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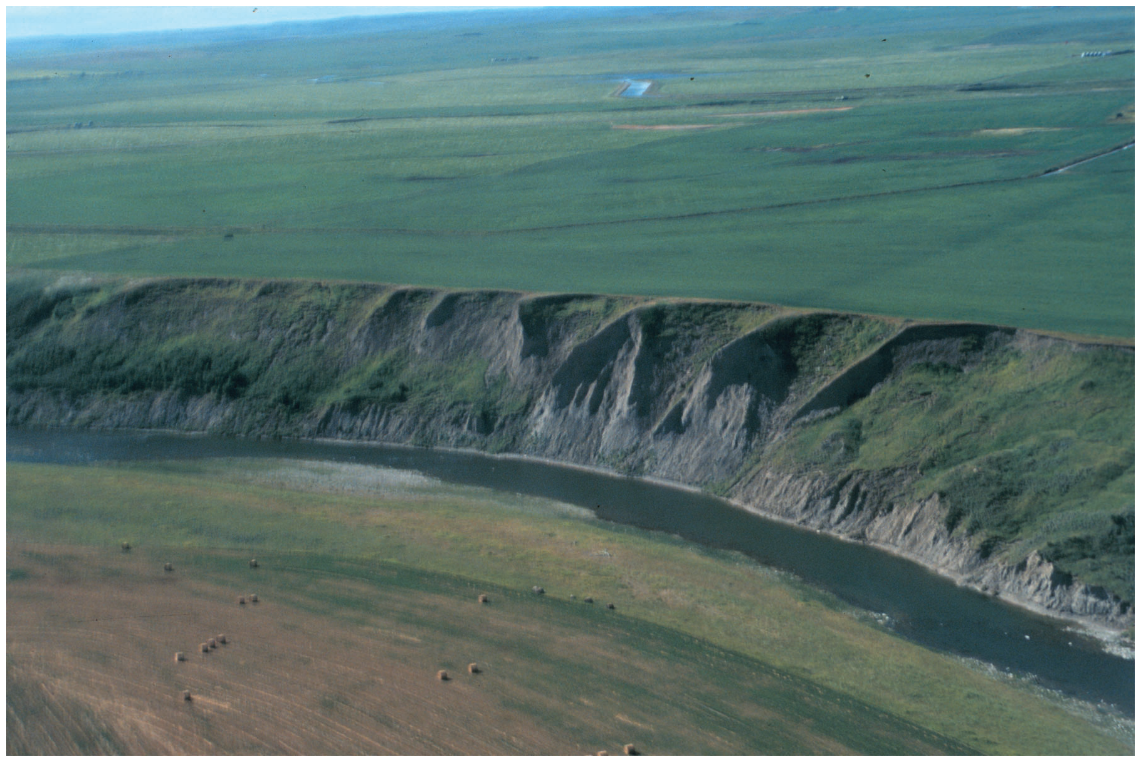

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Cover illustration
One of many impressive sections of stratified glacial diamictons and interstratified glaciolacustrine sediments infilling a former course of St. Mary River about 5 km below St. Mary Reservoir. The sediments record advances and retreats of the extreme southwestern margin of the Laurentide Ice Sheet. GSC 2008-125

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TABLE OF CONTENTS

Illustrations

Tables

Quaternary stratigraphy and geology of the Rocky Mountain Foothills, southwestern Alberta

Abstract

Surficial geology mapping at a scale of 1:50 000, cosmogenic dating, and detailed stratigraphic and sedimentological logging of 86 cliff-bank exposures and more than 3000 roadcuts and hand-driven auger borings have resolved the century-old controversy as to the number and timing of continental glaciations in the Rocky Mountain Foothills of southwestern Alberta.

The stratigraphy shows a consistent succession repeated throughout much of the area: one to several montane tills are always topped by either one continental till or a complex of continental tills, or a gravel unit containing Canadian Shield lithologies where a continental till has been eroded. Exceptions only occur along the Rocky Mountain Front, at the mouths of major valleys where no continental till is present. There is no evidence of subaerial erosion or soil-forming processes that would represent long hiatuses between glacial advances responsible for continental till deposition. The same holds true for montane tills, with the exception of those found in the subsurface of Cloudy Ridge and the sediments capping Mokowan Butte. The drift units underlying paleosols at these two sites clearly predate the last interglaciation. The upper elevation limits of glacial erratics from the Canadian Shield and their abrupt western limit indicate that montane glaciers prevented penetration of continental glacial ice up major Rocky Mountain Foothills valleys, hence continental and montane glaciers coalesced during the culmination of the maximum continental ice advance.

Paleomagnetic sampling of the oldest tills infilling buried valley systems shows that all deposition occurred during the Brunhes chron (<0.78 Ma). Cosmogenic ^{36}*Cl exposure dating of the Foothills Erratics Train and the former limits of the continental ice-sheet cover constrains the single continental glaciation to the Late Wisconsinan. The area was deglaciated by ca. 11 200 radiocarbon years before present.*

Résumé

La cartographie géologique de surface à l'échelle de 1/50 000, la datation cosmogénique et la description stratigraphique et sédimentologique détaillée de 86 falaises exposées et de plus de 3000 tranchées de route et forages manuels à la tarière ont permis de résoudre la controverse vieille d'un siècle quant au nombre et à la chronologie des glaciations continentales dans les Foothills des montagnes Rocheuses du sud-ouest de l'Alberta.

La stratigraphie comporte une succession uniforme se répétant sur une grande portion de la région : un à plusieurs tills subalpins invariablement recouverts d'un till continental ou d'un complexe de tills continentaux, ou d'une unité de gravier renfermant des lithologies du Bouclier canadien là où un till continental a été érodé.. Les seules exceptions se trouvent le long du front des Rocheuses, à l'embouchure de vallées importantes où il n'y a pas de till continental. Il n'y a pas d'indication d'érosion subaérienne ou de processus pédogénétiques qui représenteraient de longues lacunes de sédimentation entre les avancées glaciaires responsables du dépôt de till continental. Cela est aussi vrai pour les tills subalpins, à l'exception de ceux trouvés sous la surface à la crête Cloudy et des sédiments coiffant la butte Mokowan. Les unités de sédiments glaciaires sous-jacentes aux paléosols à ces deux endroits sont manifestement antérieures au dernier interglaciaire. Les limites d'altitude maximales des blocs erratiques du Bouclier canadien et la limite occidentale abrupte de leur répartition indiquent que les glaciers subalpins ont empêché la pénétration des glaces continentales dans les vallées majeures des Foothills des montagnes Rocheuses; on en déduit qu'il y a eu confluence des glaciers continentaux et subalpins durant l'apogée de l'avancée maximale de l'inlandsis.

L'échantillonnage paléomagnétique des tills les plus anciens qui remplissent les réseaux de vallées enfouies montre que tous ces tills se sont déposés durant le Chron de Brunhes (<0,78 Ma). La datation de l'exposition du ^{36}*Cl aux rayonnements cosmogéniques dans la Traînée d'erratiques des Foothills ainsi que les anciennes limites de la couverture de l'inlandsis limitent l'unique glaciation continentale au Wisconsinien supérieur. La datation au radiocarbone indique que la région était déjà déglacée vers 11 200 BP.*

SUMMARY

This report describes the results of surficial geology mapping and attendant stratigraphic investigations of an area covered by twelve 1:50 000 map sheets, centred on the Rocky Mountain Foothills from the Turner Valley area of Alberta to the border with the United States of America. This work corroborates the hypothesis that the Rocky Mountain Foothills area of southwestern Alberta has only once experienced the incursion of glacial ice from a continental ice sheet centred on the Canadian Shield. That event occurred during the Late Wisconsinan, when the extreme southwestern margin of a continental (Laurentide) ice sheet entered the area.

Fourteen stratigraphic units and subunits related to montane and continental glaciers and postglacial processes were defined in this study. Many of these can be traced and correlated in cliff-bank exposures along buried valley systems from the Rocky Mountain Front to the eastern limits of mapping.

The oldest stratigraphic unit (unit 1) is a montane gravel that likely represents outwash from the last major advance of montane glacial ice into the Interior Plains. This unit was previously referred to as part of the Saskatchewan Sands and Gravels. It is locally overlain by lacustrine sediments (unit 2) laid down in lakes created where advancing Rocky Mountain (montane) valley glaciers blocked locally ice-free tributary valleys.

Units 1 and 2 are overlain by either a single montane till, or a succession of montane tills (unit 3), which has been called Albertan Till. The glacier that deposited unit 3 never exceeded about 300 m thickness in the Rocky Mountain Foothills of the Oldman River basin. It extended into the Interior Plains almost to the present sites of Lethbridge and Granum (M1 advance). A similar piedmont glacier existed north of the Porcupine Hills, but its eastward extent and thickness have not been determined. The glacial advance that deposited unit 3 is referred to as M1.

Unit 3 is locally overlain by gravel (unit 4) deposited after retreat of the montane glacier from its maximum eastward extent, or by glaciolacustrine silt and clay (unit 5) deposited in glacial lakes formed as the margin of the continental Laurentide Ice Sheet initially advanced into and retreated from the area, damming streams draining the retreating montane glaciers.

Unit 6 includes a single continental till, or complex of tills, and interstratified sand and gravel, deposited by the most extensive advance of a continental ice sheet into the area (C1 advance). Unit 6 was formerly referred to as the Labuma Till. Near the Rocky Mountain Front, deposits associated with the maximum montane and continental advances are overlain by unit 7, a till or

SOMMAIRE

Ce rapport présente les résultats de la cartographie géologique de surface et d'études stratigraphiques connexes entreprises dans une région couverte par douze cartes à l'échelle de 1/50 000, centrée sur les Foothills des montagnes Rocheuses, depuis la région de la vallée Turner en Alberta jusqu'à la frontière canado-américaine. Cette étude vient corroborer l'hypothèse selon laquelle la région des Foothills des montagnes Rocheuses du sud-ouest de l'Alberta n'aurait subi qu'une seule fois l'incursion de glace glaciaire d'un inlandsis continental centré sur le Bouclier canadien. Cet événement s'est produit durant le Wisconsinien supérieur, alors que l'extrémité sud-ouest d'un inlandsis (laurentidien) a pénétré la région.

Quatorze unités et sous-unités stratigraphiques associées à des glaciers subalpins et continentaux et à des processus postglaciaires ont été définis dans le cadre de cette étude. Bon nombre d'entres elles peuvent être suivies et corrélées sur des falaises exposées le long de réseaux de vallées enfouies, depuis le front des Rocheuses jusqu'aux limites orientales de l'étendue cartographiée.

L'unité stratigraphique la plus ancienne (unité 1) est un gravier subalpin qui représenterait un dépôt d'épandage fluvioglaciaire de la dernière avancée majeure des glaces glaciaires subalpines dans les Plaines intérieures. On faisait antérieurement référence à cette unité comme faisant partie des Graviers et Sables de la Saskatchewan. Elle est recouverte par endroits de sédiments lacustres (unité 2) déposés dans des lacs créés là où les glaciers des vallées (subalpins) des montagnes Rocheuses ont bloqué des vallées tributaires localement libres de glace.

Les unités 1 et 2 sont recouvertes par un unique till subalpin ou par une succession de tills subalpins (unité 3), soit le Till Albertan. L'épaisseur du glacier qui a déposé l'unité 3 n'a jamais dépassé environ 300 m dans les Foothills des montagnes Rocheuses du bassin de la rivière Oldman. Le glacier s'étendait dans les Plaines intérieures presque jusqu'aux sites actuels de Lethbridge et de Granum (avancée M1). Un glacier de piémont similaire a existé au nord des collines Porcupine, mais son étendue vers l'est et son épaisseur demeurent indéterminées. L'avancée glaciaire qui a déposé l'unité 3 est désignée M1.

Par endroits, l'unité 3 est recouverte de gravier (unité 4) déposé après le retrait du glacier subalpin depuis son étendue maximale vers l'est, ou de silts et d'argiles glaciolacustres (unité 5) déposés dans des lacs glaciaires formés lorsque la marge de l'Inlandsis laurentidien s'est initialement avancée puis retirée de la région, barrant ainsi des cours d'eau drainant les glaciers subalpins en retrait.

L'unité 6 se compose d'un unique till continental, ou d'un complexe de tills, et de sable et de gravier interstratifiés, déposés par la plus extrême avancée d'un inlandsis dans la région (avancée C1). On donnait auparavant le nom de « Till de Labuma » à l'unité 6. Près du front des Rocheuses, des dépôts associés aux avancées maximales des glaciers subalpins et continentaux reposent sous l'unité 7, qui comporte un ou plusieurs tills déposés lors d'une tills deposited by a readvance of montane glaciers (M2 advance). Ice-marginal deposits (unit 8) are associated with the retreating montane readvance. Farther east, however, glaciolacustrine sediments (unit 5) are often observed between unit 6 and units 7 or 9.

South and east of the Porcupine Hills, unit 6 is overlain by unit 9, a till or complex of tills and interstratified gravel deposited by readvance of the continental ice sheet (C2 advance). North of the Porcupine Hills, only one montane and one continental till are present. The montane and continental glaciers apparently remained coalescent in that area while montane and continental ice advanced and retreated south of the Porcupine Hills.

Unit 10 is a complex of thick glaciolacustrine sediments that was dammed during retreat of continental ice from the foothills. South of the Porcupine Hills, where there was a clearly defined C2 advance, it overlies unit 9. North of the Porcupine Hills, where montane and continental ice remained coalesced and a C2 readvance may not have occurred or may have been a stillstand during retreat, unit 10 directly overlies unit 6. The stratigraphic succession is capped by units 11 to 14: late glacial and postglacial gravel, loess, and colluvium, respectively.

Moraines, erratics, meltwater channels, and lacustrine sediments associated with the maximum limits of the continental ice sheet can be traced across the north and south ends of the Porcupine Hills and along the front of the Rocky Mountains. Readvance positions of the continental ice sheet are defined by belts of hummocky moraine around the north, east, and south sides of Porcupine Hills and immediately northeast of the Rocky Mountain Front. Drift sheets associated with the upper elevation limits of Canadian Shield erratics can be traced eastward and northward into sedimentary fills, which bury the valleys of preglacial foothills river systems. These fills are widely exposed in the study area, where contemporary valleys cut across or partly exhume the buried valley systems. These exposures show units 6 and 9 to be continuous with glacial limits C1 and C2 respectively.

There is no evidence for any significant hiatus in the deposition of the glacial sediments that fill the preglacial valley systems (unit 1 up to unit 11). These sediments are all magnetically normal and consequently postdate the last geomagnetic reversal that occurred 0.78 million years ago. Cosmogenic ^{36}Cl exposure dating of erratics associated with the all-time glacial limit, readvance position, and the Foothills Erratics Train indicate these all to be Late Wisconsinan age. Based upon this, together with a lack of any apparent hiatus in deposition, and absolute dating control elsewhere in Alberta, the sedimentary fill of the buried valleys is believed to be the product of a single, Late Wisconsinan glaciation.

nouvelle avancée de glaciers subalpins (avancée M2). Des dépôts juxtaglaciaires (unité 8) sont associés au retrait de ces glaciers subalpins. Toutefois, plus loin vers l'est, des sédiments glaciolacustres (unité 5) se rencontrent communément entre l'unité 6 et les unités 7 ou 9.

Au sud et à l'est des collines Porcupine, l'unité 6 est recouverte par l'unité 9, un till ou un complexe de tills et de graviers interstratifiés déposés lors d'une nouvelle avancée de l'inlandsis (avancée C2). Au nord des collines Porcupine, on ne trouve qu'un till subalpin et un till continental. Les glaces subalpines et continentales sont apparemment demeurées accolées dans cette région, alors que les glaces continentales et subalpines se sont avancées et retirées au sud des collines Porcupine.

L'unité 10 est un complexe d'épais sédiments glaciolacustres accumulés dans un lac de barrage glaciaire durant le retrait des glaces continentales des Foothills. Au sud des collines Porcupine, là où une avancée C2 a été clairement identifiée, l'unité 10 repose sur l'unité 9. Au nord des collines Porcupine, où les glaces subalpines et continentales sont demeurées accolées et où une réavancée C2 peut ne pas avoir eu lieu ou encore où la glace peut avoir été stationnaire lors du retrait, l'unité 10 repose directement sur l'unité 6. La succession stratigraphique est recouverte par les unités 11 à 14 qui sont dans l'ordre : des graviers, des loess et des colluvions tardiglaciaires et postglaciaires.

Les moraines, les blocs erratiques, les chenaux d'eau de fonte et les sédiments lacustres associés à l'étendue maximale de l'inlandsis peuvent être suivis aux extrémités nord et sud des collines Porcupine et le long du front des Rocheuses. Les positions des réavancées de l'inlandsis sont définies par des ceintures de moraine bosselée entourant les flancs nord, est et sud des collines Porcupine et immédiatement au nord-est du front des Rocheuses. Les nappes de sédiments glaciaires associées aux limites d'altitude maximales des blocs erratiques du Bouclier canadien peuvent être suivies vers l'est et vers le nord dans les sédiments qui comblent les vallées des réseaux hydrographiques préglaciaires des Foothills. Ces sédiments de remplissage sont largement exposés dans la région à l'étude, là où des vallées contemporaines recoupent ou exhument partiellement les réseaux de vallées enfouies. À ces endroits, on constate que les unités 6 et 9 sont respectivement continues avec les limites glaciaires C2 et C1.

Il n'y a pas d'indication témoignant d'importantes lacunes de sédimentation dans les sédiments glaciaires qui comblent les réseaux de vallées préglaciaires (unités 1 à 11). Ces sédiments sont tous de magnétisme normal et sont conséquemment postérieurs à la dernière inversion du champ magnétique terrestre qui s'est produite il y a 0,78 Ma. La datation cosmogénique du ^{36}Cl dans les blocs erratiques associés à la limite glaciaire ultime, à la position de la réavancée et à la Traînée d'erratiques des Foothills indique qu'elles datent toutes du Wisconsinien supérieur. En s'appuyant sur ces données, ainsi que sur l'absence de lacune apparente dans la sédimentation et sur d'autres datations absolues en Alberta, on suppose que les sédiments comblant les vallées enfouies sont le produit d'une unique glaciation qui daterait du Wisconsinien supérieur.

The only glacial deposits predating the Late Wisconsinan are found below paleosols on Cloudy Ridge and Mokowan Butte. The latter sediments were beyond the reach of the montane and continental glaciers of the last (Late Wisconsinan) glaciation based upon the upper limits of glacial erratics elsewhere in the Rocky Mountain Foothills. The summit of Mokowan Butte represents the surface of the Interior Plains prior to a cycle of uplift and stream incision during which the extant and buried valleys of the region were cut.

The Holocene has been a period dominated by the incision of contemporary floodplains by streams, the deposition of cliff-top dunes, and local organic sedimentation.

Les seuls sédiments glaciaires antérieurs au Wisconsinien supérieur se trouvent sous des paléosols à la crête Cloudy et à la butte Mokowan. Ces derniers sédiments étaient d'ailleurs hors de portée des glaciers subalpins et continentaux de la dernière glaciation (Wisconsinien supérieur) si l'on se fie aux limites d'altitude maximales des blocs erratiques ailleurs dans les Foothills des montagnes Rocheuses. Le sommet de la butte Mokowan représente la surface des Plaines intérieures avant un cycle de soulèvement et d'incision par des cours d'eau durant lequel les vallées existantes ou enfouies dans la région ont été creusées.

L'Holocène a été une période dominée par l'incision par les cours d'eau des plaines d'inondation contemporaines, le dépôt de dunes aux sommets des falaises et la sédimentation organique locale.

INTRODUCTION

The southwestern foothills area of Alberta (Fig. 1, 2) was one of the first Canadian locations where evidence of multiple glaciations was reported (Dawson and McConnell, 1895). This conclusion was based upon the occurrence of interstratified glacial tills containing stones from the Canadian Shield (continental provenance) and stones exclusively from the foothills and Rocky Mountains (montane provenance). This region is a particularly significant area for the preservation of glacial sediments due the presence of preglacial valley systems (Stalker, 1961) that extend up to 50 m below surrounding terrain. These valleys are filled with the sediments deposited during advances and retreats of montane and continental glaciers. These deposits are accessible at numerous cliff-bank exposures. Since the end of the nineteenth century, several hypotheses about the history of Quaternary glaciation in this area have been based on varying interpretations of this stratigraphic evidence. Debate over the number of glaciations recorded in the region, and synchroneity of montane and continental glacial advances, has continued since formal research began.

Interpretation of the surficial geology in this region has been shaped largely by the work of Horberg (1952, 1954), Stalker (1963), Wagner (1966), Alley (1973), Alley and Harris (1974), Stalker and Harrison (1977), and Jackson (1980). This work largely predates the explosion of research in contemporary glacial sedimentary environments that began in the early 1970s, as well as the development of new dating techniques such as paleomagnetism (with reference to the geopolarity time scale) and cosmogenic exposure dating. Also, this work was generally based on the interpretation of stratigraphic sections with reference to reconnaissance-scale mapping of the surficial geology of the region. Clearly, by the 1990s, this important area required re-examination.

Between 1993 and 1997, the surficial geology of the Rocky Mountain Foothills region was re-examined as a part of the Geological Survey of Canada's National Mapping Program (NATMAP). This report details the Quaternary glacial stratigraphy and history of the southeastern foothills region between the Turner Valley area and the border with the

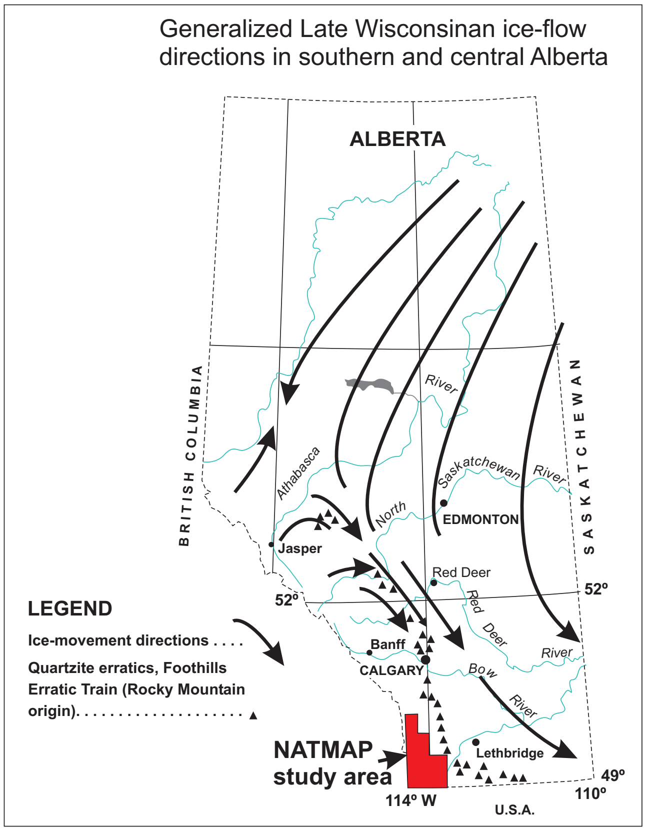


Figure 1. Location of Eastern Cordillera NATMAP project and generalized ice-flow directions (*after* Gravenor and Bayrock, 1961).

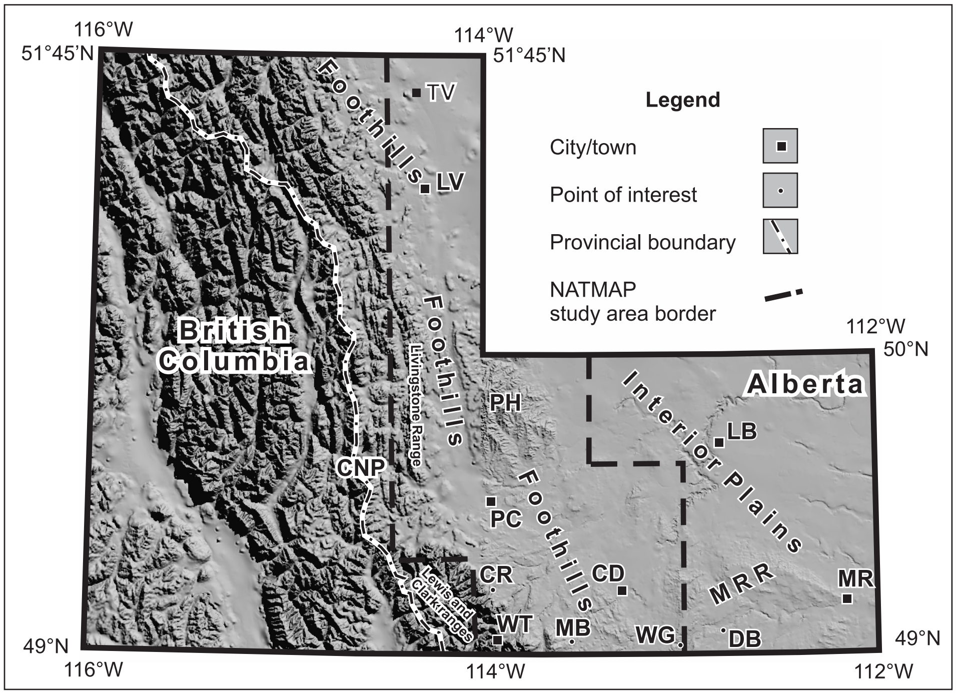


Figure 2. Digital shaded-relief map of the study area and adjacent areas of Alberta and British Columbia: Turner Valley (TV), Longview (LV), Crowsnest Pass (CNP), Pincher Creek (PC), Cloudy Ridge (CR), Whiskey Gap (WG), Del Bonita (DB), Mokowan Butte (MB), Milk River Ridge (MRR), Lethbridge (LB), Milk River (MR), the Porcupine Hills (PH), Cardston (CD), and Waterton (WT).

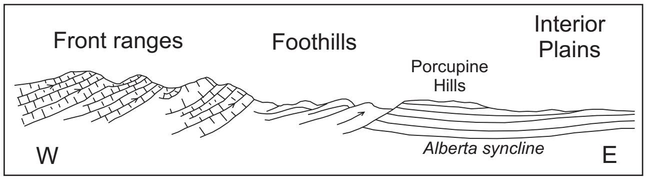


Figure 3. Generalized cross-section across study area at the latitude of Porcupine Hills (*after* Beaty, 1975). The Rocky Mountains are a complex of folded and thrusted Paleozoic carbonate and clastic rocks. The Rocky Mountain Foothills are dominated by folded and thrusted Mesozoic clastic rocks, although the Mississippian carbonate rocks of the Livingstone Range technically are part of the foothills. The Porcupine Hills are a broadly folded succession of early Tertiary clastic rocks. The Interior Plains are underlain by nearly flat-lying early Tertiary and late Mesozoic clastic rocks.

United States of America based upon surficial-geology mapping and stratigraphic investigation of the unconsolidated deposits occurring within twelve 1:50 000 map areas (Fig. 1 and 2). The re-examination of glacial stratigraphy employed contemporary (post-1970) concepts in glacial sedimentology. The stratigraphic units defined were related to glacial limits and drift sheets defined during the course of 1:50 000-scale mapping of the area. Several absolute and relative dating techniques were applied during the course of this study that were unavailable to former investigators. Paleomagnetic investigation of the stratigraphically lowest units sought to determine if early Pleistocene sediments (those preceding the last magnetic reversal) were present within the study area. Cosmogenic ^{36}Cl exposure dating was applied to determine the age of deposition of sediments exposed at the surface, and accelerator mass spectrometer ^{14}C dating refined the chronology of the stratigraphic framework.

Physiography and bedrock geology

The study area (covering twelve 1:50 000-scale map sheets) spans three main physiographic regions (Fig. 3 and 4): the Livingstone and Lewis and Clark ranges of the Rocky Mountains, the Rocky Mountain Foothills, and the Interior Plains (Beaty, 1975). Each region has a characteristic surface morphology, modified by glaciation that is closely linked to the underlying bedrock structures. A generalized cross-section from west to east across the study area at the latitude of Porcupine Hills is shown in Figure 3.

Each region also has characteristic bedrock lithologies that provide clues to the provenance of glaciers that have deposited tills in the foothills. The study area lacks any plutonic or metamorphic bedrock in situ. The Beaver Mines Formation, a Lower Cretaceous conglomerate that contains minor amounts of granitic pebbles (Douglas, 1950) is the only such source in the southern foothills (Fig. 4). These pebbles contain only white feldspar and they are easily visually distinguished from granitic rocks typical of the Canadian Shield. The Canadian Shield, although distant from the area, is an important source of distinctive lithologies in drift of the foothills.

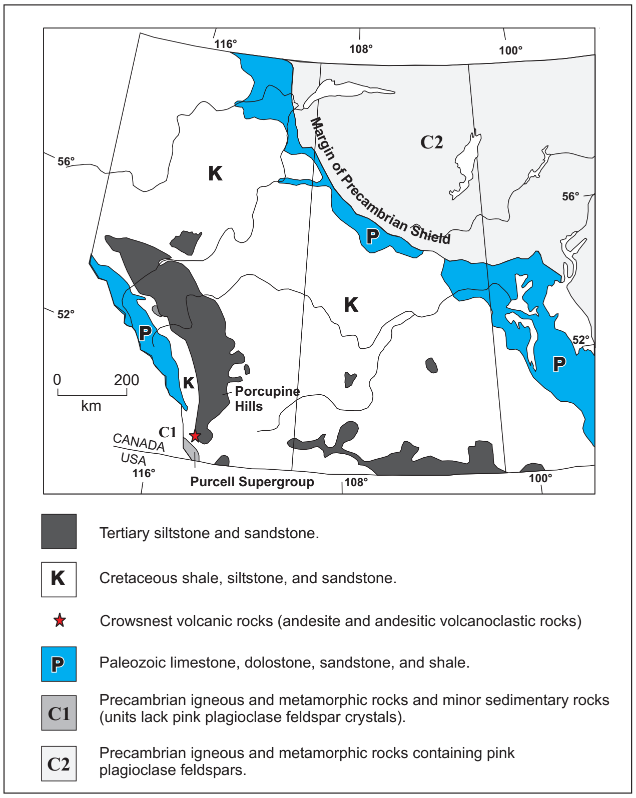


Figure 4. Physiographic subdivisions of western Canada with reference to distinctive lithologies that allow assignment of provenance to glacial drift (*modified from* Klassen, 1989).

Livingstone Range and Lewis and Clark ranges

Parts of the Rocky Mountains fall within Stimson Creek (82 J/8), Langford Creek (82 J/1), Maycroft (82 G/16) Blairmore (82 G/9), Beaver Mines (82 G/8), and Waterton (82 H/4) map areas. Structurally, the Rocky Mountains consist predominantly of carbonate and clastic sedimentary rocks that have been moved tens or hundreds of kilometres to the east/northeast along numerous low-angle thrust faults during the late Cretaceous to early Tertiary Laramide Orogeny. Between the International Border and Crowsnest Pass, summits range up to 2600 m a.s.l. and valleys as low as about 1700 m a.s.l.. North, near the Crowsnest Pass, the summits range up to 2200 m a.s.l. and the valleys are as low as 1400 m a.s.l.. This mountainous region is marked by classic alpine glacial features such as cirques, arêtes, and end moraines. Distinctive lithologies occur within the Rocky Mountains that can be used to infer ice-transport direction of former glaciers. The regions containing these distinct provenances are discussed below:

Livingstone Range

Although the Livingstone Range (Fig. 2) occurs east of the McConnell Thrust, and therefore lies within the Rocky Mountain Foothills (Mathews, 1986), its structure and stratigraphy are typical of the Rocky Mountains (Fig. 2). The western margin of the Livingstone Range comprises Paleozoic limestone and dolostone formations that are unconformably overlain by folded and faulted Mesozoic clastic rocks (e.g. quartzitic sandstone, siltstone, shale, and andesitic volcanic rocks) (McMechan and Thompson, 1992). Those volcanic rocks observed in the Rocky Mountains are unique to southern Alberta and adjacent areas of Montana and British Columbia (Stelck et al., 1972), and hence, are useful for till provenance studies. They outcrop within a narrow north-south strip in the area of Crowsnest Pass and represent an isolated Lower Cretaceous pyroclastic volcanic episode in the Canadian Rockies (Fig. 4).

Lewis and Clark ranges

South of Crowsnest Pass, the Livingstone Range gives way to the Lewis Range and Clark ranges (Fig. 2). They are largely composed of the Proterozoic Purcell Supergroup. This assemblage includes the oldest rocks in the Rocky Mountains of southwestern Alberta. Lithologies exposed at the surface in the Waterton Park area include red and green argillite, dolostone, limestone, maroon-banded quartzite, metagabbro, and dark green amygdaloidal basalt referred to as Purcell Lava (Höy, 1993).

Rocky Mountain Foothills Belt

The Rocky Mountain Foothills form an elongate belt of folded and thrust-faulted Upper Paleozoic and Mesozoic sandstone, siltstone, and shale up to 40 km wide between the Rocky Mountains and the Interior Plains (McMechan and Thompson, 1992). The region is characterized by low, rolling hills and long, linear, subparallel ridges and valleys that follow the mountain front in a northwest-southeast trend. Relief is only about 150 m with summits nearing 1500 m a.s.l. The general elevation and relief of the foothills decrease gradually to the northeast, and the eastern boundary of this physiographic region is marked by a gradual change from rolling to flat topography (Fig. 2).

Interior Plains

The Interior Plains are underlain by flat-lying Upper Cretaceous sandstone and shale thousands of metres thick. Its surface morphology is characterized by vast expanses of flat and very gently rolling surfaces cut by meltwater coulees and major river valleys that are 50 to100 m deep (Beaty, 1975). The elevation of the western edge of the Interior Plains is about 1000 m a.s.l. with a gentle regional slope to the northeast.

Porcupine Hills

The Porcupine Hills are a remnant upland surface of Paleocene and Upper Cretaceous strata that lie in a shallow syncline. Their underlying structure is more like that of the Interior Plains than the Rocky Mountain Foothills by which they are surrounded (Beaty, 1975). The highest portion of this upland is at about 1800 m a.s.l., and therefore rises about 600 to 750 m above the level of the adjacent foothills and plains. The fine-grained sandstone underlying the Porcupine Hills forms benches and cuestas along the eastern and western edges of the hills, respectively.

Canadian Shield

Although over 800 km to the northeast of the study area, the Precambrian Canadian Shield is an important source for clasts found in till and gravel units within the study area (Fig. 4). The stones have plutonic and metamorphic lithologies containing distinctive coarse-grained pink feldspar crystals. These distinctive rocks will be referred to as 'shield stones' throughout this report.

Climate, vegetation, and soils

The Interior Plains and Rocky Mountain Foothills regions fall within a continental climate zone characterized by short, warm summers and cold winters (Hare and Thomas, 1974). For example, the daily mean January temperature for Lethbridge is -8.4°C, whereas the daily mean July temperature is 18.4°C. The difference in maximum recorded temperature (39.4°C) and minimum recorded temperature (-42.8°C) is 82.2°C, exemplifying the temperature extremes affecting vegetation and geologic processes in these regions. The average annual precipitation (rain and snow) for the region is in the range of 380 mm (Environment Canada, 2002). Strong and persistent westerly winds are also characteristic in southern Alberta (Beaty, 1975). The harsh climatic conditions experienced in these regions constrain the diversity of native vegetation, which is dominated by short and medium grasses. The predominant vegetation is rough fescue, with willow and poplar trees in moist areas along watercourses (Moss, 1959). At higher elevation areas (above 1400 m a.s.l.) in the western portion of the foothills and Porcupine Hills, montane forest dominates; these forests are characterized by Douglas fir and white spruce, with minor limber pine, lodgepole pine, and poplar components (Pawluk et al., 1967).

Two Chernozemic soils dominate the area (Soil Classification Working Group, 1998): Black Chernozemic and Dark-Brown Chernozemic great groups. The Black Chernozems occur in the westernmost portion of the foothills, whereas the Dark Brown Chernozems occur farther east in the slightly more arid eastern foothills and adjacent Interior Plains (University of Alberta, 1969).

Previous work

Previous investigations for the southwestern Rocky Mountain Foothills region are summarized in Table 1. Based upon interpretations of the thick successions of glacial deposits exposed in cliff banks cut into buried valley fills, two divergent views of glacial history emerged (Prest, 1970, p. 693):

1. The southwest Rocky Mountain Foothills of Alberta have been subjected to glaciations by continental ice prior to and including the Wisconsinan Stage.
2. Continental ice reached the area only once, during the Late Wisconsinan.

The first view, most prominently articulated by Stalker (1977) and Stalker and Harrison (1977), regards continental ice sheet advances into the foothills during the last (Late Wisconsinan) glaciation as the least extensive of several advances which occurred during two or more pre-Wisconsinan glaciations. This interpretation was predicated on each of a succession of continental tills seen in several key exposures (Stalker, 1963) representing separate glaciations.

The second view emerged with the work of Horberg (1952, 1954) and culminated with the work of Wagner (1966). Wagner measured, described and correlated more than 38 major exposures of Quaternary sediments in the valleys of the Crowsnest, Castle, Oldman, Waterton, and Belly rivers, including sections investigated by Stalker and others. He interpreted the till sheets traced between these exposures to have been deposited by two advances of a continental ice sheet into the region. Both Wagner and Stalker found that the older continental till overlaid a montane till, which in turn rested on gravel that contained only montane lithologies. Wagner noted that there was a total lack of evidence of soil development between continental tills, between montane till and continental till, and between basal gravel and montane till. He concluded that the entire sequence was Late Wisconsinan in age. Others have corroborated Wagner's conclusions. Bayrock (1969) noted that vertebrate fauna in gravels correlative to the basal montane gravel seen in the foothills section of the study area indicate an age as young as Late Pleistocene for the basal gravel. Farther north, and at a lower elevation than the southwestern foothills, Liverman et al. (1989) and Young et al. (1994) determined that only a single, Late Wisconsinan–age continental advance reached the Edmonton area and the foothills to the west. As a corollary, the west to east and northeast regional elevation gradient in Alberta and regional paleo–ice-flow directions (Fig. 1) demand that only one continental ice advance reached southwestern Alberta as well (Little, 1995). Lastly, the Foothills Erratics Train and erratics marking the limit of continental glaciation have been determined to be Late Wisconsinan in age (Jackson et al. 1996, 1999).

Table 1. Chronological summary of significant investigations in southwestern Alberta and adjacent areas, relating directly to this study.

Study[1]	Study area	Conclusions	Comments	Tills recognized (oldest to most recent)	Pre-LGM?[2]
Dawson (1890) Dawson and McConnell (1895)	49°00′ to 51°00′ N 114°30′ to 111°00′ W U.S. border to Bow River. Eastern edge of Rocky Mountains to eastern edge of foothills	Deposition of Saskatchewan gravels synchronous with Albertan-age montane till in west. Followed by 'great western depression' during which thousands of feet of subsidence allowed an incursion of Arctic waters from the NW, during which drift from a first continental advance was deposited to 1615 m in the Porcupine Hills (Kansan). Followed by an interglacial ('post-Kansan interval') and one more continental advance to the Foothills (Iowan). No continental tills of Wisconsinan time.	Recognized region as a zone of interaction between montane and continental ice. Believed boulder clays (tills) were deposited along the margins of an extensive glacial sea beneath floating ice; re-emergence of the land resulted in expulsion of the sea from the region. Placed observed stratigraphic units into timescale proposed by Chamberlin (1894). Based interpretations on stratigraphic sections and scattered surface observations.	Montane: 1: Western Boulder Clay (Albertan till) Continental: 1: Lower Boulder Clay (Kansan, west to mountain front); 2: Upper Boulder Clay (Wisconsinan)	Yes
Calhoun (1906), Alden and Stebinger (1913)	Northern Montana and southwestern Alberta	Re-interpreted the 'Saskatchewan sands and gravels' as a non-glacial deposit.	Discontinued the name 'Albertan' for the lowest montane till.	Several continental and montane tills	Yes
Alden (1932)	Northern Montana and southwestern Alberta	Recognized that montane glaciers and the last (Late Wisconsinan) continental ice sheet coalesced.	The first, accurate, reconstruction of glacial limits across the International Border.	as above	Yes
Johnston and Wickenden (1931)	Southern Alberta	The upper continental provenance drift sheet in the area of the foothills is Iowan (Early Wisconsinan**)**. Montane and continental ice advances were out of phase.	Cited the interglacial nature of beds and what they interpreted to be weathering of the underlying continental till as evidence for an interglacial in post-Kansan time,	Two continental tills	Yes
Horberg (1952)	49°30′ to 50°00′ N 111°15′ to 114°15′ W From Rocky Mountain Foothills, 140 km east along the Oldman River to Lethbridge	Saskatchewan gravels are preglacial. Following an extensive montane advance, continental ice fluctuated, resulting in several till units separated by glacial lake sediments. All continental ice incursions occurred in **Wisconsinan** time: no evidence for any large hiatus.	Re-interpreted Dawson and McConnell's work and rejected their chronology. Interpreted interglacial (Lenzie) silts as proglacial lake sediments, not interglacial sediments. Based interpretations on stratigraphic sections and 1:800 000-scale mapping.	Montane: 1: Western boulder clay Continental: 1: Basal till (pre-Late Wisconsinan) 2: Lower till (Late Wisconsinan, to 1590 m) 3: Upper till (small readvance to Lethbridge moraine)	No
Horberg (1954)	49°00′ to 49°30′ N 113°15′ to 114°07′ W Rocky Mountain Front just north of the U.S. border	Three ages of montane drift: Kansan, Early and Late Wisconsinan. The latter two tills are overlapped by Outer Continental Drift (Horberg's (1952) Lower till) from a late Wisconsinan continental ice lobe. As ice retreated (with some readvances) to the Lethbridge moraine, it deposited two lower and more eastern moraine belts: Kimball moraine and Glenwoodville moraine. In every section, continental drift is stratigraphically above Montane drift. Maxima of montane and continental glaciers were synchronous.	Attempted to correlate Pleistocene events at mountain front to standard North American chronology of the Mississippi Valley. Based interpretations on stratigraphic sections and 1:200 000-scale mapping.	Montane: 1: Kennedy drift (Kansan, on Mokowan Butte) 2: Early Wisconsin drift (up to 10 km from mountain front) 3: Late Wisconsin drift (within moraines of Early drift) Continental: 1: Late Wisconsinan ice lobe with several retreat/ readvance moraine belts: Outer Continental Drift; Kimball moraine; Glenwoodville moraine; Lethbridge moraine	No

[1] The assignment of contemporary chronostratigraphic units to previous work is the authors' interpretation. Where present, these units are indicate by bold letters *e.g.* Late Wisconsinan.
[2] "Pre-LGM?" means "Did the authors recognize evidence of continental glaciation prior to the most recent?

Table 1. (cont.)

Study[1]	Study area	Conclusions	Comments	Tills recognized (oldest to most recent)	Pre-LGM?[2]
Stalker (1963)	49°20′ to 49°55′ N 114°10′ to 111°50′ W Along Castle, Oldman, St. Mary rivers	Preglacial Saskatchewan gravels overlapped by maximum advance Nebraskan montane till. Followed and buried by no less than four continental tills representing Nebraskan, Kansan, Illinoian, and Wisconsinan advances.	Based interpretations on twelve stratigraphic sections. Prominent among these was the 'Brocket' section. Units listed in the right adjacent column are based on this exposure.	Montane: 1: Albertan Continental: 1: Labuma 2: Maunsell 3: Brocket 4: 'Light brown' 5: Buffalo Lake 6: 'Younger tills'	Yes
Richmond (1965); Richmond et al. (1965)	Glacier National Park area, northern Montana	Five montane glaciations. The continental ice sheet advanced into the area during the youngest (Pinedale) montane glaciation.	Based upon interstratified tills and soils and overlapping drift sheets.	Montane: Tills correlated to the Pinedale, Bull Lake, Sacagawea Ridge, Cedar Ridge, and Washakie Point glaciations Continental: One unnamed till of Pinedale age	No
Wagner (1966)	49°15′ to 49°50′ N 112°00′ to 114°30′ W Mountains, foothills and plains southwest of Calgary and west of Lethbridge	One montane ice advance in Illinoian time, followed by a hiatus during which Cloudy Ridge soil formed. In Wisconsinan time, montane ice advanced and climaxed just before the glacial maximum of continental ice, which reached to almost 1675 m in Porcupine Hills. All continental tills in stratigraphic sections may be explained by a single continental glaciation with a fluctuating ice margin.	Based interpretations of stratigraphic sections and 1:150 000-scale mapping. Proposed one single, Late Wisconsinan continental glaciation event marked by several sub-events of retreat and readvance. Disagreed sharply with Horberg's (1954) Montane chronology and Stalker's (1963) continental stratigraphy and chronology.	Montane: 1: MI (Cloudy Ridge) 2: MII, Cirque moraines (restricted to mountains) Continental: 1: Basal till 2: Lower till (advanced to Porcupine Hills, Kimball moraine) 3: Upper till (Lethbridge moraine)	No
Bayrock (1969)	Southern Alberta, and adjacent areas in Saskatchewan and Montana	An ice-free corridor existed along the Rocky Mountain Foothills during Nebraskan, Kansan, and Illinoian time. Continental ice only advanced into southern Alberta, closing the corridor, during the late Pleistocene (Wisconsinan glacial stage).	Disagreed with Stalker's (1963) interpretation of the Brocket section. Based conclusions on physiographic and stratigraphic positions of Saskatchewan sands and gravels in Alberta, and horse and mammoth fossils (determined to be late Pleistocene) found within this unit. Subsequently contradicted by Bayrock and Reimchen (1980) who recognized pre-Wisconsinan continental till in southern Foothills).	Continental: One till, unnamed	No
Day (1971)	49°50′ to 50°05′ N 113°35′ to 114°08′ W Trout Creek drainage basin, west of Claresholm	Porcupine Hills were glaciated twice by continental ice; pre-Wisconsinan (ice reached to 1750 m), and Wisconsinan (ice reached to 1460 m). No montane ice ever reached the study area.	Disagreed with Wagner (1966) and Horberg (1952). Based interpretations on 1:60 000-scale mapping and description and sampling of 69 exposures and soil pits, 7 of which exhibited both till units discussed. No interglacial sediments or soil horizons identified in or on older till.	Continental: 1: Porcupine till (more extensive) 2: Furman till	Yes

Table 1. (cont.)

Study[1]	Study area	Conclusions	Comments	Tills recognized (oldest to most recent)	Pre-LGM?[2]
Alley (1972; 1973; Alley and Harris 1974)	49°30′ to 50°20′ N 113°30′ to 114°45′ W Continental divide to Livingstone Range, foothills, Porcupine Hills, and plains east to to Fort Macleod	Three major episodes of decreasing magnitude in which montane ice advanced and retreated significantly before continental ice advanced. Early events were pre-Wisconsinan. Latest was Early Wisconsinan. Ice never coalesced at maxima.	Grouped Stalker's Maunsell, Brocket, and unnamed tills into one Maunsell till. Based interpretations on stratigraphic sections and 1:50 000-scale mapping (not included in publication).	Montane: 1: Albertan 2: Maycroft 3: Ernst 4: Hidden Creek (valleys only) 5: Cirque moraines Continental: 1: Labuma 2: Maunsell 3: Buffalo Lake	Yes
Stene (1976)	49°40′ to 50°10′ N 114°10′ to 113°35′ W Porcupine Hills	Fossils found in alluvium and lake sediments in Porcupine Hills river valleys only date back to 14 ka BP; therefore ice must have been present in these valleys in the late Wisconsinan. Porcupine Hills were glaciated three times in late Wisconsinan time, the first time being the most extensive.	Based interpretations on re-examination of some key sections of other workers (mainly Stalker) and ^{14}C dates from fossils. Disagreed with the hypothesis that SW Alberta was not glaciated in late Wisconsinan.	Continental: 1: Labuma (deposited Shield erratics to 1675 m) 2: Maunsell (hummocky till deposits in valleys to 1370 m) 3: Buffalo Lake (deposited Foothills Erratics Train, to 1250 m)	Yes
Stalker and Harrison (1977)	48°45′ to 50°00′ N 113°00′ to 114°45′ W From mountain front to SW corner of plains, and U.S. border to Oldman River.	At least 4 major events since Illinoian time, each consisting of first one montane advance then a continental advance, decreasing in intensity and strength with time. In addition, a continental glaciation in classical Wisconsinan time reached only as far as Lethbridge and Medicine Hat. Continental ice did not reach study area during classical Wisconsinan time.	Based interpretations on data obtained from previous work by both authors and other workers. No new data was presented.	Montane: 1: Waterton I (Great glaciation) 2: II (synchronous with 4 below) 3: III (synchronous with 5 below) 4: IV (synchronous with 6 below) Continental: 1: Labuma (Great glaciation) 2: Maunsell 3: Brocket 4: Buffalo Lake 5: Foothills Erratics Train advance 6: Lethbridge and Medicine Hat advances (one event)	Yes
Bayrock and Reimchen (1980)	Alberta foothills, British Columbia to Montana	One incursion of continental ice sheets into the foothills prior to the late Wisconsinan	Based age of tills on depth of leaching and 'freshness' of topographic features such as moraines.	Montane: At least one and possibly two montane tills of pre- Late Wisconsinan age and two of Late Wisconsinan age. Continental: One pre-Late Wisconsinan till and one Late Wisconsinan till	Yes
Jackson (1980)	50°00′ to 51°00′ N 114°00′ to 114°45′	Two advances of montane and continental ice into the foothills and two readvances of montane glaciers within Rocky Mountains, all during the Pleistocene; one late Holocene (neoglacial) advance within the mountains.	Based on correlation with Stalker and Harrison (1977)	Two continental tills	Yes
Richmond (1986)	Glacier National Park and adjacent interior plains, U.S.A.	Cited evidence for seven montane glaciations and two by continental glaciers	The two youngest montane glaciations are equivalent to the two continenal glaciations. The youngest of these is late Wisconsian in age and the penultimate is considered to be Illinoian based on soils developed in them and freshness of moraines	Montane: Cutbank Creek Formation, (three tills: Late Wisconsinan) St. Mary Ridge Formation, (Two tills: Bull Lake Glaciation) Kennedy Formation (four tills: middle to early Pleistocene) Continental: Boundary Creek till (Late Wisconsinan) Emigrant Gap till (late Illinoian)	Yes

Table 1. (cont.)

Study[1]	Study area	Conclusions	Comments	Tills recognized (oldest to most recent)	Pre-LGM?[2]
Karlstrom (1988) Barendregt et al. (1991)	Mokowan Butte area (49°00′ to 49°10′ N 113°30′ to 113°35′	Four advances of early Pleistocene and Pliocene montane glaciers base on cemented diamicts interpreted as till, intervening paleosols, and relative paleomagnetic dating.	Part of a larger study of fossil soils and interstratified diamicts capping the Flaxville surface on both sides of the international border.	Montane: Four pre-Wisconsinan tills recognized Continental: none recogized	Not applicable
Liverman et al. (1989)	55°00′ to 55°45′ N 117°45′ to 118°15′ W Two river-cut sections in west central Alberta.	The study region and areas to the south and west were glaciated by continental ice only in the Late Wisconsinan, the Quaternary glacial maximum.	Based interpretations on ^{14}C dates of wood samples derived from sand and gravel stratigraphically below continental till, and lacking in Canadian Shield material.	Continental: One till, unnamed	No
Young et al. (1994)	53°00′ to 35°40′ N 113°20′ to 113°50′ W Sub-till valley fills in west central Alberta.	Dates of fossils found below continental till are between 21 and 43 ka BP. Only one Late Wisconsinan event at Edmonton, and therefore areas that are at higher elevation and further to the south and west will share the same glacial history.	Based interpretations on stratigraphic sections and 29 organic samples from preglacial Saskatchewan sands and gravels.	Continental: One till, unnamed	No
Little (1995)	49°00′ to 49°15′ N 113°00′ to 114°00′ W	Only one Late Wisconsinan major advance of continental ice reached Waterton Park region reaching a maximum of 1585 m elevation. It coalesced with existing montane glaciers, retreated, readvanced to 1430 m, before retreating out of study area.	Based interpretations on stratigraphic sections, glacial sedimentology, and 1:50 000 mapping.	Montane: 1. Late Wisconsinan till 2.Two or more early Pleistocene (*after* Karlstrom (1988) Continental: Two drift belts, one till, unnamed	No
Leboe (1996)	49°15′ to 49°45′ N 113°30′ to 114°00′ W (NTS 82 H/5, 82 H/12 and parts of 82 G/9)	Only one continental glacier reached the area following a major montane advance. Several readvances of continental ice occurred during overall retreat.	As above	Montane: One Late Wisconsinan till (unnamed). Continental: Locally as many as three tills, perhaps more due to local readvances (unnamed)	No
Jackson et al. (1996)	Southwestern Alberta	Foothills Erratics Train and erratics from the Canadian Shield at the limit of former glacial cover are late Wisconsinan age.	Application of cosmogenic ^{36}Cl exposure dating	All drift in southwestern Alberta Foothills is Late Wisconsinan	No
Holme (1998a); Holme et al. (2000)	49°15′ to 49°30′ N 114°00′ to 114°15′ W	One continental ice sheet advance reached the northeastern corner of the study area. Two montane advances were recongnized. Both coalesced with the continental ice sheet.	As above	Montane: Two Late Wisconsinan tills	No
Jackson et al. (1999)	Southwestern Alberta	Highest erratics on Porcupine Hills, maximum continental glacial advance, montane readvance and continental readvance in Waterton to Cardston area date as Late Wisconsinan.	Application of cosmogenic ^{36}Cl exposure dating. Maximum continental glaciation is Late Wisconsinan age.	Montane readvance (M2) till and maximum continental (C1) and continental readvance till (C2)	No
Karlstrom (1999)	Glacier National Park and adjacent interior plains, U.S.A.	Montane and continental glaciers coalesced immediately south of the international border during the Late Wisconsinan. Evidence is present to support a pre-late Wisconsinan coalescence of montane and continental glaciers.	Largely corroborates Richmond 1986.	Similar to Richmond (1986)	Yes

[1] The assignment of contemporary chronostratigraphic units to previous work is the authors' interpretation. Where present, these units are indicate by bold letters *e.g.* Late Wisconsinan.

[2] "Pre-LGM?" means "Did the authors recognize evidence of continental glaciation prior to the most recent?

Methodology

Surficial geology mapping

Surficial geology mapping divided the unconsolidated deposits of the study area (uppermost 1–1.5 m) according to their genesis and provenance. The morphology of deposits aided in determining genesis and defining unit boundaries. The first step in the mapping process was to define preliminary map-unit boundaries based on airphoto analysis. Field checking followed with road traverses and foot traverses.

Road traverses

A one-mile-square grid of roads and trails following the Township and Range survey system covers most of the study area. Field checking involved east-west and north-south traverses along these roads and road allowances. Auger holes were driven to 1 m (or refusal) below the surface at approximately 2 to 3 km intervals where natural exposures or roadcuts were lacking. Sediments encountered with hand auger or exposed at roadcuts were described according to texture, colour, pebble lithology, and other relevant information. In hilly areas, roadcuts are more common and more direct observations of the uppermost sediments could be made; other exposures such as river-cut banks, gravel pits, and slump scarps were described where encountered. Over 3000 such observations were made over the entire study area.

Foot traverses

Foot traverses were carried out in areas of high relief such as the Porcupine Hills, where there is little or no road access. In addition to ground-checking the airphoto interpretation, ice limits were established in these areas by identifying the highest erratics at the highest elevation derived from the Canadian Shield or Rocky Mountains. Meltwater erosion features (e.g. notches, ice-walled channels) and other glacial features (e.g. end and recessional moraines) were also noted. Overall control-point density was about one every 5 km^2. However, control-point density was increased where initial airphoto interpretation identified surficial deposit complexity. Access was denied to the Peigan 147 Indian Reserve (Fig. 5, link), consequently no field checking was done within it and map units within that area are based entirely on airphoto interpretation.

Final maps

Sediment types, surficial unit boundaries, and morphological features were mapped on airphotos. Map features on airphotos were manually transferred to topographic bases using road allowances and topographic contour lines and other physiographic features as control points. Map polygons and their labels were digitized from topographic maps using a large-format digitizing tablet for final digital cartography.

Twelve 1:50 000-scale surficial geology maps were prepared for the area (Holme 1998a, b; Jackson 1997a, b; Jackson, 1998a, b, c; Jackson and Leboe, 1998; Leboe, 1998a, b; Little 1998a, b, c). These maps, along with field notes and analytical data, are presented in Shimamura et al. (2000). They have been generalized into a 1:250 000-scale map presented in Figure 5.

Stratigraphic sections

Ninety-nine cliff-bank and artificial exposures were logged and described in detail along streams and reservoirs throughout the study area. All exposures previously visited by Stalker (1963) and Wagner (1966) were redescribed where they were still accessible, i.e. not buried by colluvium or submerged beneath a reservoirs waters. The described sections are digitally linked to locations shown in Figure 5. They can also be directly accessed in Appendix A in alphanumerical order. Along the side of each detailed described section is a generalized strip log. These are correlated along lines of section indicated on Figure 5 (e.g. A-A'). Included among these sections are sections described by Stalker (1963) and Wagner (1966) for exposures no longer accessible along Castle River due to subsequent slumping or submergence beneath the Oldman Reservoir (sections Wr20, SW1, and SW2). Section O2 along the Oldman River near Brocket is still accessible, but permission for detailed study was not granted by the Peigan First Nation. Only one short visit for the purpose of general confirmation of Stalker's (1963) and Wagner's (1966) stratigraphies was permitted as guests of local residents.

Generalized stratigraphy based on the described sections and stratigraphic units defined from them is presented in Figure 6. Many of the sections studied are exposures of sediments filling valleys that existed prior to the first incursion of a continental ice sheet into the foothills (Stalker, 1961). For the most part, extant streams have reoccupied and partly excavated these buried courses. Figure 7 depicts the location of these courses and other notable drainage changes induced by glaciation.

Unit description and measurement

Stratigraphic units were defined using a lithofacies approach similar to that of Eyles et al. (1983), but without using facies codes. For each unit, several different nongenetic properties were described: texture, colour, clast angularity and lithology, visual determination of percentage of clasts greater than 4 mm (stoniness), and sedimentary structures. The nature of each contact was described as sheared (includes sediment translated along subparallel and subhorizontal planes, isoclinally folded, or brecciated), erosional (scoured by water or polished and striated by ice), and conformable (depositional succession of units without intervening erosion) including abrupt or gradational. Where long, nearly continuous exposures were available, photomosaic pictures

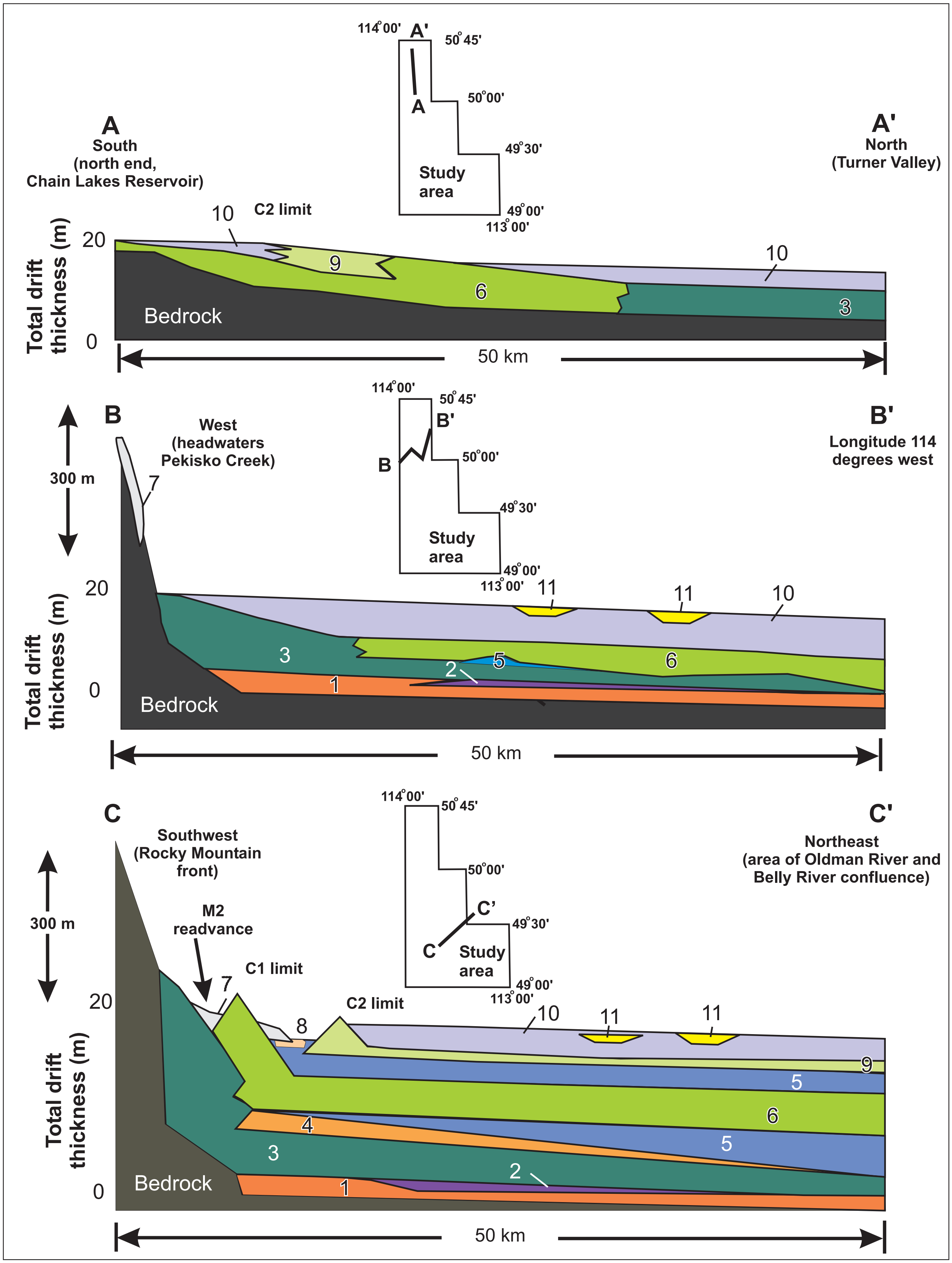


Figure 6. Generalized stratigraphy of the study area north of the Porcupine Hills (A–A' and B–B') and south of Porcupine Hills (C–C'). Based on stratigraphic data presented with Figure 5.

Drainage prior to the last glaciation and postglacial drainage changes

Drainage prior to the last glaciation (more than 30 ka ago) is indicated by red arrows. Sheep River, Highwood River, and the North and South Willow creeks followed the same valleys as they do at present. Crowsnest River followed a now buried valley south of Burmis (B) and joined Castle River near Beaver Mines (BM). The extant valley of Crownsnest River between Burmis and the gorge occupied by the Oldman River dam (D) and the course of Castle River between c-c' were cut during postglacial time. Oldman and Castle rivers merged near the site of the Town of Pincher Creek (PC) and flowed northeast toward the site of Brocket (Bt). Contemporary Pincher Creek follows the same valley. An apparently older valley (dashed yellow line) marks course of Oldman River which merged with the valleys of Drywood Creek, Waterton River and Belly River earlier in the Pleistocene. St. Mary River followed a broad valley (p-p') that is now followed by the contemporary Pinepound Creek. The present course of St. Mary River (s-s') was cut during postglacial time. Cloudy Ridge (CR) and Mokowan Butte (MB) are the only sites where (montane) glacial deposits that predate the last glaciation occur.

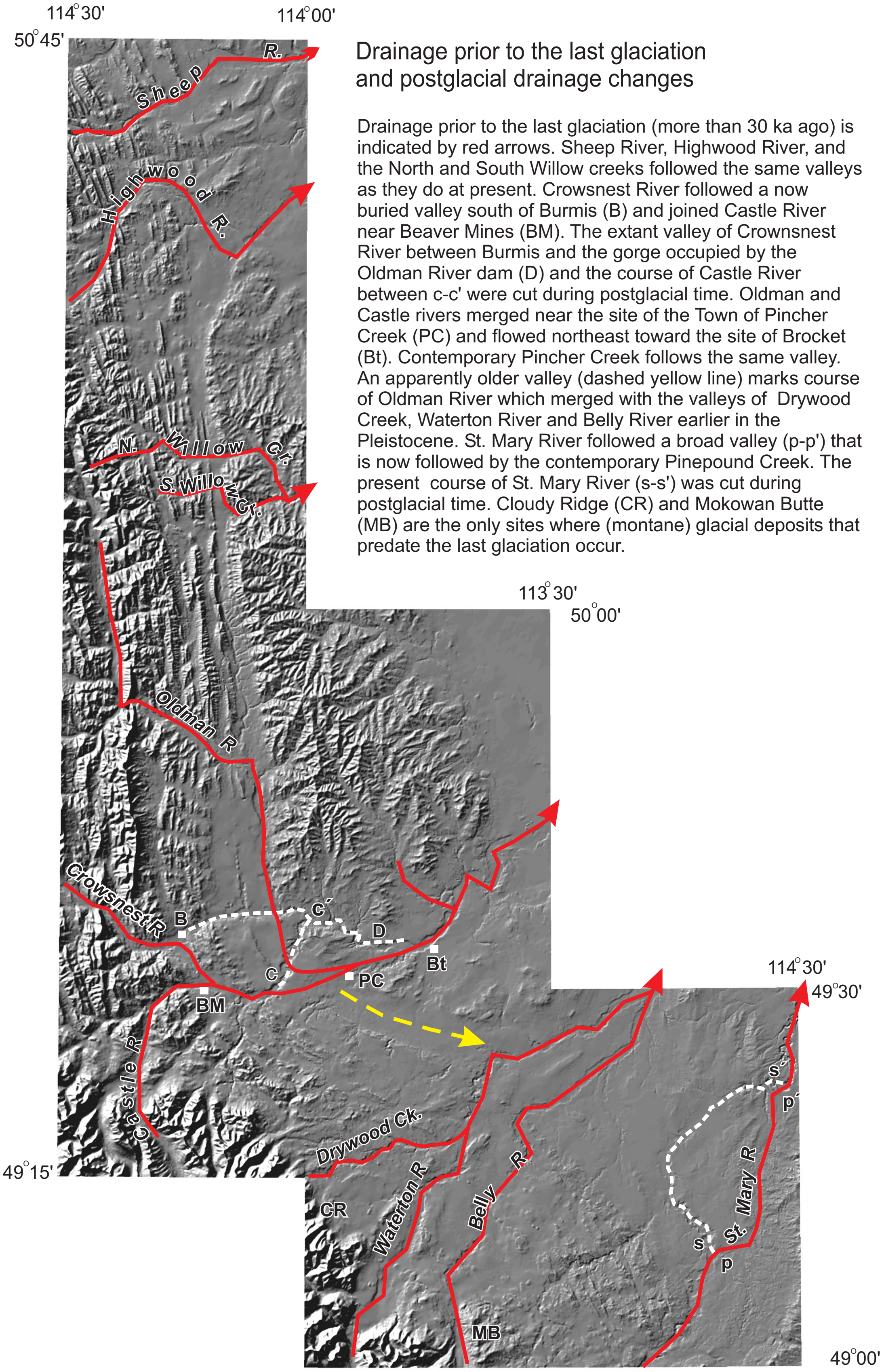


Figure 7. Preglacial drainage and postglacial drainage changes in the southwestern foothills.

were taken as an aid to correlation. These were taken from boats when on reservoirs, or from the opposite shore along rivers (Leboe, 1996). Cliff-bank exposures were studied and measured directly without climbing aids where slopes were sufficiently gentle. However, many sections were nearly vertical and these were described and sampled using a two-rope, belayed safety system (Fig. 8). This technique allowed investigations of cliff banks, which were unavailable to previous investigators due to their inaccessibility.

Three-dimensional pebble fabrics

Three-dimensional pebble fabrics (azimuth and plunge of elongated clasts) were measured in many diamicton units in order to infer glacial sedimentary environment of deposition and ice-flow direction where a subglacial environment was indicated. The orientations of between 30 and 50 rod-shaped pebbles were measured within a 1 m^2 area on the cleared face of an exposed diamicton. This data was entered into Stereo™, a three-dimensional orientation analysis and plotting program developed by RockWare Scientific Software (RockWare™,1992). This program computes eigenvalues and eigenvectors and related statistics for the three-dimensional pebble-orientation data. The results of these analyses are digitally linked to described sections that are in turn linked to Figure 5 (1:250 000 surficial geology map). They can also be accessed through digital links by directly accessing the sections in Appendix A. For each analysis, two stereograms (lower-hemisphere Schmidt nets) and related statistics are presented. The upper stereogram is a plot of pebble azimuth and plunge. Mean azimuth and plunge values are indicated by a red dot. The lower stereogram is a contoured plot. The contours, in standard deviation units, do not change between diagrams for comparison. Statistics presented with the diagrams are discussed in Appendix B. The fabrics aided in determination of the direction of the flow of glacial ice that deposited the till and provided information useful in the interpretation of the environment of deposition of tills and their stress histories (Hicock et al., 1996).

Figure 8. Two-rope system used for investigation of near vertical cliff-bank sections. Upper rope at chest is a rappel rope under the control of investigator. The lower rope is a belay rope under the control of a belayer located at the cliff top. Each rope is fixed to a separate anchor system. A two-way radio (antenna at shoulder) allows communication with belayer who takes notes and raises and lowers samples. GSC 2003-295

Pebble lithology

Provenance of all diamictons and some gravel units was determined by collecting and identifying representative samples of 50 pebbles from each unit. The results of these pebble counts are digitally linked to described sections that are, in turn, linked to Figure 5 (1:250 000 surficial geology map). They can also be accessed through digital links by directly accessing the sections in Appendix A.

Textural analysis

Diamicton samples taken from cliff-bank exposures, roadcuts, and auger holes were collected for textural analysis (weight percentage of sand, silt, and clay, and coarser-than-sand fractions). Analyses of these samples were carried out at the Sedimentology Laboratory of the Terrain Sciences Division, Geological Survey of Canada, Ottawa.

Paleomagnetism and polarity determination

Very fine-grained sand, silt, clay, and diamicton matrix may record the orientation of the Earth's magnetic field at the time of deposition (Barendregt et al., 1991; Cioppa et al., 1995). Paleomagnetic samples were taken to determine if any of the Quaternary sediments in the area predate the last magnetic reversal (ca. 780 ka; Cande and Kent, 1995). Samples were taken vertically through most of section C9 (Fig. 5, section J-J') and from the two lowest diamicton units in O2 (the Brocket Section of Stalker (1963)). These sections were suspected to include deposits spanning much of the Pleistocene (Stalker, 1963). A total of 84 samples was collected and analyzed. Samples were analyzed under the direction of R.W. Barendregt, University of Lethbridge, and R. Enkin and J. Baker at the Paleomagnetism Laboratory of the Pacific Geoscience Centre of the Geological Survey of Canada, Sidney, British Columbia. Stepwise alternating field demagnetization was carried out by treatment along three axes successively, using a Schonstedt GSC-5 magnetometer for fields up to 100 mT, and Sapphire Instruments SI-4 magnetometer for fields up to 180 mT. Measurements of natural remanent magnetization were made on fully automated Schonstedt spinner magnetometers. All of the samples had remanent magnetism consistent with the present Brunhes Chron (Appendix C).

Cosmogenic ^{36}Cl exposure dating

This dating technique employs measurements of the accumulation of cosmogenic ^{36}Cl in glacial erratics. Assuming no cosmic-ray exposure of the erratic prior to glacial transport, the accumulated ^{36}Cl, in conjunction with calculated cosmic-ray flux, can be used to estimate the time since the erratic was deposited. Upper surfaces of erratics were sampled to a depth of 2 cm by hammer and chisel or diamond drilling. Methodology, theory, and results were described in detail in Jackson et al. (1996, 1999) and in the 'Glacial history and chronology' section of this report. Cosmogenic ^{36}Cl exposure dating theory and analytical methodology were described in Phillips et al. (1996), Zreda et al. (1994), and Liu et al. (1994).

AMS radiocarbon dating

Fossil bone or shell was found interstratified with glacial deposits at several locations. Accelerator mass spectrometer (AMS) radiocarbon ages were determined on these samples in order to constrain initiation and termination of glaciation in the study area. Samples were removed with clean metal implements and stored in clean plastic bags or aluminum foil in order to avoid contamination prior to shipping to commercial labs. Sample preparation and AMS analyses were carried out at Isotrace Labs, University of Toronto, and Beta Analytic, Miami, Florida, U.S.A. (AMS analysis at Lawrence, Livermore National Laboratory, California). AMS ages determined on samples collected as a part of this study are shown in stratigraphic context in sections linked to Figure 5 and presented separately in Appendix A. These ages and relevant AMS and conventional radiocarbon ages reported in other studies are compiled in Table 2 along with analytical corrections and error values. Their implications for the chronology of glacial events are discussed in 'Glacial history and chronology'.

SURFICIAL GEOLOGY

This section describes surficial geology units defined in Figure 5. The 1:250 000-scale surficial geology map contained within this figure is generalized from twelve detailed 1:50 000-scale surficial geology maps previously referenced. An extensive stratigraphy of glacial sediments underlies the surface in many areas. These subsurface units are addressed in 'Quaternary stratigraphy'. This section describes deposits that directly underlie the surface (uppermost 1–1.5 m). Physical properties and clay mineralogy of surficial sediments, including engineering properties such as Atterberg limits and compaction (Procter density) properties, have been reported by Jackson (1987) for the northern part of the study area. His findings are applicable throughout the study area because of similarities in bedrock and surficial geology.

Glacial sediments: terminology

The last three decades of the twentieth century saw great advances in the understanding of ancient glacial sedimentary environments through the investigations of contemporary glacial environments (*see* Benn and Evans, 1997 for the most up-to-date summary of this research at this writing). These advances have led some sedimentologists to advocate that the use of the term 'till' be restricted only to a sediment which can be demonstrated to have been deposited beneath flowing ice by lodgement (Lundqvist, 1988). Classification schemes have been devised for glaciogenic deposits based upon the precise knowledge of their origin (*see* Dreimanis (1989), for a history of classification schemes). However, in practice, such schemes have very limited application for mapping of Quaternary stratigraphy over broad areas (e.g. Lundqvist, 1988) because tills from different sedimentary environments frequently have many overlapping properties which make them indistinguishable in the field without extensive detailed analysis (Dreimanis, 1989, his Appendix D; Levson and Rutter, 1988). Minor, debatable differences in observation can lead to major differences in interpretation. Furthermore, as noted by Levson and Rutter (1988) classification schemes are in a state of flux, placing existing terminology for glaciogenic sediments in peril of being superceded in a few years. In this report, the term 'till' is used *sensu lato* after Dreimanis (1982): "Till is a sediment that has been transported and is subsequently deposited by or from glacier ice with little or no sorting by water." Consequently, compatible with the mapping of surficial geology of extensive areas, a two-fold classification scheme was used here: till of basal or supraglacial origin. In this report, basal till, embracing lodgement and basal melt-out processes, indicates sedimentation beneath flowing and stagnant ice, respectively. Conversely, supraglacial till (predominantly flow till in this study area) indicates ice-marginal sedimentation or supraglacial sedimentation in areas of stagnant ice. In the discussions of surficial deposits and stratigraphic sections that follow, the terms lodgement, melt-out, and flow till will be used following the criteria of Dreimanis (1989, his appendix D).

The non-genetic (sedimentological) term ‘diamicton’ is used to denote massive or nearly massive matrix-supported stony sediments in the descriptions of the deposits so as to clearly separate observations and interpretations.

Classification of surficial materials

Late Tertiary to middle Pleistocene glaciogenic sediments (T^{MP})

These deposits are restricted to the summit of Mokowan Butte near the International Border and Cloudy Ridge, northeast of Waterton Lakes. More than 30 m of diamictons with thick paleosols developed within them are found at Mokowan Butte. Portions of these deposits have been extensively cemented to form diamictite (calcrete)-diamicton successions. Lithologies of clasts forming this succession indicate that it was derived from the Lewis Range and Clark Range immediately to the west.

The Mokowan Butte succession has been extensively studied by Karlstrom (1988), Barendregt et al. (1991), and Cioppa et al. (1995), who showed it to range from the mid Pleistocene to the Late Tertiary based on paleomagnetism and paleopedological studies. The origin of the diamictons that form this deposit is controversial (*see* Little, 1995, p. 78–85). Glacial and nonglacial origins have been suggested. However, clasts in the uppermost diamicton are clearly striated and suggest a glacial origin for it. Whether it represents sedimentation in a subglacial or superglacial environment has not been determined. The term till is assigned to this unit with a considerable amount of uncertainty. Reconstructions of glacial limits by Jackson et al. (1996) has shown that this sediment lies above the surface elevations of glaciers that existed within the study area during the most extensive known advance of montane glaciers. Thus, the till capping Mokowan Butte apparently predates all other surficial deposits in the study area by many hundreds of thousand of years. It was laid down at a time when the level of erosion was well above the present landscape (Jackson, 2002).

At Cloudy Ridge at the Rocky Mountain Front, 1 to 1. 5 m of montane-provenance till overlies a reddish-orange paleosol developed in about 7 m thick diamicton. The lower part of the diamicton has been naturally cemented into a diamictite apparently due to pedogenic processes associated with the formation of the soil. The montane till that caps the entire section is overlain by Canadian Shield erratics dated by ^{36}Cl techniques as Late Wisconsinan (Jackson et al., 1999; *see* ‘Glacial history’). The thickness and colour of the buried soil is similar to that capping Mokowan Butte, and it is clearly related to an interglaciation earlier in the Pleistocene during which a substantially warmer climate existed in the area. It remains to be studied in detail. Little (1996) investigated the diamicton which forms the parent material for this soil. He found it to have a fabric indicating that it was transported from the south (Rocky Mountains), which is compatible with its stones and matrix from that source. He was unable to determine to his satisfaction if the diamicton was glacial in origin or the remnant of an alluvial fan that formerly covered the Cloudy Ridge surface.

Morainal (till) sediments (T^M, T^C)

Morainal deposits include till and minor glaciofluvial and glaciolacustrine sediments. Included within this heading are, in order of thickness, till veneer (discontinuous patches), till blanket or ground moraine (>1 m but thin enough to reflect undulations in the underlying bedrock surface), and belts of hummocky moraine, which hide underlying topography Hummocky moraine is most commonly associated with the C2 glacial limit.

The lithology of pebbles and larger clasts within tills of the area reflect distinctive glacial provenances. The infusion of Canadian Shield lithologies into southern Alberta, in addition to geomorphic and glacial geological evidence, indicates that these materials are far travelled (>600 km) and hence, glacial transport from the Canadian Shield is the only viable mechanism to explain the presence of these lithologies in the drift of southwestern Alberta (Little et al., 2001). Notwithstanding, later reworking of Canadian Shield lithologies by both montane and continental ice sheets have, in some cases, incorporated these lithologies within their respective deposits (*see* the ‘Quaternary History’ section).

Morainal deposits on Figure 5 are subdivided largely on this basis of provenance of till clasts (*see* pebble count histograms for samples linked to the map and in Appendix A). T^M designates till deposited by glaciers originating in the Rocky Mountains (montane) and T^C designates till deposited by glacier ice originating from the Canadian Shield (Gravenor and Bayrock, 1961). The term ‘continental till’ is applied to it in this paper. It is readily identified by the presence of up to five per cent clasts of high-grade metamorphic rocks (schist and gneiss) and plutonic rocks from the Canadian Shield. There are no sources for gneissic, schistose, and plutonic rocks with the exception of very rare small gravel-sized granitic erratics within the Rocky Mountains of southern Alberta and contiguous areas of Montana (Wheeler and McFeely, 1991; Douglas, 1950, p. 23). Till matrix texture ranges predominantly from loam to silty clay loam (Fig. 9). Jackson (1987) showed that montane-provenance tills tend to be generally coarser over the textural range 32 mm to 0.002 mm (-5Φ to 9Φ) than continental-provenance tills that were deposited by glacial ice that traversed easily erodable clastic rocks (shale, mudstone, and sandstone) of the Interior Plains. He found that montane tills were particularly enriched in the 32-2 mm (-5Φ to -1Φ) textural range and attributed the greater content of clasts in this coarse size range to the following: 1) close proximity of the resistant lithologies in the Front Ranges and Rocky Mountain Foothills; 2) short distance of transport from outcrops; and 3) the rugged relief of the Front Ranges and foothills that favours glacial erosion by plucking and quarrying and rock falls onto glaciers (Jackson, 1987, p. 7; Jackson, 2002). An example of the grain-size

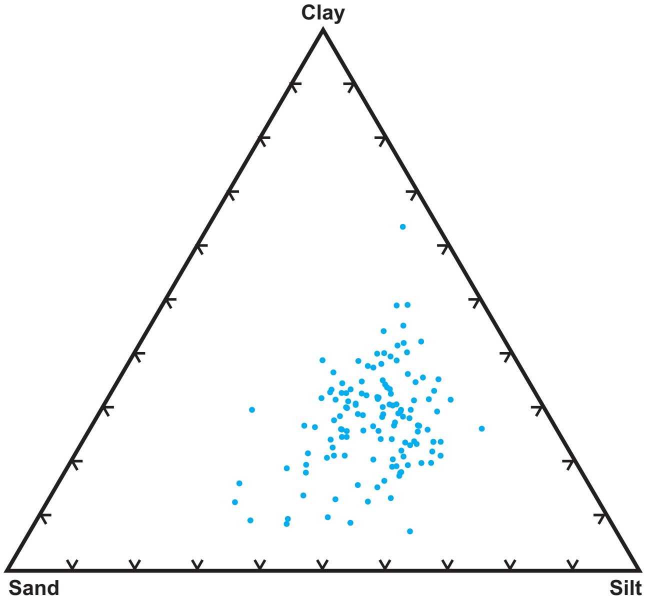


Figure 9. Textures of tills in the study area.

Figure 10. Unit 6A, till containing stones from the Canadian Shield (C1 advance) overlying montane till (unit 3; M1 advance) in section H2 along Highwood River. GSC 2003-296

contrast between montane (unit 3) and continental (unit 6) tills is given in Figure 10. Further, where montane till forms the primary surficial unit, the surface is studded with cobbles and boulders of quartzite and carbonate rock, whereas the surfaces underlain by continental till are markedly less stony.

Glaciofluvial sediments (G)

These include gravel and sand with minor silt and diamicton deposited by stream flow beneath, on, and/or along, the margins of glaciers (e.g. kames, kame terraces, and eskers), as well as those sediments deposited in distal glacial environments. Sediments range from poorly to well sorted, and stratification may range from massive to crudely planar; ice-contact environments exhibit extreme variability in sorting and lateral discontinuities whereas outwash and meltwater channel gravels are moderately to well sorted. The general texture of these deposits is usually related to distance from former ice margins — they become finer and better sorted with increasing distance from the glacial margin.

Within the map area, the most common (distribution and aerial extent) glaciofluvial deposits are associated with early deglacial channelized meltwater output. Second are late deglacial outwash plains that underlie the highest terraces of extant rivers. Deltas graded to glacially dammed lakes are the third most common glaciofluvial deposits in the study area. Thickness of glaciofluvial sediments ranges from less than 1 m to 10 m. Clasts are dominantly resistant lithologies such as quartzite, limestone, dolostone, sandstone, and gabbro. Resistant granitic and metamorphic lithologies from the Canadian Shield are common within areas influenced by continental ice.

Glaciolacustrine sediments (L)

These sediments were deposited in lakes created by the margin of the Laurentide Ice Sheet as it dammed eastward drainage in Rocky Mountain Foothills valleys. The former lake basins range from less than 1 km^2 to more than 100 km^2. Glaciers retreated down the regional gradient; therefore, the lakes migrated eastward with the margin of the ice sheet. Consequently, the distribution of glaciolacustrine sediments in any one valley does not necessarily reflect a single glacial-lake stand, but rather numerous successive glacial lakes that drained and re-formed as drainage configurations into and out of the lake were modified by ice-margin advance and retreat. Also, the constantly changing margins of these successively forming lakes inhibited the formation of lacustrine strandlines or beaches; no such features were identified within the study area. Glaciolacustrine sediments are dominated by clayey silt and fine sand and are usually well stratified, with beds ranging from laminae (<1 cm) to bedded (>1 cm). Rhythmic stratification is common, with strata thicknesses often inversely related to texture. Clay-rich sediments are dominated by laminae deposited in lake environments well removed from ice margins. Conversely, closer to former ice margins the sediments coarsen to sand and beds thicken to up to 1 m. Dropstones and soft-sediment deformation features such as slumps, flame structures, and load structures are common in former ice-proximal settings.

Alluvial sediments (A)

Alluvial sediments include contemporary stream sediments, stream terraces, and alluvial fans. They are predominantly gravel and sand with local accumulations of fine sand, silt, and clay in restricted areas of floodplains. Thickness ranges from less than1 m to 10 m. Sediments are commonly moderately to well graded. Beds range from 10 cm to 1m and are internally planar to cross-stratified (Boggs, 1995).

Colluvial sediments (C)

These include the most diverse sediments under a single heading. Colluvial sediments include all unconsolidated surficial sediments produced by the physical and chemical breakdown of bedrock. They either rest in situ upon the bedrock from which they were derived or they have been transported primarily by gravitational processes such as creep and debris flow. Colluvial sediments may contain reworked till or other glacial sediments. Texturally, colluvial sediments range from bouldery landslide and rockfall deposits to a sandy-gravel mantle on gentle slopes. Thicknesses range from less than 1 m in the case of a residual soil mantle to 10 m in landslide deposits.

Eolian sediments (E)

Thin, discontinuous veneers (<1 m thick) of fine sand and silt are common throughout the study area. These were deposited by the wind during the Holocene. Human artifacts, including whisky bottles and oil industry debris, have been found within eolian deposits, indicating that deposition continues into the present day. Thickest accumulations are cliff-top dunes. These reach thicknesses of several metres along the rivers in the area.

Organic sediments (O)

Localized, thick accumulations of *Sphagnum* sp. and other water-loving vegetation occur in areas of poor drainage in floodplains and as infillings of former lakes. Thicknesses can reach 6 m. Sediment cores taken from these accumulations have provided extensive proxy records of postglacial climate change within the study area (Mott and Jackson, 1982).

QUATERNARY STRATIGRAPHY

The Quaternary stratigraphy for the study area is based on the detailed descriptions of 86 stratigraphic sections (Figs. 5, 6 and Appendix A) observed within natural exposures. These include three sections described exclusively by Wagner (1966) and two sections described by Stalker (1963). The authors have modified Wagner's and Stalker's descriptions only so as to bring them in accord with an approach that clearly separates observation and interpretation: units that Wagner and Stalker described as till have been labelled diamicton. Unit boundaries were not always described by Wagner and Stalker to the extent that they could confidently be called sheared, depositional, eroded, etc. In those cases, the authors have indicated their nature to be undefined (indicated by '?').

To augment the stratigraphy based upon the 86 stratigraphic sections, these sections have been integrated with thousands of roadcut exposures, hand borings, and 1:50 000-scale surficial geology maps (*see* Shimamura et al., 2000). Not included in this discussion are the glacial sediments of early Pleistocene and Pliocene age that underlie the summit of Mokowan Butte, which have been extensively investigated by others (Karlstrom, 1988; Barendregt et al., 1991; Cioppa et al., 1995; Karlstrom and Barendregt, 2001). Their significance in the glacial history of the region will be discussed in the 'Glacial History' section.

A total of thirteen widely correlative primary lithostratigraphic units were defined based upon field observations and laboratory analyses (unit 14 represents colluvium that obscures exposures). These primary units were defined on the basis of lithology, texture, colour, lateral continuity, and three-dimensional pebble fabric. Gradational or abrupt contacts representing depositional, erosional, or deformational environments bound units. At the regional scale of this report, many correlative units/boundaries are interpreted as discernable and widespread events. These units are described and interpreted in the following sections. Their lateral and vertical inter-relationships are summarized in the stratigraphic correlated sections accessed by clicking on the linked ends of the sections (e.g., A or A' on Figure 5).

These stratigraphic correlations are organized geographically by river basin. This approach was taken because the streams of the area generally follow older, buried valley systems (Fig. 7; Stalker 1961) in which successions of glacial deposits were deposited. These successions can be traced and correlated downstream within a basin with certainty. Stratigraphic comparisons between basins are made on the basis of repeated successions of similar sediments. This inter-basin correlation is warranted because the physiography of the region suggests that the drainage basins should have comparable glacial histories that are outlined below:

1. All major streams originate in the Rocky Mountains and flow east or northeast onto the Interior Plains. Consequently, periods of glacial advance in the Rocky Mountains should affect all basins.

2. Continental glaciers advanced into the drainage basins from the northeast up the regional slope and dammed drainage during advance and recessional phases. Thus periods of lake formation in one basin should be broadly correlative to lake formation in adjacent basins at approximately the same elevations. Previous work by Horberg (1952, 1954) and Alley and Harris (1974) has demonstrated inter-relationships between these glacially dammed lakes.

Unit 1: basal montane gravel

This gravel is the stratigraphically lowest unit found within buried valleys of the study area that ranges in thickness from lenses incorporated into the base of unit 3 to massive deposits at least 25 m thick (Fig. 11). Where its base is exposed, it overlies bedrock along an abrupt, erosional contact. It is clast supported with a texture that ranges from cobble to pebbly-cobble gravel and contains scattered pebbly sand lenses and bouldery facies. Where matrix is present, sand and granules fill the interstices. The gravel is poorly to moderately sorted, crudely stratified, and typically coarsens up-section.

Clasts within stratified layers are commonly imbricated, dipping up-valley, indicating stream flow from the west. Clast lithologies are derived entirely from the foothills and Rocky Mountains. For example, along Oldman River, above its confluence with Castle River, pebble and cobble lithologies in unit 1 are mainly carbonate, quartzite (Livingstone Range), volcanic rocks (Crowsnest Formation, Rocky Mountain Foothills west of the Livingstone Range), and locally derived sandstone and siltstone from the foothills (e.g. sections O9 and O11). The contemporary Oldman River drains these areas. In contrast, unit 1 along theCastle River is dominated by lithologies from the Lewis and Clark ranges (Purcell Supergroup) from the headwaters of the Castle River.

In many locations, the gravels become increasingly matrix supported up-section (e.g. section O11, Fig.6). However, some successions record more than one depositional episode. For example, section S3 (Fig. 5) displays a clear hiatus in gravel deposition delimited by involutions and crude ice-wedge pseudomorphs below, and undisturbed gravels above. Over much of the foothills, unit 1 is overlain by unit 3 (e.g. sections H1, C20, and W3). At some locations, unit 2 locally intervenes between units 1 and 3 (e.g. sections O2 and O11; Fig. 10). In areas most distant from the Rocky Mountains, unit 1 is overlain by unit 6 (section St1).

Unit 1: interpretation

The degree of rounding and sorting, and the large clast size of the cobbles indicates deposition in a moderate to high-energy fluvial environment that is proximal to the gravel source. The predominance of massive or crudely horizontally bedded gravel with some imbrication of clasts suggests deposition in longitudinal bars or as fluvial lag deposits (Miall, 1978). Crude horizontal stratification, with coarse gravel layers separated by thin, finer-gravel layers may be the

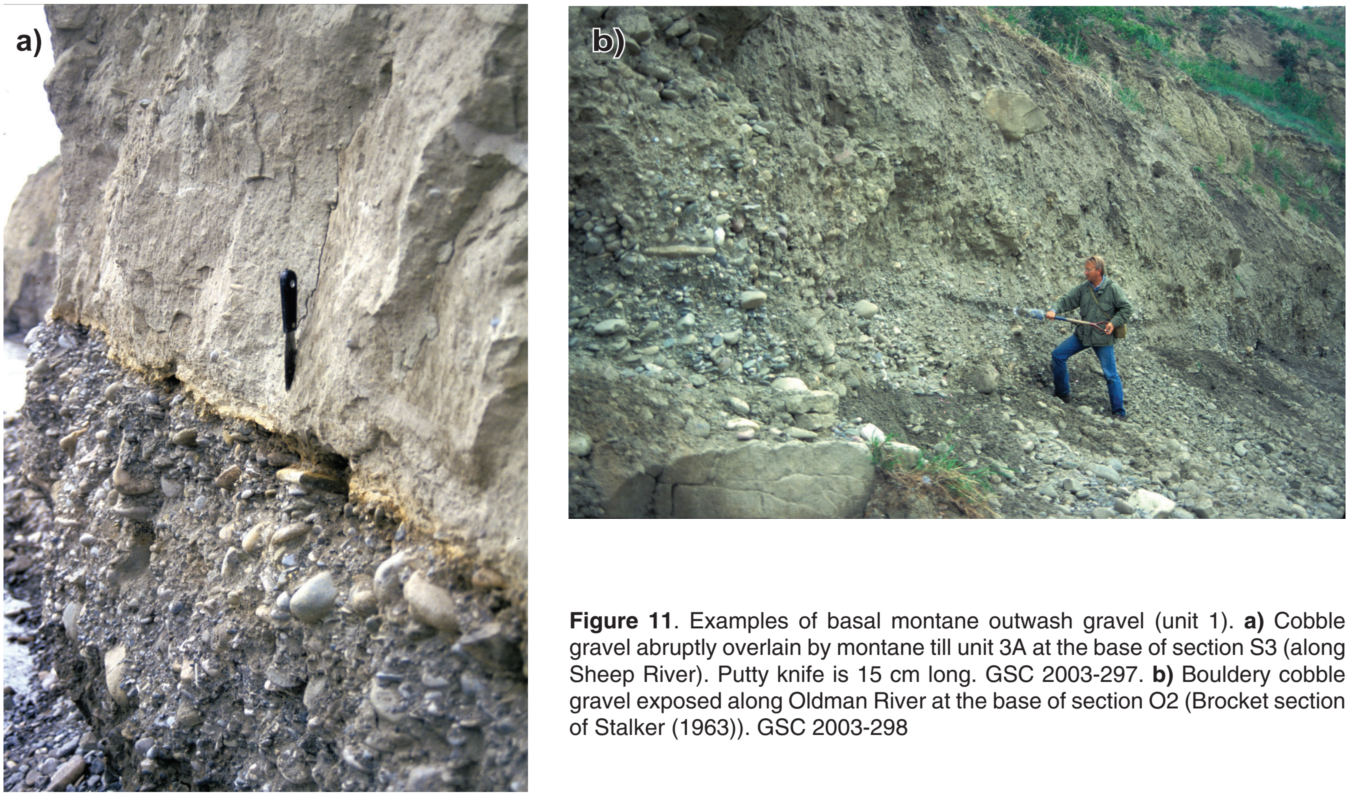


Figure 11. Examples of basal montane outwash gravel (unit 1). **a)** Cobble gravel abruptly overlain by montane till unit 3A at the base of section S3 (along Sheep River). Putty knife is 15 cm long. GSC 2003-297. **b)** Bouldery cobble gravel exposed along Oldman River at the base of section O2 (Brocket section of Stalker (1963)). GSC 2003-298

result of the aggradation of a series of diffuse gravel sheets in longitudinal and diagonal bars in a gravelly braided river (Hein and Walker, 1977). The lack of observed planar or trough crossbedding is further indicative of a shallow-water depositional environment (Church and Gilbert, 1975).

The presence of involutions and ice-wedge pseudomorphs, and lack of any organic detritus sediments suggest that it was deposited under periglacial climatic conditions when flora and fauna were sparse. Its typical coarsening and decrease in sorting upward, total lack of Canadian Shield lithologies, and succession by glaciogenic sediments suggest that this unit is entirely or in part, outwash from the oldest advance of glaciers from the Rocky Mountains which have left deposits in the buried valley systems of the foothills (Dawson and McConnell, 1895; Wagner, 1966). Unit 1 is correlated with the 'Saskatchewan sands and gravels', described here and elsewhere in southwestern Alberta by McConnell (1885), Rutherford (1937), Westgate (1965), and Stalker (1968), and clearly predates continental glaciation.

Unit 2: sheared fine-grained stratified sediment

This unit consists of sheared stratified sediments directly overlying bedrock or unit 1. It ranges up to 1 m thick, and consists of undulating and distorted laminations and beds of clay, silt, and sand with scattered pebbles and small pebble lenses (dropstones). This unit increases in stoniness upward, and generally exhibits plucked and sheared lenses of laminated clay toward the top. This unit is present within sediment successions in the Oldman River basin (Fig. 5, sections O2 and O11; Fig. 12) and possibly within the Castle River Basin (cf. section C21). Typically, it appears as local lenses or has been incorporated as stratified sediments within overlying unit 3.

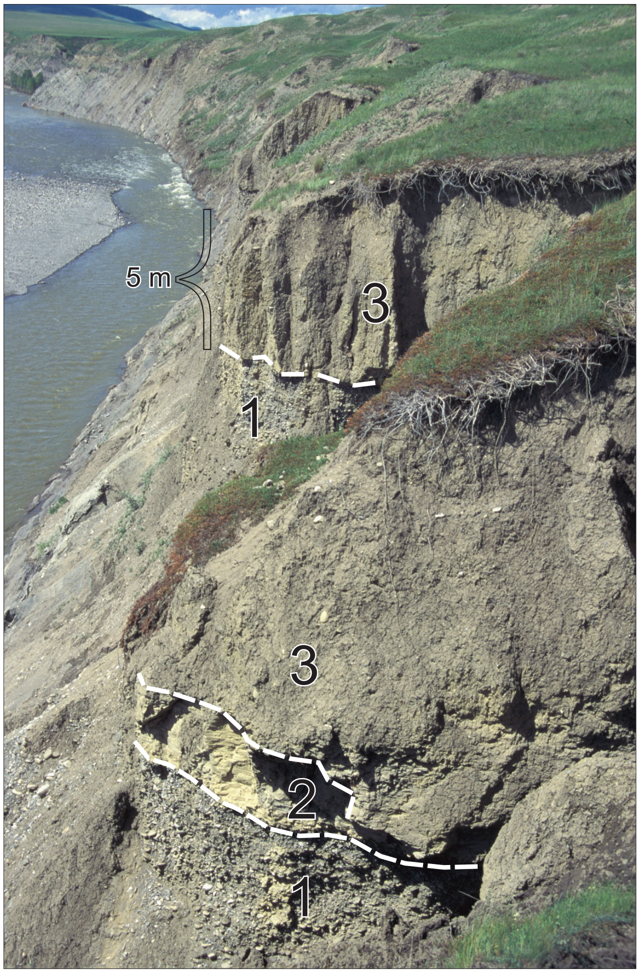


Figure 12. Succession of bouldery cobble gravel (unit 1) overlain by glaciolacustrine sediments (unit 2) and montane till (unit 3) above Oldman River (base of section O11). Unit 2 has been intensely sheared by the passage of ice that deposited unit 3. GSC 2003-299

Unit 2: interpretation

Unit 2 is typical of distal reaches of quiet-water deposition (Ashley, 1988). Scattered pebbles within laminae suggest that ice rafting was active in this glaciolacustrine environment. The stratigraphic position of unit 2 overlying bedrock or preglacial gravels (unit 1) suggests the lake was situated in a proglacial environment. The distorted nature of this unit reflects the deformation stresses imparted through the sediments as it was overrun by the advancing glacier. The presence of the first montane till (unit 3) that overlies unit 2 supports this interpretation. Where it is interstratified within unit 3, it indicates a termination of sedimentation by flowing ice and temporary existence of subglacial or proglacial environments.

Unit 3: montane diamicton complex

This unit is predominantly diamicton or a succession of diamictons. It ranges in thickness from 50 cm to more than 13 m; it can be traced along the base of buried valley systems in the study area with the exception of the St. Mary River buried valley (Fig. 7; Stalker, 1961). It occupies a stratigraphic position at, or near the base of the sections, and lacks any Canadian Shield lithologies (Figs. 10, 11A, 12). It either directly overlies bedrock, or it is separated from it by the basal gravel of unit 1 or glaciolacustrine sediments of unit 2. The unit consists of one to four montane and foothills provenance diamictons locally separated by either glaciofluvial sediments (unit 4) or interbedded fine sand, silt, and clay (unit 2). It ranges in colour from a light grey (10YR 7/2) where dry, to dark grey (10YR 4/4) or dark brown (10YR 3/3), where moist. It consists of massive, well consolidated, moderately stony (15% pebbles and larger) to very stony (25% pebbles and larger), friable, silty sand to clayey silt diamicton. It is stoniest where it overlies unit 1. Clasts are usually <10 cm, but boulders over 1 m in size are common. Resistant clasts are commonly faceted, and argillite and carbonate clasts are well polished and striated. Where it overlies mudstone and shale, its lower contact is usually sheared, with the underlying bedrock incorporated into its base. Lines of boulders locally mark this contact. Where it overlies resistant bedrock such as well cemented sandstone, the bedrock is striated and fluted. Where the unit overlies unit 1, resistant clasts are planed flat, polished and striated along the contact. In places, unit 3 contains thin lenses of clay or thin silt or fine gravel beds that are continuous over several metres.

Pebble fabrics determined on unit 3 are strong to very strong: first eigenvalues commonly above 0.6 and sometimes exceeding 0.7 (e.g. Fig. 5, section H1, fabric E; section H3, fabric A; section W3, fabric C). Fabrics are commonly bimodal but range to unimodal and girdle. Mean lineation azimuths generally parallel the directions of major foothills valleys and clasts generally plunge up-valley toward the Rocky Mountains. These orientations are consistent with long-axis-parallel striations on bullet boulders that are common within this unit and with shear structures that dip up-valley.

Unit 3: interpretation

Unit 3 is interpreted to be till formed beneath valley glaciers that originated in the Rocky Mountains and flowed in a down-valley direction. Abundant characteristics indicative of lodgement till include: over-consolidation, moderate to strong unimodal and bimodal pebble fabrics, fissility and shear planes, and sheared, comminuted or eroded lower contacts (Dowdeswell and Sharp, 1986; Mills, 1977, Hicock et al., 1996). The presence of faceted and striated clasts, as well as ‘bullet boulders’ (Dreimanis, 1989; Benn and Evans, 1997) that are striated and embedded with long-axes parallel to clast fabrics, and ‘pavements’ of boulders also indicate lodgement till deposition (Krüger, 1979, 1984). Shear planes, a basal comminution zone, bimodal particle-size distributions with poor sorting, and a high percentage of local lithologies near the till base are also good indicators of deposition at the base of an active glacier (Dreimanis, 1989).

Unit 4: proximal and distal glaciofluvial sediments

This unit is predominantly gravel and lacks any clasts from the Canadian Shield: it is entirely composed of sediments derived from the Rocky Mountains and foothills. It is found within the Highwood River basin (section P1) and within sections from the Castle River basin (sections C4, C5, C10–C13, and C15).

In places it ranges in texture from pebbly clay to laminated to pebbly sand, to poorly sorted and weakly stratified cobbly pebble gravel, to interstratified gravel and poorly consolidated diamicton. Stratification ranges from distorted and disorganized bedding to well bedded. Where it is disorganized, individual beds or lenses pinch out over very short distances (<1 m). Unit 4 ranges from 1 m up to almost 10 m in thickness where it is visible from base to top. It overlies unit 3 along an abrupt or erosional contact. It locally is interstratified with unit 3. Where unit 7 overlies unit 4, the contact is erosional and commonly sheared.

Unit 4: interpretation

This unit was deposited in a range of proximal proglacial or subglacial sedimentary environments ranging from ice-contact glaciolacustrine to moderate and high-energy fluvial environments. It marks a cessation of the major montane glacial advance that deposited unit 3 and subsequent retreat of valley glaciers prior to the readvance that deposited unit 7. Where it is stratified within unit 3, it represents local interruption of lodgement processes by sub-ice meltwater erosion and deposition. This has been reported elsewhere at various scales (Dreimanis, 1989; Shaw, 1985; Shaw et al., 1996). It likely marks the termination of the lodgement till deposition phase, and a transition to the ablation and resedimentation processes of a less active glacier.

Where it is gravelly, disorganized, and contains poorly consolidated diamicton beds and lenses, it suggests deposition in ice-marginal environments. Clay-rich sediments indicate the ponding of sediment-laden water in collapse depressions in areas underlain by ice. This is further supported by the co-occurrence of soft-sediment loading and collapse structures. These criteria are all indicative of an environment marked by sediment gravity flows from stagnant or retreating ice margins (Marcussen, 1975; DeJong and Rappol, 1983; Lawson, 1981). However, it should be noted that similar successions can be also produced in subglacial melt-out environments (Haldorsen and Shaw, 1982).

Massive or well stratified occurrences indicate distal glaciofluvial environments in Rocky Mountain Foothills valleys. For example, sections P1, C12, C13, and C15 (Fig. 5) are all situated in foothills valleys. Unit 4 clearly represents outwash deposition following a major montane valley glacier advance and preceding a montane valley glacial readvance (Holme et al., 2000).

Unit 5: mixed-provenance glaciolacustrine sediments

This unit is predominantly interbedded fine sand, silt, and clay. It locally contains thin diamicton layers and dropstones from the Rocky Mountains, Rocky Mountain Foothills, and Canadian Shield. It overlies unit 3 or is interstratified between tills bearing Canadian Shield clasts. These include units deposited by advances of the continental ice sheet margins (units 6 and 9) and valley glaciers from the Rocky Mountains that have reworked continental drift deposits (unit 7; e.g., Fig. 5, sections H1, Wc5, O11, C10, B2, and St8). Thickness ranges from 1 m to 5 m. Its basal contact is either conformable or abrupt on surfaces that have been eroded prior to its deposition. Its upper contact is usually sheared and brecciated

(Fig. 13). It is found within in the Highwood River basin (section P1) and within sections from the Castle River basin (sections C4, C5, C10–13, and C15).

Unit 5: interpretation

Unit 5 accumulated in lakes dammed by advancing or retreating continental ice-sheet margins that blocked eastward drainage from the foothills. The variable facies present in unit 5 reflect the wide variability in local environments that existed in this juxtaposition of ice and water. Nearly stoneless, laterally persistent, rhythmically bedded silt and clay facies of unit 5 indicate a distal glaciolacustrine environment dominated by seasonal fluctuations in sediment input, whereas the more silty and sandy facies reflect a more proximal glaciolacustrine environment (Smith and Ashley, 1985; Ashley, 1988). Lenses of diamicton, gravel, or dropstones mixed with clay, silt, and sand nearby are consistent with deposition of sediment gravity flow from glacier margins, ice-raft deposition, or deposition by subglacial fluvial discharge into an ice-contact lake (Ashley, 1988; Benn and Evans, 1997, chapter 8). The distorted character of the bedding of unit 5 near its upper contact suggests shearing during the deposition of the succeeding unit 6. The brecciated clay beds noted at the top of unit 5 in section C10 formed by ice advancing over frozen, interbedded clay and silt (Pederson, 1989).

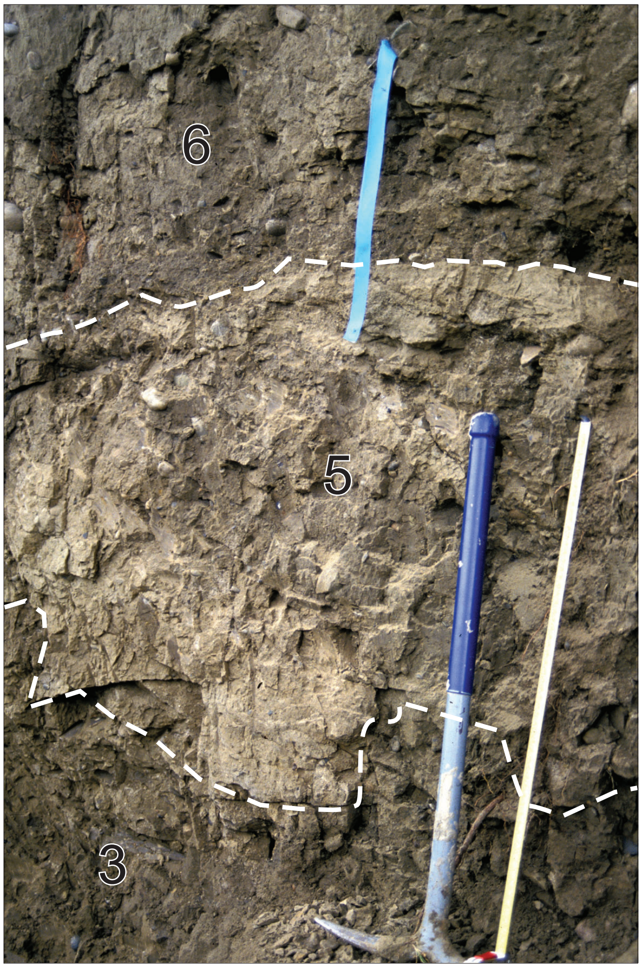


Figure 13. Exposure of a sheared lens of glaciolacustrine unit 5 (at the base of section H1) overlying montane till (unit 3) and underlying and partly incorporated into shield-stone-bearing till (unit 6). Pick length is 60 cm. GSC 2003-300

Unit 6: stratigraphically lowest continental diamicton

This unit is the stratigraphically lowest diamicton to contain Canadian Shield clasts. It is generally massive and ranges in colour from dark greyish to brown (10YR 4/2) to light olive brown (2.5Y 5/6) reflecting reworking of mudstone and shale of the Interior Plains and foothills into diamicton matrix. It commonly has a prismatic fracture pattern with vertical jointing and is locally slightly fissile, weakly stratified, or may contain thin (<20 cm thick) sand and pebble gravel beds that pinch out over a few metres. It has a matrix ranging from clayey silt to sandy silt, and a stone content of only 5 to10%. It is invariably more cohesive and less stony than unit 3 diamicton and easily visually distinguished from unit 3 at a distance. Clasts are generally smaller than 5 cm, but rare boulders up to 40 cm long were observed. Most clasts are friable sandstone and mudstone that disaggregate when handled. Consequently, pebble lithologies, linked to described sections in Figure 5 and Appendix A, are biased toward resistant rock types. Although clasts from the Canadian Shield are visually obvious in exposures, they usually account for less than 5% of the total clasts in the unit. North of Porcupine Hills in the Highwood River and Sheep River basins, shield stones commonly account for 1% or less of unit 6.

Unit 6 is over-consolidated, and has moderate to strong unimodal or bimodal pebble fabrics, sheared or eroded lower contacts, fissility, and local internal shear planes. Resistant clasts are commonly faceted and carbonate clasts are well polished and striated. It occurs in all major drainage basins of the study area (e.g., sections S6, H1, O1, C1, W2, St1, T1). It ranges from less than 1 m to 15 m in thickness. North of Porcupine Hills and at elevations above the C2 limit (*see* below), no similar diamicton units overlie unit 6 (Fig. 10). South and east of Porcupine Hills and at elevations below the C2 limit (*see* below), it is overlain by one or more similar diamictons (unit 9A). Units 6 and 9 are essentially identical in texture and pebble lithology and differ only in that unit 9 lacks the distinctive fracture pattern of unit 6. The authors do not regard this as a reliable diagnostic property. Consequently, units 6 and 9 can only be reliably distinguished where both are present in complete sections (e.g. sections St1 and O3). This presents the single greatest difficulty in correlating continental-provenance diamictons between sections in which incomplete sedimentary successions are preserved or exposed due to partial erosion, burial by colluvium, or inundation by reservoirs; or the C2 limit is uncertain. Because of this uncertainty, occurrences of single continental-provenance diamictons could be either unit 6 or 9; these are designated as unit '6?'.

Unit 6 overlies units 1, 3 and 5 along abrupt erosional and sheared contacts. Where Unit 6 overlies unit 5, rip-ups of unit 5 are common within the lower metre of unit 6. Where it overlies unit 1, gravel clasts along the top of it are planed, polished, and striated. North of the Porcupine Hills where units 3 and 6 directly underlie the surface, unit 6 grades westerly into unit 3. South of the Porcupine Hills, this gradation cannot be demonstrated, but the distribution of erratics in the area suggests that the two units were deposited penecontemporaneously (Jackson et al., 1996, Holme et al., 2000).

Unit 6: interpretation

Unit 6 is interpreted to be lodgement till, deformed lodgement till, and deformation till based upon its over-consolidation, moderate to strong unimodal or bimodal pebble fabrics, sheared or eroded lower contacts, fissility, local internal shear planes, and faceted and striated clasts. The presence of Canadian Shield material, in combination with paleo–ice-flow indicators such as pebble-fabric data, indicates that ice flow responsible for these tills was from the east and north-northeast with minor topographic influence in the extreme southwestern portions of their extent (Little, 1995). Unit 6 was deposited by the first advance of a continental ice sheet into the Rocky Mountain Foothills. The lack of overlying diamictons above unit 6 north of the Porcupine Hills and its westward gradation into unit 3 indicate that the continental ice sheet only pressed into this area once and that montane glacial ice and the continental ice sheet coalesced extensively in this area.

Although called continental till for simplicity of discussion, unit 6 (and 9A, *see* below) both underlie or occur west of the Foothills Erratics Train (Stalker, 1956; Jackson, 1994) that originated in the headwaters of the Athabasca River in the Rocky Mountains (Roed et al., 1967). Jackson (1980) determined that the surface, till containing Canadian Shield clasts associated with the Foothills Erratics Train differed from tills in central Alberta by having a lower weight percent content of heavy minerals. Furthermore, they were statistically indistinguishable from montane tills in this property. Consequently, the shield-clast-bearing tills in the foothills can be more precisely described as mixed Rocky Mountain and continental-provenance tills that formed in a zone of coalescence between a continental ice sheet and valley glaciers from the Rocky Mountains which became tributaries to the Continental ice sheet as it flowed southeastward parallel to the structural grain of the Foothills (Stalker, 1956; Roed, 1968; Alley, 1973; Boydell, 1978; Jackson, 1980, 1994).

Unit 7: montane readvance diamicton complex

All of, or at least the lower portion of this unit, is highly compacted, massive, and fissile diamicton with local gravel lenses. Sheared zones, indicating brittle deformation following initial deposition, cut this unit in places. Locally, it grades upward into a weakly stratified, less cohesive diamicton. It is distinguishable from unit 3 where both are present in stratigraphic succession or where it contains scattered clasts from the Canadian Shield. Its basal contact is usually abrupt and is characterized by polished or striated pebbles where it overlies glacial sediments. Dyke-like intrusions of sand and gravel are locally present where unit 7 overlies these sediments. Basal contacts with shale, mudstone, and friable sandstone bedrock consist of sheared contacts up to 1 m thick. The shearing of the bedrock and incorporation of it into the overlying diamicton gives the impression that the diamicton grades downward into bedrock. It grades laterally and vertically into the gravel, diamict, silt and clay mélange of unit 8. Its distribution is restricted to the exposures along upper Pekisko Creek (section P1) and numerous sections along the Crowsnest (Cn3), Castle (e.g., sections C14–17), Waterton (section W4), and Oldman rivers (section Cn1). It ranges in thickness from <1 m to approximately 10 m. Unit 7 grades into unit 3 near the Rocky Mountain Front and is entirely composed of lithologies derived from the Rocky Mountains and the foothills in that area. Where it overlaps with the areas of occurrence of units 6, 9A and 9B (Fig. 14), it contains trace (<1%) numbers of pebbles from the Canadian Shield.

Unit 7: interpretation

Unit 7 is a till deposited during a readvance of valley glaciers from the Rocky Mountains following the maximum advance of the Laurentide Ice Sheet. It contains scattered Canadian Shield clasts where readvancing montane glaciers

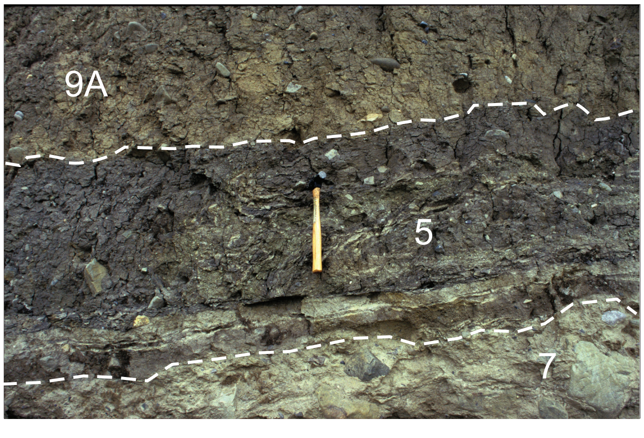


Figure 14. Succession at section O7: unit 5, broken and sheared, laminated to thinly bedded silt and clay, overlying unit 7A (till deposited during montane readvance M2) and underlying unit 9A (till deposited during continental readvance C2). Hammer length is 30 cm.GSC 2003-301

overran continental drift (units 5 and 6). In the Castle River valley where unit 7 is most extensively exposed, it frequently has multimodal fabrics and striae on stones inconsistent with mean fabric direction (Holme, 1998a). This suggests that, in this valley, the till formed by a combination of lodgement and subsequent deformation of the lodgement till that smeared the initial lodgement fabric (Hicock et al., 1996). The dyke-like intrusions of gravel and sand near its base reflect rapid loading and incorporation of unit 8 during the M2 readvance.

Unit 8: montane provenance diamicton and gravel complex

This unit is a complex of stratified to chaotic montane-provenance diamicton lenses, gravel, stony silt, and clay with dropstones. Locally it contains clasts from the Canadian Shield where it overlaps with areas of pre-existing continental drift (units 5 and 6). It grades laterally into unit 10 or is interstratified with unit 10.

Unit 8: interpretation

Unit 8 was deposited in ice-contact and proglacial environments along retreating montane glaciers following deposition of unit 3 and 7. Its interstratification with unit 10 indicates that glaciers locally terminated in lakes that were dammed to the east by the margin of the continental ice sheet (e.g. section Wr20).

Unit 9: continental drift readvance complex

Unit 9 consists of continental-provenance diamicton and interstratified sediments ranging from silt to gravel within the C2 limit (Fig. 5). It ranges in thickness from 5 to 20 m, reaching its greatest thickness in the buried valleys marking the former courses of Oldman River (sections O1–O7) and St. Mary River (sections St1–St10). Within the Oldman River basin and north of the C2 limit (Fig. 5), unit 9 can be reliably distinguished from unit 6 only where complete successions of continental-provenance sediments are preserved (e.g. sections St1–St3, O3; Fig. 5, 14) or where continental diamicton overlies unit 7 (i.e. where there is underlying montane diamicton that contains scattered shield stones, e.g. section O7; Fig. 15).

Subunit 9A

This subunit consists of massive to locally stratified, locally fissile diamicton, commonly characterized by vertical jointing and a light greyish brown colour where dry. It has a matrix ranging from clayey silt to sandy silt, and a stone content of only 5 to 10%. Clasts are generally smaller than 5 cm, but rare bullet-shaped boulders up to 40 cm long were observed. A large percentage of clasts seen in situ are friable sandstone and mudstone. Although clasts from the Canadian Shield are visually obvious in exposures, they usually only account for less than 5% of the total pebbles and larger clasts in the unit (*see* pebble lithology histograms for sections St1–St8, Fig. 5). In the St. Mary river basin (sections St1–St8), subunit 9A diamictons commonly are separated by rhythmically bedded silt and clay (unit 10). Rip-up clasts of these rhythmically stratified sediments are commonly present within subunit 9A in this area (Fig. 5, section St2). Unit 9A diamictons also locally contain thin (<20 cm thick) sand and pebble gravel beds that pinch out over a few metres.

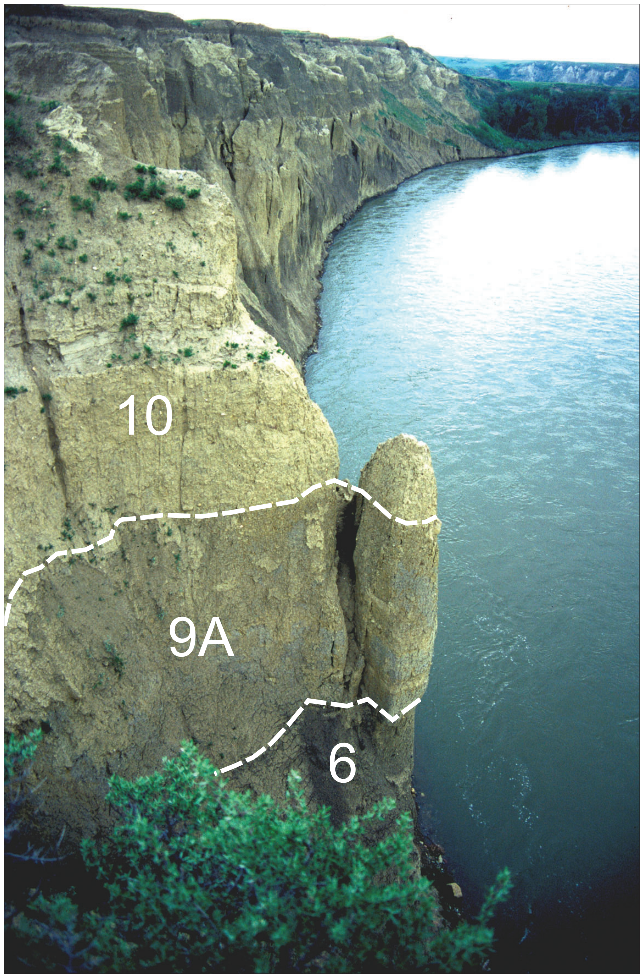


Figure 15. Units 6 and 9 (containing stones from the Canadian Shield) and overlying glaciolacustrine unit 10 exposed along an oxbow lake on the flood plain of Oldman River (section O2, Brocket section of Stalker (1963)). GSC 2003-302

Subunit 9B

This subunit is present in sections O1 to O6. It consists of layers of stratified sediments up to 4 m thick that separate the diamictons of subunit 9A. More than one subunit 9B may exist in a section. It ranges widely from poorly sorted, contorted pebble gravel of varying thickness, to layers of fine sand and silt with scattered pebbles, to stratified diamicton (similar to subunit 9A) separated by thin sheared and contorted sand layers, or massive sand containing unstructured diamicton blebs.

The upper contact of each 9B interval is often marked by rip-ups of fine sediments incorporated into the base of a overlying massive subunit 9A diamicton.

Unit 9: interpretation

The massive, consolidated diamictons of subunit 9A are interpreted to be predominantly deformed lodgement till. This is based upon evidence of shearing within and below the diamictons including

- faceted and striated clasts including striated bullet stones (up to boulder size),
- sheared zones, deformed stratified sediment rip-ups, sheared or eroded lower contacts including striated boulder pavements,
- underlying glaciotectonically deformed stratified sediments, and
- unimodal to spread bimodal to multimodal pebble fabrics (Hicock et al., 1996).

The presence of Canadian Shield material, in combination with pebble-fabric data, indicates that ice flow responsible for these deposits was from the east and northeast, confirming its identification as a continental till. Interstratified units 9B and 10 indicate episodes of glacial retreat or stagnation permitting the deposition of ice-contact glaciofluvial and glaciolacustrine sediments, respectively. The succession of these deposits by one or more tills and shearing and rip-ups of them along contacts with the underlying tills indicates renewed advance by the continental ice sheet following recession.

Unit 10: stratified sand, silt and clay succeeding and locally interstratified with stratigraphically youngest continental diamicton sequences (unit 9)

This unit overlies diamicton packages along an abrupt, depositional to gradational contact. It directly underlies much of the Sheep, Highwood, Castle, Oldman, Belly, Waterton, and St. Mary river valleys and adjacent uplands (Fig. 14). Total unit thickness can only be estimated in most exposures, because unit 10 sediments are often extensively slumped, but the thickness is known to reach 17 m. Sediments range between fine sand and silty clay. Texture generally becomes coarser up-valley and may locally become interstratified with montane ice-contact sediments (unit 8) near the Rocky Mountain Front (Fig. 10 and 15; Fig.5, section Wr20). Bedding ranges from massive to faintly horizontally stratified to clearly rhythmically laminated. Bedding is often disturbed by soft-sediment deformation features including convoluted bedding, ball-and-pillow and flame structures. Sediments range from stoneless to scattered pebble- and cobble-sized dropstones to intermixing of stratified sediments and lenses of diamicton. In most exposures, sediments are usually normally graded with stony sediments at the base of an exposure to stoneless stratified sediments farther up-section. Pebble lithologies include metamorphic or granitic rocks from the Canadian Shield.

Unit 10: interpretation

The texture, stratification, dropstones, and soft-sediment deformation structures are consistent with high rates of deposition of proximal and distal glaciolacustrine environments (Ashley, 1988). The distribution of unit 10 is consistent with the blocking of Rocky Mountain Foothills drainage by a digitate continental glacier margin in the foothills as has been previously recognized by Horberg (1952), Wagner (1966), and Alley and Harris (1974). Within a given valley, deposition did not occur in a single lake, but rather a succession of lake basins that progressively drained and reformed as ice margins retreated and thinned in an eastward or northeastward direction. Gravels interstratified within the glaciolacustrine sediments indicate local and short lived readvance of the ice margin during overall retreat. Stoneless to nearly stoneless laminated sediments reflect distal glaciolacustrine conditions whereas stony successions with interstratified diamictons indicate ice-marginal environments.

Unit 11: recessional outwash gravel

This unit is a clast supported, poorly to moderately well sorted pebble or cobble gravel with a sandy matrix. It has a sharp, erosional basal contact with units 6, 9, and 10. At some localities, e.g. sections C6 and O2, it is interstratified with unit 10 and may have an erosional basal contact with underlying unit 10 and a depositional contact with overlying unit 10. The basal contact is occasionally marked by a boulder lag. Clasts are generally rounded to subangular, and may range up to 20 or 30 cm in diameter. The unit ranges from massive and disorganized to horizontally stratified with lenses of silty sand, and stratified imbricated clasts. In some exposures, it fines upward from a boulder lag at its base, through a cobble gravel, to a pebble gravel with a coarse sand matrix.

Unit 11: interpretation

A moderate to high-energy fluvial environment is interpreted for this gravel unit. The absence of strong stratification or crossbedding suggests that this deposit was laid down in the coarse bed proximal zone of a wide and shallow glacial outwash plain, where stratification is predominantly massive to crudely horizontal, with only a subordinate amount of cross-stratification (Smith, 1985). Westward to southward imbrication and the predominance of montane lithologies indicate a deposition by streams flowing from the Rocky Mountains. It is equivalent to surficial unit G (Fig. 5).

Stratigraphically, this unit is typically erosionally inset into units 9A and 10, which indicates that it was deposited following the retreat of continental ice from the area, and following the draining of a proglacial lake dammed by the retreating ice. Where it is overlain by unit 10 (e.g. section O2), a temporary reformation of a glacial lake by a minor local readvance of the retreating continental ice sheet is indicated. Northwestward to southwestward imbrication and the predominance of montane clast lithologies indicate a deposition by streams flowing from the Rocky Mountains.

Unit 12: terrace gravel

This unit includes gravel and sand that underlie flights of terraces along contemporary valleys. They range from less than 1 to up to 5 m in thickness. These sediments contain faunal remains that clearly identify them as postglacial (*see* 'Glacial history').

Unit 13: massive sandy silt

This is the uppermost unit of many cliff-bank exposures. It is generally less than 1 m thick, and is a massive, uniform silt or sandy silt, containing a few animal burrows or small plant roots or bones of *Bison* sp. The latter show signs of butchering and are associated with human artifacts and hearths. In some sections (e.g. C5 and C9), the otherwise massive sediment contains faint, thin layers of coarse sand, granules, and a few pebbles that roughly parallel the ground surface slope. This unit abruptly overlies older sediments.

Unit 13: interpretation

The uniform silty texture and nonstratified nature of the sediment point to deposition by wind. The high winds prevalent in the study area are conducive to the entrainment and transport of fine sediment. The stratigraphic position of unit 13 at the top of the cliffs suggests that it was deposited following the complete retreat of ice from the study area and incision of streams. The incorporation of *Bison* sp. bones into the unit and occasional human artifacts indicates a Holocene age.

The coarser layers paralleling the slope surface within otherwise massive silt that are found at sections C5 and C9 formed when fine sediments were winnowed by slope wash and transported to the cliff edge across cliff-top dune sediments. Subsequent eolian deposition led to interstratification of massive silt and sandy silt.

GLACIAL HISTORY AND CHRONOLOGY

This section integrates the surficial geology and Quaternary stratigraphy of the study area to reconstruct the glacial history. A schematic representation of the events immediately prior to and during the last (Late Wisconsinan) glaciation is presented in Figure 16 A-G. These portray generalized ice limits and stream flow on a digital hillshade model prepared from 1:50 000-scale topographic data supplied by Geomatics Canada. Each contains a diagrammatic cross-section representing the positions of glaciers, drift, and the growth of an idealized stratigraphy at various stages for the northern and southern regions of the study area. These will be referred to during the course of this discussion.

Pre-Wisconsinan montane glaciations

Evidence for middle to early Pleistocene or late Tertiary montane glacial advances has been described along the southern margin of the study area and south of the 49th Parallel in northern Montana. This includes a till overlain by a paleosol on Cloudy Ridge, and five interstratified diamictons and associated paleosols on Mokowan Butte, collectively called the Kennedy Drift (*see* 'Late Tertiary to middle Pleistocene glaciogenic sediments') As noted previously, the uppermost diamicton in the Mokowan Butte sequence has many of the characteristics of till including a high content of highly striated stones. It is entirely derived from the Lewis and Clark ranges. A thick paleosol has been developed in it (Karlstrom, 1988). The age of the diamicton has been estimated at between 0.5 Ma and 0.65 Ma by Karlstrom (1988), based on time required for the development of a thick paleosol and the normal remnant magnetism of the paleosol The diamictons beneath it are calcretes and are difficult to study as a result. Their glacial origin is also uncertain (Little, 1995).

The diamictons on Mokowan Butte and underlying the buried soil at Cloudy Ridge were likely deposited prior to cutting of the valley systems that now contain the basal gravel of unit 1 (Fig. 7), and all overlying deposits. Elsewhere in the foothills, glacial limits are defined by the highest occurrence of glacial erratics from the Rocky Mountains and the Canadian Shield (Fig. 5). The upper elevation limit of erratics from the Rocky Mountains is in accord with an advance of montane glacial ice up to 300 m thick (Jackson et al., 1996). The top of Mokowan Butte was clearly beyond the reach of glaciers at that time. Furthermore, no paleosols equivalent to the one developed in the uppermost drift unit on Mokowan Butte exists elsewhere in the Rocky Mountain Foothills of southwestern Alberta. The drift units on Mokowan Butte and sediments below the buried soil on Cloudy Ridge appear to be remnants of a former drift-covered landscape that existed when regional erosion was above the floors of contemporary valleys and the summits of present ridges.

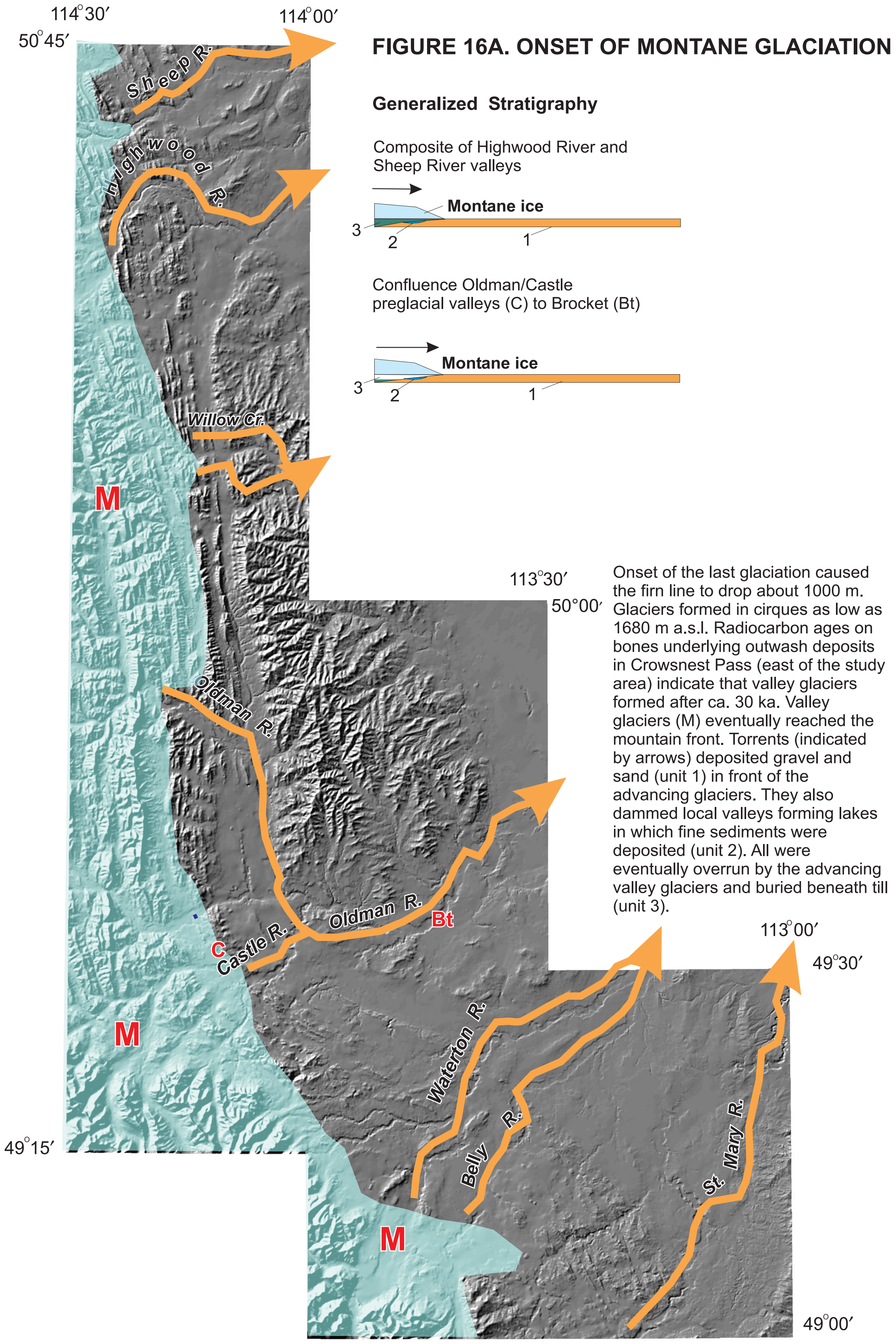


FIGURE 16A. ONSET OF MONTANE GLACIATION

Generalized Stratigraphy

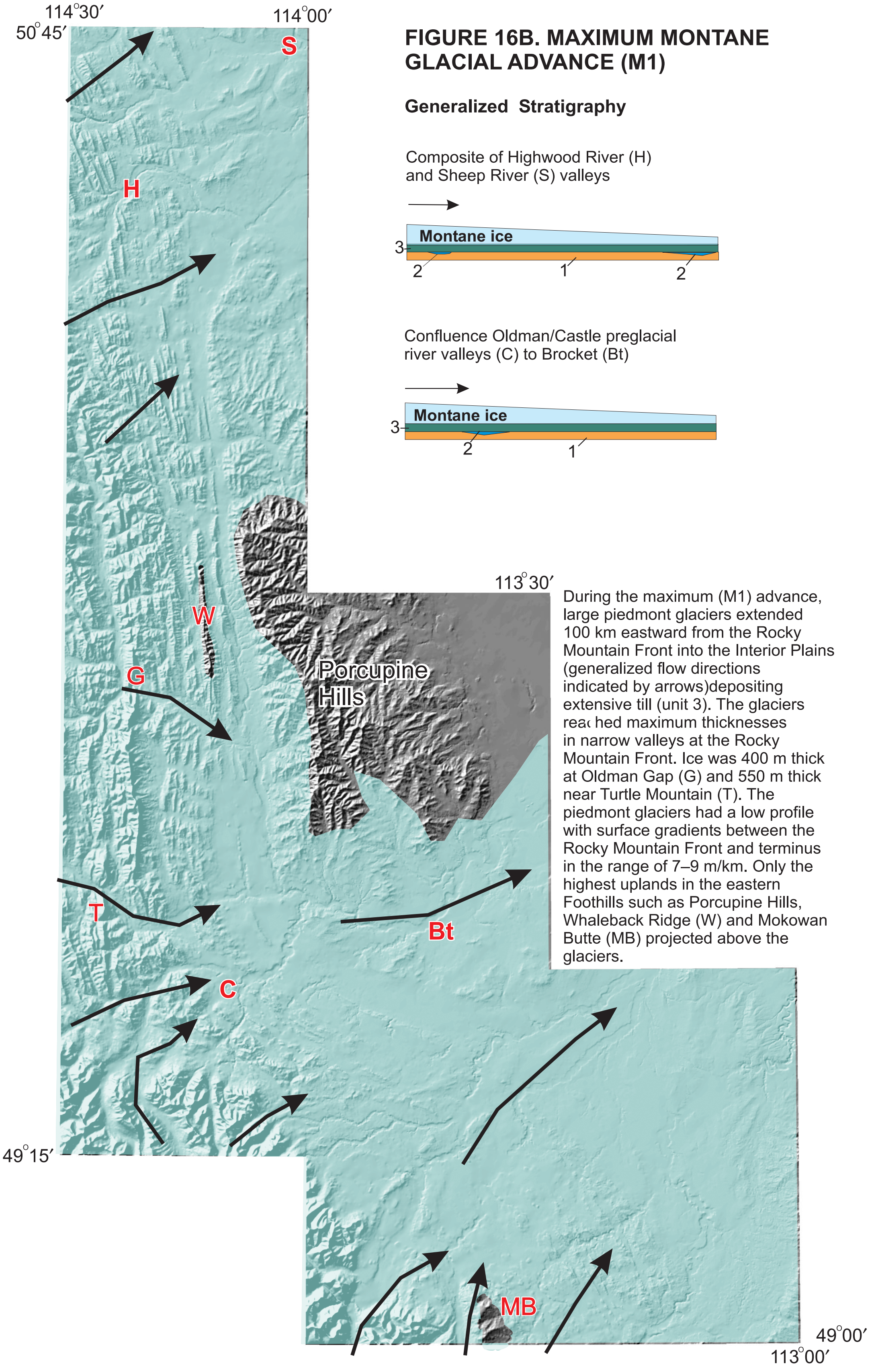
Composite of Highwood River and Sheep River valleys

Confluence Oldman/Castle preglacial valleys (C) to Brocket (Bt)

Onset of the last glaciation caused the firn line to drop about 1000 m. Glaciers formed in cirques as low as 1680 m a.s.l. Radiocarbon ages on bones underlying outwash deposits in Crowsnest Pass (east of the study area) indicate that valley glaciers formed after ca. 30 ka. Valley glaciers (M) eventually reached the mountain front. Torrents (indicated by arrows) deposited gravel and sand (unit 1) in front of the advancing glaciers. They also dammed local valleys forming lakes in which fine sediments were deposited (unit 2). All were eventually overrun by the advancing valley glaciers and buried beneath till (unit 3).

Figure 16. Schematic reconstruction of glacial events, and evolution of Quaternary stratigraphic units. Glacial cover and related lakes and surface drainage are draped on the same digital shaded-relief model as was used for Figure 5. Arrows indicate relative movement directions of ice margins, i.e., advance or retreat relative to east and west margins of the study area.

FIGURE 16B. MAXIMUM MONTANE GLACIAL ADVANCE (M1)



Generalized Stratigraphy

Composite of Highwood River (H) and Sheep River (S) valleys

Confluence Oldman/Castle preglacial river valleys (C) to Brocket (Bt)

During the maximum (M1) advance, large piedmont glaciers extended 100 km eastward from the Rocky Mountain Front into the Interior Plains (generalized flow directions indicated by arrows)depositing extensive till (unit 3). The glaciers reached maximum thicknesses in narrow valleys at the Rocky Mountain Front. Ice was 400 m thick at Oldman Gap (G) and 550 m thick near Turtle Mountain (T). The piedmont glaciers had a low profile with surface gradients between the Rocky Mountain Front and terminus in the range of 7–9 m/km. Only the highest uplands in the eastern Foothills such as Porcupine Hills, Whaleback Ridge (W) and Mokowan Butte (MB) projected above the glaciers.

Figure 16. (cont.)

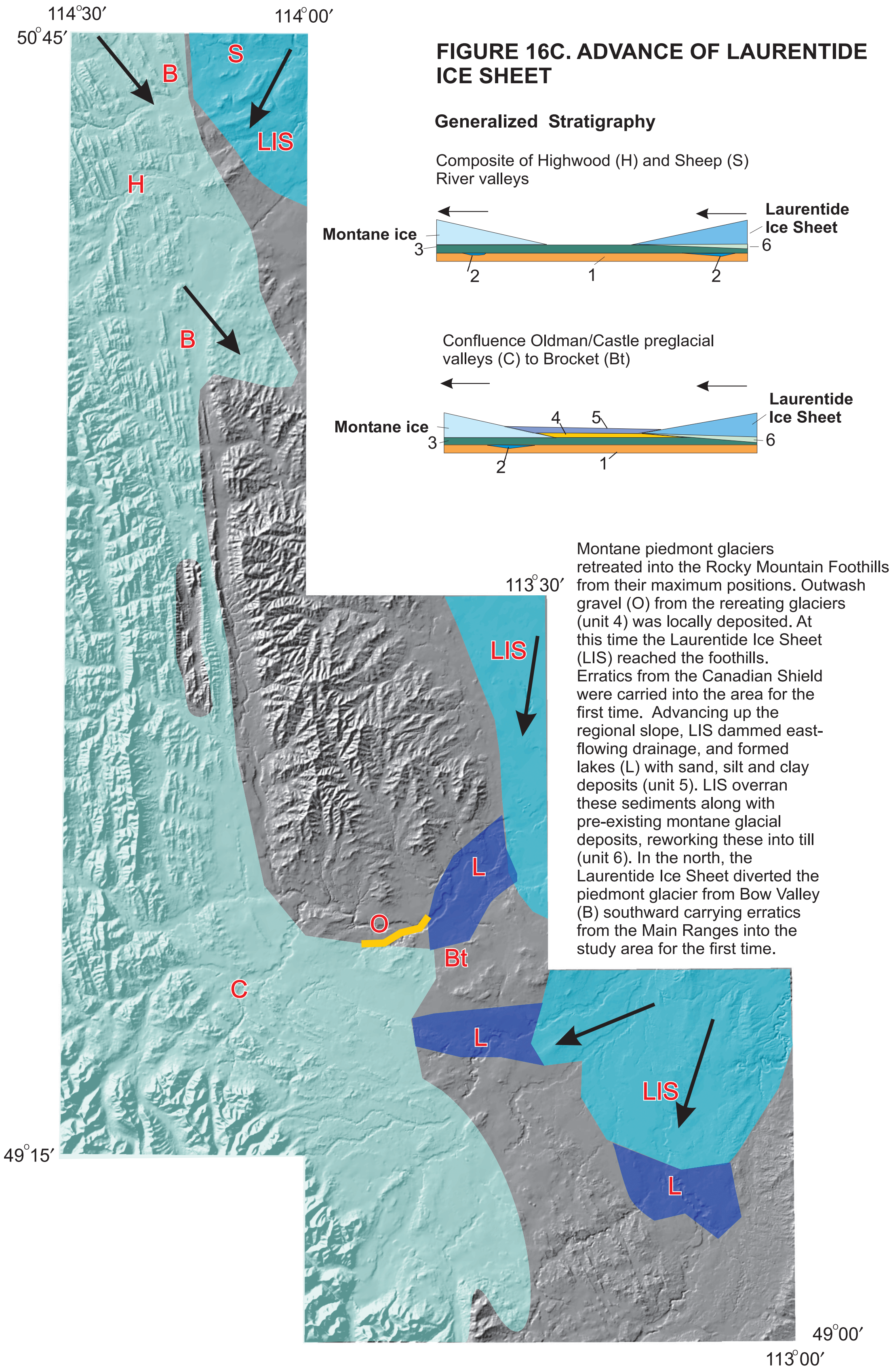


FIGURE 16C. ADVANCE OF LAURENTIDE ICE SHEET

Montane piedmont glaciers retreated into the Rocky Mountain Foothills from their maximum positions. Outwash gravel (O) from the rereating glaciers (unit 4) was locally deposited. At this time the Laurentide Ice Sheet (LIS) reached the foothills. Erratics from the Canadian Shield were carried into the area for the first time. Advancing up the regional slope, LIS dammed east-flowing drainage, and formed lakes (L) with sand, silt and clay deposits (unit 5). LIS overran these sediments along with pre-existing montane glacial deposits, reworking these into till (unit 6). In the north, the Laurentide Ice Sheet diverted the piedmont glacier from Bow Valley (B) southward carrying erratics from the Main Ranges into the study area for the first time.

Figure 16. (cont.)

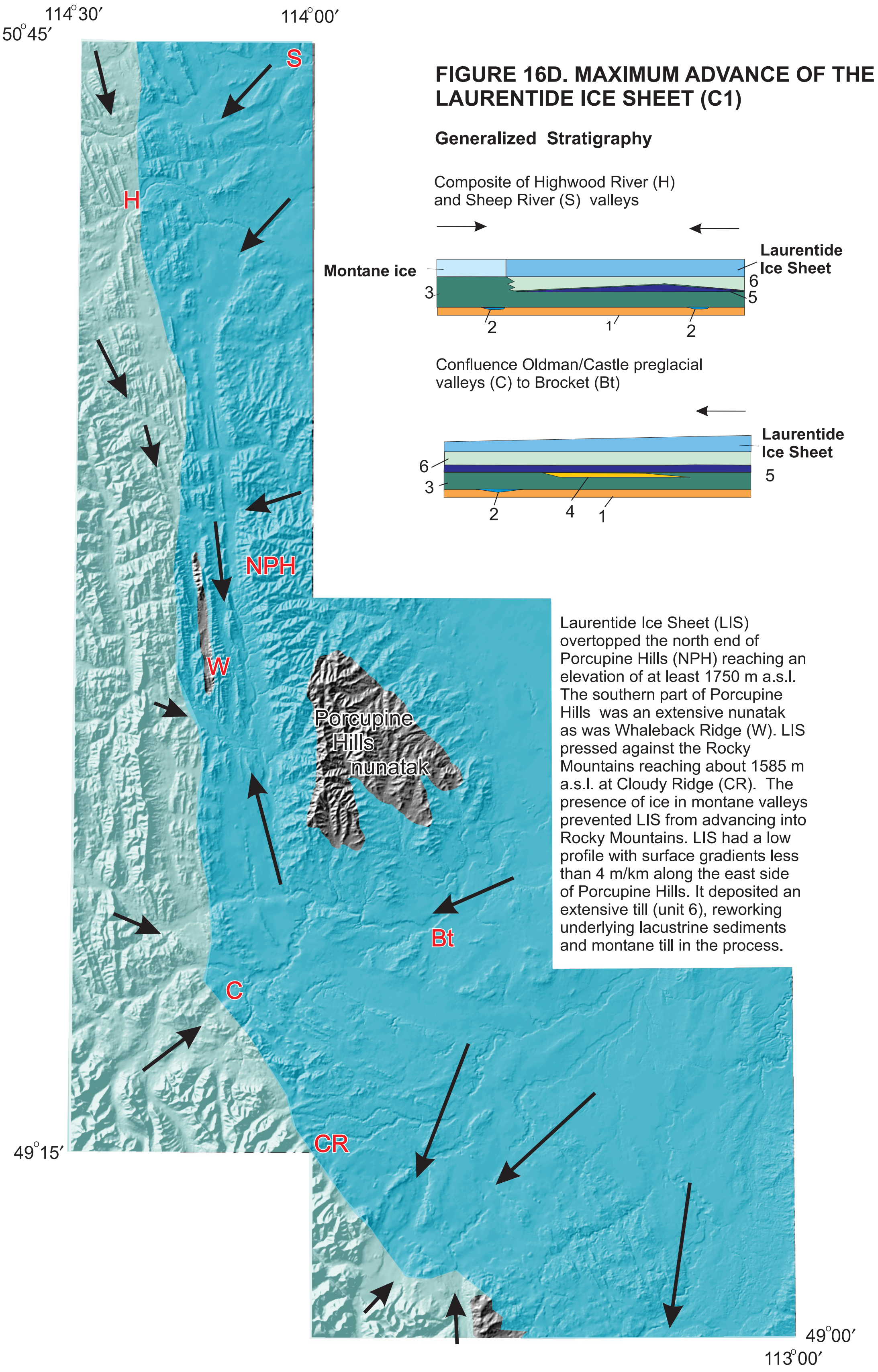


FIGURE 16D. MAXIMUM ADVANCE OF THE LAURENTIDE ICE SHEET (C1)

Generalized Stratigraphy

Composite of Highwood River (H) and Sheep River (S) valleys

Confluence Oldman/Castle preglacial valleys (C) to Brocket (Bt)

Laurentide Ice Sheet (LIS) overtopped the north end of Porcupine Hills (NPH) reaching an elevation of at least 1750 m a.s.l. The southern part of Porcupine Hills was an extensive nunatak as was Whaleback Ridge (W). LIS pressed against the Rocky Mountains reaching about 1585 m a.s.l. at Cloudy Ridge (CR). The presence of ice in montane valleys prevented LIS from advancing into Rocky Mountains. LIS had a low profile with surface gradients less than 4 m/km along the east side of Porcupine Hills. It deposited an extensive till (unit 6), reworking underlying lacustrine sediments and montane till in the process.

Figure 16. (cont.)

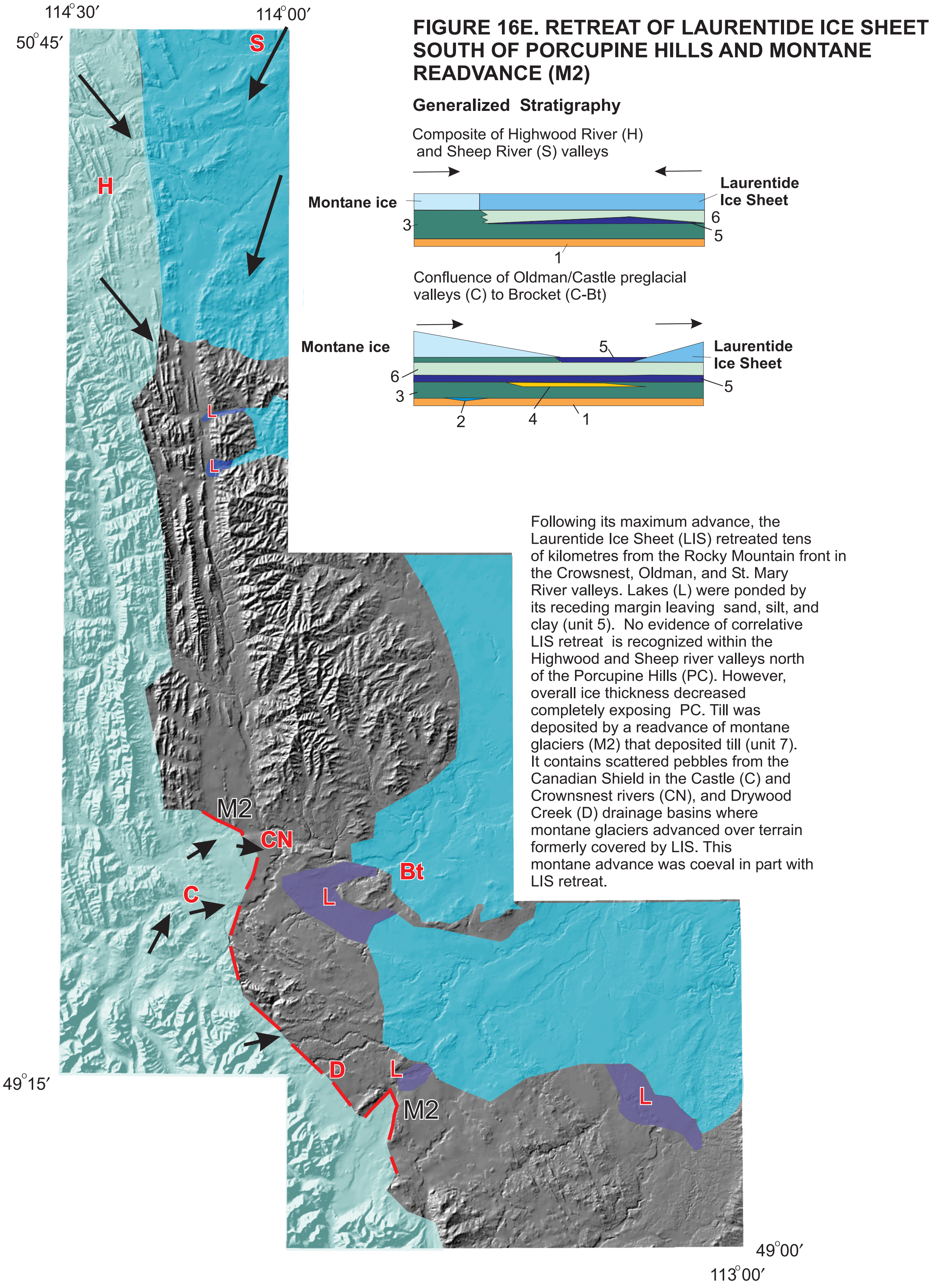


FIGURE 16E. RETREAT OF LAURENTIDE ICE SHEET SOUTH OF PORCUPINE HILLS AND MONTANE READVANCE (M2)

Generalized Stratigraphy

Composite of Highwood River (H) and Sheep River (S) valleys

Confluence of Oldman/Castle preglacial valleys (C) to Brocket (C-Bt)

Following its maximum advance, the Laurentide Ice Sheet (LIS) retreated tens of kilometres from the Rocky Mountain front in the Crowsnest, Oldman, and St. Mary River valleys. Lakes (L) were ponded by its receding margin leaving sand, silt, and clay (unit 5). No evidence of correlative LIS retreat is recognized within the Highwood and Sheep river valleys north of the Porcupine Hills (PC). However, overall ice thickness decreased completely exposing PC. Till was deposited by a readvance of montane glaciers (M2) that deposited till (unit 7). It contains scattered pebbles from the Canadian Shield in the Castle (C) and Crownsnest rivers (CN), and Drywood Creek (D) drainage basins where montane glaciers advanced over terrain formerly covered by LIS. This montane advance was coeval in part with LIS retreat.

Figure 16. (cont.)

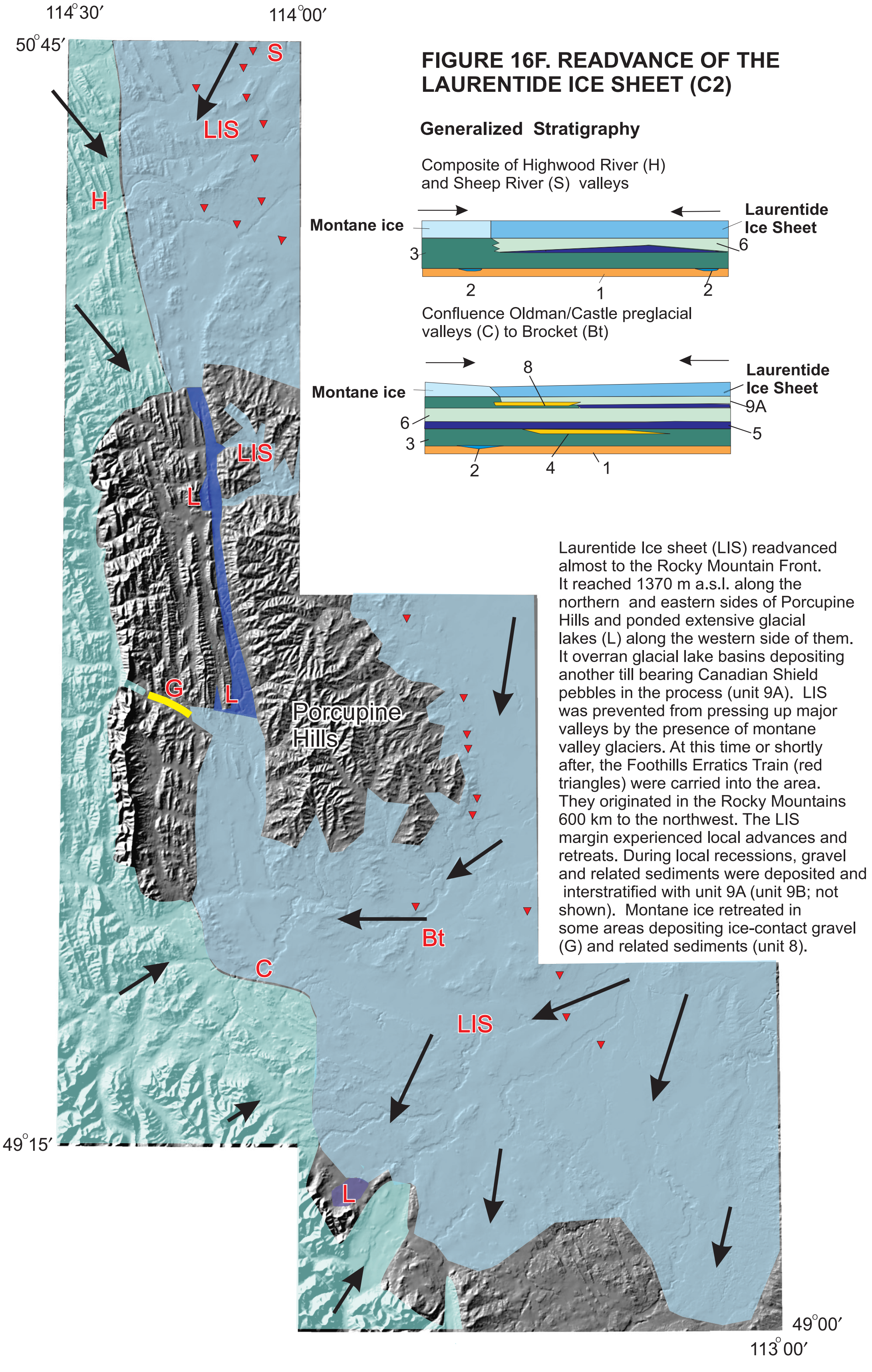


FIGURE 16F. READVANCE OF THE LAURENTIDE ICE SHEET (C2)

Generalized Stratigraphy

Composite of Highwood River (H) and Sheep River (S) valleys

Confluence Oldman/Castle preglacial valleys (C) to Brocket (Bt)

Laurentide Ice sheet (LIS) readvanced almost to the Rocky Mountain Front. It reached 1370 m a.s.l. along the northern and eastern sides of Porcupine Hills and ponded extensive glacial lakes (L) along the western side of them. It overran glacial lake basins depositing another till bearing Canadian Shield pebbles in the process (unit 9A). LIS was prevented from pressing up major valleys by the presence of montane valley glaciers. At this time or shortly after, the Foothills Erratics Train (red triangles) were carried into the area. They originated in the Rocky Mountains 600 km to the northwest. The LIS margin experienced local advances and retreats. During local recessions, gravel and related sediments were deposited and interstratified with unit 9A (unit 9B; not shown). Montane ice retreated in some areas depositing ice-contact gravel (G) and related sediments (unit 8).

Figure 16. (cont.)

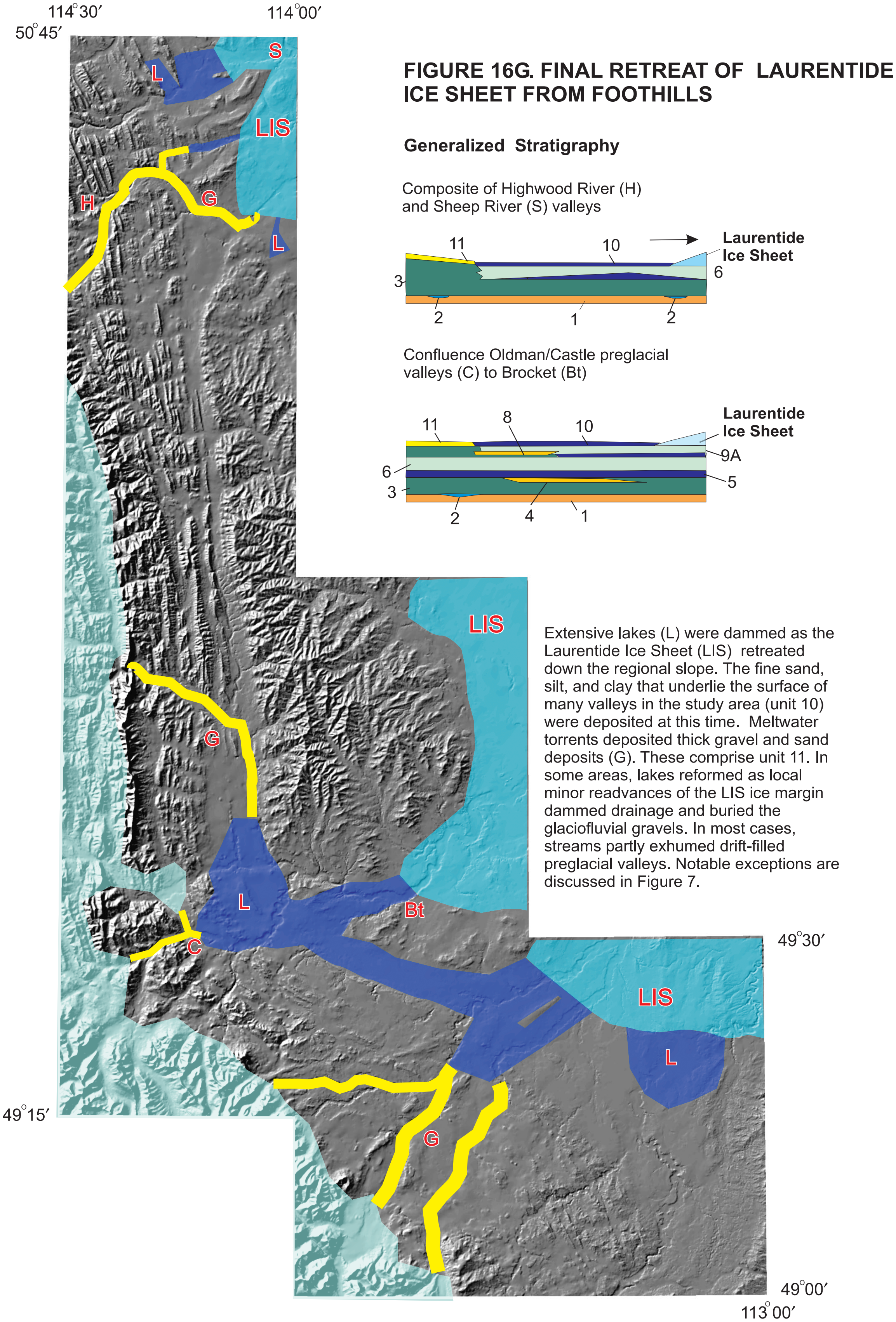


FIGURE 16G. FINAL RETREAT OF LAURENTIDE ICE SHEET FROM FOOTHILLS

Generalized Stratigraphy

Composite of Highwood River (H) and Sheep River (S) valleys

Confluence Oldman/Castle preglacial valleys (C) to Brocket (Bt)

Extensive lakes (L) were dammed as the Laurentide Ice Sheet (LIS) retreated down the regional slope. The fine sand, silt, and clay that underlie the surface of many valleys in the study area (unit 10) were deposited at this time. Meltwater torrents deposited thick gravel and sand deposits (G). These comprise unit 11. In some areas, lakes reformed as local minor readvances of the LIS ice margin dammed drainage and buried the glaciofluvial gravels. In most cases, streams partly exhumed drift-filled preglacial valleys. Notable exceptions are discussed in Figure 7.

Figure 16. (cont.)

Paleodrainage predating the last glaciation of the foothills

Figure 7 portrays the major drainage systems of buried valleys located in the study area (Stalker, 1961). With a few exceptions, drainage was similar to today: contemporary drainage has reoccupied and partly exhumed valleys that were filled with drift during the last glaciation. Some of the exceptions are noteworthy. In the parts of the Oldman River basin, drainage courses were dramatically different than today. The reach of the Crowsnest River between Burmis and the Oldman River gorge did not exist. The Crowsnest River joined the Castle River south of Lundbreck, flowed south and then northeast, joining the ancestral Oldman River in the area of the present town of Pincher Creek. Together they probably followed the course of contemporary Pincher Creek to the contemporary valley of the Oldman River west of the present town of Brocket. A large, dry valley to the west of Pincher Creek marks what may be an even older course of Oldman River. Good natural exposures across this valley were not available, and therefore its sedimentary fill remains to be investigated.

Onset and maximum of montane glacial advance (M1)

Water and sediment discharged from glacier ice expanding in the west and south along the Great Divide caused aggradation of major streams in the Rocky Mountain Foothills (Fig. 16A). We assume that the basal gravel (unit 1) was deposited as a result of this aggradation. Although it is undated, it lacks any evidence of weathering or any other indication that its deposition greatly predated the deposition of overlying drift units. If earlier montane glaciations affected these valleys, their sediments were removed prior to the deposition of unit 1. Involutions and ice-wedge pseudomorphs are locally present within unit 1 (Fig. 5, sections S3 and S4), indicating that a periglacial climate, consonant with the onset of glacial conditions, existed during deposition.

The expansion of montane glaciers culminated in the inundation of much of the foothills and adjacent Interior Plains by piedmont lobes. Locally, the ice advance dammed small lakes into which fine sediments were deposited as unit 2. Over most of the study area, ice advanced from the Rocky Mountains east of the continental divide but in the Crowsnest valley, glacier ice crossed Crowsnest Pass from the Elk River drainage basin west of the divide. This overwhelmed local valley glaciers. This is evident by the changing composition of montane till in the Castle River valley. Pebbles and larger clasts within the lower parts of montane till commonly reflect local source areas, whereas clasts at higher levels in the till commonly include Crowsnest volcanic clasts indicating the incursion of ice from the Crowsnest Pass.

At the maximum of the montane advance, only the summits of ridges above about 1600 m a.s.l., such as the summit of the Porcupine Hills, Whaleback Ridge, and Mokowan Butte, escaped burial beneath glacial ice (Fig. 16C). This maximum extent of montane glaciers is referred to as M1. The basal till and related sediments of stratigraphic unit 3 were deposited at this time. Montane ice reached as far east as Lethbridge based upon our correlation with the occurrence of montane till near the Belly River–Oldman River confluence and the occurrence of ice-contact montane gravels near Kipp, immediately west of Lethbridge (Fig. 17; Stalker, 1963; Wagner, 1966, Jackson et al., 1996). The eastward extent of

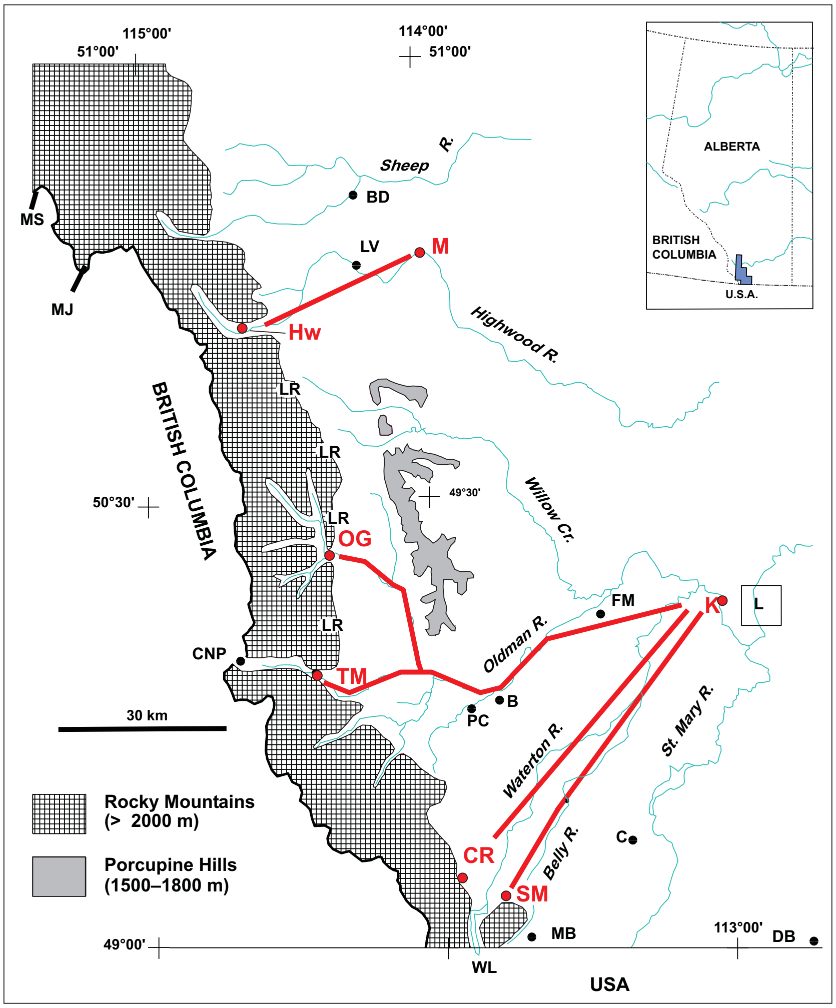


Figure 17. Heavy lines denote paths along which paleo–ice surface gradients listed in Table 3 were calculated: WL - Waterton Lakes, MB - Mokowan Butte, C - Cardston, DB - Del Bonita, SM - Sofa Mountain, CR - Cloudy Ridge, PC - Pincher Creek, K - Kipp Section L - Lethbridge, B - Brocket, FM - Fort Macleod, TM - Turtle Mountain, CNP - Crowsnest Pass, OG - Oldman Gap, LV - Longview, BD - Black Diamond MJ - Mt. Joffre, MS - Mt. Sir Douglas, LR - Livingstone Range, Hw - south end of the Highwood Range, crossing of the eastern margin of the study area by Highwood River.

M1 glaciers emanating from the Highwood River and Sheep River basins farther north is not known but it reached at least the eastern boundary of the study area (Fig. 5, section H1). The lack of erratics from the Canadian Shield within the basal gravels and overlying montane till indicates that no advances of continental ice preceded this montane advance.

During M1, the paleofirn line fell to between 1680 and 1820 m a.s.l. based upon the method of estimating it as lying between the elevations of lowest cirques and the highest terrain lacking them. This constituted a drop of approximately 770 to 910 m below the contemporary firn line in this region (Jackson et al., 1996). The thickness of the piedmont glaciers generally ranged from between 400 and 550 m where they exited the Rocky Mountains to about 300 m near the south end of the Porcupine Hills (Table 2; Fig. 17); valley glacier-surface gradients ranged between 8.5 and 9.1 m/km. based on the ice-limit features at the Rocky Mountain Front and the highest montane erratics on unglaciated Rocky Mountain Foothill ridges (Jackson et al., 1996).

Incursion and maximum of continental glacial advance (C1)

Following the montane (M1) glacial maximum, ice retreated westward into the foothills and continental ice advanced from the north and northeast and eventually flowed around the Porcupine Hills overtopping its northern summit and leaving a nunatak along the southern part of this upland (Figs. 16C, D). The advance of the continental ice created barriers to eastward drainage and glacial lakes formed between montane and continental ice margins. The stratified lacustrine sediments of stratigraphic unit 5, which separates the stratigraphically lowest montane till from the stratigraphically lowest continental till, were deposited in these glacial lakes. Sections O2 and O9–O11 (Fig. 5) best record these advances. Continental glaciers deposited a basal till bearing abundant clasts from the Canadian Shield stones (unit 6), the stratigraphically lowest unit to contain these.

This all-time maximum advance of a continental (Laurentide) ice sheet in the study area is named C1. The upper limit reached by continental ice (Fig. 5, C1 limit) is reconstructed based upon the highest occurrence of Canadian Shield erratics (shown as symbols on Fig. 5). Continental ice overtopped the north end of Porcupine Hills exceeding 1750 m a.s.l. (Fig. 18, point A). However, north of the Porcupine Hills, the western limits of shield stones lies at about 1370 m a.s.l.. The continental till grades into montane till in this area (Fig. 6). Within this zone of intergrading, the till contains clasts from the Rocky Mountain Main Ranges. On the basis of this evidence, we concur with Jackson (1980) that glaciers of Rocky Mountain and continental provenances coalesced north of the Porcupine Hills. The montane valley glaciers from the Highwood, Sheep, and Bow river basins (and others to the north) became tributaries to the continental ice sheet and joined with it in its southwestward flow along the foothills (Fig. 1).

Along the southern limits of the Porcupine Hills, continental ice reached 1590 m a.s.l. (Table 3; Fig. 18, point B) and terminated along the foot of the Rocky Mountains. The C1 limit in these areas is defined by the highest occurrence of Canadian Shield erratics and the highest occurrence of glacial lake sediments deposited where the continental ice-sheet margin dammed drainage against the mountain front. These can be found to 1525 m a.s.l. (Fig. 19; Leboe, 1996). The continental ice sheet overtopped ridges within the Interior Plains and crossed the International Border (49th Parallel) into northern Montana. Only a small nunatak area around the present site of the village of Del Bonita escaped glaciation north of 49 degrees in this area (Fig. 20). The elevation of the C1 limit progressively rises from approximately 1280 m a.s.l. along the Del Bonita upland to ca. 1450 m a.s.l. along the eastern flanks of Mokowan Butte to maximum elevation of 1585 m a.s.l. at Cloudy Ridge (Fig. 20; Little, 1995, Little et al., 2001). However, opposite major valleys of the Rocky Mountains such as the Belly, Waterton, Castle, Crowsnest, and Oldman, the C1 limit falls below adjacent areas and decreases to the east or northeast. Wagner (1966), Jackson et al. (1996) and Holme et al. (2000) concluded that this was due to the coalescence of the continental glacier with montane glaciers actively flowing out of mountain valleys. Furthermore, Little et al. (2001) investigated the cause of the overall increase in the C1 limit between Del Bonita and Cloudy Ridge and concluded, on the basis of computer modelling, that postglacial isostatic rebound was not significant enough to explain this superelevation. Rather, they concluded that compressive flow in the continental glacier due to coalescence with montane glaciers and foothills topography were the primary causes of this anomalous superelevation.

The conclusion that montane and continental ice coalesced in the Oldman basin south of Porcupine Hills corroborates the earlier findings of Horberg (1954) and Wagner (1966) and runs counter to those of Alley (1973) and Stalker and Harrison (1975).

Retreat from the C1 limit and montane (M2) and continental (C2) readvances

Following the maximum of continental ice sheet advance (C1), the ice sheet thinned and retreated to below 1400 m north of the Porcupine Hills, (Fig. 16E). The presence of only one surface till in this area, with clasts grading from shield provenance in the east to strictly montane provenance in the west, suggests that continental ice remained coalescent with montane glaciers during this episode of recession. More extensive retreat occurred in the Porcupine Hills, and south and west of them continental ice retreated many tens of kilometres from its former position at C1 (Fig. 5). The summit of the Porcupine Hills became entirely ice-free and an ice-free area emerged between montane and continental glaciers south of the Porcupine Hills. The contrast in the extent of continental glacier retreat between north and south of the Porcupine Hills is attributed to the southern

Table 2. Radiocarbon ages dating onset of glaciation, deglaciation, and Holocene fluvial incision within or adjacent to the study area.

Age (^{14}C years)	Lab number	Latitude/ longitude	Material	Stratigraphic setting	Comments	Reference
14 470 ± 610	RL-362[1,2]	49°40.0'N 114°35.0'W	Charcoal	Terrace	Minimum age for deglaciation	Driver (1978)
34 860 ± 470	TO-6350[3,4]	49°37.0'N 114°38.0'W	Bone *(Marmota caligata)*	Cryoturbated bone-rich cave sediments underlying a glaciofluvial gravel near the mouth of Eagle Cave	Ages place maximum age of advance of glacier ice across continental divide from the Elk River basin. Supercedes ^{14}C ages 22 700 ± 1000 (sample GaK 2336) and >37000	This study. Also *see* Burns (1984) for cave stratigraphy.
29 180 ± 300	TO-6351[3,4]					
11 220 ± 60	Beta-79915[5,6]	49°56.80'N 114°8.7'W	Molar (*mammuthus* sp.)	Molar found at top of recent roadcut apparently washed out of glaciolacustine sediments	Minimum age for deglaciation of foothills west of Porcupine Hills	This study
6460 ± 60	TO-4984[3,4]	49°38.4'N 114°7.5"W	Bone (*Bison* sp.)	Overbank sediments overlying stream terrace gravel along Todd Creek	Maximum age for incision of Todd Creek due to headward erosion of a nick point	This study
10 220 ± 70	TO-4980[3,4]	49°48.25'N 114°7.8"W	Freshwater shell (*Stagnacola* sp., *Gyralus* sp., and *Pisidium* sp.)	Lacustrine sediments overlying outwash gravel along Callum Creek near confluence with Oldman River	Minimum age for deglaciation. Hard water effect may make this age erroneously too old.	This study
18 300 ± 380	GSC-2668[7,8]	50°39.5'N 114°33.5'W	Aquatic moss (*Drepanocladus crassicostatus*)	Base of a 6 m core of bog/lake sediment sequence. Lake was formed by damming of a former meltwater channel by prograding alluvial fans.	Ages have been shown to be too old by at least one ^{14}C half-life due to dead carbon incorporation.	Mott and Jackson (1982)
18 400 ± 1090	GSC-2670[7,9]					
10 400 ± 70	TO-149[3,4]	50°49.0'N 114°36.0'W	Wood fragments	Base of a 6 m core from kettle-lake-bottom sediments in the Rocky Mountain Foothills immediately north of the study area.	Minimum age for deglaciation of the foothills	MacDonald et al. (1987)
10 600 ± 100	GSC-2162[7,10]	50°32.5'N 114°27.5'W	Freshwater shell (*Stagnacola* sp.)	Shells are present in the lacustrine fill of former kettle lake.	Minimum age for deglaciation of the foothills immediately west of northern part of study area.	Jackson (1980)

[1] Age is anomalously old when compared with associated archaeological material. Dead carbon contamination suspected

[2] Latitude and longitude estimated from site description

[3] Average of analysis of two targets and corrected to a natural and sputtering fractionation to a base of δ^{13}C = -25 ‰

[4] Uncalibrated, error represents 68.3% confidence limits

[5] Collagen extract with alkali. Laboratory reports good collagen extraction after full pretreatment

[6] Measured ^{14}C age11170 ± 60 BP; corrected for ^{13}C/^{12}C fractionation = -22.0 ‰; error value 1 standard deviation

[7] Conventional ^{14}C age

[8] ^{13}C/^{12}C fractionation = -32.6 ‰; NaOH leach omitted because of small size; mixed with dead gas, 3-day count in 2 L counter

[9] ^{13}C/^{12}C fractionation = -32.4 ‰; NaOH leach omitted because of small size; mixed with dead gas, 4-day count in 2 L counter

[10] ^{13}C/^{12}C fractionation = -25.0 ‰; 20 % leach with HCl; mixed with dead gas; one 2-day count in 5 L counter

Table 3. Maximum thickness of montane ice at Rocky Mountain Front (M1 advance) and estimates of piedmont glacier gradients

Geomorphic feature, Fig. 17 (geographic description)	Feature	Elevation (m)	Glacier thickness at Rocky Mountain Front (m)	Distance over which glacier gradient estimated[1] (km)	Profile line, Fig. 17	Average ice slope m/km (degrees)
Hw (south end, Highwood Range)	Meltwater channel	1740	260	42	**Hw-M**	16 (0.9)
OG (Oldman Gap)	Break in slope at limit of glacial erosion	1770	400	132	**OG-K**	6.6 (0.4)
TM (Turtle Mountain)	Break in slope at limit of glacial erosion	1800	550	105	**TM-K**	8.6 (0.5)
CR (Cloudy Ridge)	Upper limit of moraine	1680	125	91	**CR-K**	8.5 (0.5)
SM (Ridge north of Sofa Mountain)	Upper limit of lateral moraine	1770	490	95	**SM-K**	9.1 (0.5)

[1] Gradient determined by taking the difference between ice-limit elevation at the Rocky Mountain Front and elevation of the easternmost occurrence of montane drift divided by the length of the profile line.

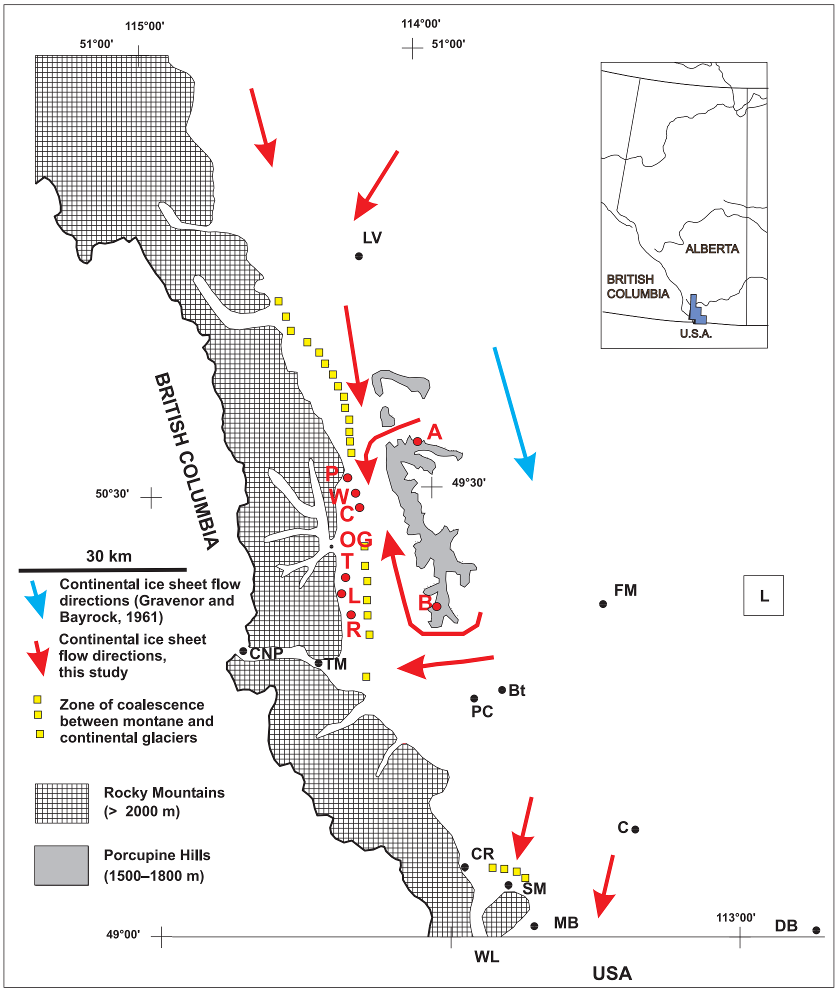


Figure 18. Ice-flow directions based on till pebble fabrics determined during this study (Fig. 5; Appendix A; red arrows) and generalized continental ice-sheet flow directions based on flutes and drumlins mapped by Gravenor and Bayrock (1961; blue arrow) for areas immediately east of the study area. Zones of coalescence between montane glaciers and continental ice (heavy yellow dashed lines) are based on the highest and farthest west occurrences of Canadian Shield erratics from continental and montane glaciers in the Rocky Mountain Foothills (Table 4). Points A, and B mark the upper limits of erratics from the Canadian Shield in Porcupine Hills; W, C, T, P, R, and L mark the highest occurrences of erratics and geomorphic features that mark the upper limits of glacial ice in the Foothills (Table 4). Towns and geographic features: WL - Waterton Lakes, MB - Mokowan Butte, C - Cardston, DB - Del Bonita, SM - Sofa Mountain, CR - Cloudy Ridge, PC - Pincher Creek, L - Lethbridge, Bt - Brocket, FM - Fort Macleod, TM - Turtle Mountain, CNP - Crowsnest Pass, OG - Oldman Gap, LV - Longview.

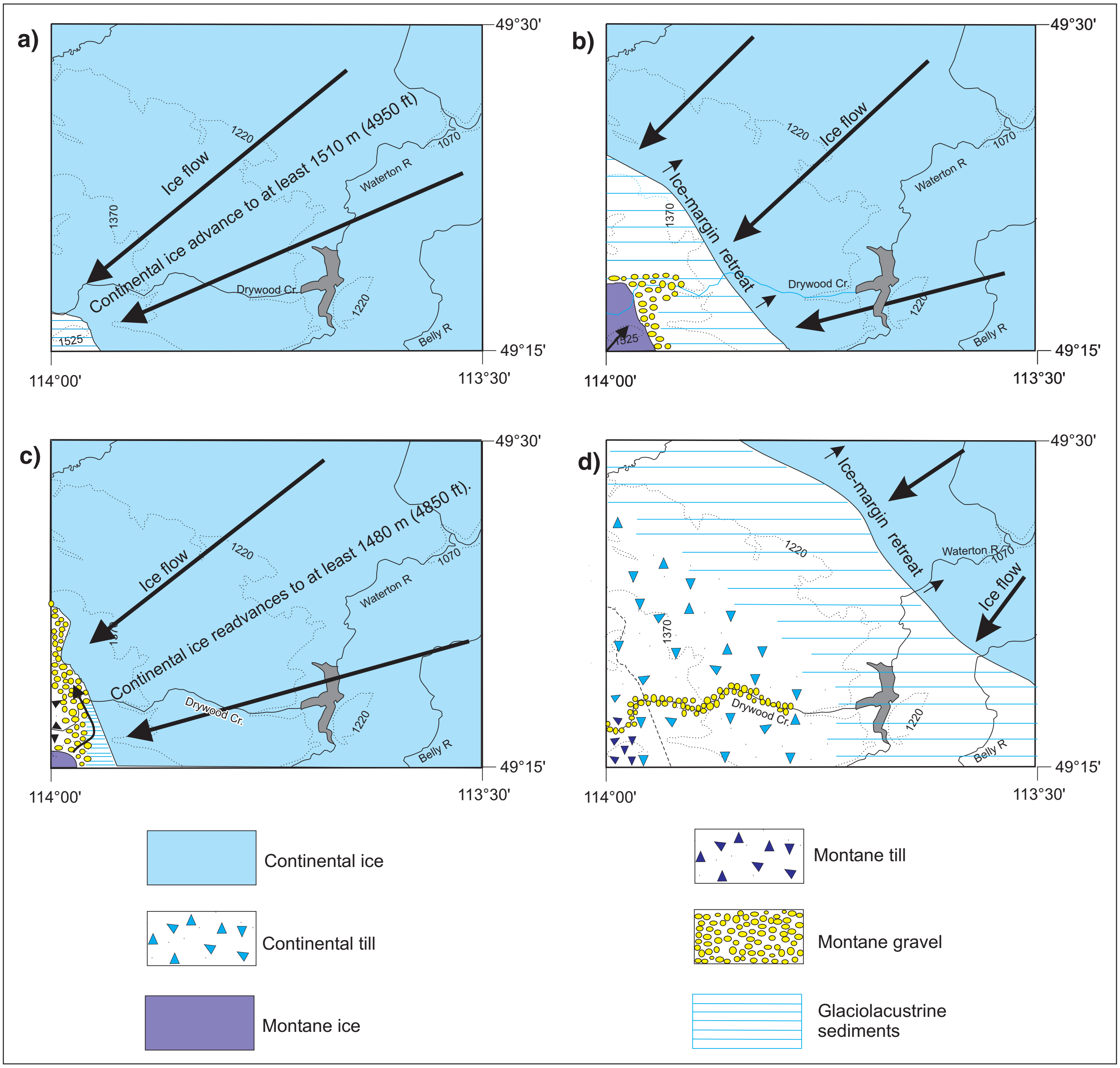


Figure 19. Events responsible for the formation of overlapping till sheets and associated lacustrine sediments in the southwest corner of the Pincher Creek map area: **a)** maximum advance of ice into area (C1); **b)** retreat of ice from maximum position; **c)** readvance of ice to 1480 m a.s.l. (C2); and **d)** final retreat of ice from area (*after* Leboe, 1996).

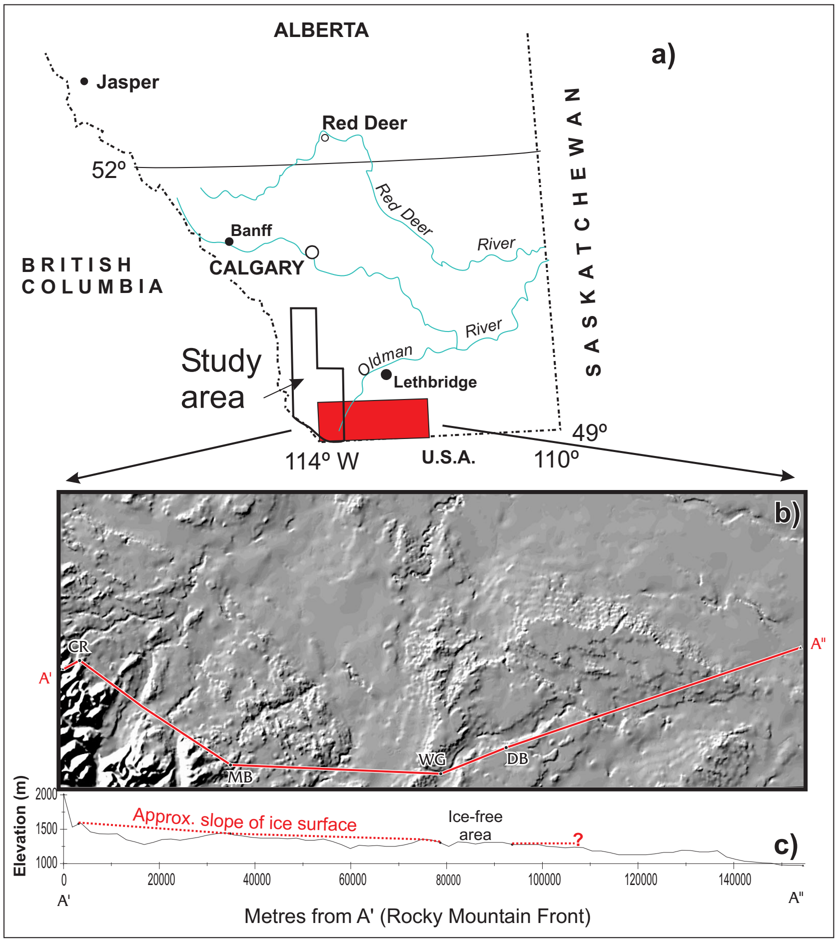


Figure 20. a) Location of digital elevation model (DEM) shaded-relief map and NATMAP project area. **b), c)** Transect A'-A" links upper limits of Canadian Shield erratics deposited at the all time maximum advance of a continental ice sheet (C1). Only a small area surrounding Del Bonita and the summit of Mokowan Butte were free of glacial ice cover during C1. Upper ice limits: Del Bonita (DB), 1280 m; Whiskey Gap (WG); Mokowan Butte (MB), 1450 m; Cloudy Ridge (CR), 1585 m (*modified from* Little et al., 2001).

area being more distal from the sources of the continental ice sheet and tributary montane valley glaciers and the Porcupine Hills, which acted as a barrier to ice flow into the area. The recession of the continental ice sheet was followed by a readvance. The digitate margin of the continental ice sheet ponded drainage during recession and readvance resulting in a succession of transient lake basins (Fig. 16E). Sediments deposited in the lake basins (unit 5) were later overrun by the advancing continental ice. Sediments of these lakes are best preserved in sections along the St. Mary River and its tributaries (Fig. 5, sections St1, 2, 3, 7, 8, 10).

Continental retreat was accompanied by a readvance of montane glaciers (Fig. 16E). Montane ice advanced 10 km or more beyond the mountain front into areas that were formerly inundated by continental ice. Till deposited by readvancing montane glaciers (unit 8) contains scattered shield stones reworked from continental drift in areas of overlap. It is in turn locally overlain by drift deposited by the subsequent readvance (C2) of the continental ice sheet (Fig. 5, sections O7, St10, Cn2; Wagner, 1966; Alley, 1972; Leboe, 1996, Holme, 1998a). In addition, this montane readvance overran C1 continental till north of Waterton Park (Fig 16E) in the extreme southwest corner of study area (Little, 1995) producing a train of montane lithology erratics along its margin (M2). The readvancing montane glaciers also overran montane outwash (unit 4) laid down in its advance (e.g., section C15, Fig. 5), and lacustrine sediments deposited in lakes ponded by either the advancing montane or continental glaciers (e.g. sections Cn3 and O15, Fig. 5 and Appendix A).

The limit of the continental readvance is denoted as limit C2 Fig. 5, 16F. This limit is widely traceable as belts of hummocky moraine, ice-marginal channels and glacially dammed lakes. It can be traced around the northeast and south end of the Porcupine Hills as a prominent belt of hummocky moraine. It descends from about 1460 m a.s.l. along the north end of Porcupine Hills to about 1370 m a.s.l. at their south end. Ice tongues pushing south and north along the west side of Porcupine Hills and up Willow Creek dammed an extensive chain of lakes along their west side. The highest stand of these lakes, named Glacial Lake Westrup by Alley and Harris (1974), is marked by former deltas reached 1400 m a.s.l. (Jackson 1980; 1998a) (Fig.16F).

A belt of hummocky moraine discontinuously marks the C2 limit between Drywood Creek and the southeastern boundary of the study area (Kimball moraine (Horberg, 1954)). The largest gap in the moraine occurs opposite the mouth of Waterton River valley where the most elevated occurrence of erratics from the Canadian Shield retreats to the northeast, indicating that montane and continental ice were coalescent during the C1 and C2 maximums in this area (Fig. 16D, F). West of Drywood Creek, the surface till grades between montane and continental provenance indicating that montane ice from the Castle and Crowsnest valleys were also coalescent with continental ice at the C2 maximum. The south (Rocky Mountain) side of the moraine is marked by an integrated system of meltwater channels which carried meltwaters to the southeast across the 49th Parallel into the Missouri River system. The transport of the pebbly quartzite blocks of the Foothills Erratics Train (Stalker, 1956; Jackson 1993) into the area was apparently synchronous with the C2 readvance. They are entirely east and north of the C2 limit (Figs. 5 and 16F).

Figure 21. a) Flights of former ice-walled channels cut into bedrock and partly floored by glaciofluvial gravel (enhanced by dotted lines), along the eastern slopes of Porcupine Hills (view to southwest). These were created by successions of meltwater streams flowing between the edge of the down-wasting Laurentide Ice Sheet and the hillside. GSC 2003-303. **b)** View to the northeast from point B: large foothills erratic (foreground) is situated within a former ice-walled channel. People provide scale. Arrows denote equally large erratics farther down the slope. Zero-erosion cosmogenic ^{36}Cl ages of 13.5 and 14.2 ka were determined on these erratics (Table 5, samples AE95103001 and AE951030002). GSC 2003-304

The Drywood Creek valley, near the southwesternmost boundary of the study area, contains the most instructive exposures revealing the relationships of M2 drift and the C2 limit (Fig. 19). Although not visible in a single exposure, and consequently not represented by a section diagram in Figure 5, moderately stony C2 (Kimball) hummocky moraine clearly overlies bouldery hummocky moraine of montane origin, but with scattered shield stones reworked from pre-existing continental drift (Fig. 6C). A bouldery outwash channel that carried meltwater away from montane glaciers disappears beneath the continental drift along Drywood Creek. This indicates that the M2 readvance culminated prior to the C2 advance into this area.

Final retreat of continental glaciers from the study area

During its retreat from the study area, the digitate margin of continental glacier ice retreated northeastward down major valleys (Fig. 16G). As uplands between valleys emerged, successive ice-marginal channels were cut around them. The best examples of these occur along the east margin of the Porcupine Hills in the Willow Creek basin (Fig. 21). Lakes formed along the retreating ice which migrated northeastward with the retreating margin as previously noted by Bretz, 1943; Horberg, 1954; Wagner, 1966, and Leboe, 1996.

In the Oldman River basin, retreat was not continuous. The continental ice margin retreated and advanced south of the Porcupine Hills depositing thick successions of till and interstratified gravel and diamicton (unit 9B in Fig. 5, sections O2–O5). The thick accumulation of these sediments in the area of Brocket is attributed to local fluctuations in the margin of the continental ice during overall retreat.

Postglacial events

Following the retreat of glaciers from the study area, some rivers carved new courses. The most significant one that features postglacial fluvial erosion is the new course of the Crowsnest River between Burmis and the site of the Oldman Dam (Fig. 7). Thick fills of glaciolacustrine sediments buried the former courses of the Oldman and Crowsnest rivers diverting them across bedrock thinly covered by drift. The Oldman River cut a 50 m deep gorge through friable sandstone and mudstone bedrock. Headward erosion from this diversion resulted in nick points along the Oldman and Crowsnest rivers and tributaries such as Todd Creek. The nick points separate stream reaches that are incised in box canyons (downstream) from those occupying broad-floored valleys (upstream). Lundbreck Falls near Burmis is the most spectacular of these nick points. The lower course of Pincher Creek represents another significant drainage diversion. Between Brocket and the town of Pincher Creek, it follows a partly exhumed, drift-filled valley that formerly carried the combined flows of the Oldman, Crowsnest, and Castle rivers (Stalker, 1961).

Flights of terraces cut in gravel fill characterize many stream valleys in the study area that have headwaters in the Rocky Mountains. The history of these terraces was not investigated as a part of this study, but detailed studies of similar fills within the Bow Valley (Jackson et al., 1982; Wilson, 1983) have shown that the gravel fills represent early postglacial alluviation as a result of high sediment loads during that period. If the analogy holds, most terraces cut in gravel fills were present by mid-Holocene times and the contemporary floodplain level was reached shortly thereafter.

Holocene incision of streams has destabilized slopes in many areas leading to landsliding on various scales. Glacial steepening of valley sides in the Rocky Mountains has caused massive landsliding (Jackson, 2002; Jackson and Lebel, 1998).

In addition to fluvial erosion and landsliding, retreat of glacial cover laid the region exposed to strong winds typical of the foothills. These transported and deposited silt, blanketing the landscape with an eolian cover ranging from a thin veneer to about a metre of massive silt. On inclined land and riverbanks, slopewash processes dominated, resulting in the interstratification of silt and coarser layers. The mid-Holocene Mazama tephra is commonly found in eolian and resedimented eolian sequences.

Age of glaciation

No absolute ages are available to directly date units 1 to 3 and by inference, M1. However, paleomagnetic sampling of units 3 in section C9, and units 2 and 6 in section O3, show that all glacial sediments are normally magnetized (Appendix C). Consequently, they were deposited following the last magnetic reversal, 780 ka (Cande and Kent, 1995).

Indirect evidence of the age of M1 comes from Eagle Cave in Crowsnest Pass (Fig. 2, 17). The mouth of Eagle Cave is 100 m above Crowsnest Lake in Crowsnest Pass. Meltwater flowing along the margin of glacier ice, which crossed Crowsnest Pass from west of the continental divide, deposited cobble gravel on top of nonglacial cave sediments rich in faunal remains (Burns, 1984; Burns, personal communication, 1997). Accelerator mass spectrometry (AMS) radiocarbon dating of bone from *Marmota caligata* sp. (marmot) taken from the nonglacial beds yielded ages of 34 860 ± 470 BP (TO-6350) and 29 180 ± 300 BP (TO-6351). A major flow of glacial ice from west of Crowsnest Pass contributed to the large eastward extent of the M1 piedmont glacier that advanced from the Crowsnest and Oldman River basin. This advance of ice terminated nonglacial sedimentation in Eagle Cave and is suspected to have been associated with M1 (*see* below).

The ages of C1, M2, and C2 are dated as Late Wisconsinan through the following means:

- Erratics associated with C1, M2 and C2 tills have been directly dated by cosmogenic ^{36}Cl exposure dating (Jackson et al., 1996, 1999; Table 5): Canadian Shield erratics on the northern summit of the Porcupine Hills, Cloudy Ridge, and beyond the C2 limit (outer drift of Horberg, 1952) south of Cardston clearly indicate C1 drift (unit 6) to be Late Wisconsinan in age. These ages are consistent with same age range for the stratigraphically younger M2 and C2 erratics and the Foothills Erratics Train: all yield Late Wisconsinan

Table 4. Geomorphic features and erratics that establish maximum ice-limit features in the Rocky Mountain Foothills

Feature (location, Fig. 18)	Location	Elevation	Comments
Cross-ridge meltwater channels (**W**)	Whaleback Ridge between 49°52' and 50°00'N, 114°13' W	Common up to 1680 m	Upper limit of montane glacial ice
Montane erratics on ridge top and cross-ridge meltwater channels (**C**)	Unnamed ridge west of Callum Creek, between 49° 52' N and 49°53', 114°9.5' W	Montane erratics to 1520 m, meltwater channels to same elevation	Upper limit of Canadian Shield erratics to about 1500 m a.s.l.
Cross-ridge meltwater channel (**T**)	Unnamed ridge north of Todd Creek area of 49°47.5' N 114°16' W	Channels up to 1680 m	Upper limit of montane ice
Highest montane erratic, cross-ridge meltwater channel (**L**)	Unnamed ridge, headwaters Wildcat Creek 49°44' N, 114°15' W	Montane erratics to 1520 m, cross-ridge channel at 1590 m.	Upper limit of montane ice
Cross-ridge meltwater channels (**P**)	Unnamed ridge east of Centre Peak 49°43.5' N, 114°17' W	Meltwater channels up to 1650 m	Upper limit of montane ice
Cross-ridge meltwater channels (**R**)	Unnamed ridge north of Ross lake 49°41' N, 144°14' W	Meltwater channel at 1520 m	Upper limit of montane ice
Highest erratics (**B**)	South end of Porcupine Hills, area of 49°44' and 49°44.5' N, 113°49' and 114°3' W	Highest Canadian Shield erratic 1585 m, highest limestone 1598 m, highest quartzite 1611 m	Upper limit of continental ice and possibly montane ice although highest montane erratics could have been reworked and emplaced by continental ice

Table 5. Cl and K_2O concentrations, ^{36}Cl/Cl ratios, topographic shielding corrections and cosmogenic ^{36}Cl ages determined on erratics associated with the C1, M2, and C2 limits of the Laurentide Ice Sheet in southwestern Alberta (*after* Jackson et al., 1999)

Sample	Latitude/ longitude	Limit	Cl (ppm)	^{36}Cl/10^{15}C (±)[1]	CaO (wt %)	K_2O (wt %)	S_T[2]	Zero erosion age (ka) no snow correction (±)[1]	5 mm/ka erosion age (ka) no snow correction (±)[1]	Zero erosion age (ka) with snow correction (±)[1]	5 mm/ka age (ka) with snow correction (±)[1]
PH1	50° 03' 26"N/ 114° 01' 43"W	C1	37	413 (75)	3.05	0.74	0.94	11.3 (8.9)	10.8 (8.2)	11.9 (8.9)	12.5 (8.2)
PH2		C1	26	681 (75)	2.17	1.35	0.94	13.7 (0.6)	13.3 (0.6)	14.4 (0.6)	14.1 (0.6)
CR1	49° 12' 42"N/ 113° 56' 56"W	C1	36	887 (43)	1.2	3.33	0.94	14.8 (0.7)	14.7 (0.7)	15.6 (0.8)	15.5 (0.8)
CR2		C1	144	419 (32)	1.07	4.84	0.82	15.5 (0.9)	14.4 (0.8)	16.3 (0.9)	15.1 (1.0)
CR3		C1	36	823 (40)	1.24	3.23	0.82	14.6 (0.8)	14.6 (0.8)	15.3 (0.8)	15.3 (0.8)
SR1	49°11' 01"N/ 113° 48' 08"W	M2	222	150 (14)	0.46	3.49	0.99	18.3 (1.8)	16.0 (1.5)	19.2 (1.8)	16.7 (1.6)
SR2	49° 10' 54"N/ 113° 48' 32"W	M2	270	142 (6)	0.25	4.64	0.99	17.6 (0.8)	15.7 (0.7)	18.5 (0.9)	16.4 (0.8)
SR3	49° 10' 54"N/ 113° 48' 39"W	M2	222	119 (6)	0.33	2.68	1.00	15.4 (0.8)	13.2 (0.7)	16.3 (0.8)	13.9 (0.7)
AC1(a)	49° 03' 21"N/ 113° 18' 35"W	C1	86	122 (24)	0.02	1.07	1.00	11.7 (2.3)	9.8 (2.0)	12.3 (2.5)	10.2 (2.1)
AC1(b)		C1	86	130 (8)	0.03	0.88	1.00	13.3 (0.8)	10.9 (0.6)	14.0 (0.8)	11.4 (0.7)
AC2	49° 03' 23"N/ 113° 18' 38"W	C1	93	266 (14)	8.61	1.37	1.00	14.7 (0.8)	14.2 (0.8)	15.5 (0.8)	15.0 (0.8)
AC3	49° 03' 16"N/ 113° 18' 25"W	C2	123	234 (15)	8.38	1.66	0.98	16.7 (0.9)	16.0 (0.9)	17.2 (1.0)	16.5 (0.9)

Note: all ages are expressed as ka.

[1] The uncertainties are one sigma, in parentheses, based only on the analytical uncertainties in the ^{36}Cl/Cl measurement.
CaO concentration <0.01 for all samples.

[2] Cosmic ray topographic shielding correction factor (unitless).

ages (Fig. 5, Table 6; Jackson et al., 1996, 1999). Subsequent to the completion of this study, cosmogenic ^{36}Cl exposure dating was completed on erratics associated with the C1 till in the Del Bonita area (Jackson and Phillips, 2003). All ages were consistent with a Late Wisconsinan age for the till.

- The Late Wisconsinan age for C1 is corroborated by a compelling argument involving radiocarbon documentation of a single glaciation of central Alberta (Liverman et al., 1989; Young et al., 1994). This is summarized in Figure 22. The Edmonton area lies approximately 750 m lower in elevation and 500 km up former ice-flow from the southwestern foothills. The source of all former continental ice sheets to the northeast or north of central and southern Alberta and the elevation difference between the Edmonton area and the front of the Rocky Mountains dictate that any continental ice sheet reaching the southwestern foothills must cover central Alberta (Little, 1995). The only alternative would be highly speculative, currently undocumented, ice-movement dynamics or ice-sheet configurations that allowed continental ice flowing from the east and northeast avoid low lying central Alberta whilst inundating southern Alberta and northern Montana.
- A Late Wisconsinan extrapolated age for the all-time glacial limit in the Interior Plains of southern Alberta and northern Montana was extrapolated from radiocarbon ages from the Alberta Interior Plains (Campbell and Campbell, 1997).

The dating of C1 as Late Wisconsinan has a direct bearing on the age of M1. Stratigraphic investigations carried out as a part of this investigation found a complete lack of soils, weathering horizons, or other indicators of an extended hiatus between deposition of drift from M1, C1, M2, and C2 advances. The two reports of buried soils between drift units in this area (excluding Mokowan Butte and Cloudy Ridge paleosols) were found to be without foundation: the Drywood soil (Horberg, 1954) was reported to lie beneath a continental till along Drywood Creek (ca. UTM 12 U 301600, 5463600). It was re-examined by Wagner (1966, p. 60) and found to be a limonite-stained clay and not a soil. Also, contrary to Horberg, Wagner reinterpreted the stratigraphy as montane till overlying and underlying the clay band which contained some of the enclosing till. No similar unit was encountered in the course of the present study in the Drywood Creek area or elsewhere in the study area. Karlstrom (1988) reported an organic-rich

Table 6. Cl and K_2O concentrations, $^{36}Cl/Cl$ ratios, topographic shielding corrections and cosmogenic ^{36}Cl ages for erratics from the Foothills Erratics Train (*after* Jackson et al., 1996).

Sample	Latitude/ Longitude	Cl (ppm)	$^{36}Cl/10^{15}Cl$	K_2O (ppm)	S_T[1]	Zero[2] erosion age (ka) (±)	5 mm/ka[2] age (±)
AE95110101	49°22'52"N/ 113°19'25"W	64	850 ± 22	3.66	0.98	53.3 (1.5)	47.2 (1.4)
AE95103103	49°24'53"N/ 113°27'00"W	67	290 ± 71	3.67	0.99	17.6 (4.5)	16 (3.9)
AE95103102	49°24'53"N/ 113°27'00"W	70	239 ± 69	4.10	0.99	14.2 (4.3)	13.2 (3.8)
AE95103101	49°26'12"N/ 113°25'38"W	57	182 ± 9	2.70	1.00	12 (0.6)	11 (0.6)
AE95102901	49°57'20"N/ 113°50'10"W	64	382 ± 10	5.60	0.96	15.8 (0.4)	15.5 (0.4)
AE95102903	49°57'24"N/ 113°50'03"W	79	269 ± 61	2.91	1.00	17 (4)	14.8 (3.2)
AE95103001	50°31'55"N/ 114°08'18"W	76	325 ± 8	3.81	1.00	13.5 (0.5)	12.4 (0.45)
AE95103002	50°31'55"N/ 114°08'18"W	35	503 ±16	5.06	0.99	14.2 (0.4)	14.3 (0.5)

Note: all ages are expressed as ka. Shielding by annual snow cover assumed to be zero because of the arid, windy setting of the erratics.

[1] Cosmic ray topographic shielding correction factor (unitless).

[2] The uncertainties are one sigma, in parentheses, based only on the analytical uncertainties in the $^{36}Cl/Cl$ measurement. CaO concentration <0.01 for all samples.

soil developed in lacustrine sediments and underlying continental till along the St. Mary River near the hamlet of Kimball (in the area of UTM 12U, 337400, 5439350). A radiocarbon age of ca. 9700 BP was determined on this soil taken by Michael Wilson (personal communication, 2000). The clearly Holocene radiocarbon age and the similarity of the soil to other early Holocene soils in the region indicate that the stratigraphic position of the soil was misinterpreted. The lack of any weathered horizons between the oldest till units 3 (M1 age) and 6 (C1 age) suggest that unit 3 immediately predates unit 6. This supports the conclusion that unit 3, deposited during M1, postdates the nonglacial beds of Eagle Cave.

Age of deglaciation

The oldest postglacial radiocarbon ages in the study were determined on aquatic moss obtained from the base of a 6 m piston core taken from a bog/lake sequence west of Turner Valley (Fig. 5) (Mott and Jackson, 1982; Table 2). A later investigation (MacDonald, et al., 1987) determined that these ages were likely too old by at least 6400 years due to incorporation of radiometrically 'dead' carbon from dissolved mineral carbonate sources. A similar problem is suspected for an age of 10 600 ± 100 BP (GSC-2162) for gastropod shells from a kettle lake fill east of Longview and an age of 10 220 ± 70 BP (TO-4980) determined on shells from lacustrine or overbank deposits overlying outwash or early postglacial fluvial gravel near the confluence of Callum Creek and Oldman River (Table 2). The oldest radiocarbon age, determined on a sample collected as a part of this study and thought to be reliable is 11 220 ± 60 BP (Beta 79915) determined on a molar of *Mammuthus* sp. (mammoth; Fig. 23). With the notable local exception of Wrangel Island (Vartanyan et al., 1995) in the Bering Sea, mammoths became extinct at the end of the Pleistocene. The molar was found at the top of a roadcut along Callum Creek (Fig. 5, section O15) west of the Porcupine Hills. It was apparently eroded out of the lacustrine or glaciolacustrine sediments that cap the exposure. The area was probably deglaciated several thousands of years before the molar was deposited, based on radiocarbon ages suggesting that ice-free areas existed in the foothills and Interior Plains to the north and east (Jackson and Pawson, 1984; MacDonald et al., 1987; Campbell and Campbell, 1997), and tephrostratigraphic and proxy climatic dating of deglaciation in adjacent northern Montana (Carrara, 1987, 1995; Cararra et al., 1986; Elias 1996). Moreover, following completion of fieldwork related to this study, a spectacular find of extinct megafaunal remains, trackways from these creatures and Clovis archaeological material were discovered in the St. Mary Reservoir area located in the southeastern part of the study area (Fig. 5). Radiocarbon ages in the range of 11 100 to 11 300 BP have been determined on bison and horse remains (Hills et al., 1999; Kooyman et al., 2001). This site also indicates that the Foothills had been deglaciated well before this time.

All other radiocarbon ages determined on samples from the study area were determined on materials from stream terraces or kettle lakes and are clearly Holocene (Table 2).

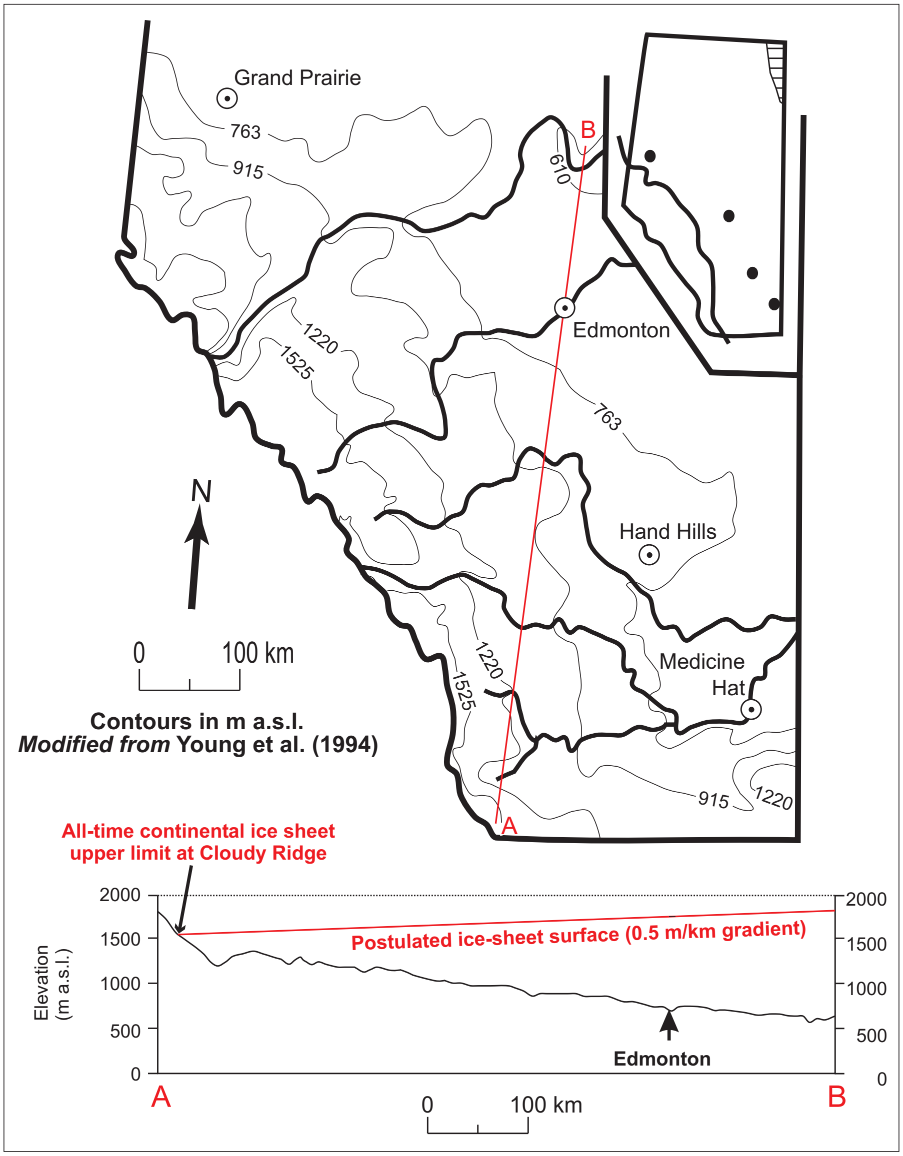


Figure 22. Contour map of southern Alberta and summary of the argument linking the age of continental ice-sheet advance C1 with the finite radiocarbon ages from gravel below the single continental provenance till in the Edmonton area (central Alberta). Contours trending northwest to southeast illustrate general elevation descent to the east and northeast. Inset map of Alberta shows generalized all-time limits of continental glacial ice (thick black line) according to Young et al. (1994) and the location of the Canadian Shield (hatched area) in the extreme northeastern corner of Alberta. Any continental ice sheet (CIS) entering the central and southern Alberta region would advance from the north or northeast and retreat to the northeast. Cross-section A-B illustrates the difference in elevation between the C1 limit at Cloudy Ridge (Rocky Mountain Front) and Edmonton where only a single incursion of a CIS occurred during the entire Pleistocene. A postulated ice sheet surface with a gradient rising to the north at 0.5 m/km is extrapolated to the Edmonton area in order to show how thick an ice sheet would have been in central Alberta if it reached Cloudy Ridge. The actual ice sheet gradient is unknown. Local differences in ice limits A and B in Porcupine Hills indicate gradients as much as 4 m/km.

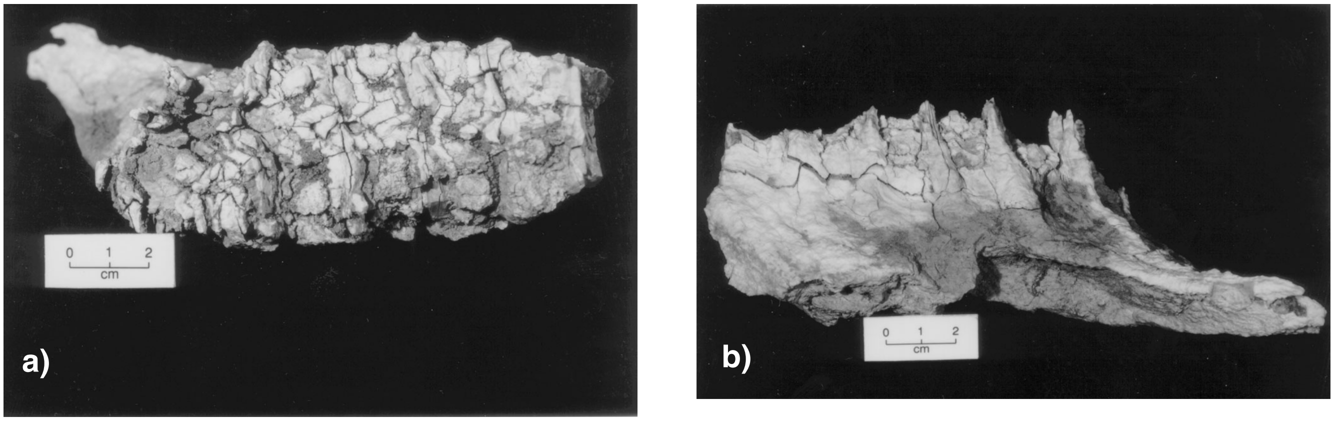


Figure 23. Mammoth molar found along Callum Creek radiocarbon dated at 11 220 a (Beta 79915). **a)** top view, **b)** oblique lateral view (National Museum of Nature photos 1995-013d and 1995-013c respectively).

CONCLUSIONS

With the exception of sediments preserved on high interfluves along the Rocky Mountains near the International Border (Cloudy Ridge and Mokowan Butte), all surficial and subsurface sediments in the study area are Late Wisconsinan. It was only during this glaciation that a continental ice sheet (Laurentide Ice Sheet) reached the southwestern Rocky Mountain Foothills. Successions of tills deposited by glacier ice bearing clasts from the Canadian Shield are the result of the fluctuation of the margin of the Laurentide Ice Sheet during this single glaciation. This corroborates the earlier previous conclusions of Horberg (1952), Wagner (1966), Bayrock (1969), Liverman et al., (1989), Young et al., (1994), Little (1995), Leboe (1996), and Holme (1998) that the only incursion of continental ice into southern Alberta was during the Late Wisconsinan. It also corroborates the reconstruction of Late Wisconsinan/Pinedale glacial extents by Alden (1932). The 770 to 910 m depression of the firn line calculated for the M1 maximum on the basis of the lowest cirque floor method is consistent with estimates of firn line depression during the acme of the Pinedale and penultimate Bull Lake glaciations at 49°N by Richmond et al. (1965, his Fig. 1).

However, a single continental glaciation of the southwestern foothills may conflict with the conclusions of Fullerton and Colton (1986), Richmond (1986), and Karlstrom (1999) who recognized tills predating the Late Wisconsinan beneath the Interior Plains of Montana south and east of the NATMAP study area, primarily on the basis of soils developed in them and the freshness of constructional morainal landforms. It also potentially conflicts with the findings of Barendregt and Irving (1998) who cite evidence for two continental ice sheet advances predating the Late Wisconsinan in southeastern Alberta between Lethbridge and Medicine Hat.

Assuming that the tills recognized by these authors do represent continental ice sheet advances predating the Late Wisconsinan, they are not necessarily incompatible with the record within the study area. Barendregt and Irving (1998) concluded that there has been a progressive enlargement of continental ice sheets in North America since continental glaciations began during the late Pliocene. These purported older tills may represent east-to-west ice flow in older ice sheets. The southeasterly flow of continental ice along the foothills (Fig. 1) may well have been unique to the Late Wisconsinan. The lack of evidence of tills predating the Late Wisconsinan in the southwestern foothills may indicate that it was either beyond the reach of previous ice sheets or that montane glaciers prevented the ice sheet from entering the area. Future collaborative studies across the International Border and correlation of drift units across southern Alberta will be required in order to resolve this problem.

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