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BOREHOLE AND OUTCROP STRATIGRAPHY COMPARED WITH ILLUSTRATIONS FROM THE MEDICINE HAT AREA OF ALBERTA

A. MacS. STALKER
J.E. WYDER

Canada

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Preface

The study on which this report is based was designed to compare the results obtained from a study of surface materials with those obtained from the interpretation of logs and samples of boreholes drilled expressly for this purpose in the same deposits. The Medicine Hat area contains excellent Quarternary exposures and much was already known about these deposits due in part to the presence of abundant vertebrate fossils which made correlation between various exposures possible.

Although originally approved for publication in 1977 major delays were encountered in processing this report. While the results of the study are directly applicable only to the Medicine Hat region, it is felt that the information presented may aid in interpreting results obtained from drilling in surficial materials elsewhere and thus the study is being published now as part of the ongoing record of scientific work of the Geological Survey of Canada.

R.A. Price
Director General
Geological Survey of Canada

OTTAWA, December 1982.

Avant-propos

L'étude sur laquelle est fondé ce rapport a été conçue de façon à permettre la comparaison des résultats obtenus de l'étude des matériaux de surface avec ceux obtenus de l'interprétation des diagraphies et des échantillons prélevés de trous de sonde forés dans les même dépôts expressément à ces fins. La région de Medicine Hat possède d'excellents affleurements d'âge Quarternaire et les dépôts à cet endroit étaient déjà bien connus en raison, surtout, du fait que la présence d'une abondance de fossiles vertébrés avait permis d'établir la corrélation entre les divers affleurements.

En dépit du fait que la publication de présent document avait déjà été approuvée en 1977, des délais important se sont présentés qui ont empêché son impression. Bien que les résultat de l'étude s'appliqent spécifiquement à la région de Medicine Hat, on estime que les reseignements présentés peuvent contribuer à l'interprétation des résultats obtenus des forages effectués ailleurs dans des matériaux de surface et, on a donc décidé de procéder à la publication de la présente étude dans le cadre des comptes rendus de travaux scientifiques en cours que publie la Commission géologique du Canada.

R.A. Price
Directeur général
Commission géologique du Canada

OTTAWA, décembre 1982.

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BOREHOLE AND OUTCROP STRATIGRAPHY COMPARED WITH ILLUSTRATIONS FROM THE MEDICINE HAT AREA OF ALBERTA

Abstract

This bulletin presents the results of a study that evaluated the relative merits of outcrop and borehole investigations of surficial deposits for stratigraphic purposes and to assist in future interpretations of geophysical logs. Seven boreholes were drilled near thick surficial deposits, each near a previously studied outcrop. The boreholes were logged immediately for self-potential, single point resistivity, natural gamma, porosity and bulk density, and were sampled at selected depths. A composite section for each site was prepared from the outcrop and borehole sequences. In general, the information provided by both outcrop and borehole appeared reliable, and most borehole units were readily identified and correlated with the nearby outcrop.

The results obtained from outcrop and borehole investigations were generally complementary. Information from a borehole is usually superior to that from an outcrop for recording the entire section, determining unit thickness and depth, revealing oxidized zones, and obtaining uncontaminated samples for pollen and carbonate studies. Borehole data are less successful in indicating whether beds of fine material are alluvial, eolian, lacustrine or merely bedrock inclusions, even with the use of samples. The borehole logs neither revealed thin volcanic ash beds and soils nor enabled inclusions in till sheets and duplications of beds from slumping or thrusting to be distinguished from regular bedding. Boreholes are of little value for macrofossil studies.

The outcrop provided more information about type of material, origin, distribution and continuity of beds; structures, deformation and slumping; and direction of movement of the depositing agent. They were far superior for fabric studies and stone counts, and for collecting large samples for radiocarbon dating or other purposes.

From the borehole logs certain beds were extremely difficult to distinguish from tills. These were mostly mixtures of material, such as alluvium and colluvium laid down and churned by permafrost, and alluvium formed from older, fine lake deposits or bedrock to which stones had been added.

In order to outline stratigraphy accurately, a hole should be logged by as many methods as possible, and abundant samples should be taken.

Résumé

Le présent bulletin expose les résultats d'une étude qui cherche à établir s'il est préférable de déterminer la stratigraphie des dépôts meubles par l'étude d'affleurements et de trous de sonde, de façon à apporter des éléments nouveaux à l'interprétation des diagraphies. On a foré sept trous près d'épais dépôts meubles, tous proches d'un affleurement étudié auparavant. Dans chacun des sondages, on a immédiatement effectué des diagraphies de la polarisation spontanée, de la résistivité ponctuelle, du rayonnement naturel gamma, de la porosité et de la densité apparente; de plus, on a recueilli des échantillons à diverses profondeurs. On a préparé une coupe composite de chaque site, à partir des successions identifiées par l'étude des affleurements et des trous de sonde. En général, l'information obtenue à partir des sondages et des affleurements semblait fiable et on a pu facilement identifier la plupart des unités révélées par les sondages, et établir une corrélation entre celles-ci et les affleurements proches.

Les résultats qu'a donné l'examen des affleurements et des sondages étaient généralement complémentaires. L'examen des sondages est en général préférable à celui des affleurements pour la description de la coupe toute entière, la détermination de la puissance et de la profondeur des unités, la reconnaissance des zones oxydées, et la collecte d'échantillons destinés aux études palynologiques et à la détermination des carbonates. Les données fournies par les sondages ont donné de moins bons résultats, même lorsqu'on s'est servi d'échantillons, lorsqu'il s'agissait de déterminer si les lits composés de matériaux de granulométrie fine étaient d'origine alluviale, éolienne, lacustre, ou tout simplement composés d'inclusions de roche de fond. Les diagraphies de sondages n'ont pas révélé la présence de lits et sols composés de cendre volcanique fine, ni permis de distinguer la présence d'inclusions dans les nappes de till et les répétitions de couches causées par des glissements de terrain ou des charriages, d'une stratification régulière. Les sondages sont peu utiles, en ce qui concerne l'étude des macrofossiles.

Par contre, les affleurements ont fourni plus de renseignements sur le type de matériau, sur l'origine, la distribution et la continuité des lits, sur les structures, les déformations et les glissements de terrain, et sur la direction dans laquelle se déplaçait l'agent de sédimentation. Ils ont donné des résultats bien plus concluants, en ce qui concerne l'étude de la fabrique des matériaux et le calcul de l'abondance en fragments pierreux, et la collecte d'échantillons de grande taille, destinés à la datation au radiocarbone ou à d'autres usages.

Certains lits identifiés dans les diagraphies de sondages ont été extrêmement difficiles à distinguer des tills. En général, il s'agissait d'un mélange de matériaux, tels que des alluvions et colluvions déposées puis géliturbées, et des alluvions formées à partir de dépôts lacustres plus anciens à granulométrie fine ou bien de roche de fond, auxquels se sont ajoutées des pierres.

Pour décrire avec précision la stratigraphie, il faut réaliser des diagraphies de chaque trou de sonde au moyen de méthodes aussi diverses que possible, et prendre de nombreux échantillons.

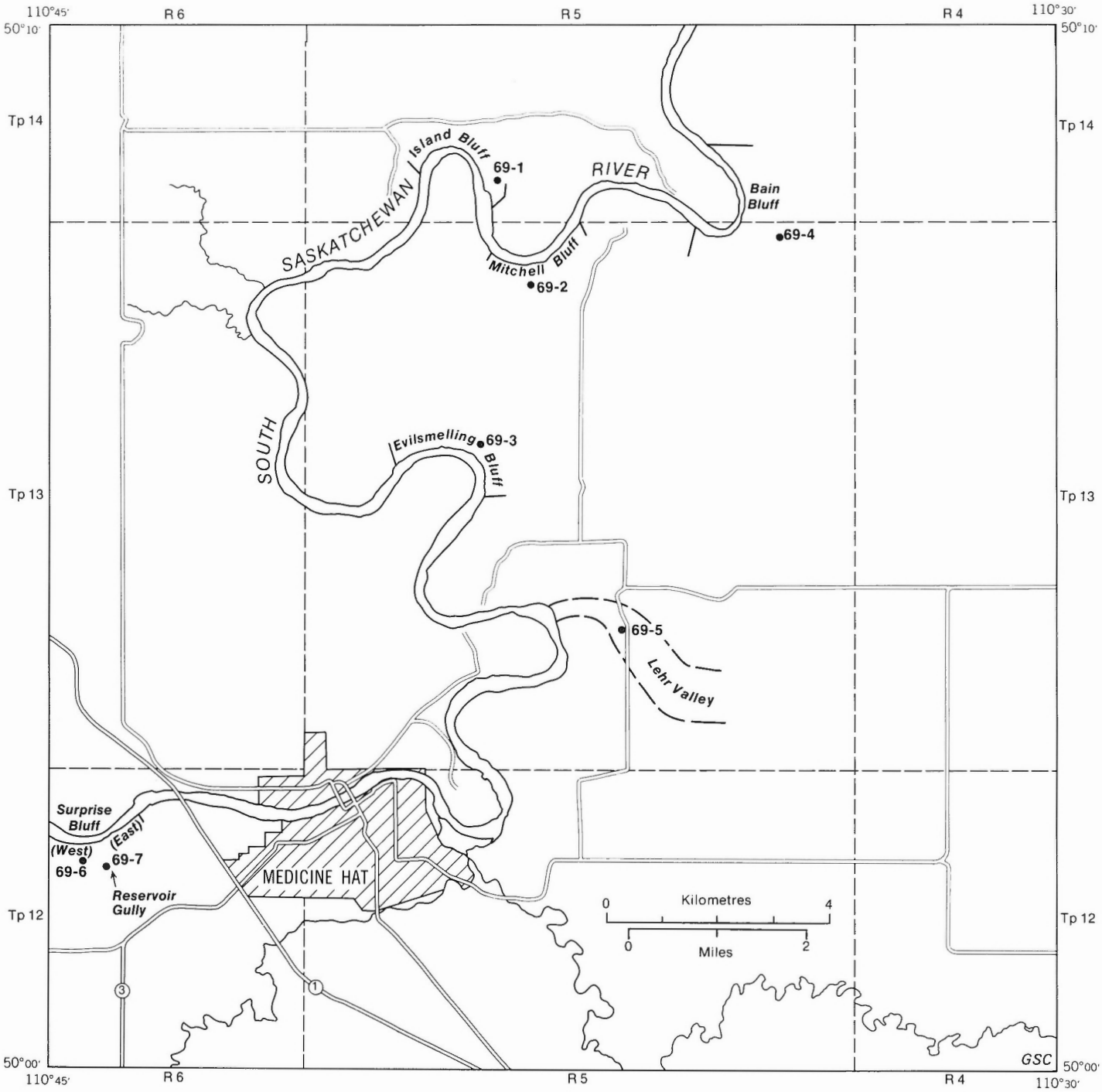


Figure 1. *Medicine Hat area showing locations of outcrops and boreholes.*

INTRODUCTION

General

This paper presents the results of a study that evaluated the relative accuracy, reliability and completeness of information gathered from borehole and outcrop studies of the same deposit and also provides information about interpretation of the results of borehole investigations. Wyder, who conceived the project, arranged for and supervised the drilling and logging, and interpreted the well logs; Stalker chose the sites, studied the outcrops and compared the stratigraphy from the outcrops with that recorded from the boreholes. Although the results of the study are directly applicable only to the Medicine Hat region of southwestern Alberta where the study was conducted, the information presented here may aid in interpreting results obtained from drilling in surficial deposits elsewhere.

Drilling for stratigraphic information about surficial deposits, a term which here is used to include all materials lying above the Cretaceous bedrock formations of the area, has become common in recent years. It is being done not only in areas where outcrops are absent and no other way of obtaining necessary information is available, but also in areas where outcrops are present to provide supplementary information, and in some cases even to replace the tedious study of outcrops. The Medicine Hat area (Fig. 1) appeared ideally suited for a comparative study of the two sources of information. Not only did it have thick and complex surficial deposits with numerous exposures and easy access to them, but also the deposits included beds that contained abundant vertebrate fossils. The fossils appeared to provide a unique opportunity to determine ages of some of the beds and to enable correlation between the various exposures. Also, due to these factors, the Medicine Hat region has been the focus of intensive examination of outcrops, and as a result much already was known about the Quaternary deposits there (Stalker, 1969, 1972, 1973; Stalker and Churcher, 1970, 1972; Stalker and Mott, 1972; Szabo et al., 1973).

In June 1969 seven boreholes were drilled close to outcrops that previously had been studied. The holes were logged by geophysical methods and sampled with a sidewall sampling device. The borehole information was compared with that gathered from earlier studies of the nearby outcrops in order to determine how the various types of materials reflected on geophysical logs, and thus improve the accuracy of borehole interpretations made in areas where no outcrops were available for comparison. Another objective of the drilling program was to collect information on the surface deposits for incorporation into other papers concerning the stratigraphy of the area.

The topography of the Medicine Hat area is depicted on National Topographic System map sheet 72 L/2 (Medicine Hat) at a scale of 1:50 000. Figures 1 and 2 (Figure 2 in pocket) show the study region and the location of outcrops and borehole sites (see Table 1 for borehole locations). Table 2 presents a simplified composite column through the Medicine Hat surficial section, which was prepared by correlating between some 15 outcrops found in the area. Not all units are found in each outcrop, and some (units V, VI, VII, XVI, XVII and perhaps XV) are found at any of the boreholes or outcrops described in this report. The thickness of the units varies considerably from exposure to exposure; in general, the thickest exposure of the unit found in any of the outcrops was used for the composite column.

The outcrops are located along the banks and in the tributary gullies of South Saskatchewan River. This deeply entrenched, meandering stream is merely the latest in a series of rivers that have crossed the region during the Cenozoic era. The first and most important flowed east or north, the exact course has not been determined, across the region for several million years during late Tertiary time and carved a deep, broad valley. During the Quaternary period, the initial glacier to invade the region deflected this ancestral river and largely filled its valley. As the ice retreated, the river resumed its flow and incised a new valley from prairie level. This sequence was repeated with each glacier. None of the later valleys attained the size of the preglacial one, but most were about as deep and as tortuous as the present valley. It is the drift, alluvium, and lake deposits contained in these successive valleys that form the topic of the present study.

Table 1. Borehole locations

Borehole number	Nearest outcrop	Altitude (above sea level)	Location						
			L.S.D.*	Sec.	Tp.	Rge.	Mer.	Latitude	Longitude
		ft							
69-1	Island Bluff	2355	NW of 5	4	14	5	4	50°8'31"	110°38'15"
69-2	Mitchell Bluff	2305	SE of 6	33	13	5	4	50°7'31"	110°37'54"
69-3	Evilsmelling Bluff	2340	SE of 9	20	13	5	4	50°5'36"	110°38'30"
69-4	Bain Bluff	2475	SE of 13	36	13	5	4	50°8'00"	110°34'4"
69-5	Lehr Valley	2320	SE of 11	10	13	5	4	50°4'13"	110°36'27"
69-6	Surprise Bluff West	2440	NW of 15	27	12	6	4	50°1'58"	110°44'32"
69-7	Reservoir Gully	2455	NW of 16	27	12	6	4	50°1'56"	110°44'10"

* Land survey division.

The broad, deep valley of the ancestral South Saskatchewan River not only largely determined the subsequent pattern of local drainage but, along with the Cypress Hills farther south, an upland to the east, and the general rise of the prairie to the west, largely controlled flow of the Quaternary glaciers in the district. This influence was enhanced because here the glaciers were near their limits of advance and so were thin.

Like the present river in the Medicine Hat region, most of its Quaternary predecessors flowed north or northeast. The high land to the west, east and south effectively precluded other courses; it also predisposed the formation of glacial lakes in the valleys when glaciers advanced southward up them or retreated to the north down them. Lake and floodplain deposits intervene between several till sheets and these contain the vertebrate fossils found in the area.. These deposits and the till sheets were preserved because, being in valleys, they were partly protected from the full force of subsequent glaciers.

Acknowledgments

The authors acknowledge, with grateful thanks, the kindness of Mr. Hargrave Mitchell of Medicine Hat for permitting the drilling of boreholes 69-1, 69-2, 69-3 and 69-4 on his property and for giving access to the nearby outcrops. They similarly wish to thank the authorities of the City of Medicine Hat for allowing the drilling of boreholes 69-6 and 69-7 on city property and for giving access to nearby outcrops. Thanks are extended to Mr. L.O. Lindoe of the same city for information provided from his vast knowledge of the exposures in the region. Mr. R.A. Hodge , then with the Geological Survey of Canada, operated the logging equipment; and the drilling was done under contract by McHarg Drilling Limited of Regina, Saskatchewan. The authors express their thanks to Mr. Hodge and the members of the drilling crew for their capable work and for their interest in bringing the project to a successful conclusion.

*Table 2. Medicine Hat composite section and suggested correlations with the borehole logs**

Unit	Maximum thickness ft	Origin	Suggested age		Type of material
XXIII	75	Mostly alluvium	Postglacial	(f)	sand, gravel, silt
XXII	65	Glacier deposit	Classical Wisconsin		yellowish-buff till
XXI	65	Mostly alluvium	Classical Wisconsin	(f)	sand, gravel, silt
XX	40	Glacier deposit	Classical Wisconsin		dark grey, contorted till
XIX	30	Alluvium	Mid-Wisconsin		sand, gravel, silt
XVIII	35	Mostly alluvium and swamp deposit	Mid-Wisconsin		organic silt, clay
XVII‡	15	Alluvium	Mid-Wisconsin		sand gravel
XVI‡	80	Mostly lake deposit	Mid-Wisconsin	(f)	silt, clay
XV	10	Alluvium	Mid-Wisconsin		lag sand and gravel
XIV	20	Glacier deposit	Pre-Classical Wisconsin		dark to light grey till
XIII	60	Glacier deposit	Pre-Classical Wisconsin		light, greyish-brown till
XII	10	Alluvium and lake deposit	Pre-Classical Wisconsin	(f)	silt, clay, sand, gravel
XI	40	Glacier deposit	Pre-Classical Wisconsin		dark, greyish-brown till
X	35	Alluvium	Sangamon	(f)	sand, silt, gravel
IX	10	Alluvium	Sangamon	(f)	gravel, sand, silt
VIII	45	Mostly alluvium	Sangamon	(f)	sand, silt
VII‡	45	Glacier deposit	Illinoian		black till
VI‡	60	Alluvium and outwash	Illinoian		sand, gravel
V‡	5	Glacier deposit	Illinoian		black till
IV	230	Mostly (glacial?) lake deposit	Yarmouth		clay, silt, sand
III	10	Flood plain deposit	Kansan to Yarmouth	(f)	carbonaceous silt and clay
II	25	Alluvium	Kansan	(f)	coarse gravel, silt
I			Upper Cretaceous		bedrock

† Units are listed by the reference letters used in the text.

‡ Apparently not present in sections being described, but found at other bluffs near Medicine Hat.

(f) Vertebrate fossils present.

* Units not here listed in the borehole logs are those whose correlations are in doubt, or which occur only locally, generally only in one borehole, and so are of minor importance for correlation purposes.

The Sites

The boreholes are named after the nearby outcrops (Table 1). The names Surprise Bluff West, Mitchell Bluff and Island Bluff have been used previously (Stalker, 1969). The locations of the bluffs (Figs. 1, 2) and the origins of their names are given below.

Island Bluff

This outcrop (Fig. 3) is named for the small island found at its base. The bluff follows the outer side of a meander for almost 2 mi (3.0 km) (mostly in the north half of sec. 5, tp. 14, rge. 5, W 4th mer.) on the north bank of South Saskatchewan River.

Mitchell Bluff

Mitchell Bluff (Figs. 3, 4, 5) was named after Mr. H. Mitchell of Medicine Hat, on whose property it lies. His homestead is situated a short distance to the east. The bluff is on the right bank of the river (in sec. 35, tp. 13, rge. 5, W 4th mer.) to the southeast of and across the river from Island Bluff. It follows the outer bank of the next meander downstream from Island Bluff for 1 1/2 mi (2.5 km).

Evilsmelling Bluff

This bluff (Fig. 6) gained its name from the 'Evilsmelling Band' found about halfway up its face. The bluff lies on the right side of the river on the outer side of a curve (mostly in sec. 19 and 20, tp. 13, rge. 5, W 4th mer.).

Bain Bluff

Bain Bluff, on the right bank of the river downstream from Island Bluff, carries the name of the early, local homesteader. It follows the outer side of a meander for about 2 mi (3.0 km) (crossing sec. 35 and 36, tp. 13, rge. 5, and sec. 1 and 2, tp. 14, rge. 5, W 4th mer.).

	Borehole log†						
Unit	69-1 (Island Bluff)	69-2 (Mitchell Bluff)	69-3 (Evilsmelling Bluff)	69-4 (Bain Bluff)	69-5 (Lehr Valley)	69-6 (Surprise Bluff West)	69-7 (Reservoir Gully)
XXIII	Q	O	L		J	O	Q
XXII	P	N	K	U		N	P
XXI		M				M	N,O
XX	N	L	I,J		H,I	L	M
XIX			H		G		L?
XVIII			G		F	K	K?
XVII							
XVI			F?		E?		
XV					D?		
XIV	L?					I?	
XIII	K			Q,R,S,T?			E,G,I
XII	J	K		P			
XI	I	J		O?			E
X	H	H,I	F?			H	
IX	G	G	E			G	C
VIII	F,G	E,F	D			F	B
VII							
VI							
V							
IV	D,E	C,D	B,C	D-M?	C?	D,E	
III	C	B		C	C	C	
II	B	B		B	B	B	
I	A	A	A	A	A	A	A

Figure 3

Island Bluff as seen from Mitchell Bluff, with location of borehole 69-1 indicated by an arrow. GSC 153516

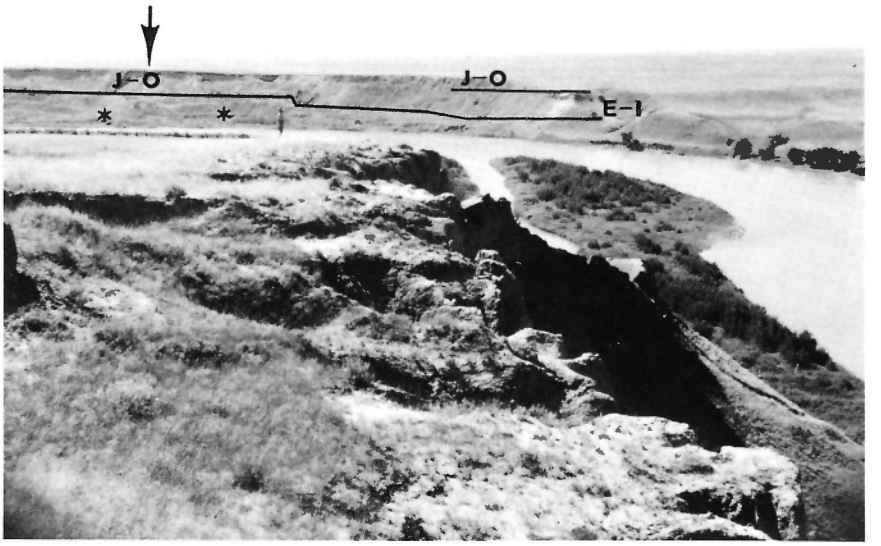
Island Bluff
Q = surface sand and silt
P = till
O = sand
K,M,N = tills and intertill clays and sands
j = sand, gravel
I = till
H = sand and clay
G = sands, silts
F = gravel, containing first occurrence of Shield stones
** = slump*

Mitchell Bluff
H,I = sands and clays
G = silty gravel and sand

Figure 4

Centre and west end of Mitchell Bluff as seen from Island Bluff; white patch at right is site of excavations shown in Figures 3 and 5. Location of borehole 69-2 indicated by an arrow. GSC 119716

J-O = tills, intertill deposits, and surface gravel and sand
E-I = sands, silts, and clays found between first occurrence of Shield stones and first till
** = slump*



Lehr Valley

Lehr Valley is the name applied here to a former valley of South Saskatchewan River, now partly filled, that trends east for several miles from the present river (sec. 9, tp. 13, rge. 5, W 4th mer.). The western segment of the valley crosses the property of Mr. R. Lehr of Medicine Hat.

Surprise Bluff West

This name was given to the bluff because a certain bed in it, which was expected to be barren, very unexpectedly was found to contain abundant bones. The bluff forms the south bank of South Saskatchewan River (sec. 34 and 35, tp. 12, rge. 6, W 4th mer.). Surprise Bluff West, which is the part described here, lies in sec. 34.

Reservoir Gully

Reservoir Gully (Fig. 7) derives its name from a small gully that rises at the Medicine Hat Reservoir near the western limits of the city (sec. 26 and 27, tp. 12, rge. 6, W 4th mer.).

Method

Study of the outcrops commenced in 1963 and has continued intermittently to 1975. It has involved description of the beds; investigation of their contacts, interrelationships and structures; collection of bones and other fossils; determination of environments and ages; along with stone counts and fabric studies for most of the tills. Seven bluffs were chosen for drilling, and six of the seven boreholes were sited as close as practical to their respective bluffs. The other borehole (69-5) was drilled at the lowest part of Lehr Valley,

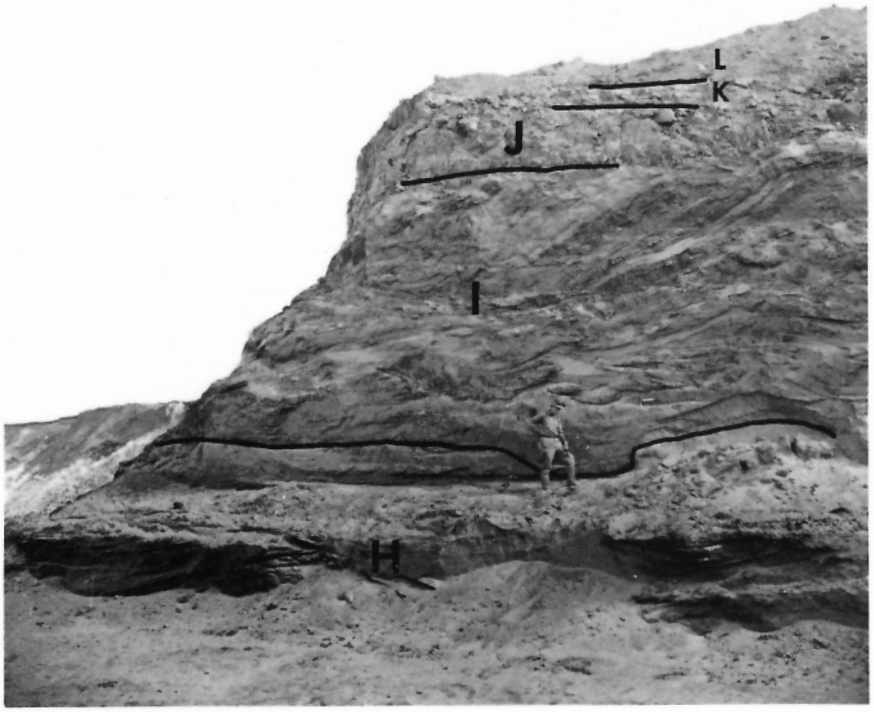


Figure 5

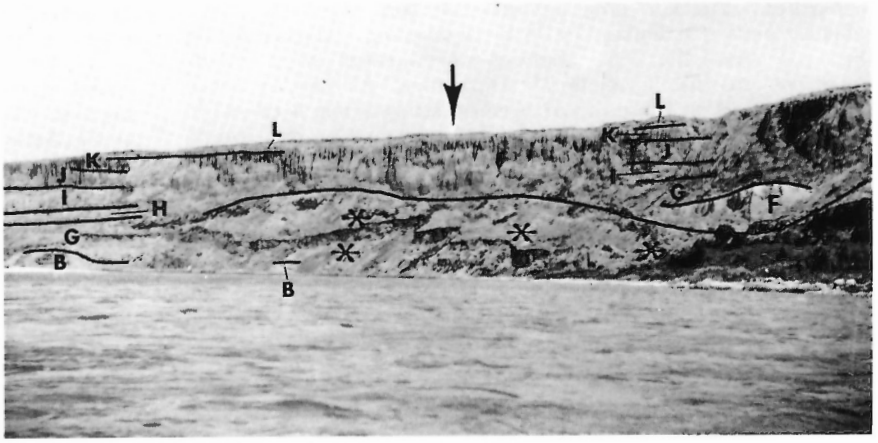
Upper part of Mitchell Bluff west.

L = till
K = silt and clay, fossiliferous
J = till
I = silt, clay, sand, contorted
H = sand and gravel, fossiliferous

Figure 6

Central part of Evilsmelling Bluff, with location of borehole 69-3 indicated by an arrow.

L = surface silt
K = till
J = till
I = contorted till
H = sand, gravel
G = Evilsmelling Band
F = sand
B = sand, gravel
** = slump*



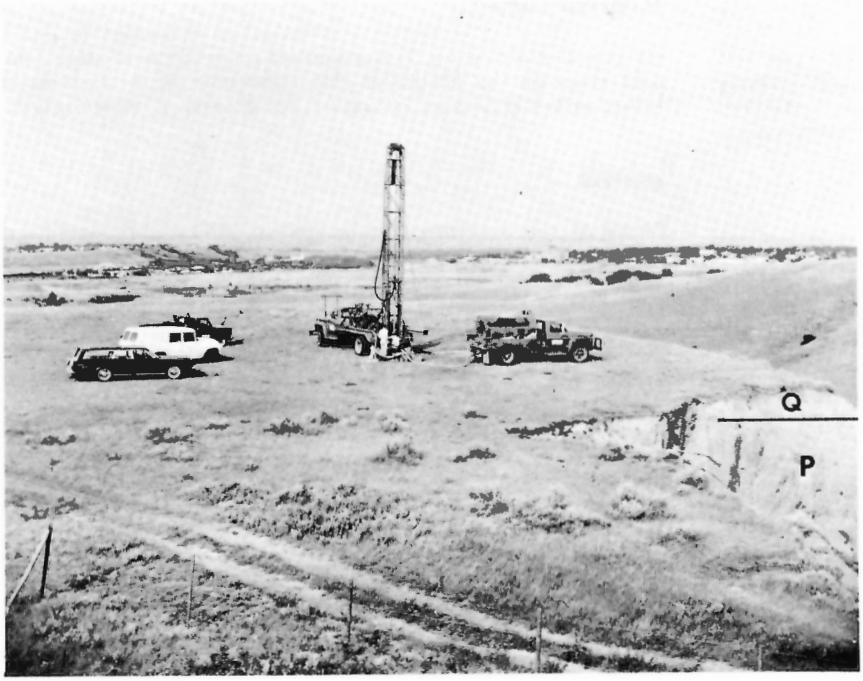


Figure 7

Drilling borehole 69-7 at Reservoir Gully, with South Saskatchewan River valley and the city of Medicine Hat in the background.

Q = surface sand, silt
P = till

about 2/3 mi (1 km) from South Saskatchewan River. The borehole sites are listed in Table 1 and are shown in Figures 1 and 2. A Failing 1500 drill rig, equipped to drill with both air and water (Fig. 7) was used to drill the holes; water and mud were used exclusively for the drilling. The holes were drilled chiefly with 4 1/2 in. (11.4 cm) finger bits, but rock bits were used to drill through rocks embedded in the sediments and through gravel and boulder layers. Each hole was electrologged immediately, although in borehole 69-3 rapid loss of water prevented completion of the electrologging. Natural gamma, porosity, bulk density and hole diameter measurements followed. Sidewall samples (Morrison, 1966) were taken at depths chosen on the basis of the electrologs. Using the method described by Rutter and Wyder (1969) a stratigraphic interpretation of each borehole was prepared using information obtained during drilling and logging, and this interpretation was compared with the stratigraphic interpretation obtained by study of the nearby outcrops. Where discrepancies arose, attempts were made to resolve or explain them through restudy of the outcrops; usually these attempts were successful. Subsequently, the sidewall samples that were suitable were analyzed for sand, silt and clay fractions, and for carbonate content. These analyses, particularly the sand percentages, aided in separating the surficial deposits of the logs into their various beds and units, and in distinguishing and correlating between the tills. The analyses necessitated some modifications to the borehole stratigraphies, further to those already made on the basis of outcrop study (Figs. 8 to 14, in pocket). The analyses also provided a means of confirming revisions made to either the outcrop or borehole stratigraphies during their combination.

Pollen content of a few samples was studied, mostly in samples taken from thick lake clays found in the central segment of the borehole at Bain Bluff (Fig. 11), in expectation that it would reveal something about age of the deposits and the environment during their deposition. However, pollen content was low, and results were disappointing.

SECTIONS

General Description

The outcrops near the boreholes at Island and Mitchell bluffs give good exposures to river level, and Surprise Bluff West is well exposed about 1/3 mi (0.5 km) west of the borehole. The upper part of Bain Bluff also is well exposed, but slump covers most of its middle and lower parts; this is the most severely slumped of the bluffs, and the slumps extend as far as 1/2 mi (0.8 km) back from the river. Slump also obscures the middle part of Evilsmelling Bluff (Fig. 6), but the Evilsmelling Band and overlying beds are well exposed. Only the upper and lower parts of the section at Reservoir Gully are exposed, and the Lehr Valley deposits outcrop only near the river, about 1/2 mi. (0.8 km) west of the borehole.

In general the original borehole logs showed the presence of more till than the outcrop did but less sand, silt and clay. This is largely because outcrop studies concentrated on places where the river and lake sediments were thickest, for those sediments yielded valuable vertebrate remains and gave the most information about sequence of deposition; the borehole sites avoided this bias. In addition certain nontill beds, such as the Evilsmelling Band in borehole 69-3, were interpreted incorrectly as till in the borehole logs, adding to the discrepancy.

The borehole sections generally were thicker than those derived from the corresponding outcrops, mainly because the boreholes, except at Bain Bluff, were located a short distance back from the valley edge and so were on higher ground than the top of the outcrop section. In addition, several boreholes penetrated material below river level, which was inaccessible at the outcrop.

Most correlations between boreholes were made by comparison of the various sequences and juxtapositions of the deposits. The same method was used for correlation between the outcrops, but here the vertebrate faunas were also a valuable aid. Furthermore, examination of the bluffs had demonstrated that certain beds or features could serve as marker horizons for correlation purposes. The lowest marker was the 'preglacial gravel', which is near the base of the sequence and directly above bedrock (Table 2, unit II).

Typically this is a coarse, rounded, quartzite or hard sandstone gravel completely lacking stones from the Precambrian Shield, which hereafter are called 'Shield stones'. This gravel was found in all boreholes except at Reservoir Gully and Surprise Bluff West and in the outcrops is missing only at Reservoir Gully. Identification of this deposit is based largely on its lack of Shield stones, which generally can only be determined in outcrops; thus, recognition of this marker unit in boreholes is normally through analogy with what is found in the nearby outcrops.

A carbonaceous clay is the next oldest marker bed (Table 2, unit III). It is found towards the base of several outcrops, notably Island and Mitchell bluffs, Lehr Valley and other bluffs that were not drilled. This marker also is difficult to identify in boreholes. Higher in the surficial section the initial appearance of Shield stones, heralding the approach of the first glacier, forms the most important and valuable marker of all. In the region the first occurrence of Shield stones is in a dark till (Table 2, unit V), but at the sites drilled this till has been destroyed, and so the stones first appear in a lag deposit (Table 2, unit VIII). This horizon also is not readily determined in the boreholes.

A less important marker is the Evilsmelling Band (Table 2, unit XVIII), exposed at Evilsmelling Bluff and Lehr Valley, and described under the former. It is recognizable in boreholes, once its characteristics are known, but only with intensive study of the logs. In addition, certain tills have peculiar traits that show on the borehole logs, perhaps better than in the outcrops, which allow them to serve as markers, but again only after intensive study of all drill logs. Perhaps the best example is the contorted till, which in most cases is the second till from the top (Table 2, unit XX). This till has been strongly deformed by permafrost or subsequent glaciers, and its peculiarities are apparent both in outcrop and in borehole logs.

The local bedrock formations are deficient in carbonate, and this provides a valuable means of distinguishing bedrock or bedrock inclusions from other surficial deposits. The limestone and dolomite of the surficial material came from the mountains farther west and from the Paleozoic formations found along the southern margin of the Shield, some 500 to 700 mi (800 to 1125km) to the north or northeast. Fine carbonate is fairly plentiful in most of the deposits (see Appendix). Carbonate clasts from the mountains are rare, for most were ground into fine material during river transport to this area. Those from the margin of the Shield were brought in by glaciers and thus occur only in material laid down after the advent of the first Laurentide glacier. As is the case with Shield stones, their initial appearance in abundance is a good marker horizon for this event, but once again this cannot be determined in boreholes. In addition, carbonate stones and carbonate contents of the matrix are extremely useful in correlating tills from site to site, for their percentages vary markedly from one till to another. On the other hand, calcite-dolomite ratios in each till fluctuate widely and appear to be of little use in correlation. This may be a peculiarity of the Medicine Hat region; elsewhere, where glaciers advanced over bedrock formations that had vastly differing carbonate contents, the studies of calcite-dolomite ratios may be much more rewarding.

In the following discussions of the bluffs studied, most attention is directed towards the till sheets and to units that show discrepancies between the borehole and outcrop sections. Units that are not discussed generally are similar in thickness and composition in both borehole and outcrop sequence or else could not be examined in the outcrop.

Description of individual sites

Island Bluff: borehole 69-1 (Figs. 3 and 8)

At this bluff the beds, and particularly the till sheets, change rapidly in thickness along the outcrop. Both the outcrop and borehole descriptions, however, are from sites near each other at the east end of the bluff. The section is well exposed, and the borehole and outcrop stratigraphy could be compared better here than at any other borehole. In general the sequences are similar.

The deposits below the bottom till, consisting of units B to H, are about 50 ft (15m) thinner in the borehole than in the outcrop. This is mostly because the outcrop was studied preferentially where the sand and silt beds were thick, but in addition the upper part of unit H may have been eroded from the borehole vicinity by the glacier that deposited unit I, thereby decreasing the amount of alluvium encountered during drilling.

Units A and B lie below river level at the east end of the bluff and so are not shown on the outcrop section. Unit A is bedrock. Where exposed at the west end, unit B is a complex mixture of near horizontal beds of gravel, sand, and clay, overlain by a peaty band (unit C) -- the carbonaceous clay marker bed mentioned above. Bones are plentiful in the middle of this unit. The complexity of unit B is reflected by marked variations in the geophysical logs.

Steep-faced beds of silt seen in the outcrops of units D, E and G were not recognized either in borehole logs or from mechanical analyses; in the borehole these units are represented by sand with thin gravel beds. The absence of the silt beds is difficult to explain, for they are both widespread and thick in the cliff face.

The first occurrence of Shield stones in the outcrop appears in a coarse, poorly sorted gravel bed found directly above a steep-faced silt bed; both beds extend the full length of the bluff. The gravel bed is correlated with unit F, found at a depth of 230 ft (70m) in the borehole, although the first occurrence of Shield stones cannot be determined in the borehole.

In the outcrop, unit H consists mainly of a pebbly sand, whose grains are composed of clay or shale fragments ripped up from pre-existing lake deposits. This unit shows well developed crossbedding and cut-and-fill structures. The older deposits that provided its material may have been the equivalents of the thick lake deposits found in units C to N at Bain Bluff (Fig. 11). The borehole did not show any corresponding material at that depth (143 to 165 ft or 43.6 to 50.3m), and in the original borehole interpretation the till of the overlying unit I was extended across that interval. The modified borehole log retains unit I there, for the sidewall samples from that segment are too sandy to come from material composed essentially of fragments of clay and shale. Unit H seen in outcrop may well be missing from the borehole, perhaps removed by the glacier that deposited unit I. On the other hand, this material may be at lower elevation in the borehole than in the outcrop. This is the assumption made for the modified borehole log, where unit H has been placed below the till of unit I and at a lower position than at the outcrop. The mechanical analyses and the geophysical logs amply justify the presence of a distinct unit at that position, but it remains uncertain whether this material corresponds to the outcropping beds of fragmented clay and shale. The problems associated with unit H are far from resolved.

The thickness of unit I fluctuates abruptly along the bluff, and evidently the borehole pierced one of its thickest parts, whereas the outcrop was studied at one of its thinnest. This unit consists of clayey and sandy, dark grey till; but a white sand band, about 1 ft (30cm) thick, traverses the middle of the unit in the outcrop. This sand band probably is denoted by fluctuations on the geophysical logs

at a depth of 132 ft (40m). The till of unit I has been strongly contorted and deformed, perhaps by overridding ice; and therefore the stone fabric is weak. However, a trend from the northwest is indicated, and stone counts show about 43 per cent carbonate stones. This material slumps readily, and the cliff face retreats rapidly across it.

Unit J contains bones from large mammals and thus represents a significant span of time. These fossils, and hence the length and importance of this interval, cannot be recognized in the borehole logs, nor is its duration indicated by significant weathering or oxidization in either this unit or the underlying till.

Units K and L were combined into one till unit in the original borehole interpretation, and mechanical analysis shows that their grain size composition is almost identical. The carbonate and stone contents of the two units differed however, and study of the outcrops supported some indication from the logs that they should be treated as separate units. Whether the differences could be merely due to unit L being an oxidized upper portion of unit K is not known, but the difference in directions of ice movement shown by their fabrics (from N68°W for unit K; from N20°W for unit L) indicates that the two units are, at least, different phases of the same glacier even if they do not represent two entirely separate glaciers.

Unit K is a dark brown till, with sand lenses near its base, that has only a few stones. Though this is one of the few cases where a till unit is thicker in the outcrop than in the borehole, there was no hesitation in correlating it between the two sequences. Unit L is a dark grey till, stonier than the till of underlying unit K, with nearly 60 per cent of the stones being carbonates. The unit is equally thick in the outcrop and the borehole, and its correlation between the two sequences undoubtedly is correct. The sands and clays of unit M separate till units L and N in the borehole. This unit is very thin in outcrop, where it easily could be mistaken for a lower clay band of unit N.

Unit N consists of alternating bands, 1/2 to 4 ft (15cm to 1.2m) thick, of silt and very dark till. The till is much sandier than the lower tills. The entire unit represents the contorted till, here as at the other sites, the second till from the top; its confused, variable nature is reflected in the geophysical logs. Fabric studies rarely are of value in this deformed till.

The sand of unit O separates the till of unit N from the very different till of unit P. Unit P is a light brown, sandy, moderately stony till. About 52 per cent of the stones are carbonates, and the fabric indicates deposition by ice moving S25°W. The till is thicker in the borehole than in the outcrop, probably a result of local removal by South Saskatchewan River right after the last glaciation.

Table 3 gives some average physical characteristics of the till sheets at Island Bluff.

Table 3. Physical features of the Island Bluff tills

	Size composition						
	Coarse (>2 mm)	Fine (<2 mm)			Carbonate content		Fabric
Unit		Sand	Silt	Clay	Stones	Matrix	
	%	%	%	%	%	%	
P	5.7	41.7	33.2	25.1	52	8.2	N25°E
N	0.8	32.8	36.2	30.9		8.8	
L	1.6	23.3	40.7	36.0	60	6.7	N20°W
K*	1.2	23.4	41.1	35.5		10.6	N68°W
I	0.5	16.2	48.0	35.8	43	11.1	NW

* The sample at 85 ft (25.9 m) depth, which totally lacks the sand component and so may not be till but rather an inclusion or alluvial parting, has been omitted.

Mitchell Bluff: borehole 69-2 (Figs. 3, 4, 5 and 9)

No single exposure displays the full section at Mitchell Bluff, and thus the outcrop sequence is a compound one. The top part of the section is described from outcrops near the borehole site, but information about this part of the sequence remains incomplete. The middle part of the section (units D to L) and units A and B are well displayed at the west end of the bluff (Figs. 4, 5), where they have received extensive study and the description is reliable. The east end of the bluff gives a good view of the lowermost beds except for the bedrock of unit A and the bottom part of unit B, which there lie below the level of South Saskatchewan River. Overall the exposures show beds that vary markedly in thickness along the bluff but little in composition.

In general, correlations between outcrop and borehole stratigraphy are less satisfactory here than at Island Bluff. The section below the till of unit J, however, closely parallels the lower part of Island Bluff (units A to H) in both order and thickness of units, and comments made for those units at Island Bluff generally apply to the corresponding units here. The first occurrence of Shield stones is well shown in the outcrop, and its placement at the base of gravel unit E in the modified borehole log is justified.

Unit G is a prolific producer of vertebrate fossils and as such has been excavated extensively and has received more study than any other unit in the Medicine Hat region. It is typically a poorly sorted gravel with tight clay and silt matrix. The mechanical analysis from this unit (see Appendix, depth 145 ft or 44m) shows abundant clay, much sand, and a significant quantity of material greater than 2 mm in diameter.

The thin bed at depth 130 ft (39.6m), which forms the base of unit I (Fig. 5), was called till in the original borehole interpretation, and it may well be a till band resembling those found near the top of the unit. More plausibly it is a fine gravel with compact silt and clay matrix. In addition, the top 9 ft (2.7m) of this unit was called till in the original borehole interpretation and was included with the overlying till unit J; however, it is much sandier than till of unit J. In outcrop it resembles unit H at Island Bluff and like it this top part of unit J here is composed mainly of fragments torn from older beds of lacustrine silt and clay, to which a few extraneous stones have been added, resulting in a till-like composition. This upper part of unit J however does, indeed, contain interfingering stringers or bands of till.

Unit J is a dark grey, stony till consisting mostly of silt and clay. It is less deformed than the corresponding till sheet of unit I at Island Bluff and has a steep face at the outcrop. Stones are about 54 per cent carbonates; deposition by ice moving from N65°W is indicated.

Unit K has yielded bones and wood and therefore appears to represent a significant interstade. It probably corresponds to fossiliferous unit J at Island Bluff, and if so must be fairly widespread. Despite this, the unit was not recognized and may be missing in the borehole.

Unit L is a silty and clayey till with an oxidized upper part and an unoxidized lower part separated by a sand bed. The till is dark bluish grey and contains few stones. This is the contorted till, found once again as the second till from the top. The intensity of its deformation is well displayed in the outcrops and by fluctuations in the geophysical logs. As is characteristic of this contorted till, many of its stones are carbonates, 77 per cent in this case. Till fabrics from the

Table 4. Physical features of the Mitchell Bluff tills

Unit	Size composition: Coarse (>2 mm)	Fine (<2 mm): Sand	Silt	Clay	Carbonate content: Stones	Matrix	Fabric
	%	%	%	%	%	%	
N	2.6	43.7	30.8	25.5	28	7.9	N50°E
L	2.0	30.7	41.8	27.5	77	11.2	N45°E; N40°W
J	0.7	16.7	46.9	36.4	54	8.6	N65°W

contorted till are of little use, and here, perhaps due to the deformation, two possible directions of ice movement were obtained, from N45°E and from N40°W.

The upper portion of unit N appears to be missing from the outcrop, presumably destroyed by South Saskatchewan River as it started to downcut following the last glaciation; and so the borehole shows a thicker segment of this unit. It consists of an oxidized, yellow-brown, sandy till that, apparently, was deposited by ice moving from N50°E. Only 28 per cent of its stones are carbonates, which is low for a till in this area.

Table 4 gives some average physical characteristics of the till sheets.

Evilsmelling Bluff: borehole 69-3 (Figs. 6 and 10)

Not only is the bottom part (units A to F) of the outcrop at this bluff largely covered by slump, but the beds are deformed by slumping, faulting and jointing. Although these factors impeded correlation with the lower part of the borehole log, no major discrepancies appeared, and this lower section resembles the sequence below the lowest till at Island and Mitchell bluffs.

The top part of the bluff (units G to L) is well exposed. Unit G is the Evilsmelling Band. This is the lowest unit readily investigated in the outcrop, and it is a complex mixture of silt, clay, sand and stones, along with much finely disseminated organic matter. It is typically grey, but at its face the outer 1 to 3 ft. (0.3 to 0.9m) is dark blue or reddish to purplish brown, is damp, and has a strong, obnoxious odour. The band is interpreted as material laid down in an abandoned river valley under permafrost conditions. It includes slope wash, slide and solifluction debris, dust blown in by wind, organic material from plants growing in the valley, and much alluvium laid down when the river intermittently reoccupied this channel, presumably at times of large scale flooding. As this deposit aggraded, its upper part was constantly churned and mixed, although locally some rudimentary bedding has survived. The organic material appears to have been preserved from decomposition by rapid freezing and burial and only now is oxidizing and rotting as it slowly is uncovered, giving off the odour that has earned for this unit the name 'Evilsmelling Band'. This band, in turn, has given its name to the bluff. In a borehole such material is almost impossible to distinguish from till, and originally in this borehole, as probably in some others, it was classed as till.

Unit H is extremely variable in thickness and is missing along much of the bluff. Its outcrop was examined where thickest, but more commonly it has the thickness shown by the borehole log. Most of the unit is river alluvium, and it is extremely variable in composition. Basically it consists of oxidized silt and sand with pockets of gravel, and in places it contains small pieces of wood, insect remains and rodent bones. The presence of these fossils and the fact that the unit is substantially more oxidized than the Evilsmelling Band indicate deposition during a warmer interval that intervened between deposition of underlying unit G and overlying unit I, when severely cold conditions prevailed.

Unit I is the contorted till, and its character is displayed better here than at any of the other outcrops. It is a dark, bluish grey till with low sand content, and about 70 per cent of its stones are carbonates. Its lower contact is extremely irregular; large plumes or flames of silt and sand from the underlying unit H penetrate the lower portion of unit I, and in turn tongues of till penetrate the upper part of unit H. Each unit also encloses pockets of material from the other unit; in many places the intermixing of these two units is so thorough as to obscure their boundary. Although fabric studies in this unit generally are not reliable, here they indicate deposition by ice flowing S75°W.

Originally unit J was combined with unit I in the outcrop descriptions and with unit K in the borehole interpretation. It is intermediate between these two units in many properties, such as its colour and steepness of face along the outcrop, where in places it appears to be part of the lower till and elsewhere part of the upper. Unit J may not represent a separate ice advance but, if not, it is uncertain whether to include it with unit I or with unit K. If it is a less contorted phase of underlying unit I, the silt bands that interfinger in its upper part denote a separation from unit K, as indicated in Table 2 where units I and J are grouped together in unit XX. However, it probably is a distinct till, as implied in the modified borehole log, and the mechanical and carbonate analyses indicate that it corresponds to unit N at Island Bluff, unit L at Mitchell Bluff, and perhaps unit L at Surprise Bluff West and unit M at Reservoir Gully.

Unit K is a light brown, oxidized, sandy till apparently deposited by ice travelling S72°W. About 43 per cent of its stones are carbonates. In all respects it resembles the typical surface till seen over most of the region.

Table 5 gives some average physical characteristics of the till sheets.

Bain Bluff: borehole 69-4 (Fig. 11)

The borehole at Bain Bluff was sited near the bottom of a small valley tributary to South Saskatchewan River valley, at a point about 40 ft (12m) below the general prairie level. The base of the outcrop is at river level, but the borehole penetrated an additional 25 ft (7.6m) of surficial material and 10 ft (3m) of bedrock below river level before bottoming; thus the borehole log extends some 35 ft (10.7m) beyond the base of the outcrop. All but the upper part of the outcrop is badly obscured by slump.

Table 5. Physical features of the Evilsmelling Bluff tills

Unit	Size composition: Coarse (>2 mm)	Fine (<2 mm): Sand	Silt	Clay	Carbonate content: Stones	Matrix	Fabric
	%	%	%	%	%	%	
K	0.9	39.0	33.5	27.5	43	6.7	N72°E
J	1.8	36.5	35.0	28.5		9.9	
I	2.0	22.3	41.7	36.0	70	9.6	N75°E

Units B and C include a thick sequence of interfingering beds of coarse gravel, clay, and silt; these units are mostly below river level and thus are reported only from the borehole. The bottom part of this sequence is chiefly gravel, but clay and silt beds increase in importance upwards until the gravel is fully replaced. This sequence resembles that found near river level at the west end of Island Bluff and the east end of Mitchell Bluff (Table 2, units II and III). At Bain Bluff the first beds exposed above river level are towards the top of unit C, and they contain sticks of carbonaceous material similar to those found in the beds that elsewhere form the carbonaceous marker of unit III in Table 2. The sequence undoubtedly represents flood plain deposition by the ancestral South Saskatchewan River shortly before arrival of the first glacier to reach the area.

The greater part (units D to M) of the Bain Bluff section consists of a series of lake clays and silts (Table 2, unit IV), which are thicker here than at any other site. These beds are chiefly responsible for the excessive amount of slumping at Bain Bluff, and they had previously gone unnoticed because of slump cover. They are exposed in the scarp forming the northern boundary of the slumped area and as small, isolated exposures amidst the slump blocks. The sequence derived from these outcrops is not overly reliable, but it does support the stratigraphy deduced from the borehole. A scarcity of pollen in this material may indicate that much of it was deposited under frigid, inhospitable conditions, probably in a long-lived proglacial lake that was dammed by glacier ice advancing southward up South Saskatchewan Valley towards the area.

The upper part of the section (units N to V) is well exposed, but its till sheets are difficult to correlate with those found at other sites. At this site the outcrop and borehole stratigraphies of this upper part agree well, although some minor adjustments were needed in the till boundaries of the borehole sequence. Restudy of the borehole logs has indicated that these changes, which mainly affect boundaries between units Q, R and S, are acceptable. The significance of clay unit P is not known fully, but it probably represents a major break in the Preclassical Wisconsin, and therefore it is placed in unit XII of Table 2. Unit V, like Unit Q at Island Bluff and unit O at Mitchell Bluff, consists mostly of alluvium, but it has not undergone as much surface modification by wind as the latter units.

Tills with low sand content, such as those represented by unit I at Island Bluff, unit J at Mitchell Bluff and unit I at Evilsmelling Bluff, are noticeably missing from the Bain Bluff sequence.

Table 6 gives some average physical characteristics of the till sheets.

Table 6. Physical features of the Bain Bluff tills

	Size composition				
	Coarse (>2 mm)	Fine (<2 mm)			Carbonate Content
Unit		Sand	Silt	Clay	Matrix
	%	%	%	%	%
U	6.1	45.6	29.3	25.1	6.6
T*	4.0	42.0	32.7	25.3	11.3
S	14.0	35.3	33.8	30.9	12.8
Q	3.3	29.7	37.9	32.4	11.5
O	1.9	32.5	36.3	31.2	10.2

* The sample at 56 ft (17 m) depth, which came from a 3 ft (0.9 m) thick sand bed or inclusion within till unit T, has been omitted.

Lehr Valley: borehole 69-5 (Fig. 12)

Comparison of the borehole and outcrop sequences for this site is difficult because the borehole is about 1/2 mi (0.8km) east of the juncture of the upper end of Lehr Valley with South Saskatchewan Valley, where the best outcrops are found. In addition, only the lower part of the section is exposed there, and that none too clearly. Exposures of the upper part are limited to poor outcrops along the gully of the modern, small stream in Lehr Valley.

Unit B, directly above bedrock, contains much coarse gravel and probably is a flood plain deposit of preglacial South Saskatchewan River (see Island Bluff, unit B; Mitchell Bluff, unit B; Bain Bluff, unit B). This deposit was below present river level and so could not be studied in outcrop. Unit C, a silt and clay unit outcropping locally near river level, also is preglacial. It contains the carbonaceous marker horizon and correlates with unit C at Island Bluff, unit B at Mitchell Bluff and unit C at Bain Bluff (Table 2, unit III). Unit D and the lower part of unit E are flood plain deposits of an aggrading river, which grade upward to lake sediments in the upper part of unit E. In the outcrop these consist largely of varved silt and clay. These latter sediments were laid down in a proglacial lake that steadily deepened as the glacier blocking South Saskatchewan River approached from the north.

Previous studies of Lehr Valley had pointed to the presence of the Evilsmelling Band but failed to reveal its exact position. Initial comparison of the borehole and outcrop sequences indicated, incorrectly, that it was the base of unit E; but further examination of the various logs, mechanical and carbonate analyses of sidewall samples, and comparison with the Evilsmelling Band (unit G) at Evilsmelling Bluff finally revealed it to be unit F. At Lehr Valley, as at Evilsmelling Bluff, this unit was called till during the initial borehole study. Its designation as the Evilsmelling Band is supported by the similarity of the overlying unit G to the unit (H) that overlies the Evilsmelling Band at Evilsmelling Bluff.

The till of unit H is basically silty with low sand content. However, its size composition and carbonate content are extremely variable, and the geophysical readings fluctuate widely across it; it appears to be the contorted till. The position of the till in the sequence corresponds to that of the contorted till at other bluffs, i.e., unit I at Evilsmelling Bluff and unit N at Island Bluff. Unit I at Lehr Valley, which also is silty and has low sand content, may be an upper and slightly different facies of till unit H, as indicated in Table 2, unit XX.

Unit J represents deposits laid down by small streams since disappearance of the last glacier and also, possibly, by meltwater that flowed along this valley as the last glacier melted.

Table 7 gives some average physical characteristics of the two till sheets found at Lehr Valley.

Table 7. Physical features of the Lehr Valley tills

	Size composition				
	Coarse (>2 mm)	Fine (<2 mm)			Carbonate Content
Unit		Sand	Silt	Clay	Matrix
	%	%	%	%	%
I	2.2	21.4	43.4	35.3	11.3
H	5.5	26.6	43.7	29.7	10.3

Surprise Bluff West: borehole 69-6 (Fig. 13)

Borehole 69-6 was sited between Reservoir Gully and Surprise Bluff West in the expectation that it would synthesize the outcrop sections from those two localities. It failed to do this, however, for the bottom part of the Surprise Bluff West sequence, including the basal preglacial gravel unit (B), was missing, as was also a larger segment of the Reservoir Gully outcrop section. The borehole sequence, therefore, was compared solely with the section exposed at Surprise Bluff West, which is about 0.4 mi (0.6km) away, and borehole 69-7 subsequently was drilled nearer to Reservoir Gully.

The sandy unit shown directly above bedrock in the original borehole interpretation has been subdivided, because of information derived from sidewall samples, into unit C which is clayey silt, unit D which is mostly sand at the base but becomes silty upward, and unit E which in the borehole is practically all silt and clay. These three units undoubtedly represent a sequence of continuous deposition in a deepening lake that may correlate in part, with the lacustrine beds of units D to M at Bain Bluff (Table 2, unit IV).

Unit E apparently corresponds to beds of silt and fine sand that intervene, in the outcrop, between units of coarser material. The upper (unit F) of these two coarse units is mostly silt and gravel composed of fragments of shale and silt torn from the local bedrock, with an admixture of foreign stones up to 5 in. (12.7cm) long. It displays well developed channel bedding. Unit F was called till during the original borehole interpretation. Similar material in unit H at Island Bluff and in unit I at Mitchell Bluff also was called till during the preliminary borehole studies, and it is difficult to devise a practical means of preventing similar errors with such material where outcrops are lacking. Although not a till, unit F does mark the introduction of Shield stones and so heralds the initial approach of Laurentide ice.

The boundary between units G and H marks a change from medium sand beneath to a poorly sorted and strongly channel-bedded mixture of sand, grit and silt above. The thin band shown directly above this boundary in the original borehole log, where it was incorrectly classed as till, probably represents an even more poorly sorted, but largely clay, bed of unit H.

Unit I is a massive, light grey till containing few stones. Sand unit J of the outcrop is lacking at the borehole.

Unit K includes those deposits found between depths of 66 and 93 ft (20.1 to 28.3m). In the original borehole interpretation this interval encompassed one complete till unit, parts of two other till units and a thin sand unit. Obviously, unit K is extremely variable, but overall its characteristics indicate a correlation with the Evilsmelling Band (Table 2, unit XVIII).

The borehole and outcrop sequences are similar through units L to O. Unit L is a dark grey till with the traits of the contorted till and also its normal position of second till from the surface. Unit M has yielded poorly preserved bones and so denotes a significant interval between ice advances. It corresponds to fossiliferous units N and O at the Reservoir Gully site. Unit N is a light grey or brown, sandy till with pronounced columnar structure, and it correlates with the top till found at all other sites except, perhaps, Lehr Valley (Table 2, unit XXII).

Table 8 gives some average physical characteristics of the till sheets.

Table 8. Physical features of the Surprise Bluff West tills

	Size composition				
	Coarse (>2 mm)	Fine (<2 mm)			Carbonate Content
Unit		Sand	Silt	Clay	Matrix
	%	%	%	%	%
N	1.4	46.9	30.4	22.7	8.3
L	2.0	23.9	45.4	30.7	6.3
I	0.4	34.6	37.0	28.4	

Reservoir Gully: borehole 69-7 (Fig. 14)

Borehole 69-7 was drilled when borehole 69-6 failed to pierce much of the Reservoir Gully section. It was sited on the highest ground for a distance of several miles and was as near Reservoir Gully as possible (Fig. 7) The top 80 ft (24.4m) of the section (units N, O, P, Q) could be examined at the gully, but the bottom 30 ft (9.1m) (units A, B, C) could be seen only at Surprise Bluff, about 0.4 mi (0.6km) to the northeast. The middle part was fully covered by slump and vegetation and could not be examined. Shield stones were present in even the lowest unit, and unit C, near the base, yielded abundant bones of Sangamon Age. It thus appears that all six tills reported from the borehole are of Wisconsin Age. This is the greatest number of tills of that age found at any site, and undoubtedly some of them should be combined. In addition, some may be incorrectly classified as till, but it is difficult to determine this with confidence, as was found during the studies of unit H at Island Bluff, unit I at Mitchell Bluff and unit F at Surprise Bluff West. The task is especially difficult here because of the deficiency of exposures.

The thin sand, silt and gravel beds of unit B were not found in the borehole; such a discrepancy is not surprising if one considers how far the borehole is from the outcrop of the lower part of the section. In addition, the greater elevation of bedrock in the borehole than in the outcrop indicates that the lower part of the surficial section is missing.

Unit C consists of poorly sorted sand and gravel, with many angular stones and pieces of coal. Its variable nature results in wide fluctuations in the geophysical logs.

Mechanical analysis of the sidewall samples (Appendix) shows that unit D is mainly a silt and clay such as would be laid down in quiet water. It probably was deposited in a lake ponded by the same glacier that subsequently deposited the till of overlying unit E.

The tills of units E, G and I (Table 2, unit XIII) may represent fluctuations of a single glacier. They are sandy with remarkably low clay content, except for the basal part of unit E which has incorporated much fine material from the underlying silt and clay lake beds. The intervening units F and H are either inclusions of older deposits incorporated into the till of units E, G and I or else merely sandy and silty phases of this till.

The geophysical logs and borehole samples indicate that at a depth of 123 ft (37.5m) unit K is divided into two parts by a fairly sharp boundary. The upper part of this unit is abnormally silty and remarkably deficient in sand for a till of the region, and in many ways it resembles the Evilsmelling Band. If that band is represented in this borehole, it is either here or else includes all of unit K as shown in Figure 14; if the latter is the case, one of the six Wisconsin tills is eliminated from the borehole sequence. Other evidence supports putting Evilsmelling Band here. First, at least part of this unit correlates with unit K at Surprise Bluff West, which previously was tentatively assigned to the Evilsmelling Band (Table 2, unit XVIII). Further, the overlying silt of unit L presumably corresponds to the sediments found at Evilsmelling Bluff (unit H) and at

Table 9. Physical features of the Reservoir Gully tills

Unit	Size composition: Coarse (> 2 mm)	Fine (< 2mm): Sand	Silt	Clay	Carbonate Content: Stones	Matrix
	%	%	%	%	%	%
P	4.9	41.9	31.3	28.6	38	6.7
M	0.4	25.0	47.0	28.0		8.0
K (upper part)	4.0	20.8	51.0	28.2		9.8
K (lower part)	0.9	36.1	36.0	27.9		10.8
I	4.2	40.9	40.5	18.6		10.3
G	3.6	41.3	39.9	18.8		10.4
E (upper part)	1.4	40.9	39.0	20.1		9.0
E (lower part)	0.9	28.9	47.4	29.8		10.7

Lehr Valley (unit G) directly above that Band (Table 2, unit XIX). Therefore, the Evilsmelling Band, if present, must be below unit L, and unit K is the only likely unit.

Unit M is the contorted till (Table 2, unit XX), and it is in the normal position of second till from the surface. This unit probably was once much thicker, but the top part was removed by the streams that deposited the sediments of unit N. In the original borehole interpretation unit M also was assigned the lower 7 ft (2.1m) of unit N, but this segment was reassigned to unit N when grain size analysis demonstrated that it consisted of sand.

The sand and gravel of units N and O are mostly alluvial, and they are strongly oxidized in both outcrop and borehole. This oxidization and replacement with iron oxide has so altered the once abundant plant remains in the unit that no reliable radiocarbon dates have been obtained from it. Bones are abundant, however, although generally they are scattered and much weathered, and these indicate a Classical Wisconsin Age.

Unit P (Fig. 7) is the light brown, sandy till that normally is the top till (Table 2, unit XXII). Its correlation between borehole and outcrop is accurate. Only 38 per cent of the stones are carbonates, and the matrix also is low in carbonate. It appears to be a typical, nondeformed basal till, but despite this has failed to yield a good stone orientation.

Table 9 gives some average physical characteristics of the units classed as tills; only the top till was available for stone counts.

DISCUSSION

General

The relative merits and drawbacks of outcrop and borehole study of surficial deposits are summarized in Table 10 and are discussed below, following the sequence of topics shown in the table. Comparison of the original outcrop and borehole sequences and their syntheses (Figs. 8 to 14) will give insight into the problems that can arise in outcrop and borehole interpretations and into how they may be resolved. It will also give insight as to where and why changes were made during production of the final, modified logs.

The ideal situation for study of surficial stratigraphy would be a complete, readily accessible and nearly vertical outcrop that is fresh, undeformed and free of vegetation and slump. With such ideal conditions at an outcrop, drilling would be superfluous; but unfortunately such outcrops are rare. The other extreme is to have no outcrop at all, and in such a case drilling must be the source of information; a typical example of the latter case would be a deep valley, carved into bedrock, that had been so completely filled with debris that it could no longer be recognized on the surface. The following discussion is based on a more common situation, such as exists in the Medicine Hat region, where outcrops range in quality from the poorly exposed beds at Reservoir Gully to the well exposed section at Island Bluff. Not all the relative advantages or disadvantages of borehole or outcrop study described apply at any one site. In addition, many of the relative merits or drawbacks are self-evident and need not be discussed in detail.

If the beds are near horizontal, as is normal with surficial deposits, depths and thicknesses are measured more rapidly and efficiently in a vertical borehole than in an outcrop, largely because most outcrop faces slope unevenly and commonly are obscured by slumping, faulting and vegetation. Although the beds are normally horizontal however, this cannot be assumed with certitude in a borehole; and if the beds dip steeply, the measured thickness in a borehole may be much exaggerated. The best situation exists where the attitude of the beds can be determined in the outcrop, the thickness measured in the borehole, and the necessary corrections made for any dip present. In general, borehole study has a marked advantage in anything pertaining to measurement of depth or thickness, and therefore this item is not discussed under the individual topics: it mainly affects topics 2a, 3c, 5, 6, 7a, 7b and 7d of Table 10.

Location of Study

Factors associated with selection of a drilling site or discovery of a suitable outcrop were not a major concern of this study. Accessibility or location, however, is definitely an extremely important consideration. In general, finding a satisfactory outcrop requires more time but less money than selecting and drilling a suitable borehole site. However, good outcrops are rare; they seldom occur where the section is best; and they typically only reveal a part of the surficial section with important beds or units missing. This is well shown at many of the Medicine Hat sites. Boreholes, on the other hand, can be sited almost anywhere, and at times they may be prior indications of the best site to drill. For example, previous surface geophysical studies or examination of the topography may eliminate areas of shallow bedrock or else may indicate areas with thick drift — perhaps even the ideal situation of a deep, buried valley. Nearby outcrops or records of previous boreholes drilled in the region also may suggest good locations. But usually it is impossible to foretell whether a borehole site is a significant or favourable one, and even after drilling it remains problematical whether the best location was drilled. As a result, drill sites must be chosen in a largely haphazard manner.

Section

A borehole gives a more complete and trustworthy record of the sequence and thickness of deposits than is presented by a typical outcrop, and this alone could be sufficient reason for drilling near an important outcrop. For example, the surficial material commonly extends deeper than the outcrop, and much of the rest of the section may be overgrown or just not exposed. In addition, outcrops on cliffs or steep slopes are prone to slumping and to deformation, thus rendering the sequence and thickness of beds difficult to ascertain. All of these problems are illustrated by the Medicine Hat Bluffs. For example, in five of the seven bluffs described above, surficial material extended below river level; large parts of the sections at Bain, Mitchell and Evilsmelling bluffs were covered by slump; large parts of the

sections at Reservoir Gully and Surprise Bluff West were hidden by vegetation; and much of the section at Lehr Valley just was not exposed. A steep face, as at Evilsmelling Bluff, also can render part of an outcrop inaccessible.

A borehole study avoids the above drawbacks, for the borehole can be drilled through the full section and, if drilled far enough back from the cliffs, can avoid some of the slumping and faulting. Large inclusions and intense deformations, however, do cause difficulties (see Deformation).

Distribution of Beds and Units

This topic, which deals mostly with lateral or vertical variations in the sequence, points out some of the chief deficiencies of borehole stratigraphy. Any outcrop of at least moderate extent offers some view of the continuity of the beds represented locally, whether they vary in thickness or even disappear in places, whether locally they are repeated, and whether lenses and large inclusions of different materials are present. On the other hand, such features are difficult to determine in a borehole where, for example, a large inclusion in a till sheet readily could be mistaken for a separate bed or unit, causing the till unit to be incorrectly interpreted as two separate till sheets. This may have happened with the interpretation of the borehole at Reservoir Gully (Fig. 14). Though the similarity of the till above and below the inclusion might raise doubts as to whether two separate tills were actually present, this problem could not be resolved in a borehole. Similarly, a bed could be missing in a borehole, or doubts might again arise concerning slumping and faulting. At present no methods of overcoming these difficulties in interpreting borehole information, other than drilling of additional holes, can be suggested.

Material

Determination of the lithology of the beds, although in itself insufficient for stratigraphic purposes, is the most important facet of a study for it forms the basis of all other investigations. Lithology is readily determined in outcrops and generally can be determined in boreholes. The items discussed below, however, do cause difficulty in borehole studies, although most of the problems can be resolved through careful study of well selected samples.

Geophysical logs do not necessarily discriminate between clay, silty clay and silt (4a, 4b of Table 10) on the one hand and till, fine material in bedrock inclusions, or beds formed of coarse but weakly indurated fragments from older beds of clay or silt on the other. Such fine materials, however, generally yield sidewall samples adequate for making the necessary distinctions. For example, samples from even the most clayey till usually contain a few extraneous grains of sand, which are not found in most of the lake clays and silts. In addition, the size gradation and fine, horizontal lamination found in most quiet lake deposits commonly are preserved in the samples and offer an even more reliable method for this distinction and also a method for separating fine alluvium from till. The crossbedding, current ripples, imbrication and general variableness of the fine alluvium also serve to distinguish it from lake deposits. The very low carbonate content of the bedrock in the Medicine Hat area, as compared with the significant amount in the surficial deposits (Appendix), offers another means of distinguishing bedrock inclusions from the till, alluvium, and lake deposits. Presence of Quaternary pollen also indicates that a deposit is not bedrock; however presence of older pollen, - near Medicine Hat generally of Cretaceous age - does not necessarily denote bedrock, for the Quaternary deposits contain much pollen picked up from older deposits.

Sand or gravel deposits (4c, 4d of Table 10) composed of fragments of largely incoherent clay or silt from older beds (Table 2, units VIII and X) are found in unit H at Island Bluff, unit I at Mitchell Bluff and unit F at Surprise Bluff West. Such materials are extremely difficult to separate from lake or alluvial clays. Not only do their sand and gravel fragments disintegrate readily during treatment for size analysis, but their carbonate content resembles that of the other deposits. Visual examination of fresh sidewall samples should disclose the fragmented, discontinuous nature of the sediment, but usually outcrop studies are necessary for reliable separations.

No attempt was made to separate loess from water deposited silt; size analysis would be the best, although not infallible, means of doing this. Coarse, loose sand commonly is difficult to collect in sidewall samples, but usually its presence can be determined from geophysical logs. Differentiating between gravel and coarse sand presents problems because both are difficult to obtain in sidewall samples and both give similar geophysical readings. Grab samples obtained during the original drilling, along with the roughness and degree of difficulty of drilling through gravel, offer the best methods of distinguishing between the two.

Volcanic ash (4e of Table 10) outcropped only in the recent deposits at Island and Bain bluffs, where it was recognized easily by its brilliant whiteness and gritty feel. It probably was not present in any of the boreholes, but even if it were, it would be difficult to recognize unless a sample was taken fortuitously from it. On geophysical logs it generally would be interpreted as silt or fine sand, if sufficiently thick to be detected.

Organic material (4f of Table 10), such as peat and carbonaceous clay, is perceived readily in outcrop and sidewall samples but is difficult to recognize in geophysical logs. Normally it is discerned during the drilling. Particular difficulty arises where organic material is finely disseminated through other material; this was a major problem in recognizing all occurrences of the Evilsmelling Band (Table 2, unit XVIII). Even in outcrop that band was discovered through its odoriferous weathered product rather than through the carbonaceous component of its unweathered part. Mainly due to their thinness soils, too, are difficult to recognize in a borehole but their colour makes them conspicuous in an outcrop. On the other hand, thick oxidized zones are recognized more readily in a borehole, where they are distant from the surface weathering that obscures them on an outcrop face.

In boreholes, certain mixtures of material (4g of Table 10) also are difficult to interpret, one example being the Evilsmelling Band mentioned above. At Evilsmelling Bluff, Surprise Bluff West, Lehr Valley and Reservoir Gully this band was first called till, and in no locality was its true nature perceived directly from the borehole, even with the aid of good sidewall samples. Only information obtained from nearby outcrops permitted its identification, which still remains somewhat uncertain in the boreholes, and further occurrences of it still may be unrecognized.

Stony alluvium is also difficult to identify, especially if it is crossbedded and consists of thin beds of different sized materials. Thus the bottom and top parts of alluvial unit I at Mitchell Bluff and unit F and part of unit H at Surprise Bluff West originally were called tills in the borehole logs, whereas part of unit I in the borehole at Island Bluff, now classed as till; and one or more of the units classed as till in the borehole at Reservoir Gully may, in reality, be alluvium. Even with good sidewall samples, no sure method can be suggested for determining, from boreholes, whether such materials are till or alluvium.

The recognition of tills is most important, for only they can substantiate the former presence of a glacier. Unfortunately, in boreholes till commonly is the most difficult material to separate from certain other deposits; some of the difficulties have been described previously in the discussions of some of those other deposits.

*Table 10. Relative advantages of outcrop and borehole investigations of surficial deposits**

Reference number	Topic	Outcrop	Borehole	Comments
1	Location of study	Predetermined; random and not necessarily in best place	At any location accessible to equipment, random selection unless topography, outcrop or earlier drilling indicates suitable site	Drilling more filexible as regards site location
2	Section			
	(a) completeness	Full section rarely exposed	Full section accessible	Borehole superior
	(b) sequence of beds	Normally manifest	Well defined	In most cases the borehole is superior
	(c) access	Parts of outcrop may not be accessible	Full section accessible	Borehole much superior
3	Information on distribution of beds and units			
	(a) lateral	Provided for local area	Not disclosed	Outcrop much superior
	(b) continuity	Disappearance or lensing of beds indicated	Not disclosed, may miss beds present elsewhere in area	Outcrop much superior
	(c) thickness	Commonly difficult to measure. Variability displayed, and studies can be made where suitable thickness present	Easily measured, but variations not indicated	Both outcrop and borehole have advantages and disadvantages
4	Material			
	(a) clay	Readily recognized	Readily recognized	No marked advantages to either outcrop or borehole
	(b) silt	Readily recognized	Readily recognized	
	(c) sand	Readily recognized	Readily recognized, but sand and gravel may be difficult to separate on geophysical logs	Outcrop generally superior
	(d) gravel	Readily recognized		
	(e) volcanic ash	Readily recognized	Thin beds commonly missed, samples generally necessary for recognition	Outcrop superior
	(f) organic beds	Readily recognized	Recognized only in samples	Outcrop superior
	(g) mixtures	Readily recognized	Commonly difficult to interpret	Outcrop superior
5	Samples	Readily collected in any quantity at selected sites; carbonate content may be affected by surface weathering; sampling slow	Small, can be collected at depths selected by geophysical logs; coarse material difficult to sample; easy to collect samples for carbonate and size analyses; sampling rapid	Both outcrop and borehole have advantages and disadvantages

6	Fossils	If present, readily collected in any quantity at selected sites; however, they may be damaged by surface weathering, and pollen may be destroyed by oxidization	Discovery only by chance, and only small fossils can be collected, but depth of sample can be determined accurately; pollen samples commonly of good quality generally difficult to obtain sufficient material for radiocarbon dating	Outcrop generally much superior
7	Structure			
	(a) contacts	Position, type, strike, dip, and continuity of contact generally can be determined	Position and type of contact generally indicated, but its strike, dip, continuity and any contortion rarely revealed	Outc. p superior
	(b) lenses, inclusions	Revealed	Easily mistaken for separate beds	Outcrop superior
	(c) joints, fissility	Revealed	Not indicated	Outcrop superior
	(d) bedding	All types can be studied	Gross bedding normally revealed, cross bedding and laminations indicated only in sidewall samples of fine material	Outcrop superior
	(e) imbrication	Revealed	Not revealed	Outcrop superior
	(f) fabric	Orientation and other studies possible in many cases	Orientation studies generally impossible	Outcrop much superior
8	Deformation			
	(a) slumps	Well displayed	Not recognized, may be interpreted as separate units	Outcrop much superior
	(b) faults	Well displayed	Generally mistaken for contact	Outcrop superior
	(c) folds and contortions	Well displayed	Generally not recognized	Outcrop much superior
9	Origin of unit	Can be determined in most cases	Generally can be assumed correctly	Outcrop generally superior
10	Age of unit	Can be determined in some cases by fossils, direct dating, or by correlation with units of known age	In some cases can be determined by direct dating or by correlation with units of known age	Outcrop much superior

* The assessment is based on an outcrop with moderately steep face that has undergone moderate surface weathering, slumping and plant growth, and on a single, well placed borehole logged by equipment similar to that used in this study.

Samples

The only samples taken from boreholes were sidewall samples and the driller's original grab samples; the sidewall samples were used for size and carbonate analyses, and to a limited extent for pollen studies. On the other hand, numerous samples for multiple purposes were taken from outcrops. For sampling, both outcrops and boreholes have advantages and disadvantages.

At an outcrop, samples of any desired size can be collected from a broad, lateral expanse, and both the best beds and the best spots in them for sampling chosen. Oriented samples can be obtained as required. The samples, however, may have been disturbed by surface movement, plant roots, burrowing animals, desiccation or addition of water, weathering and oxidization, and also the exact original position of the material sampled may be uncertain. A borehole avoids most of the above pitfalls, for in it the materials are protected from surface disturbances and climatic effects, the material is generally in its original state, and the correct positions of the samples are known. Also, being distant from any weathered face causes the samples to be better, for many purposes, than the corresponding outcrop samples. This is a major consideration when sampling for carbonate and pollen studies. Further, the samples are obtained more rapidly than at an outcrop, and their depths more easily determined.

Sampling in a borehole, however, has its limitations, some of them severe. First, thin but important bands, such as beds of volcanic ash and buried soils, may not have been noted during drilling and thus not sampled, unless accidentally. Such beds normally are conspicuous and easily sampled at an outcrop. To this is added the frustration of never knowing with certainty whether such beds were present. Further, it is difficult to decide where to sample, for selection can only be made on the basis of the geophysical logs and the driller's original grab samples. In this study, sites just below and above either contacts or marked variations in the logs usually were chosen, along with samples taken at regular, generally 5 ft (1.5 m), intervals. Another severe handicap for some purposes is the restricted size of the individual sample, which is controlled by the size or length of the sampler and the diameter of the borehole. This was not a major handicap in the present study, for generally enough material was obtained for the analyses desired. Another drawback is the difficulty of obtaining oriented samples, such as might be desired for paleomagnetic or microfabric studies. There is also the problem of sampling certain loose materials, such as coarse sand and gravel, which rarely yield samples adequate for study of structures and other details.

Fossils

The advantages of an outcrop over a borehole are perhaps more obvious for paleontology, and particularly for vertebrate paleontology, than for any other facet of study. At an outcrop the most prolific site can be selected; and if fossils are present, as many specimens as desired can be collected.

Some paleontological sampling, of course, can be done in a borehole. Bands with carbonaceous material, especially plant remains, may show up during drilling, and careful sampling, perhaps by taking several samples from the same horizon, may amass sufficient material for radiocarbon dating (Wyder, 1971, p. 267). In addition, samples obtained from a borehole generally are less affected by modern weathering and oxidization than those collected from near the face of an outcrop, and this helps preserve the pollen and is an advantage for the study of microfossils. On the other hand, little macrofossil work can be done at boreholes.

Structures

The structures referred to here include contacts, lenses and inclusions, joints, dips, current and ripple bedding, cross-bedding and channelling forms, fabrics, imbrication of stones and the ratios of various types of stones, fine laminations, presence of thin beds and stringers, and deformation of any type. At an outcrop most of these items can be studied, commonly with fair ease, permitting conclusions to be drawn as to origin of the beds, method of deposition and direction of movement of the depositing agent.

Conditions are much less auspicious with a borehole, where most details about structure go unrecognized. Generally little is revealed about jointing, folding and deformation, imbrication, strikes, dips, continuity of the beds, or about lenses and inclusions; in fact large lenses and inclusions easily can be mistaken for separate beds. Coarse crossbedding and channel bedding normally go unrecognized, and macrofabric studies and stone counts are impossible to perform if one has to rely solely on geophysical logs and sidewall samples. To obtain samples adequate for such studies, methods of sampling other than those used in the present study, such as split spoon or drive sampling, are necessary. On the other hand the borehole logs usually do show the position and type of contact and whether it is sharp or gradational, while the sidewall samples normally will indicate an absence of bedding, as in tills, or show the fine laminations, thin varves and fine crossbeds or ripple marks found in many deposits of other origins. In general, this inability to recognize many of the structures is a major disadvantage in borehole studies, making it very difficult to determine the origin of many beds, their method of deposition, their source of material and the direction of movement of the depositing agent.

Deformation

Only rarely can deformation in beds and units be recognized in a borehole, and duplication of beds caused by slumping can readily be mistaken for separate units. Similarly, a fault commonly would be mistaken for a contact. There are exceptions, for example the contorted till (Table 2, unit XX) did reveal its inconsistancy in boreholes, but only after its presence at a nearby outcrop or its expected presence at a predetermined position in the sequence had induced a careful search for it in the logs. At an outcrop, on the other hand, slumping, faulting and folding are readily recognized, if only because of the difficulties they cause in studying the sections.

Origin of Unit

Whether a bed was laid down in a lake, by a glacier, by a river, or by wind, sliding or slumping usually can be determined at an outcrop. In a borehole the origin cannot be ascertained directly, and in many cases the origin must remain uncertain; this was the case with several units in the study. Even in a borehole, however, the origin generally can be determined from the lithology and sorting of the material, although mistakes cannot be avoided. Errors have mostly to do with recognition or misrecognition of tills, as shown by the common misidentification of the Evilsmelling Band (Table 2, unit XVIII) as till and probably similar misidentifications of alluvium.

Age of Unit

The age of a bed or unit is difficult to determine either in outcrop or borehole, but particularly in the latter. On rare occasions in a borehole it can be decided directly through radiocarbon dating or using microfossils. Normally, however, it can be found only by correlation with beds of

recognized age found elsewhere, generally in outcrop, and such correlations often are doubtful. During the drilling at Medicine Hat not one bed could be dated directly, and ages could only be suggested by rather tenuous correlations.

All methods employed in boreholes, and many others besides, can be used in outcrops, and often to much better advantage. As a result, correlations between outcrops are much more trustworthy than correlations between boreholes or between an outcrop and a borehole. If paleontological evidence is used, outcrops generally supply better means of correlation, although the abundance of vertebrate fossils at Medicine Hat is very unusual. Ash bands in outcrops, if they can be dated directly or correlated with ash bands or volcanic flows of known age found elsewhere, are another valuable aid to dating or correlation. If the bands are thin, they rarely are recognized in boreholes.

Illustrations

The following descriptions illustrate the role played by borehole study in solving some problems raised by the outcrop stratigraphy at Medicine Hat. They also indicate some of the difficulties that arose in combining the outcrop and borehole sequences.

Discrepancies

The deposits at Island Bluff (Fig.8) were well exposed, and the geophysical logs and the sidewall samples obtained from the borehole were of good quality. Nevertheless, discrepancies appeared between the original outcrop and borehole sequences. In particular, each sequence had one till unit not found in the other. In the original borehole interpretation units K and L were combined into one till unit, but in the outcrop sequence they appeared as discrete units separated by a thin silt band. Re-examination of the outcrop confirmed that they were, indeed, separate till sheets with marked differences in dolomite content, stone content and direction of movement of the depositing glaciers, although they were similar in appearance and in sand, silt and clay ratio. In this case the tills could not have been separated solely by borehole information. In the outcrop, on the other hand, it was difficult to reach satisfactory divisions for the interfingered till, sand and clay beds of unit L, M and N. Here the geophysical logs and mechanical analyses enabled the contacts to be established in a satisfactory manner, and the final composite sequence uses the borehole divisions for this part of the sequence.

The outcome, therefore, after re-examination of the outcrop with all available information on hand, was to incorporate the extra divisions of each sequence. As a result, the composite section shows a total of five till units, in lieu of the four shown by each sequence separately.

Misidentification of Beds

Misidentification of a bed during the original borehole interpretation is best illustrated by the Evilsmelling Band (Table 2, unit XVIII). The difficulty of identifying that band at each occurrence has been discussed already (see discussion on Evilsmelling Bluff, Lehr Valley, Surprise Bluff West, Reservoir Gully; 4f of Table 10). Even at its type locality (Evilsmelling Bluff), where its presence and approximate location in the sequence were known, the band was extremely difficult to locate in the borehole log, and it still may be incorrectly positioned there.

Solution of Stratigraphic Problems

A major reason for drilling the Lehr Valley borehole (69-5) was to determine when South Saskatchewan River excavated and used that valley as its main channel, and the number of glaciations since that excavation. Previous study of nearby exposures had not resolved these points satisfactorily. The borehole revealed two tills in the valley fill (Fig. 12, units H, I), both of which correspond to unit N at Island Bluff, unit L at Mitchell Bluff, and units I and J at Evilsmelling Bluff (Table 2, unit XX). As those units are interpreted as Classical Wisconsin in age, the valley apparently was in use and probably was incised during mid-Wisconsin time. The number of glaciations since incision of the valley, however, remains uncertain, for if the above correlations are correct, and admittedly they are highly tenuous; the higher till unit P at Island Bluff, unit N at Mitchell Bluff, unit K at Evilsmelling Bluff, unit N at Surprise Bluff West and unit P at Reservoir Gully (Table 2, unit XXII) is missing from the Lehr Valley sequence. Possibly the final Wisconsin ice advance, which left that upper till elsewhere, failed to deposit it in the valley, or else it was removed when meltwater from the last glacier flowed down the valley. On the other hand, the correlations could well be wrong; and an older Classical Wisconsin till, perhaps the one corresponding to unit I at Evilsmelling Bluff and units K or L at Island Bluff, could be the one that is missing. No matter how the tills correlate, however, the Evilsmelling Band (unit F) is a good marker horizon. At Evilsmelling Bluff, where it is unit G, it has yielded radiocarbon dates of 28 630 ± 800 years B.P. from near the base of the unit (GSC-578; Lowdon et al., 1967), 25 000 ± 800 years B.P. from about 5m higher (GSC-1370; Lowdon et al., 1971), and 24 490 ± 200 from near the top (GSC-205; Dyck et al., 1965). The presence of this unit below the lowest till at Lehr Valley, therefore, reinforces the conclusion that the valley was incised before Classical Wisconsin time. Thus, even though it has not indicated the number of glaciations since incision of Lehr Valley, the borehole did show that the valley was excavated fully by the end of the mid-Wisconsin.

Borehole Capabilities

The potentialities and limitations of borehole stratigraphy are well illustrated by the studies at Bain Bluff (Fig. 11). Cursory examination of the poorly exposed outcrop in the field and study of it from a distance had indicated that the part below the lowest till was largely bedrock. However, the borehole went through a thick section of clay and silt that carbonate tests showed was not bedrock, a result confirmed when the hole reached coarse, preglacial gravel below the level of South Saskatchewan River. Without the drilling, most of the section below the lowest till would have remained unstudied and unknown, and certainly the deposits lying below river level could not have been reached by other means. In addition, the borehole gave a complete section through the tills that could not have been obtained solely through study of the outcrop.

On the other hand, the borehole did not yield a means of determining the age of those deposits it had disclosed, and correlations with outcrops found elsewhere were the only basis for estimating ages of units B, C, U and V at Bain Bluff. The ages of the thick clay and silt deposits and the lowest tills there (units D to T) still can only be assumed and will be determined only when they can be studied in outcrop.

CONCLUSIONS

Although the results of the study apply specifically to the region around Medicine Hat, many of the findings undoubtedly can be applied elsewhere, especially to studies conducted in other parts of the Canadian Prairies. The major conclusions from the study follow.

1. Properly conducted borehole investigations are a generally accurate and powerful tool for the investigation of surficial deposits.

2. As many different methods of logging and study as are practical should be used to enable the cross-checking of results.

3. Sidewall samples are a valuable method of obtaining information from boreholes; and in many cases they, or samples obtained by other methods, are necessary for the correct interpretation of geophysical logs.

4. Borehole and outcrop studies are complementary, and neither can entirely replace the other. Each yields information not obtainable or not readily acquired by the other method; if possible, each method of investigation should be checked by the other.

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APPENDIX
GRAIN SIZE ANALYSES AND CARBONATE CONTENT

Grain size and carbonate content analyses were made on all suitable sidewall samples obtained from the seven boreholes. Each sample is identified by borehole depth. The results are given in weight percentage of dry material, inclusive of carbonates and humus. Fraction division are:

Coarse	> 2 mm
Sand	2 to 0.063 mm
Silt	0.063 to 0.0039 mm
Clay	< 0.0039 mm

The unit reference letters are the same as those used throughout the text.

Sample depth	Unit	Grain size analyses*				Carbonate analyses*		
		Coarse (>2 mm)	Fraction (<2 mm)					
			Sand	Silt	Clay	Calcite	Dolomite	Total
ft					%			
Island Bluff (borehole 69-1)								
4	Q	0.0	82.13	9.10	8.77	1.7	0.0	1.7
6		3.4	53.10	23.90	23.00	1.6	2.4	4.0
8		0.5	90.60	4.30	5.10	0.0	5.2	5.2
10	P	7.0	38.51	35.01	26.48	2.0	7.4	9.4
15		20.2	47.63	28.62	23.75	1.9	7.4	9.3
20		1.4	43.16	32.06	24.78	2.0	5.1	7.1
25		0.5	43.68	32.92	23.40	1.8	4.4	6.2
30		4.5	44.36	32.15	23.49	1.4	4.7	6.1
35		0.3	32.42	37.85	29.73	3.9	7.7	11.6
40		4.9	42.48	35.57	23.95	3.8	3.6	7.4
45	O	0.0	81.49	8.73	9.78	6.2	5.4	11.6
50	N	0.5	33.14	37.81	29.05	2.1	7.2	9.3
55		1.0	32.64	34.58	32.78	2.3	5.9	8.2
60	M	32.0	90.06	4.90	5.04	-	-	-
65		0.1	13.45	39.68	46.87	2.2	2.4	6.6
70	L	1.2	27.09	32.75	40.16	-	-	-
75		2.3	20.37	36.79	42.84	2.4	4.7	7.1
80		1.2	22.29	52.49	25.22	2.6	3.6	6.2
85	K	0.9	0.00	67.26	32.74	3.1	7.4	10.5
90		0.0	34.96	28.26	36.78	2.2	7.6	9.8
95		0.5	15.21	49.46	35.33	4.8	8.3	13.1
100		0.1	23.68	42.21	34.11	2.3	8.8	11.1
105		6.7	36.49	28.27	35.24	2.3	7.9	10.2
110		0.3	15.23	48.49	36.28	2.7	7.7	10.4
115		0.0	14.70	50.02	35.28	2.6	6.5	9.1
120	J	0.7	28.85	42.34	28.81	5.2	5.8	11.0
125	I	0.6	18.86	44.57	36.57	3.2	6.4	9.6
130		0.1	16.81	43.18	40.01	4.4	4.0	8.4
135		1.8	15.12	49.77	35.11	4.4	13.0	17.4
140		1.1	19.15	41.79	39.06	2.8	17.0	19.8
145		0.0	16.88	46.87	36.25	2.4	5.9	8.3
150		0.0	14.98	49.84	35.18	2.0	7.6	9.6
155		0.1	15.20	47.95	36.85	1.9	7.4	9.3
160		0.3	16.81	49.47	33.72	3.6	5.0	8.6
163		0.0	17.33	49.42	33.25	3.8	4.0	7.8
164		0.3	14.41	51.22	34.37	4.0	11.4	15.4
165		0.4	14.94	47.35	37.71	-	-	-

* Results of grain size analyses, and carbonate analyses are given in weight percentage of dry material.

Sample depth	Unit	Grain size analyses: Coarse (>2 mm)	Fraction (<2 mm): Sand	Silt	Clay	Carbonate analyses: Calcite	Dolomite	Total
ft					%			
Island Bluff (borehole 69-1) continued								
170	H	0.4	62.98	14.78	22.24	--	--	--
174		1.0	57.20	23.16	19.64	3.4	3.3	6.7
177		0.0	78.20	12.83	8.97	3.7	5.3	9.0
180		0.0	10.17	66.64	23.19	3.5	4.2	7.7
182		0.0	28.48	51.02	20.50	3.2	8.7	11.9
185	G	0.3	85.56	7.26	7.18	6.0	2.8	8.8
190		4.1	84.47	6.96	8.57	--	--	--
193		0.0	83.35	8.04	8.61	4.9	3.8	8.7
195		0.0	87.85	5.84	6.31	--	--	--
199		0.0	84.50	8.82	6.68	3.4	12.0	15.4
201.5		0.0	83.10	8.83	8.07	6.8	7.2	14.0
205		0.0	86.90	7.87	5.23	3.8	5.8	9.6
210		0.2	58.74	26.09	15.17	3.4	6.0	9.4
215		0.0	78.71	7.10	14.19	5.2	6.6	11.8
220		0.0	70.36	14.96	14.68	4.4	22.8	27.2
225		0.0	48.01	26.70	25.29	2.4	4.4	6.8
230	F	11.0	50.04	17.62	32.34	5.6	8.0	13.6
236	E	0.0	60.64	28.31	11.05	3.2	6.3	9.5
237		0.0	56.76	24.88	18.36	2.8	4.6	7.4
240		0.0	36.13	45.90	17.97	2.2	5.2	7.4
246		0.0	53.63	28.72	17.65	1.8	5.3	7.1
250		0.0	78.95	11.73	9.32	6.6	6.9	13.5
255	D	0.0	83.78	10.77	5.45	3.6	3.0	6.6
261		0.0	53.54	17.51	28.95	4.8	8.4	13.2
265		0.9	55.85	24.22	19.93	2.8	10.3	13.1
270		0.0	51.49	19.19	29.32	--	--	--
275	C	1.3	55.93	16.91	27.16	3.0	5.0	8.0
276		11.1	59.95	20.66	19.39	1.8	2.4	4.2
277		0.3	--	--	--	4.0	4.4	8.4
278	B	41.6	44.13	25.01	30.86	0.2	3.5	3.7
299	A	0.2	8.28	29.08	62.64	3.2	3.6	6.8
Mitchell Bluff (borehole 69-2)								
5	O	46.1	87.52	5.30	7.18	--	--	--
10	N	0.1	41.24	32.52	26.24	2.4	6.3	8.7
15		13.4	42.46	30.23	27.31	2.8	3.2	6.0
20		0.8	42.42	31.34	26.24	1.9	7.5	9.4
25		2.0	44.96	31.05	23.99	--	--	--
30		3.0	47.84	27.81	24.35	1.8	6.0	7.8
35		0.4	44.38	31.32	24.30	3.0	4.2	7.2
40		0.3	41.54	33.10	25.36	1.7	6.3	8.0
45		0.9	44.53	28.86	26.61	4.0	4.4	8.4
50	M	0.0	7.27	63.79	28.94	3.8	5.2	9.0
55	L	0.5	28.69	46.79	24.52	2.7	8.1	10.8
60		0.9	27.40	49.38	23.22	3.3	6.8	10.1
65		3.2	38.69	36.20	25.11	3.0	9.3	12.3
70		3.9	32.78	44.40	22.82	2.6	4.5	7.1
75		2.2	29.61	41.25	29.14	4.0	7.8	11.8
80		0.5	29.14	35.50	35.36	2.3	8.9	11.2

Sample depth	Unit	Grain size analyses: Coarse (>2 mm)	Fraction (<2 mm): Sand	Silt	Clay	Carbonate analyses: Calcite	Dolomite	Total
ft					%			
Mitchell Bluff (borehole 69-2) continued								
85	J	1.2	18.41	42.46	39.13	2.4	3.8	6.2
90		0.7	15.74	48.52	35.74	2.8	6.4	9.2
95		0.0	15.75	49.13	35.12	4.0	6.6	10.6
100		0.9	19.46	44.83	35.71	2.1	6.4	8.5
105		0.9	16.18	47.85	35.97	3.6	3.5	7.1
110		0.3	14.76	48.65	36.59	3.4	6.8	10.2
115	I	5.8	31.43	34.75	33.82	3.1	12.9	16.0
120		1.2	27.29	38.70	34.01	3.0	8.8	11.8
125		0.0	79.60	9.68	10.72	4.8	4.4	9.2
130		1.4	27.08	37.95	34.97	3.0	9.1	12.1
135	H	0.0	55.20	28.27	16.53	2.4	7.8	10.2
140		0.0	58.73	25.20	16.07	4.2	4.6	8.8
145	G	6.7	34.82	15.08	50.10	--	--	--
150	F	0.0	71.90	14.72	13.38	4.0	5.8	9.8
160		0.0	60.93	17.91	21.16	--	--	--
170		0.0	87.17	5.86	6.97	--	--	--
180	E	23.0	66.59	19.78	13.63	5.6	6.4	12.0
189	D	23.6	59.23	23.47	17.30	3.2	4.0	7.2
190		13.4	68.17	19.45	12.38	2.6	6.2	8.8
195	C	8.7	41.81	38.31	19.88	3.4	3.4	6.8
200		0.0	69.01	15.73	15.26	4.8	8.4	13.2
205		21.2	53.20	24.09	22.71	6.6	2.8	9.4
210		0.0	63.33	19.44	17.23	2.1	6.5	8.6
214	B	15.7	46.00	23.05	30.95	5.8	3.3	9.1
225		20.7	62.97	21.00	16.03	1.7	1.3	3.0
226		0.0	17.88	56.84	25.28	2.9	0.9	3.8
235	A	0.0	26.20	41.70	32.10	1.2	1.5	2.7
240		0.0	7.64	49.65	42.71	2.0	11.6	13.6
Evilsmelling Bluff (borehole 69-3)								
10	K	0.5	32.83	37.75	29.42	1.6	3.9	5.5
20		0.1	41.24	31.23	27.53	2.0	4.6	6.6
30		1.9	42.59	30.49	26.92	2.4	3.8	6.2
40		2.1	45.30	27.70	27.00	1.9	5.9	7.8
50		2.1	44.31	29.00	26.69	2.0	8.6	10.6
60		0.4	27.69	44.64	27.67	2.7	7.2	9.9
70	J	1.8	36.49	35.05	28.46	--	--	--
80	I	3.0	32.43	34.57	33.00	2.3	8.9	11.2
90		4.9	21.94	41.74	36.32	3.6	4.9	8.5
100		0.0	19.01	44.19	36.80	2.1	6.4	8.5
110		0.0	15.88	46.22	37.90	3.4	6.8	10.2
120	H	0.5	7.85	41.61	50.54	2.9	4.3	7.2
130	G	0.1	15.47	48.38	36.15	3.0	9.1	12.1
140		0.3	16.98	39.76	43.26	2.4	5.0	7.4

Sample depth	Unit	Grain size analyses: Coarse (>2 mm)	Fraction (<2 mm): Sand	Silt	Clay	Carbonate analyses: Calcite	Dolomite	Total
ft					%			
Evilsmelling Bluff (borehole 69-3) continued								
145	F	0.0	86.31	7.32	6.37	6.0	3.2	9.2
150		0.0	14.00	61.41	24.59	3.8	7.9	11.7
153		0.0	14.38	62.51	23.11	2.0	4.7	6.7
156		0.0	91.86	3.73	4.41	4.8	4.8	9.6
159		0.2	88.40	4.22	7.38	--	--	--
162		0.0	84.59	10.68	4.73	4.6	5.2	9.8
165		0.0	76.99	13.45	9.56	3.2	6.5	9.7
168		0.3	91.83	2.94	5.23	--	--	--
196		0.0	95.35	1.54	3.11	--	--	--
210	E	0.0	24.46	31.87	43.67	4.6	7.4	12.0
230	D	41.7	78.25	10.80	10.95	--	--	--
240	B	8.2	37.27	40.41	22.32	4.9	1.4	6.3
250	A	0.0	5.81	33.72	60.47	--	--	--
260		2.7	6.21	30.70	63.09	--	--	--
Bain Bluff (borehole 69-4)								
5	V	0.0	92.13	3.01	4.86	3.2	3.6	6.8
8		0.0	85.61	7.28	7.11	17.6	3.3	20.9
12		0.0	28.25	53.33	18.42	2.1	3.3	5.4
15		0.0	32.04	55.74	12.22	1.4	3.1	4.5
20		0.0	31.91	47.97	20.12	2.5	4.2	6.7
23		0.0	28.58	51.27	20.15	0.5	1.6	2.1
25		1.5	50.31	36.57	13.12	2.4	3.5	5.9
30		2.1	41.81	31.85	26.34	1.9	3.9	5.8
32		1.2	47.83	29.91	22.26	1.6	2.4	4.0
35	U	9.0	42.42	30.62	26.96	1.9	5.8	7.7
40		0.6	47.44	29.96	22.60	1.4	5.1	6.5
45		8.3	46.44	30.46	23.10	2.0	4.3	6.3
48		11.5	41.23	34.91	23.86	1.3	3.7	5.0
50		1.0	46.28	25.90	27.82	2.1	5.0	7.1
56	T	3.1	33.80	36.88	29.32	4.2	11.4	15.6
60		1.4	42.35	33.00	24.65	2.1	8.0	10.1
65		7.6	45.27	34.69	20.04	1.6	3.5	5.1
70		6.3	42.06	32.86	25.08	2.2	8.0	10.2
75		1.1	40.86	33.12	26.02	2.6	8.5	11.1
80		2.4	42.20	32.01	25.79	2.6	9.2	11.8
85		9.2	41.90	32.55	25.55	2.2	8.9	11.1
90		0.6	42.53	32.58	24.89	1.8	7.5	9.3
95	S	13.2	34.80	33.70	31.50	3.3	8.6	11.9
100		14.8	35.78	33.79	30.43	3.0	10.7	13.7
105	R	3.5	43.98	28.06	27.96	1.2	3.5	4.7
110	Q	2.2	29.14	39.07	31.79	2.6	8.2	10.8
115		2.3	29.59	37.74	32.67	2.5	8.8	11.3
120		5.4	30.97	36.61	32.42	4.0	8.5	12.5
125	P	1.0	4.71	23.38	71.91	--	--	--

Sample depth	Unit	Grain size analyses: Coarse (>2 mm)	Fraction (<2 mm): Sand	Silt	Clay	Carbonate analyses: Calcite	Dolomite	Total
ft					%			
Bain Bluff (borehole 69-4) continued								
130	O	0.2	33.78	36.23	29.99	3.8	8.2	12.0
135		2.0	33.16	35.79	31.05	2.8	7.8	10.6
139		0.3	32.06	36.34	31.60	2.8	7.4	10.2
140		2.0	32.26	36.34	31.40	3.9	6.2	10.1
145		6.4	32.76	36.69	30.55	3.0	7.7	10.7
150		1.0	32.59	36.10	31.31	3.0	6.1	9.1
155		1.0	33.16	35.30	31.54	3.0	7.2	10.2
160		3.8	31.88	36.14	31.98	3.2	5.4	8.6
165		0.6	31.91	37.32	30.77	2.9	7.0	9.9
170	N	4.8	11.16	40.34	48.50	6.0	3.2	9.2
175		3.3	6.29	16.46	77.25	--	--	--
180	M	6.4	15.17	49.30	35.53	4.8	8.4	13.2
185		0.0	16.18	57.56	26.26	5.2	3.4	8.6
190		0.0	12.51	63.38	24.11	4.2	5.0	9.2
195		0.0	3.94	69.76	26.30	3.0	4.6	7.6
200		0.0	9.08	63.53	27.39	4.8	6.8	11.6
203		0.0	5.77	70.18	24.05	3.9	5.4	9.3
210	L	0.0	60.93	24.31	14.76	3.0	4.9	7.9
213	K	0.0	10.74	29.56	59.70	4.4	2.7	7.1
217		0.0	8.38	48.44	43.18	3.8	4.2	8.0
220		1.7	9.39	42.81	47.80	4.0	4.7	8.7
225	J	1.6	5.41	25.25	69.34	--	--	--
230		2.0	4.87	14.65	80.48	--	--	--
235		2.6	6.73	18.32	74.95	--	--	--
240		2.4	8.98	21.09	69.93	--	--	--
245		2.9	2.62	24.74	72.64	--	--	--
250		3.6	4.25	21.19	74.56	--	--	--
253		4.1	2.60	30.38	67.02	--	--	--
255		0.0	3.03	20.51	76.46	--	--	--
260		0.0	3.10	41.82	55.08	--	--	--
266		0.0	2.63	40.22	57.15	--	--	--
270	I	0.0	4.04	20.34	75.62	--	--	--
275		1.0	4.19	17.73	78.08	--	--	--
280	H	2.3	0.00	43.14	56.86	--	--	--
285		0.0	0.00	47.85	52.15	--	--	--
290		0.0	4.60	40.47	54.83	--	--	--
295	G	0.0	0.00	20.91	79.09	--	--	--
300		7.9	2.16	22.23	75.61	--	--	--
305		3.4	2.00	19.46	78.54	--	--	--
310		0.0	2.35	24.68	72.97	--	--	--
315		0.0	7.91	25.54	66.55	--	--	--
320		0.0	2.71	43.04	54.25	--	--	--
325		2.5	7.24	19.23	73.53	--	--	--
330		0.0	0.14	29.12	70.74	--	--	--
335		7.5	6.25	25.03	68.72	--	--	--
340		0.0	2.63	25.30	72.07	--	--	--

Sample depth	Unit	Grain size analyses: Coarse (>2 mm)	Fraction (<2 mm): Sand	Silt	Clay	Carbonate analyses: Calcite	Dolomite	Total
ft					%			
Bain Bluff (borehole 69-4) continued								
345	F	0.0	2.66	38.07	59.27	--	--	--
350		0.0	2.43	35.26	62.31	--	--	--
355		2.9	2.73	32.14	65.13	--	--	--
357		0.0	4.70	39.03	56.27	--	--	--
360	E	4.4	7.76	68.86	23.38	8.0	2.8	10.8
365		4.0	9.44	65.19	25.37	8.4	2.8	11.2
370		1.0	16.34	55.46	28.20	2.0	2.4	4.4
375	D	1.7	20.93	46.61	32.46	2.8	1.4	4.2
380		42.1	17.29	37.59	45.12	4.0	5.2	9.2
385		0.0	23.10	49.19	27.71	2.4	2.0	4.4
389		2.6	7.45	50.98	41.57	1.6	4.2	5.8
391	C	0.0	4.20	29.85	65.95	--	--	--
396		0.0	10.03	28.48	61.49	--	--	--
400		0.0	7.09	52.68	40.23	2.6	6.2	8.8
416	A	20.0	41.95	26.23	31.82	--	--	--
420		3.4	6.80	32.68	60.52	--	--	--
425		0.0	6.08	36.08	57.84	--	--	--
Lehr Valley (borehole 69-5)								
60	J	22.5	68.27	15.48	16.25	--	--	--
62	I	1.0	23.13	43.77	33.10	5.2	8.4	13.6
65		0.6	22.87	36.95	40.18	6.3	8.5	14.8
70		3.5	22.67	45.83	31.50	4.1	5.2	9.3
75		0.6	19.92	44.81	35.27	3.0	7.5	10.8
80		5.5	18.78	44.89	36.33	4.0	4.0	8.0
85	H	1.0	30.92	44.97	24.11	3.0	8.1	11.1
90		6.9	32.52	42.76	24.72	2.5	5.8	8.3
95		12.1	31.06	43.00	25.94	3.2	8.4	11.6
100		1.8	11.73	44.34	43.93	6.8	3.2	10.0
105	G	0.0	34.91	37.90	27.19	2.7	6.5	9.2
110	F	0.3	13.60	39.62	46.78	3.6	9.2	12.8
115		0.0	23.03	34.39	42.58	4.4	4.4	8.8
120		0.4	10.86	33.13	56.01	3.4	8.5	11.9
125		0.0	9.18	31.30	59.52	2.4	8.5	10.9
130	E	0.0	3.36	12.30	84.34	--	--	--
135		0.0	7.29	57.95	34.76	4.0	5.2	9.2
140		0.0	5.79	62.87	31.34	4.6	6.8	11.4
145		12.4	6.80	65.56	27.64	3.8	4.2	8.0
150		1.8	4.28	72.96	22.76	3.2	2.7	5.9
155		0.0	6.28	65.20	28.52	2.2	6.0	8.2
160		0.0	10.28	67.75	21.97	4.4	7.2	11.6
165		0.0	35.12	43.21	21.67	3.0	4.4	7.4
166		77.7	33.20	32.91	33.89	--	--	--
168	D	21.4	68.69	16.89	14.45	4.0	4.0	8.0
170		5.5	84.03	8.95	7.02	3.2	6.8	10.0
172		0.0	87.21	6.09	6.70	--	--	--
174		5.1	78.96	12.82	8.22	4.8	3.2	8.0
175		13.5	81.01	11.63	7.36	6.0	27.6	33.6
176		6.3	67.15	18.58	14.27	--	--	--
178		0.0	80.77	9.11	10.12	--	--	--

Sample depth	Unit	Grain size analyses: Coarse (>2 mm)	Fraction (<2 mm): Sand	Silt	Clay	Carbonate analyses: Calcite	Dolomite	Total
ft					%			
Lehr Valley (borehole 69-5) continued								
180	C	0.0	26.56	44.93	28.51	--	--	--
185		8.1	23.18	51.19	25.63	4.1	6.5	10.6
190	B	0.0	85.56	6.61	7.83	--	--	--
195		0.0	88.97	7.12	3.91	5.6	8.4	14.0
199	A	2.6	15.33	31.12	53.55	3.2	2.4	5.6
201		3.6	25.09	30.24	44.67	--	--	--
230		5.1	23.94	29.17	46.89	--	--	--
235		3.0	6.04	33.81	60.15	--	--	--
Surprise Bluff West (borehole 69-6)								
3	O	0.0	21.64	53.24	25.12	2.8	4.1	6.9
5		1.0	76.88	9.45	13.67	1.3	4.2	5.5
10		1.6	57.91	35.16	6.93	3.2	2.0	5.2
15	N	0.1	44.71	32.64	22.65	1.1	3.9	5.0
20		1.1	43.17	30.06	24.77	2.8	5.6	8.4
24		3.0	52.92	26.47	20.61	7.2	4.4	11.6
46	M	0.7	80.73	8.91	10.36	1.3	3.9	5.2
50	L	4.3	28.99	46.15	24.86	2.5	3.3	5.8
55		0.0	22.47	44.04	33.49	3.2	3.8	7.0
63		1.5	20.13	46.24	33.63	2.5	3.7	6.3
65		2.1	18.94	46.69	34.37	2.6	3.8	6.4
70	K	4.2	16.76	54.35	28.89	3.2	6.0	9.2
75		1.4	17.74	49.54	32.72	--	--	--
80		1.0	19.74	49.02	31.24	4.5	7.5	12.0
85		17.7	63.96	17.48	18.56	6.8	3.8	10.6
86		4.3	70.19	14.74	15.07	3.6	13.6	17.2
90		0.3	12.74	48.87	38.39	5.2	6.0	11.2
95	I	22.0	29.28	38.76	31.96	--	--	--
100		0.8	28.12	40.20	31.68	4.6	5.0	9.6
105		0.4	33.11	36.21	30.68	4.4	5.3	9.7
110		0.2	29.14	39.82	31.04	4.3	6.0	10.3
115		0.1	44.61	30.72	24.67	4.0	5.4	9.4
120		0.4	43.77	36.06	20.17	3.6	8.6	12.2
122	H	0.2	46.90	40.01	13.09	2.4	5.5	7.9
125		0.0	38.90	42.69	18.41	2.8	8.1	10.9
128		0.9	43.30	40.39	16.31	4.9	5.7	10.6
130		1.6	44.87	34.93	20.20	3.9	6.3	10.2
132		1.3	52.55	29.16	18.29	3.9	7.1	11.0
135	G	5.1	88.77	6.19	5.04	--	--	--
138		0.0	69.55	17.67	12.78	6.0	5.2	11.2
140		0.3	89.44	5.58	4.98	--	--	--
142		0.6	88.00	7.42	4.58	4.0	4.4	8.4
145	F	0.3	33.19	54.13	12.68	1.0	1.2	2.2
150		13.8	22.98	34.44	42.58	3.2	5.2	8.4
155		2.5	34.66	40.65	24.69	3.8	6.7	10.5
160		0.0	33.28	48.21	18.51	3.7	6.6	10.3
165	E	0.0	3.10	62.21	34.69	5.5	2.5	8.0

Sample depth	Unit	Grain size analyses: Coarse (>2 mm)	Fraction (<2 mm): Sand	Silt	Clay	Carbonate analyses: Calcite	Dolomite	Total
ft					%			
Surprise Bluff West (borehole 69-6) continued								
170	D	0.0	30.35	44.48	25.17	3.2	5.3	8.5
175		0.4	72.31	16.46	11.23	3.4	5.4	8.8
180		0.0	55.91	27.76	16.33	3.2	5.6	8.8
185		0.0	67.00	20.91	12.09	8.4	1.2	9.6
190		0.0	79.64	11.32	9.04	5.6	5.6	11.2
195		0.0	66.67	19.80	13.53	2.8	12.4	15.2
203	C	0.0	13.55	63.54	22.91	1.9	6.9	8.8
205		0.3	35.44	29.53	35.03	4.4	7.0	11.4
210		0.0	28.87	40.95	30.18	3.0	5.4	8.4
215		0.0	23.09	43.81	33.10	3.1	6.9	10.0
220		0.3	35.09	21.57	43.34	4.4	5.5	9.9
225		0.0	31.26	33.42	35.32	4.6	5.0	9.6
229		0.0	35.82	29.68	34.50	3.0	2.8	5.8
238	A	0.0	3.35	34.41	62.24	--	--	--
Reservoir Gully (borehole 69-7)								
5	P	8.4	41.82	28.29	29.89	3.2	2.8	6.0
10		1.0	34.51	34.27	31.22	2.8	5.0	7.8
15		2.3	47.64	28.12	24.24	1.8	5.6	7.4
16		0.7	37.15	36.07	26.78	2.0	3.7	5.7
18		0.9	39.81	36.22	23.97	1.5	2.7	4.2
20		4.1	45.84	28.27	25.89	2.6	4.6	7.2
24		17.2	46.76	27.59	25.65	2.8	5.7	8.6
85	N	5.5	71.25	15.88	12.87	4.2	4.2	8.4
90		0.6	77.53	15.99	6.48	2.0	8.2	10.2
95	M	0.3	23.92	47.69	28.39	2.6	4.2	6.8
100		0.4	25.98	46.42	27.60	2.3	6.8	9.1
102	L	0.3	16.22	70.01	13.77	2.1	4.8	6.9
105		2.7	44.39	39.26	16.35	1.5	4.4	5.9
110	K	2.9	27.80	42.75	29.45	2.8	6.8	9.6
115		5.2	17.51	51.93	30.56	3.1	6.1	9.2
120		0.0	17.22	58.41	24.37	5.3	5.3	10.6
125		1.5	31.18	40.25	28.57	4.3	5.6	9.9
130		0.2	41.10	31.65	27.25	3.5	8.1	11.6
135	J	5.3	74.58	14.52	10.90	3.5	6.9	10.4
140	I	6.6	42.97	39.33	17.70	3.1	6.8	9.9
145		1.7	38.75	41.73	19.52	3.3	7.3	10.6
150	H	0.2	36.31	45.64	18.05	3.9	9.6	13.5
155	G	1.8	51.21	33.08	15.71	4.2	6.9	11.2
160		3.0	47.99	35.43	16.58	3.2	5.8	9.0
165		6.1	24.91	51.08	24.01	3.4	7.6	11.0
170	E	1.4	40.94	38.99	20.07	3.1	5.9	9.0
175		0.9	22.85	47.36	29.79	4.4	6.3	10.7
180	D	0.0	3.54	15.91	80.55	--	--	--
185		0.0	3.84	21.75	74.41	--	--	--
190		0.2	4.61	24.39	71.00	--	--	--
191		0.0	4.65	31.59	63.76	--	--	--
210	A	0.0	61.15	16.07	22.78	--	--	--
215		0.0	2.97	29.71	67.32	--	--	--