08.5	2.2-2.0	0.8-01.2
10	11.2	-	19.8	5.6-09.9	2.2-1.9	1.4-03.0

For explanation of symbols see Table 3

and Ehrlich (1978) in their study of fluvial channels in Carboniferous coal deposits. Such results show that the paleohydraulic method is providing estimates of at least the correct order of magnitude. Greater accuracy than this may require the use of modelling techniques such as those developed by Bridge (1978).

BASIN EVOLUTION AND REGIONAL IMPLICATIONS

The Lake Hazen intermontane basin probably was formed in the Eocene following a period of uplift and erosion during the Late Cretaceous and Paleocene. In many parts of the Arctic Islands, the Eureka Sound Formation is Maastrichtian or Paleocene to Eocene in age, but limited palynological data from the report area suggest that the Paleocene is not represented here and that the youngest beds may be Neogene (Oligocene?) in age.

Formation of the basin took place as a result of subsidence on the southern flank of northeastern Sverdrup Basin. Initially most sediment was transported from the Hazen Plateau area to the south. Sandstones are quartzose arenites, probably derived mainly from the Imina (Ordovician-Silurian) and Hazen (Cambrian-Ordovician) Formations. It is not known whether the central part of Sverdrup Basin - that part now comprising the British Empire and United States Ranges of northern Ellesmere Island - was also uplifted and providing sediment. There is limited paleocurrent evidence that this was the case, but it is impossible to date the strata with precision and in the early stages of basin development areas to the north of Lake Hazen probably were characterized by subdued topography, and may even have been partially occupied by the sea, although there is no evidence for the latter. The exposed Tertiary sediments at Lake Hazen are entirely fluvial in character, and all the evidence is consistent with an interpretation of them as the fill of an enclosed, intermontane basin (Fig. 8).

Tectonically the basin can be described as "intermontane" in the sense that this is a common term for a successor basin in a young fold belt filled with nonmarine deposits, but sedimentological evidence suggests that, during the first period of basin development, relief in surrounding source areas was not strong. The lower of the two stratigraphic units, the sandstone-mudstone member, was deposited by relatively small, high sinuosity, probably single channel, mixed load streams of classic "meandering" type (Fig. 9). Grain size rarely reaches coarse sand or pebble grade, and in places much of the succession consists of mudstone, probably formed under swamp conditions, implying an absence of high energy sedimentation in the vicinity. Climate was humid, as indicated by the presence of laterally extensive coal seams.

Lenses of coarser sediment (coarse sand to conglomerate) in the sandstone-mudstone member record deposits of higher energy, bedload streams containing within-channel bar forms. They may have been braided, in the classic sense, but no information is available regarding their sinuosity. Variations in fluvial style may have been caused by temporary dry periods. This would cause a decrease in vegetation cover and an increase in discharge variability, giving rise to more "flashy" run-off and consequent higher energy sedimentation. Alternatively, the locally distributed coarser material may represent temporarily increased stream competency as a result of rejuvenation events caused by spasmodic tectonic uplift.

During the Neogene, tectonic movement took place on the Hazen Fault Zone, causing the Lower Paleozoic rocks north of the fault zone to be thrust southward over the Permian-Eocene section. Permian to Lower Cretaceous strata are deformed into an asymmetic syncline with a locally overturned northern limb between two thrust faults (Fig. 3). Uplift during and following this tectonic activity of the area to the north of the fault zone (Grantland Uplift of Trettin et al., 1972) had two effects on sedimentation, which may have continued in the basin without interruption. The sediments coarsened upward into boulder conglomerate, and transport directions underwent a reversal, so that the northern flank of the basin became predominant as a sediment source area. The upper, conglomerate member of the Tertiary is the product of syntectonic sedimentation, representing an alluvial fan fringe prograding southeastward from the active fault zone into the basin (Fig. 8). The date of this tectonic episode is unclear. Sparse palynological evidence suggests that the conglomerates are Neogene, and the apparent conformable contact with the Eocene sandstone-mudstone member would indicate that the conglomerates are Oligocene in age. However, Oligocene strata are not known from elsewhere in the Arctic Islands, whereas a coarse clastic unit of Miocene age, the Beaufort Formation is widespread. If the conglomerate member is Miocene, it would imply that it rests on a major disconformity. The gradational contact at the base of the member does not suggest such an interpretation but it may, in fact, be difficult to demonstrate a disconformity in a coarse fluvial succession. In this report the conglomerate member and the fault movement which produced it are tentatively dated as Oligocene, but the alternative interpretation remains a possibility.

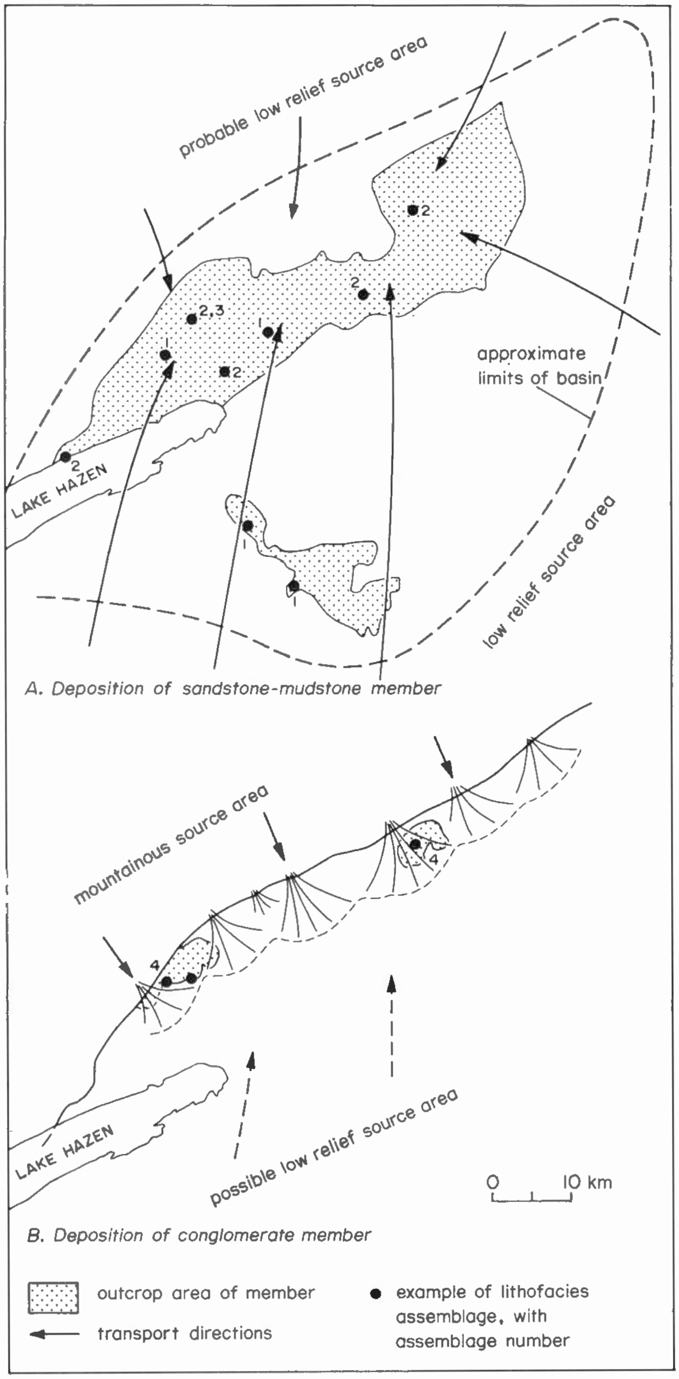


FIGURE 8. *Paleogeography of the Lake Hazen area during the Tertiary; A: Eocene, B: Oligocene (or Miocene?).*

It is not known whether the southern sediment source continued to be active during the Neogene, because the conglomerate member is present in only two outliers near the northern bounding fault of the basin, and their lateral equivalents to the south have been removed by erosion. Sandstones in the base of the conglomerate member are lithic arenites and were derived from a more varied suite of source rocks than those of the sandstone-mudstone member, including the Grant Land Formation (Cambrian), Carboniferous to Mesozoic sedimentary rocks and diabase sills.

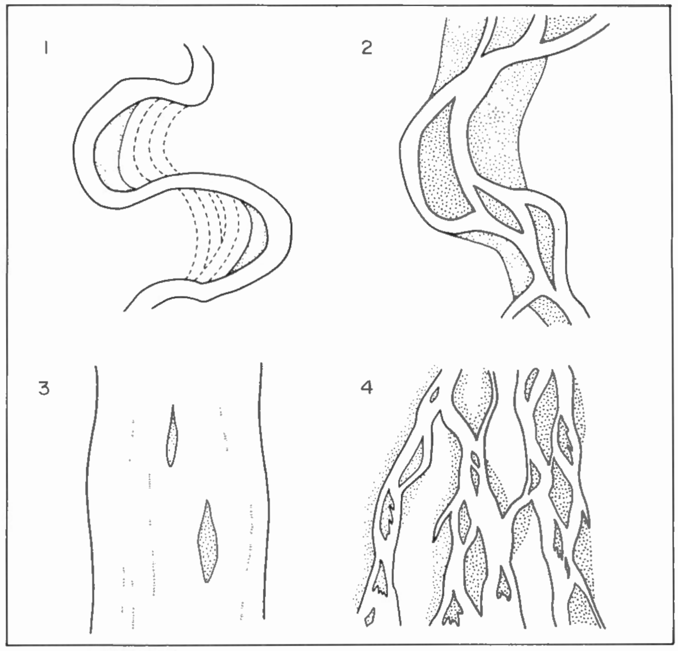


FIGURE 9. *Interpreted fluvial styles of the rivers forming the four lithofacies assemblages.*

Sedimentation probably was terminated during the Neogene by uplift of the basin. A remnant of the basin exists at the present day in the form of Lake Hazen, and may have been caused by renewed subsidence along old structural lines during the Quaternary.

Each of the Tertiary molasse basins in the Canadian Arctic appear to have had a different history. In different places sedimentation commenced in the Maastrichtian (western Banks Island, Ringnes Islands), Paleocene (eastern Banks Island, central Ellesmere Island, Bylot Island) or Eocene (eastern Axel Heiberg Island, Lake Hazen) (Bustin et al., in press; Miall, in press and unpublished data). In some areas there is a conformable passage from marine Cretaceous to nonmarine Tertiary deposits, but a disconformable contact between the Eureka Sound Formation and older units is more common, as in the present report area.

If the conglomerate member at Lake Hazen is Oligocene and a conformable part of the Eurekan Sound Formation, it is unusual, as Oligocene strata have not been demonstrated previously in this unit and conglomerates are rare. A syntectonic conglomerate of Paleocene age is now known to be present on Judge Daly Promontory (Miall, unpublished data), and conglomerates are also present in the subsurface of western Banks Island (Miall, in press), but most other major Tertiary conglomerate units in the Arctic Islands have been assigned to the Miocene Beaufort Formation.

The genesis of the Eureka Sound Formation was related to the Eurekan Orogeny, which Balkwill (1978) divided into three broad phases: "1. a Late Cretaceous to late Paleocene phase of uplift and erosion of the Sverdrup Basin rim". Grantland Uplift and Hazen Plateau conform to this pattern, and the intermontane basin at Lake Hazen probably did not appear until the Eocene. "2. a middle Eocene to early Miocene phase of compressive folding and faulting" in the eastern Sverdrup Basin. The interpretation given herein is that compressive movement on Hazen Fault Zone took place in the Oligocene, although a Miocene age for the tectonism remains a possibility. If the latter is proved to be correct it would fall within Balkwill's final phase: "3. a Miocene (and possibly Pliocene and later) phase of rejuvenated uplift and erosion" of some of the intrabasin arches.

As further information regarding Eureka Sound sedimentation and tectonism become available, it is clear that in detail the picture is more complicated than that summarized by Balkwill; for example the wide variation in the age of the earliest molasse sediments (Maastrichtian to Eocene) indicates a corresponding local variation in the time of basin initiation. Also, the syntectonic conglomerate at Judge Daly Promontory appears to be the record of a Paleocene phase of compressive movement. How this complex picture relates to the Tertiary plate tectonic history of the region will be the subject of further research by the writer.

REFERENCES

Alexander-Marrack, P.D. and Friend, P.F.
1976: Devonian Sediments of East Greenland III: The eastern sequence, Vilddal Supergroup and part of the Kap Kolthoff Supergroup; Meddelelser øm Gronland, Bd. 206, No. 3.

Allen, J.R.L.
1963: The classification of cross-stratified units, with notes on their origin; Sedimentology, v. 2, p. 93-114.

1965: The sedimentation and palaeogeography of the Old Red Sandstone of Anglesey, North Wales; Yorkshire Geological Society, Proceedings, v. 35, p. 139-185.

1966: On bed forms and paleocurrents; Sedimentology, v. 6, p. 153-190.

1967: Notes on some fundamentals of paleocurrent analysis, with reference to preservation potential and sources of variance; Sedimentology, v. 9, p. 75-88.

1970: Studies in fluviatile sedimentation: a comparison of fining-upward cyclothems with special reference to coarse-member composition and interpretation; Journal of Sedimentary Petrology, v. 40, p. 298-323.

Balkwill, H.R.
1978: Evolution of Sverdrup Basin, Arctic Canada; American Association of Petroleum Geologists, Bulletin, v. 62, p. 1004-1028.

Blackadar, R.G.
1954: Geological reconnaissance north coast of Ellesmere Island, Arctic Archipelago, Northwest Territories; Geological Survey of Canada, Paper 53-10.

Bluck, B.J.
1971: Sedimentation in the meandering River Endrick; Scottish Journal of Geology, v. 7, p. 93-138.

Bridge, J.S.
1978: Paleohydraulic interpretation using mathematical models of contemporary flow and sedimentation in meandering channels; in Fluvial sedimentology, A.D. Miall, ed.; Canadian Society of Petroleum Geologists, Memoir 5, p. 723-742.

Bustin, M., Balkwill, H.R. and Hills, L.V.
in press: The Eureka Sound and Beaufort Formations, Axel Heiberg and west-central Ellesmere Island, District of Franklin, Arctic Canada; Canadian Society of Petroleum Geologists, Bulletin.

Cant, D.J.
1978: Development of a facies model for sandy braided river sedimentation: Comparison of the South Saskatchewan River and Battery Point Formations; in Fluvial Sedimentology, A.D. Miall, ed.; Canadian Society of Petroleum Geologists, Memoir 5, p. 627-640.

Christie, R.L.
1964: Geological reconnaissance of northeastern Ellesmere Island, District of Franklin; Geological Survey of Canada, Memoir 331.

1974: Northeastern Ellesmere Island: Lake Hazen region and Judge Daly Promontory; Geological Survey of Canada, Paper 74-1A, p. 297-299.

1976: Tertiary rocks at Lake Hazen, northern Ellesmere Island; Geological Survey of Canada, Paper 76-1B, p. 259-262.

Christie, R.L. and Rouse, G.E.
1976: Eocene beds at Lake Hazen, northern Ellesmere Island; Geological Survey of Canada, Paper 76-1C, p. 153-156.

Coleman, J.M. and Gagliano, S.M.
1964: Cyclic sedimentation in the Mississippi River deltaic plain; Gulf Coast Association of Geological Societies, Transactions, v. 14, p. 67-80.

Curray, J.R.
1956: The analysis of two-dimensional orientation data; Journal of Geology, v. 64, p. 117-131.

Dolan, R., Hayden, B.P., Hornberger, G.M., Zieman, J. and Vincent, M.K.
1972: Classification of the coastal environments of the World Part I: The Americas; National Technical Information Service, United States Department of Commerce.

Douglas, R.J.W., Norris, D.K., Thorsteinsson, R. and Tozer, E.T.
1963: Geology and petroleum potentialities of northern Canada; Geological Survey of Canada, Paper 63-31.

Dury, G.H.
1965: Principles of underfit streams; United States Geological Survey, Professional Paper 452A.

Embry, A.F. and Klovan, J.E.
1976: The Middle-Upper Devonian clastic wedge of the Franklin Geosyncline; Bulletin of Canadian Petroleum Geology, v. 24, p. 485-639.

Ethridge, F.G. and Schumm, S.A.
1978: Reconstructing paleochannel morphologic and flow characteristics: methodology, limitations and assessment; in Fluvial sedimentology, A.D. Miall, ed.; Canadian Society of Petroleum Geologists, Memoir 5, p. 703-722.

Friend, P.F., Alexander-Marrack, P.D., Nicholson, J. and Yeats, A.K.
1976: Devonian sediments of East Greenland I: Introduction, classification of sequences, petrographic notes; Meddelelser om Gronland, Bd. 206, Nr. 1.

Friend, P.F. and Moody-Stuart, M.
1972: Sedimentation of the Wood Bay Formation (Devonian) of Spitsbergen: Regional analysis of a late orogenic basin; Norsk Polarinstitutt Skrifter, Nr. 157.

Hack, J.T.
1957: Studies of longitudinal stream profiles in Virginia and Maryland; United States Geological Survey, Professional Paper 294-B.

Harms, J.C., Southard, J.B., Spearing, D.R. and Walker, R.G.
1975: Depositional environments as interpreted from primary sedimentary structures and stratification sequences; Society of Economic Paleontologists and Mineralogists, Short Course No. 2.

Jackson, R.G. II
1976a: Largescale ripples of the lower Wabash River; Sedimentology, v. 23, p. 593-624.

1976b: Depositional model of point bars in the lower Wabash River; Journal of Sedimentary Petrology, v. 46, p. 579-594.

1978: Preliminary evaluation of lithofacies models for meandering alluvial streams; in Fluvial Sedimentology, A.D. Miall, ed.; Canadian Society of Petroleum Geologists, Memoir 5, p. 543-576.

Kerr, J.Wm.
1974: Geology of Bathurst Island Group and Byam Martin Island, Arctic Canada; Geological Survey of Canada, Memoir 378.

Leeder, M.R.
1973: Fluviatile fining-upward cycles and the magnitude of paleochannels; Geological Magazine, v. 110, p. 265-276.

McGowen, J.H. and Garner, L.E.
1970: Physiographic features and stratification types of coarse grained point bars; modern and ancient examples; Sedimentology, v. 14, p. 77-112.

Miall, A.D.
1973: Markov chain analysis applied to an ancient alluvial plain succession; Sedimentology, v. 20, p. 347-364.

1974: Paleocurrent analysis of alluvial sediments: a discussion of directional variance and vector magnitude; Journal of Sedimentary Petrology, v. 44, p. 1174-1185.

Miall, A.D.
1977: A review of the braided river depositional environment; Earth Science Reviews, v. 13, p. 1-62.

1978a: Permian stratigraphy at Piper Pass, northern Ellesmere Island, District of Franklin; Geological Survey of Canada, Paper 78-1A, p. 541-544.

1978b: Lithofacies types and vertical profile models in braided river deposits: a summary; in Fluvial Sedimentology, A.D. Miall, ed.; Canadian Society of Petroleum Geologists, Memoir 5, p. 597-604.

in press: Mesozoic and Tertiary geology of Banks Island, Arctic Canada: the history of an unstable craton margin; Geological Survey of Canada, Memoir 387.

Miall, A.D. and Gibling, M.R.
1978: The Siluro-Devonian clastic wedge of Somerset Island, Arctic Canada, and some regional paleogeographic implications; Sedimentary Geology, v. 21, p. 85-127.

Nanson, G.C.
in press: Point bar and floodplain formation on a meandering river, northeast British Columbia, Canada; Sedimentology.

Nicholson, J. and Friend, P.F.
1976: Devonian sediments of East Greenland V: The central sequence, Kap Graah Group and Mount Celsius Supergroup; Meddelelser om Gronland, Bd. 206, Nr. 5.

Nijman, W. and Puigdefabregas, C.
1978: Coarse-grained point bar structure in a molasse-type fluvial system, Eocene Castisent Sandstone Formation, South Pyrenean Basin; in Fluvial Sedimentology, A.D. Miall, ed.; Canadian Society of Petroleum Geologists, Memoir 5, p. 487-510.

Okada, H.
1971: Classification of sandstone: analysis and proposal; Journal of Geology, v. 79, p. 509-525.

Padgett, G. and Ehrlich, R.
1978: An analysis of two tectonically controlled integrated drainage nets of mid-Carboniferous age in southern West Virginia; in Fluvial Sedimentology, A.D. Miall, ed.; Canadian Society of Petroleum Geologists, Memoir 5, p. 789-800.

Petryk, A.A.
1969: Mesozoic and Tertiary stratigraphy at Lake Hazen, northern Ellesmere Island, District of Franklin; Geological Survey of Canada, Paper 68-17.

Potter, P.E.
1959: Facies model conference; Science, v. 129, p. 1292-1294.

Puigdefabregas, C.
1973: Miocene point-bar deposits in the Ebro Basin, northern Spain; Sedimentology, v. 20, p. 133-144.

Rust, B.R.
1978: A classification of alluvial channel systems; in Fluvial Sedimentology, A.D. Miall, ed.; Canadian Society of Petroleum Geologists, Memoir 5, p. 187-198.

Schumm, S.A.
1977: The fluvial system; John Wiley and Sons.

Shepherd, R.G.
1978: Distinction of aggradational and degradational fluvial regimes in valley-fill alluvium, Tapia Canyon, New Mexico; in Fluvial Sedimentology, A.D. Miall, ed.; Canadian Society of Petroleum Geologists, Memoir 5, p. 277-286.

Terrell, T.T.
1977: Interim hierarchical regional classification scheme for coastal ecosystems of the United States and its Territories; United States Department of Commerce, National Technical Information Service, PG-272 691.

Thorsteinsson, R. and Tozer, E.T.
1970: Geology of the Arctic Archipelago; in Geology and Economic Minerals of Canada, R.J.W. Douglas, ed.; Geological Survey of Canada, Economic Geology Report No. 1, p. 547-590.

Tozer, E.T.
1963: Mesozoic and Tertiary stratigraphy; in Geology of the north-central part of the Arctic Archipelago, Northwest Territories (Operation Franklin); Geological Survey of Canada, Memoir 320, p. 74-95.

Trettin, H.P.
1971: Geology of Lower Paleozoic formations, Hazen Plateau and southern Grant Land Mountains, Ellesmere Island, Arctic Archipelago; Geological Survey of Canada, Bulletin 203.

Trettin, H.P., Frisch, T.O., Sobczak, L.W., Weber, J.R., Niblett, E.R., Law, L.K., Delaurier, J.M. and Witham, K.
1972: The Innuitian Province; in Variations in tectonic styles in Canada, R.A. Price and R.J.W. Douglas, eds.; Geological Association of Canada, Special Paper 11, p. 83-179.

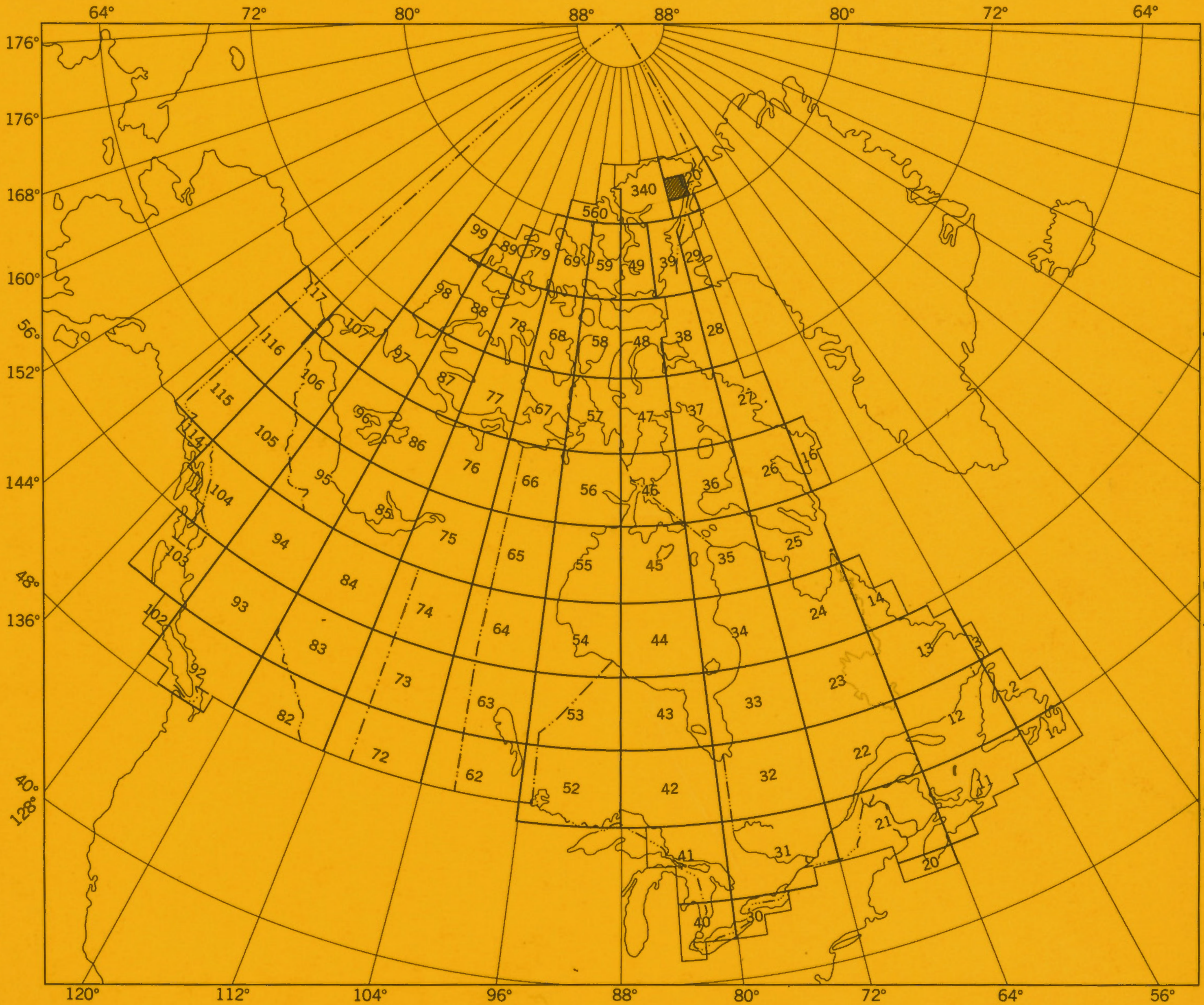
Troelsen, J.C.
1950: Contributions to the geology of northwestern Greenland, Ellesmere Island and Axel Heiberg Island; Meddeleser øm Gronland, Bd. 149, Nr. 7.

Van Houten, F.B.
1969: Molasse facies: records of worldwide crustal stresses; Science, v. 166, p. 1506-1508.

1973: Meaning of molasse; Geological Society of America, Bulletin, v. 84, p. 1973-1975.

Walker, R.G.
1976: Facies models #1: general introduction; Geoscience Canada, v. 3, p. 21-24.

Winston, D.
1978: Fluvial systems of the Precambrian Belt Supergroup, Montana and Idaho, U.S.A.; in Fluvial Sedimentology, A.D. Miall, ed.; Canadian Society of Petroleum Geologists, Memoir 5, p. 343-360.



64°
72°
80°
88°
88°
80°
72°
64°
176°
176°
168°
160°
152°
144°
136°
56°
48°
40°
128°
8°
0°
8°
16°
24°
32°
40°
56°
48°
40°
48°
120°
112°
104°
96°
88°
80°
72°
64°
56°
340
560
120
99
89
79
69
59
49
39
29
98
88
78
68
58
48
38
28
117
107
97
87
77
67
57
47
37
27
116
106
96
86
76
66
56
46
36
26
16
115
105
95
85
75
65
55
45
35
25
114
104
94
84
74
64
54
44
34
24
14
103
93
83
73
63
53
43
33
23
13
3
102
92
82
72
62
52
42
32
22
12
2
1
11
21
20
31
41
40
30