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**UPPER PROTEROZOIC - LOWER CAMBRIAN
SEDIMENTARY ROCKS
OF THE MOUNT HARPER GROUP,
OGILVIE MOUNTAINS, YUKON**

by

Peter Steele Mustard, B.Sc, M.Sc.

**A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Doctor of Philosophy**

**Ottawa-Carleton Geoscience Centre
and
Department of Earth Sciences**

**Carleton University
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**The undersigned hereby recommend to
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MOUNT HARPER GROUP, OGILVIE MOUNTAINS, YUKON
submitted by Peter Steele Mustard, B.Sc., M.Sc.
in partial fulfilment of the requirements
for the degree of Doctor of Philosophy**

.....
**Chairman, Department of
Earth Sciences**

.....
Thesis Supervisor

.....
External Examiner

Carleton University

February 28, 1990

ABSTRACT

In the Ogilvie Mountains, west-central Yukon, the upper Proterozoic to lower Cambrian Mount Harper group (informal name) contains strata equivalent to both basal Windermere Supergroup and lower Cambrian rocks in other areas of the North American Cordillera. Strata of the Mount Harper group are directly time-constrained: the basal Windermere equivalents by a ca. 750 Ma U-Pb age from a volcanic complex which both conformably overlies and intertongues with the sedimentary rocks; the disconformably overlying units by the presence of lower Cambrian trace fossils.

The lower Mount Harper group (LMHG) unconformably overlies a thick succession of dolostones informally named the Fifteenmile group. A breccia layer is discontinuously preserved on the unconformity surface. This breccia contains silcretes and calcretes that record several episodes of subaerial exposure. Rare interbedded debris flows suggest that the most recent of these episodes was coincident with initial deposition of the LMHG conglomerates. Silcretes and calcretes in this succession suggest that, at the onset of Windermere deposition in this area, a temperate to equatorial, probably semi-arid to arid climate regime prevailed. Elsewhere, basal breccias in Windermere-equivalent strata generally have been interpreted as fault-related, but some contain features compatible with a karstic origin.

A syndimentary normal fault forms the southern margin of an asymmetric, east-trending half-graben basin which contains the lower Mount Harper group. Basin fill appears to have been derived exclusively from source areas to the south. Proximal facies consist of fault-talus breccia and up to 1100 m of debris-flow conglomerates that were deposited in coalescing alluvial fans. Intermediate and distal facies include mid-to-lower fan conglomerates and sandstones deposited by sheetfloods, distal debris flows and braided channel streamflows. A basin-fill coarsening-upward megasequence in the eastern part of the study area records a change from lacustrine redbeds to lower alluvial fan sandstones and conglomerates.

The LMHG half-graben basin was formed, and sedimentation was controlled, by normal faulting along the southern margin. Synsedimentary faulting and minor back-stepping of the fault controlled development of the internal sequences. Volcanism conformably postdates this sedimentation, but northerly derived coarse clastic rocks of the upper Mount Harper group (UMHG) intertongue with the volcanic rocks, and are not directly related to LMHG deposition. A basin model proposed for this succession involves slightly diachronous, opposed-symmetry half-grabens in which volcanism was concentrated in the accommodation zone between overlapping half-grabens. The continental rift system of East Africa provides a modern analogue.

Strata of the upper Mount Harper group are divided by a subtle disconformity into a lower succession of rift-related clastics and an upper succession of marine shelf deposits. The disconformity represents a major time gap, possibly > 150 Ma, indicating the lack of a direct temporal connection between the lower rift-related deposition and the immediately overlying sedimentary rocks in this study area. Deposition below the disconformity occurred in the younger of two opposed half grabens, coincident with a final stage of volcanic activity. Evidence of glacial deposition is lacking, although non-glacial poorly sorted conglomerates (diamictites), limestones, and rare pyroclasts, all of which are present, could be mistaken for such evidence.

Units overlying the disconformity contain facies of shoreface to outer shelf marine environments. The shallowest preserved part of the basin is in the northeastern part of the study area, where deposition was generally in a shoreface environment. All trace fossils were found in the upper 50 m of this facies. Clastic input from the north was from a dolostone source terrane. The siliciclastics probably were eroded from felsic volcanic rocks of the Mount Harper Volcanic Complex, exposed to the east and south. Marine shelf carbonates of the overlying CDb map unit appear to be separated from the UMHG by, at most, a minor hiatus.

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CHAPTER 1

Introduction

Purpose

One or more periods of late Proterozoic to early Cambrian extension have been proposed by many authors for the proto-Pacific margin of North America (e.g. Stewart 1972, Eisbacher 1985). In much of the North American Cordillera, the evidence for Proterozoic-Cambrian extension events is complicated by effects of subsequent metamorphic alteration, the extent of Mesozoic structural deformation, and the lack of direct age constraints on the relevant strata. Preliminary mapping (Thompson and Roots 1982) in the Ogilvie Mountains led to recognition of the well-preserved, relatively well time-constrained, essentially unmetamorphosed and homoclinal Mount Harper group sedimentary rocks. The unusually pristine preservation of these rocks provides a rare opportunity to examine late Proterozoic sedimentation in an extensional tectonic setting. Detailed documentation of the stratigraphy of the Mount Harper group also allows correlation with other upper Proterozoic strata in the North American Cordillera, thus permitting discussion of the significance of the tectonic evolution of this unusually well-preserved and little deformed area to presumably equivalent strata of the North American Cordillera.

Methods of Study

This study was initiated as part of the Ogilvie Mountains Project, a regional mapping program of the Geological Survey of Canada (project 800022) with Dr. R. I. Thompson of the Cordilleran Division, G.S.C. as coordinator and principal researcher. The 1:250,000 and 1:50,000 mapping of Thompson (Thompson and Roots 1982) provided the initial base maps for this study, and provided preliminary subdivision of the relevant strata into map units. Mapping by Roots (1987) as part of a PhD study of the Mount Harper Volcanic Complex also contributed significant geological information for this study. However, all sedimentary rocks in the study area were remapped by the author at 1:50,000 (back-pocket Figs. B-1 and B-2) in two three-month field seasons (summers of 1986 and 1987), plus two weeks of field work in 1988. In addition to geologic mapping, thirty stratigraphic sections were measured through Mount Harper group sedimentary rocks. Graphic logs with section descriptions are presented in Appendix I.

The field data were supplemented by preparation and examination of 165 thin sections and polished slabs. This included examination using cathodoluminescence of cements in the breccias detailed in Chapter 2 (10 polished thin sections), plus a few microprobe and X-ray diffraction analyses of conglomerate and breccia cements of the lower Mount Harper group. These analyses confirmed that original textures are generally preserved even at the microscopic scale, that post-depositional diagenetic alteration was minor and in most cases not relevant to the study, and that the rocks are essentially unmetamorphosed. Because the microscopic examinations provided little more than confirmation of the field observations, it was not considered necessary to separately compile the petrographic descriptions.

Thesis Format

This thesis consists of "stand-alone" chapters, with data and analytical techniques detailed as appendices, and two 1:50,000 geologic maps presented as back-pocket figures. Each subsequent chapter is self-contained, essentially in a form suitable for journal submission. A disadvantage of this format is an unavoidable repetition of some text and figures, especially in the introductory parts of chapters. As one concession to minimize repetition, references are combined at the end of the main body of the thesis, rather than at the end of each chapter. The format of individual chapters follows the format recommended by the journal to which the chapter will be submitted for publication consideration, except that Canadian spelling conventions are used throughout. Text outside chapters 2, 3, and 4 comply with style guidelines of the Canadian Journal of Earth Sciences.

Actual or Proposed Disposition of Chapters

Chapter 2: Paleokarst breccias ... : Journal of Sedimentary Petrology

Chapter 3: Lower Mount Harper group: Geological Society of America Bulletin

Chapter 4: Upper Mount Harper group: Canadian Journal of Earth Sciences

Related Research

Several published articles indirectly resulted from this research project and are not included as part of the formal PhD thesis. A preliminary report on the Upper Mount Harper group trace fossils discovered during field work in 1987 is presented

in Mustard and Donaldson (1988). The paleocurrent analysis was carried out with the computer software program Lotus 1-2-3, using spreadsheet templates developed to correct for bed-tilt and fold-plunge effects on trend data and to perform statistical analysis of the corrected data (Mustard 1989). A method of calculating and plotting ternary diagrams by means of this software package was also developed (Mustard and Richardson in press). Examination in 1989 of middle Proterozoic rocks in the Wernecke Mountains, Yukon (probable equivalents of strata underlying the Mount Harper group in the Ogilvie Mountains) resulted in Mustard *et al.* 1990.

General Terminology

The most common sedimentary rock types in the Mount Harper group are mudstones, sandstones and conglomerates in which the clastic detritus is predominantly of dolomitic composition. Examination of the conglomerates and sandstones clearly show that this carbonate originated as terrigenous rather than allochemical detritus. For this reason the terminology suggested by Folk (1959, 1974) for terrigenous carbonate clastics is used for the detailed description of these rocks in terms of grain size (dololutite, dolosiltite, dolarenite/dolowacke, dolorudite). Siliciclastic sandstones are described using the classification scheme of Dott (1964) and breccias are described using the non-genetic scheme of Morrow (1982). The general terms mudstone, sandstone and conglomerate are used for discussions of inferred depositional processes. Descriptions of matrix and cement also follow Folk (1974), using terms such as dolomicrite and dolosparite.

The terms Windermere Tectonic Assemblage and Windermere Supergroup are used in the thesis where the regional setting or significance of the Mount Harper group is discussed. The Windermere Supergroup was first defined (as "Windermere Series") in the southern Canadian Cordillera (Walker 1926), but the term has been extended to include most upper Proterozoic formations and groups recognized as correlative to the type strata (reviewed in Eisbacher 1981, 1985; Young *et al.* 1982). The formations and groups which make up the Windermere Tectonic Assemblage are shown on the compilation map of Tipper *et al.* (1981), updated in Wheeler and McFeely (1987), and briefly discussed in Gabrielse and Yorath (1989). This tectonic

assemblage is defined on the basis of broadly similar interpreted depositional and tectonic settings. The Mount Harper group initially appeared to fit this criteria. The discovery of Cambrian trace fossils in the uppermost part of the Mount Harper group in the late stages of this project has led to the realization of a major time gap between the uppermost three map units of the group and the underlying succession (documented in chapter 4). Thus although the informal group status is retained for this thesis, it is now clear that the upper three map units are a separate package from the rest of the Mount Harper group and are not strictly part of the Windermere Tectonic Assemblage (defined as entirely upper Proterozoic).

The terms "basal Windermere" and "basal Windermere Tectonic Assemblage" are used in this thesis to refer to the varied successions of conglomerate-rich sedimentary rocks and, in some places, associated volcanic rocks, which make up the lowest part of what is uncontroversially accepted as Windermere Supergroup. This usage parallels that of many previous workers (Eisbacher 1981, Young *et al* 1984, Yeo 1981, 1984, Young 1984, Jefferson and Parrish 1989). Diamictite-rich rocks of the basal Windermere, as defined above, have been interpreted by many workers as being wholly or in part glacially derived. Most of these rocks also have been suggested to be related to a major extensional event. The basal Windermere for the purposes of this thesis includes the Toby Formation in S.E. British Columbia (Aalto 1971, Root 1985, Bennett and McClay, *in press*); the lowest units of the upper Tinder Group of western Yukon and eastern Alaska (Young 1972); and the Shezal and Sayunei formations of the Rapitan Group in the Mackenzie Mountains (Eisbacher 1981, 1985; Yeo 1981, 1984). However, in the Mackenzie Mountains, a local succession of carbonates, evaporites, redbeds and minor conglomerates (the Coates Lake Group) would be included as part of the basal Windermere by some workers (Aitken 1981, Morris and Aitken 1982, Aitken *pers. com.* 1990), although others argue that the Coates Lake Group should be considered separate from the Windermere Supergroup (Young *et al.* 1982, Jefferson and Parrish 1989, Jefferson *pers. com.* 1990). The relevance of this controversy to the rocks of this thesis is discussed in more detail in the final sections of chapters 3 and 4.

CHAPTER 2

**Paleokarst breccias, calcretes, silcretes and fault talus
breccias at the base of upper Proterozoic "Windermere"
strata, northern Canadian Cordillera**

Journal Style: Journal of Sedimentary Petrology

ABSTRACT

In the Ogilvie Mountains, west-central Yukon, the upper Proterozoic lower Mount Harper group (informal name) is stratigraphically equivalent to basal Windermere Supergroup rocks that occur in other areas of the North American Cordillera. Breccias at the base of the lower Mount Harper group are of two different, but in part coeval, origins. A normal fault that was active during late Proterozoic time forms the southern boundary of the lower Mount Harper group, and is genetically related to a wedge of paleotalus breccia that thins rapidly northward from the fault. A different breccia layer is preserved on a disconformity surface that separates lower Mount Harper group strata from a thick succession of underlying dolostones. This disconformity breccia contains silcretes and calcretes that provide evidence of several episodes of subaerial exposure. Rare interbedded debris flows display features that suggest coincidence of the last exposure event with initiation of deposition of the Mount Harper group sediments. Silcretes and calcretes in this succession suggest that, at the onset of Windermere deposition in this area, a temperate to equatorial, probably semi-arid to arid climate regime existed. Basal breccias in Windermere-equivalent strata of other areas in the Cordillera generally have been interpreted as fault-related, but some of these breccias also contain features compatible with paleokarst origin.

INTRODUCTION

Examples of Precambrian paleokarst and silcretes/calcretes are rare. The review article of Retallack (1986) noted less than a dozen examples from the Proterozoic, spanning more than two billion years. In addition, Estaban and Klappa (1983) stated their suspicion that "karst and caliche facies, before the Silurian, without higher plant influence, had different features..." compared to Silurian or younger examples. This paper documents silcrete and calcrete (caliche) features at the base of rocks correlated with the base of the Windermere Tectonic Assemblage, the major upper Proterozoic stratigraphic succession in the non-suspect North

American terrane of the Canadian Cordillera (Fig. 1A, defined in Tipper et al. 1981). Many of the features of these subaerial weathering products are identical to those of Phanerozoic examples.

The breccias interpreted as paleokarst are coincident with, although physically separate from, talus breccia that formed along a preserved late Proterozoic fault scarp. Extensional faulting was common during initial Windermere deposition, and breccias from other basal Windermere strata have generally been interpreted to be the products of this faulting. However, coeval fault talus breccia and paleokarst breccia documented herein suggest that some breccias previously interpreted as fault-induced could be products of subaerial weathering. Many conglomeratic successions at or near the base of the Windermere Tectonic Assemblage (including possible U.S. equivalents) have been interpreted as glacial deposits (reviewed in Eisbacher 1985). The presence of extensive silcretes and calcretes, generally cited as indicating a warm climate, does not support a cold-climate interpretation for at least the initial period of Windermere sedimentation.

REGIONAL FRAMEWORK

The informally named Mount Harper group crops out from 75 to 125 km northwest of Dawson, Yukon, within the Ogilvie Mountains, the northwesterly extension of the Cordilleran foreland fold-and-thrust belt in Canada (Figs. 1A,B). Sedimentary and volcanic rocks of the Ogilvies, ranging in age from mid-Proterozoic to Jurassic, were telescoped northward in response to late Mesozoic - early Tertiary deformation. Within the Dawson map area, Proterozoic rocks relevant to this study are generally confined to a broad, east-trending erosional inlier (Figs. 1B,C).

Figure 2 illustrates the general stratigraphy of this inlier. The oldest rocks consist of a thick (>2 km) succession of fine-grained siliciclastics, dolostones and cross-cutting heterolithic breccias. These rocks correlate with the middle Proterozoic Wernecke Supergroup in the Wernecke mountains to the east (Thompson

and Roots 1982; Delaney 1981; Lane 1990), the stratigraphic equivalent of the Belt/Purcell Supergroups of the northern U.S. and British Columbia (Young et al. 1979, 1982). Wernecke Supergroup strata in the inlier are unconformably overlain by >2 km of platformal, stromatolitic dolostones, and less abundant basal mudstones and conglomerates. This succession, informally termed the Fifteenmile group, is currently of uncertain regional correlation.

The Mount Harper group disconformably overlies the Fifteenmile group and is preserved along the southern and western margins of the inlier (Figs. 1C,D). The Mount Harper group consists of three units. The oldest is a conglomerate-rich alluvial fan-to-lacustrine succession (<1100 m thick), termed the lower Mount Harper group. This unit is conformably overlain by the Mount Harper Volcanic Complex (<1200 m thick), a bimodal suite related to deep crustal rifting at $751 \pm 26/-18$ Ma (U-Pb on zircons: Roots and Parrish 1988). The upper unit of the Mount Harper group comprises conglomerate, sandstone, mudstone and minor limestone (300-1400 m thick). Complex trace fossils from the top of this unit demonstrate that its age spans the Precambrian-Cambrian boundary (Mustard et al. 1988a,b). Strata within the inlier are unconformably overlain by archeocyathid-bearing lower to middle Cambrian dolostone.

Mount Harper group and Fifteenmile group sedimentary strata comprise an essentially unmetamorphosed homoclinal succession that dips 20°-40° southwest. The Mount Harper group appears to have been deposited in half-grabens formed during late Proterozoic extension (Thompson et al. 1987). Correlation of the pre-Cambrian part of the Mount Harper group with Windermere Supergroup and equivalent rocks in the Canadian Cordillera is warranted by the age of the volcanic rocks, and similarities of tectonic and depositional history (Roots 1987, Thompson et al. 1987).

HARPER FAULT BRECCIA

A high-angle normal fault, named the Harper Fault by Thompson et al. (1987), forms the southern limit of the main exposure of the lower Mount Harper

group (Fig. 1D). Reverse faulting during Mesozoic-Tertiary compression overprinted much of the original fault zone, but the original normal fault is preserved along strike for more than 6 km (Figs. 1D, 3A,B). Offset of the older Fifteenmile group, depositional characteristics of the lower Mount Harper group sediments, and overlap of the fault by Mount Harper Volcanic Complex rocks indicate that the original Harper Fault was active during both lower Mount Harper group sedimentation and initial volcanism (Roots and Thompson in press; Mustard in preparation).

A thick breccia is preserved along the downdropped side of the fault (Figs. 1D [labelled fault breccia], 3C). This unit occurs as a tapering wedge which unconformably overlies dolostones of the Fifteenmile group, and intertongues laterally (northward) with proximal alluvial fan conglomerates of the lower Mount Harper group. The breccia has a minimum thickness of 290 m immediately north of the Harper Fault, and pinches out less than 1200 m north of the fault. The basal contact of this unit is not exposed; the upper contact with conglomerates of the lower Mount Harper group is gradational over 5-15 m of highly altered breccia (discussed below). The typical Harper Fault breccia is a medium grey rubble packbreccia (following descriptive terminology of Morrow 1982). The breccia comprises >90% angular fragments in <5% fine- to coarse-grained, pale yellow-orange weathering, massive, dolowacke matrix (Fig. 4A) cemented by 3 to 7% dolomite. The breccia is poorly sorted, with breccia fragments ranging from <1 cm to >100 m diameter (most are 10 cm to 5 m). Large blocks are generally broken with internal crackle breccia and fracture fills of pale yellow-orange cement or dolowacke matrix. One poorly exposed 2.5 m thick layer of contorted dolosiltite separates two breccia layers low in the main slope (Fig. 3C). Bedding is not apparent in the breccias, but vague clusters of similar fragment sizes define layers 2 to >50 m thick. The thickest breccia layer contains abundant fragments >5 m diameter. Several partly exposed tabular megablocks with minimum long axes of several 10's of metres (rarely >100 m) occur in this layer. The long axes of these megablocks are subparallel to the regional lower Mount Harper group bedding.

The most common rock type in the breccia fragments is medium grey laminated dolostone, commonly cryptalgal or stromatolitic. This rock type can confidently be assigned provenance from the upper part of the Fifteenmile group. Slightly less common are fragments of medium grey, massive and thin-bedded dolostone and dolostone-chert breccia, both containing 10 to 30% grey or white chert as nodules, lenses and interbeds. Most megablocks are composed of this rock type, which resembles a lithologic unit several hundred metres thick which commonly occurs in the Fifteenmile group immediately below the upper stromatolitic unit. Single-fragment lithologies tend to predominate over short intervals in the breccias, although slight mixing of different fragments is apparent in some layers, especially where the fragments are <1 m diameter. Although clasts derived from both the lower Fifteenmile group and Wernecke Supergroup are common in upper layers of the overlying alluvial fan conglomerates, such clasts are absent in the fault breccia.

Fault breccia fragments are unaltered, except within millimetres of their outer margins, where they show a slight increase in grain size. Although the breccia cement is dolomite, it shows remarkable fabric preservation. The cement types are relatively simple, with a consistent change from an isopachous rim of bladed prismatic dolomite to, in most places, a central fill of blocky dolosparite which coarsens inward (Fig. 4B).

Neither calcrete nor silcrete were observed in the fault breccia. At the gradational upper contact to lower Mount Harper group conglomerates, a 5 to 15 m thick layer of rubble floatbreccia consists of 50 to 60% sand- to pebble-size corroded fragments of chert cement and replacement chert (chalcedony and megaquartz). These fragments are supported in a pale greyish orange matrix of finely crystalline dolomite that contains rare silicified patches (Figs. 5A,B). The chert fragments are identical to those in the disconformity-surface regolith described in the next section.

The rubble floatbreccia is overlain by pebble-cobble conglomerate typical of the lower Mount Harper group, although this conglomerate is finer grained and better sorted than other conglomerates in this region. Two discontinuous lenses of

dolomitized ooid to pisoid grainstones are interbedded with this conglomerate (Figs. 3C, 6A,B). In the uppermost 10 cm, the upper bed displays planar crossbeds which indicate northerly transport, a paleocurrent direction also suggested by clast imbrication in the conglomerates above and below the grainstones (Fig. 3C). These distinctive grainstones represent a lithologic component of the lower Mount Harper group that is unique to this location. Ooids 1 to 2 mm in diameter predominate over pisoids, which in a few places are up to 5 mm. Both consist of well-developed concentric cortices of microcrystalline dolomite which rim an angular clastic nucleus. Nuclei include fragments of dolosparite, chalcedony/megaquartz cement, dark brown "clotted" micrite (eroded from calcrete?) and broken segments of earlier-formed ooids (Fig. 6C). Rare micritic laminar coatings a few cm long drape and link the tops of adjacent ooids (Fig. 6B). The ooids are cemented by early isopachous fibrous dolomite (the habit compatible with a primary aragonite/calcite precursor), and late sparry dolomite (Fig. 6C). Rarely, a dark cloudy cement is preserved at grain contacts and in the corners of pore spaces (Fig. 6D), causing the distinctive pore-rounding characteristic of meniscus cements (Dunham, 1971). The micritic aspect of this cement does not rule out a meniscus origin. Similar micritic meniscus cements have been documented in Pleistocene dolarenites (Knox, 1977). Fabric preservation appears to be almost complete in both the dolomite cements and ooid coatings. Patchy silicification of the micritic coatings is apparent in some ooids. The oolitic beds are overlain by cobble-boulder conglomerates typical of the lower Mount Harper group in this area.

Interpretation of Harper Fault breccia

Two features suggest that the Harper Fault breccia fragments have been transported rather than formed *in situ*: slight mixing of fragment lithologies in adjacent layers, and the similarity of clastic matrix in the breccia to matrix in the overlying conglomerate. Restriction of the breccia to areas adjacent to the preserved normal fault, a thinning wedge geometry away from the fault, distribution of Fifteenmile group megablocks relative to the fault, mixing of

fragments derived from two distinctive units in the Fifteenmile group, and a lack of pervasive alteration (except in the top 5-15 m of the unit), are consistent with deposition as talus along an active fault scarp. All clast lithologies match those of the two major map units which form the uppermost part of the Fifteenmile group; no clasts from lower stratigraphic units are present. This implies that the talus breccia represents deposition during early stages of fault movement.

The chert rubble floatbreccia which caps the Harper Fault breccia had a more complex history. The complete lack of original carbonate clasts or matrix suggests that this chert breccia was derived from a highly weathered residue mantle, possibly a chalky calcrete (cf. Esteban and Klappa 1983). Alternatively, the chert clasts may represent insoluble residues concentrated during a complex history of subaerial weathering and burial alteration. This interpretation has been invoked for chert rubble horizons at the top of a well-preserved paleokarst succession on Mississippian limestones in New Mexico (Meyers 1988). The identical nature of the fragments of chert and chalcedony cement and crust fragments in the floatbreccia to those of the disconformity breccia described in the next section supports an origin related to subaerial exposure. However, both the paleotalus breccias below this weathering horizon and the conglomerates above are genetically related to the Harper Fault to the south. For this reason, the weathering must have occurred during a short episode of nondeposition in an isolated area of the alluvial fan paleoenvironment of the lower Mount Harper group, rather than during a major hiatus.

Preservation of the chert floatbreccia along the Harper Fault requires that the breccia was sheltered from erosion during deposition of the coarse conglomerates typical of the lower Mount Harper group. Protection of this breccia is supported by the presence of two lenses of dolomitic oolitic grainstone a few metres above the breccia. Crossbedding, excellent sorting, and the abundance of clastic nuclei (including broken fragments of previously formed ooids) all indicate clastic deposition in an open, agitated setting (cf. Esteban and Pray 1983). Although

the ooids formed in an agitated environment, it was of low energy compared to processes responsible for the accumulation of hundreds of metres of overlying proximal debris flows in the lower Mount Harper group strata of this area, the rare occurrence of bedding-parallel laminar crusts of micrite draping ooids suggest quiescent intervals of subaqueous cementation. The oolitic grainstones are interbedded with conglomerates that are unusually fine-grained and well-sorted in comparison to the proximal conglomerates typical of this area. This may also reflect subaqueous deposition in an area sheltered from the gravity flows generated on steep slopes typical of the area. One possible origin for the oolitic beds is subaqueous deposition in a small ponded area developed on a bench at the top of the fault talus breccia. The underlying rubble breccia (with a calcrete matrix) could have provided an impermeable floor which caused water to pond on the otherwise permeable breccias and coarse conglomerates.

This study primarily reports results from field observations, supplemented by petrographic studies. The remarkable retention of breccia and oolite cement fabrics suggests either early mimetic replacement of precursor calcite/aragonite cements, or a primary origin for the dolomite cement. The latter possibility was suggested by Tucker (1982a,b 1983) for similar cement fabrics in the Beck Spring Dolomite, although Zenger (1982) and Ricketts (1982) questioned this interpretation.

DISCONFORMITY SURFACE AND BRECCIA

The disconformity surface which separates the Fifteenmile group from the overlying lower Mount Harper group is gently undulating, with broad shallow troughs and rises that are oriented roughly north-south, 100's to 1000's of metres in wavelength. The paleorelief is typically a few tens of metres, but in places is up to 100 m. Palcoslopes are generally shallow, but rare steeply dipping normal faults have locally dropped the north side a few 10's of metres. The rock type of the Fifteenmile group immediately below the disconformity typically consists of light grey, finely crystalline, locally cherty dolostone. This dolostone is commonly

cyrtolgally laminated, and contains rare beds of laterally linked and branching columnar stromatolites, as well as ooids, oncoids and intraclast breccia.

Breccia generally is not preserved on the disconformity surface (Fig 7A). However, in most places the uppermost few metres to decimetres of Fifteenmile group strata are extensively fractured (Fig. 7B), and in places these fractures contain an infill of orange sparry dolomite and white chert cement. Similarity of these fracture fills to cements in the karst breccia described below, suggests that these areas represent eroded remnants of the weathering surface. The general lack of alteration or large-scale structures characteristic of karst exposure is attributed to erosional stripping of the disconformity surface during initial deposition of the Mount Harper group. This interpretation is supported by abundance, in the lower conglomerate beds of the lower Mount Harper group, of clasts identical to the karst breccia described below.

Disconformity Surface Breccia

Rare discontinuous lenses of breccia are preserved on the disconformity surface, but not near known late Proterozoic faults. Most occurrences are poorly exposed and are centimetres to decimetres in both vertical and lateral extent. The only extensive and well-exposed occurrence crops out north of Mount Harper, where an almost continuous layer of breccia is preserved along about 3 km of the exposed disconformity surface (Figs. 1D, 7C). This breccia, up to about 50 m in thickness, mantles irregular paleotopography of the disconformity surface. The basal contact typically is gradational from unaltered Fifteenmile group dolostone, through fractured crackle breccia to abundant rubble breccia. The upper contact of the breccia merges gradationally with debris flow conglomerates of the lower Mount Harper group. Laterally, the upper part of the breccia unit appears to intertongue with lower Mount Harper group conglomerates which overlie the disconformity surface in areas that lack breccia.

The breccias are massive, unsorted and have no definable bedding (Fig. 8A). They typically weather pale yellow-orange or light grey, and consist of 70 to 90%

angular fragments in a chert- and dolomite-altered dolowacke matrix. Breccia fragments commonly range from pebble to small boulder size, but some blocks larger than 2 m were observed. Almost all fragments consist of dolostone similar to rocks of the upper Fifteenmile group, although they have been extensively altered by chert replacement and recrystallization. Recognizable protolith characteristics of the breccia fragments generally are the same within correlative vertical intervals, suggesting that minimal transport has occurred. The upper portion of the breccia immediately north of Mount Harper contains abundant clasts (including blocks >3 m diameter) of alternating grey and buff coloured, thin-bedded to laminated, dololutite (Fig. 8B). Clasts of this rock type tend to occur in laterally correlative vertical intervals. Many clasts have been rotated, but do not appear to have been transported more than a few metres. Other clasts appear to have been broken and altered *in situ* (Fig. 8C). This rock type, which does not occur in either the Fifteenmile group or the overlying lower Mount Harper group, is inferred to represent a local deposit on the disconformity surface, brecciated during a subsequent episode of subaerial exposure.

Silcrete and Calcrete Layers

The best-preserved calcrete, occurring in the lower ten metres of the breccia, comprises buff-coloured, massive to faintly laminated layers <1 m thick that are laterally discontinuous over tens of metres (Fig. 9A). Vague partly silicified patches, discontinuous silcrete layers and rare discontinuous silicified pisolitic layers within the calcrete layers have formed by partial replacement of the calcrete by silcrete (described below). In thin section, the clotted micritic and floating textures characteristic of calcretes (Esteban and Klappa 1983) is readily apparent (Fig. 9B). Relic clasts float in the calcrete groundmass. Most clasts are laminar crusts, possibly reworked products of pre-existing duricrusts, or extensively altered dolosparite (possibly relics of the breccia dolostones replaced by calcrete).

In addition to the well-preserved calcrete layers, the breccia contains other evidence of calcrete formation. Most of the matrix between breccia clasts contains

remnant patches of clotted micrite, and displays floating textures characteristic of the well-preserved calcretes. However, these textures generally are almost totally overprinted by silicification.

Silcrete occurs as distinct 1 to >10 cm layers of dark grey, laminated chert which drape or infill between breccia fragments. These layers are laterally continuous for 1-10 m, and overlap other layers (Figs. 9A,C). Massive silcrete occurs as a partial replacement of calcrete, a common texture where these alteration products coexist (Goudie 1983; Summerfield 1983a; Khalaf 1988). Massive silcrete showing typical F and C fabric predominates (terminology of Summerfield 1983a,b). In these silcrete types, partially silicified clasts of the original rock type (generally calcrete) float in a groundmass of microcrystalline quartz and sand-sized detrital quartz grains (Figs. 9D-E). Many of the detrital quartz grains are fragments derived from quartz cements, crusts, and replacements, attesting to a complex history for the breccias, calcretes and silcretes.

Although silcrete occurs as distinct crusts and lenticles replacing calcrete, general silicification of much of the breccia also is apparent. Breccia clasts are commonly coated and partially replaced by white chert crusts, and a network of white and dark chert veinlets has replaced much of the precursor matrix (probably representing a pre-existing weathered horizon) (Fig 10A). Less common orange dolomite coatings and fracture fills typically are partially replaced by chert. Elongate bedding-parallel vugs millimetres to decimetres long are common in the upper 20 to 30 metres of the breccia (Figs. 10B,C). These vugs are complexly filled by multiple layers of radial-fibrous chalcedony, subhedral to euhedral megaquartz and a final fill of blocky megaquartz (Figs. 10C,D). Chalcedony also occurs as coalesced spherulites that display pseudo-uniaxial extinction crosses. All chalcedony is length-fast, negating the possibility that they formed as replacements of evaporite minerals (cf. Folk and Pittman 1971). However, a single fragment containing length-slow chalcedony was observed in the chert-rubble breccia that overlies the Harper Fault breccia (Fig. 5B). Geopetal cavity-fills decimetres in size also occur

(Fig 10E). A complex history of multiple cement/alteration events is reflected by cross-cutting relationships and brecciation of early crusts, coatings and vugs (Fig. 10F).

Rare (<5%) pale yellow-orange weathering conglomerates are interbedded with the breccias and silcrete/calcrete horizons (Fig. 11A). These conglomerates contain 30 to 80% pebble- to boulder-size clasts, randomly oriented and very poorly sorted in a dolowacke matrix of medium-grained to granule grain size (Fig. 11B). These beds vary laterally from matrix- to clast-supported, and most are ungraded. Bedding is obscure, but subtle vertical changes in clast percentages and size segregations suggest 1 to 3 m thick beds. Better defined lenses 4 to 7 m long and <2 m thick are present. Forty to ninety percent of the clasts consist of fragments of the unconformity surface breccia (Fig. 11C); the remainder are dolostone identical to the unit of the upper Fifteenmile group that crops out immediately below the disconformity. Post-depositional clast and matrix silicification has occurred, but not as extensively as in the typical breccias. The presence of reworked regolith clasts, and a matrix similar to that of the overlying Mount Harper group conglomerates, together suggest that the conglomerates were deposited by gravity flow during early lower Mount Harper group time. Some of these beds occur low in the breccia unit, suggesting that the final brecciation event at least partially overlapped initial deposition of the lower Mount Harper group.

Interpretation of Disconformity Breccia

Estaban and Klappa (1983) noted that a preserved exposure surface only records of the last exposure event. The multiple generations of silica and dolomite cements, many of which coat eroded fragments of early cement, strongly suggest that the sub-Harper disconformity surface was subjected to several periods of exposure, alteration and erosion. Rare unaltered conglomerate interbeds provide clear evidence of gravity flow, suggesting that at least the last exposure event was coeval with initial deposition of the Mount Harper group. These characteristics also

indicate that the breccias were at least in part formed on surface, rather than by subsurface cave collapse.

Pervasive multi-generation alteration of the original breccia fragments and matrix has obliterated many of the primary features, preventing detailed interpretation of their origin. However, they appear to be essentially *in situ* products of subaerial weathering, although some components possibly have been transported short distances. Classification as mantling paleokarst breccias, following James and Choquette (1988), seems appropriate. The extensive occurrence of vugs and geopetal cavities within the breccias suggests a collapse breccia origin for some of these bodies, but the quality and amount of outcrop is insufficient for recognition of the megascopic features which distinguish karst collapse breccias (cf. Esteban and Klappa 1983).

Interpretation as surface karst breccia is compatible with the initial setting of the Mount Harper group. The normal faulting which initiated Mount Harper group deposition could have promoted karst weathering, if other conditions for karsting were present (carbonate substrate, proper paleoclimate, etc.). Esteban and Klappa (1983) have pointed out that extension creates new joints and fractures in carbonate host rocks, increases topographic irregularities, and initiates slope failures and collapse of speleothem features. The rare interbedded conglomerates may represent episodes of slope failure, or debris flow triggered by faulting.

DISCUSSION

This study documents two breccias of different, but essentially coeval, genesis. The Harper Fault breccia lacks evidence of the pervasive alteration characteristic of the disconformity breccias, and is inferred to represent fault-scarp paleotalus formed at the beginning of Mount Harper group deposition. However, the mantle of weathering rubble containing fragments of chert and chalcedony crusts and cements identical to those that cap the disconformity surface, indicates that subaerial weathering also occurred after paleotalus deposition.

Figure 12 schematically illustrates the relationship of the unconformity surface breccia to faulting and formation of the fault-scarp paleotalus. The unconformity surface breccia shows no obvious relationship to the normal faulting which initiated alluvial fan deposition of the lower Mount Harper group. However, the unconformity surface breccia does show features characteristic of karst weathering and silcrete/calcrete formation. Interbedding of conglomerates typical of the lower Mount Harper group alluvial fans suggests that the last event of exposure coincided with initial alluvial fan deposition. This has important implications for the climate during initial Windermere deposition. Calcrete occurrences are generally cited as evidence of semi-arid or arid, temperate-to-tropical environments (Estaban and Klappa 1983; Klappa 1983; James and Choquette 1984; Wright, V.P. 1988), although Seminiuk and Searle (1985) have documented calcrete from subtropical humid climates. A rare example of cold climate calcrete (Swett 1974) occurs as thin (<2 cm) accretionary encrustations, in contrast to the deeply weathered zones typical of warm-to-hot climate calcretes.

Silcretes are generally associated with semi-arid to arid environments, but warm, humid climates also have been proposed (Summerfield 1983b). A temperate-to-equatorial, semi-arid to arid climate is consistent with other features of the lower Mount Harper group (redbeds, abundant desiccation, alluvial fan sieve deposits).

Subaerial exposure surfaces and breccia in other Windermere Strata

Evidence for karsted surfaces and calcrete/silcrete horizons has not been published for the base of the Windermere Supergroup or for equivalent strata. Specific studies of lower Windermere strata in the Mackenzie Mountains include studies of the glacially derived Rapitan Group by Yeo (1981, 1984, 1986), and regional studies of the Windermere strata in the Mackenzie Mountains and Wernecke Mountains of the eastern Yukon by Eisbacher (1981, 1985). Eisbacher (1985 p. 237) reported exposures of the unconformity surface as "abrupt, scoured, and locally polished" and he illustrated (Eisbacher 1981, p. 23) one flat, polished, iron-stained and crusted

surface, which he inferred to be the result of subglacial erosion. Eisbacher (1981 p. 25) also described one 150 m-thick unit of "tightly packed, oligomictic sharpstone conglomerate which displays crude layering on a 10 m scale," which he interpreted as a local fault-scarp facies. He also described two occurrences, about 100-110 metres thick, of "chaotic sharpstone diamictite" consisting of locally derived limestone clasts "floating in a particulate calcareous matrix" (his sections 5 and 6, 1981 p. 31-32). These occurrences appear sufficiently similar to those of the basal Mount Harper group breccia to warrant re-evaluation for evidence of subaerial weathering. Products of subaerial weathering and karsting also are present at the unconformity which separates the Rapitan Group from the underlying Coates Lake Group locally in the Mackenzie Mountains, and within the Coates Lake Group (Jefferson and Parrish 1989, Jefferson pers. comm. 1989). Evidence for extensive subaerial weathering and related silicification is also preserved in upper parts of basaltic lavas preserved at the top of the Mackenzie Mountains Supergroup in the Mackenzie Mountains (Morris and Aitken 1982). Aitken (1981) also reported that alteration of carbonate rocks at the top of the Little Dal Group is most common subjacent to the sub-Rapitan unconformity.

Rocks of the Windermere Supergroup and equivalents have been subjected to more metamorphic alteration and structural deformation in British Columbia than in the Yukon and N.W.T. This may have masked or obliterated evidence of subaerial exposure. However, the unpublished study of Root (1987, p. 117) documented an isolated occurrence of decimeter-sized irregular cavities in dolostones immediately below the sub-Toby Formation unconformity. Root interpreted those cavities as paleokarst features.

Strata commonly correlated with the Windermere Supergroup in the western U.S. include the Kingston Peak Formation in Death Valley (Young et al. 1982). Miller (1985) interpreted several occurrences of Kingston Peak Formation basal breccia to have been locally derived as a result of faulting and uplift. However, the Beck Spring Dolomite, which locally is unconformably overlain by the Kingston

Peak Formation, has provided abundant petrographic and isotopic evidence for subaerial weathering during early diagenesis at or near the upper contact (Zempolich et al. 1988).

Finally, diamictites in northern Utah, generally interpreted as glaciogenic, unconformably overlie rocks that probably are equivalent to the Belt/Purcell Supergroups. The unconformity surface displays many features suggestive of intense subglacial erosion (Ojakangas and Matsch 1980); any features formed during preglaciation exposure apparently have been eroded.

CONCLUSIONS

Subaerial weathering produced paleokarst breccias, calcretes and silcretes before and before and during initial deposition of the lower Mount Harper group, which is interpreted to be the stratigraphic equivalent to basal Windermere Supergroup rocks recognized elsewhere in the North American Cordillera. The paleoclimate was within a range of temperate-to-equatorial, and probably was semi-arid to arid, although a humid climate cannot be completely dismissed. The youngest of the exposure-related deposits formed concurrently with major normal faulting and with concomitant deposition of fault-talus breccia. Subaerial weathering at the top of the fault-talus breccia is evident. Elsewhere in the Canadian Cordillera, evidence exists for similar subaerial exposure surfaces at the base of probably correlative Windermere strata, although basal Windermere breccias have generally been interpreted as related to extensional faulting that initiated Windermere sedimentation. Re-examination of the reported breccia occurrences, with emphasis on examination of both the basal unconformity and the breccias for evidence of subaerial exposure, seems warranted. Additional discoveries and detailed studies of exposure-related breccias could increase the now sparse evidence for paleoclimate and paleolatitude coincident with initiation of the major rifting event related to Windermere sedimentation at the western margin of North America.

The discrimination of fault-talus breccia from subaerial exposure breccias

requires a combination of detailed field observations and complementing petrographic examination, as we have attempted to demonstrate in this paper. Because faulting coincides with subaerial weathering in many settings, regardless of age, efforts to recognize the subtle differences between breccias formed by faulting and weathering are worthwhile. The failure to recognize the co-existence of breccia types can lead to misinterpretations, or to interpretations which fail to fully access all paleoclimatic and paleotectonic indicators.

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FIGURE CAPTIONS

Figure 1. Regional setting. A) Distribution of the upper Proterozoic Windermere Tectonic Assemblage in the Canadian Cordillera (after Tipper et al. 1981). B) Distribution of middle and upper Proterozoic to lower Cambrian strata in the Ogilvie, Wernecke and Mackenzie Mountains (after Tipper et al. 1981, Jefferson and Ruelle 1986, Roots 1987). C) Simplified geology of the Coal Creek inlier (modified after Roots 1987, Thompson et al. 1987). D) Simplified geology of the western exposures of the lower Mount Harper group.

Figure 2. Generalized stratigraphy of the Coal Creek inlier (modified from Roots 1987). Units show significant lateral gradations in thickness. Stratigraphic relationships before Mesozoic-Tertiary deformation are shown schematically in upper right inset; breccias at base of the lower Mount Harper group are represented by black triangles.

Figure 3. A) Area of best exposure of the Harper Fault, looking west. Taken with a telephoto lenses resulting in some scale distortion of foreground vs. background. B) Interpretive sketch of Harper Fault area illustrated in Fig. 3A. The stepped normal fault at center forms the southern boundary of the lower Mount Harper group, and continues to the west where it is overlapped by volcanic rocks of the Mount Harper Volcanic Complex, demonstrating that faulting is of late Precambrian age.

Subvertical segments of the stepped faults north of the main fault do not cut conglomerate beds above, attesting to the coeval relationship between the faulting and lower Harper group deposition. Reverse fault near south side of photo is a result of post-Devonian (probably late Mesozoic-Tertiary) deformation which reactivated segments of the late Precambrian faults. Measured section (330 m thick) north of the fault is shown in Figure 3C. C) Measured stratigraphic section through Harper Fault breccia. Alluvial fan conglomerates above the breccia are > 500 m thick in this area. Paleocurrent rose diagrams are for clast imbrication in conglomerate beds above and below the upper oolitic grainstone (N = number of measurements). Clustered arrows represent individual paleocurrent measurements

of planar crossbedding in the upper oolitic dolarenite bed (N = 6).

Figure 4. Harper Fault breccia. A) Polished slab of small breccia fragments of laminated dolostone. Fragments are unaltered, and their angular margins are well preserved. B) Photomicrograph of typical breccia cements consisting of isopachous bladed dolomite cement and late dolosparite infill which shows increasing crystal size away from fragment margins. Crossed nicols. Scale bar equals 0.5 mm.

Stratigraphic top toward top of photo.

Figure 5. Chert rubble floatbreccia at top of fault breccia A) Slab showing angular chert fragments floating in buff dolomicrite matrix. Large-scale divisions in cm. B) Photomicrograph of breccia showing layered chalcedony fragment surrounded by a micritic matrix with clotted texture. The chalcedony is zebraic (Z), radiating fibrous length-slow (quartzine) (Q), and radiating fibrous length-fast (C). The presence of zebraic chalcedony and quartzine have been suggested to indicate the replacement of evaporites (Folk and Pittman 1971; Milliken 1979), although alternative origins have been subsequently demonstrated (Keene 1983). Crossed nicols. Scale bar equals 0.5 mm. Stratigraphic top toward the right.

Figure 6. A) South-facing outcrop showing dolomitized ooid grainstone (this is the ooid grainstone bed at 310 m in Fig. 3C), one of two grainstone beds interbedded with conglomerates. The lower contact of the dolomitized ooid grainstone with the underlying conglomerate is irregular (± 10 cm), but this irregularity is exaggerated in the photo due to dark patches of lichen and grass. The upper contact of the grainstone is sharp and slightly wavy, reflecting erosion before deposition of the overlying conglomerate. B) Polished rock slab of ooids and pisoids illustrating variations in their size and shape and the general abundance of cements. A thin irregular microcrystalline dolomite crust (arrowed) marks the abrupt contact with an overlying bed of small ooids. Scale in cm; stratigraphic top toward the right. C) Photomicrograph of ooids. Well-preserved concentric micritic cortices coat a variety of nuclei including older ooids (1), a fragment composed of dolosparite (2) and probable fragments of calcrete (3). Ooids are cemented by isopachous fibrous

dolomite with a subsequent infill of dolosparite which coarsens toward center of the voids. Crossed nicols. Scale bar equals 0.5 mm. Stratigraphic top toward top of photo. D) Photomicrograph in plane-polarized light of ooids showing remnants of possible meniscus cements (arrowed) at contacts of ooids, showing characteristic pore-rounding habit. Scale bar equals 0.5 mm. Stratigraphic top toward right.

Figure 7. A) Typical disconformity surface (about 6 km northwest of Mt Harper) showing unaltered dolostone of Fifteenmile group, sharp but slightly irregular disconformity surface, and coarse debris flow conglomerates of the overlying lower Mount Harper group. Most clasts in the conglomerates can be assigned with confidence to upper Fifteenmile group provenance; some clasts of chert and dolomite-altered breccia are similar to the breccia preserved on the disconformity surface north of Mt Harper (shown in Figure 7C). Jacob's staff, 1.5 m long, is subdivided into 10 cm segments in lower 50 cm. B) Vertical outcrop face showing sharp disconformity surface. Dolostone of Fifteenmile group dolostone immediately below this surface is extensively fractured, possibly the relic of a regolith eroded before, or during, deposition of the lower Harper group. Fracture infills of white chert and orange dolomite cements were noted in some occurrences. C) View looking east-southeast showing distribution of breccia above disconformity surface north of Mt Harper, preserved on a dip slope overlying platform dolostones of the Fifteenmile group. Strata dip 30 to 40 degrees southwest. The lower Mount Harper group along the horizon is about 150 m thick.

Figure 8. Breccia at disconformity surface. A) Pervasively altered breccia in which original clast boundaries have been obscured by both calcrete (light grey) and silcrete (dark grey). Photo is of an exposure perpendicular to bedding, about 50 cm thick and with stratigraphic top toward top of photo. B) Hand sample of ribbon dolostone. Cross-cutting fracture is filled with white chert at margin and orange dolomite in central part. Scale in cm. Stratigraphic top toward top of photo. C) Vertical exposure of remnant ribbon dolostone clasts in a highly altered chert and dolomite matrix. *In situ* brecciation and later alteration is suggested by similar

orientation and thickness of laminae and bedding within adjacent clasts.

Figure 9. A) Massive buff-coloured calcrete in outcrop, partially replaced at base by dark lenses of silcrete. The overlying breccia contains clasts of the calcrete, but is also slightly silicified. B) Photomicrograph illustrating clotted texture of calcrete matrix containing floating grains of chert and quartz. The clasts possibly represent remnants of previous silicification, including silcrete replacement of the calcrete. Crossed nicols. Scale bar equals 0.5 mm. Stratigraphic top unknown. C) Laminated silcrete (dark grey, arrowed) draping clast in conglomerate bed within the breccia unit. Partly obscured by white lichen. D) Photomicrograph of F-fabric massive silcrete. Fragments of quartz are in a matrix consisting predominantly of microquartz. Remnant dark calcrete (right side of photo) is partly replaced by silica. Crossed nicols. Scale bar equals 0.5 mm. Stratigraphic top toward left. E) Photomicrograph of C-fabric massive silcrete composed of microquartz with abundant detrital grains, including pebbles derived from previously formed silcretes. The silcrete pebble in this photo includes coalescing chalcedony spherulites with pseudo-uniaxial extinction crosses. Crossed nicols. Scale bar equals 0.5 mm. Stratigraphic top toward left.

Figure 10. A) Pervasively silicified breccia in outcrop. Breccia fragments are obscured or replaced by a complex series of chert crusts, vugs and direct replacement of dolostone by chert. Stratigraphic top toward upper left corner of photo. B) Polished rock slab with abundant vugs complexly infilled by chert and megaquartz. Dark patches are chert replacements of dolostone. Stratigraphic top toward top of photo. C) Polished slab showing vug initially lined by a crust of laminated dolomite, progressively infilled by megaquartz, then by black chalcedony and finally by quartz crystals with euhedral central terminations. Stratigraphic top is unknown (sample from float). D) Photomicrograph composite of void fill shown in (C). Layers from the dolomitic margin (left) to center are: radial fibrous dolomite (A), euhedrally terminated megaquartz (B), microquartz and fanning chalcedony (C), progressively coarser euhedrally terminated megaquartz (D), radiating

chalcedony overprinting fine brown lamina (originally opal?) (E), coarse mosaic quartz as the most central fill (F), chalcedony of symmetrical fill from opposite margin (G). All of the chalcedony is length-fast. Crossed nicols. Scale bar equals 1 mm. E) Cavity containing geopetal fill, about 30 cm wide and 20 cm high. The cavity is lined with a crust of white chert, subsequent layers of buff laminated microcrystalline dolomite and a final infill of dark grey massive microcrystalline dolomite. Arrows point to fragments of early chert crust surrounded by geopetal fill. Stratigraphic top toward top of photo. F) Photomicrograph showing fragments of micritic dolostone (dark) and remnants of a previous episode of silicification (S), cemented by fibrous chalcedony and microquartz. An early micritic coating that is thickest on the top (toward right in photo) of some clasts (arrows), possibly is a geopetal feature. Crossed nicols. Scale bar equals 0.5 mm.

Figure 11. A) Poorly sorted conglomerate within breccia unit. This example shows vague reverse grading of gravel-sized clasts at base. Jacob's staff, 1.5 m long, is subdivided into 10 cm segments in top 50 cm. Stratigraphic top toward top of photo. B) Polished slab of conglomerate. Clasts show better rounding, less post-depositional alteration, and greater variety of clast lithologies than typical breccias. Most large pebbles in this example are laminated dolostones, probably derived from uppermost unit of the Fifteenmile group. The unaltered dolowacke matrix is identical to that of alluvial fan conglomerates which overlie this breccia. Stratigraphic top toward the right. C) Clast of partly silicified breccia in conglomerate (about 20 cm in diameter). Stratigraphic top toward top of photo.

Figure 12. Schematic diagram showing inferred stages of breccia formation. Not to scale. A. Pre-faulting subaerial exposure of the Fifteenmile group resulted in a mantling karst regolith composed of brecciated protolith, extensive calcrete, and later silcrete formation (black lenses). Subsurface karst features are speculative. B. Early faulting induced reworking of some of the mantling breccia as debris flows. Minor synthetic and antithetic faults probably existed in addition to the major Harper Fault. These faults (most not preserved) could have caused the rare debris

flows that are interbedded with the regolith breccia. The area of preserved paleokarst breccia may have been downdropped and protected from surface erosion by the faulting. This could also explain the unique dololutite preserved here, the product of subaqueous carbonate deposition in a local paleolow. C. Continued movement of the Harper Fault resulted in a fault-scarp breccia and initiated extensive alluvial fan deposition on the scoured disconformity surface, incorporating most regolith breccia in the alluvial conglomerates which filled the half-graben, and covering the locally preserved disconformity surface breccia. D. Subaerial weathering continued during initial alluvial fan deposition, as indicated by extensive formation of silcretes above debris flow deposits containing clasts of earlier-formed breccias, and *in situ* brecciation and alteration of the dololutite (shown as dashed breccia fragments. E. Subaerial weathering locally formed a chert rubble layer on a sheltered topographic bench at the top of the fault-scarp breccia, possibly acting as an impermeable base for local ponding and formation of ooid and pisoid grainstones.

Figure 1.

Figure 2.

Figure 3 ▶ ▶ ▶ ▶

FIGURE 4

FIGURE 5

Figure 6

FIGURE 8

Figure 9

Figure 11

Figure 12.

CHAPTER 3

Normal faulting and half-graben alluvial fan deposition at the base of the Windermere Tectonic Assemblage (upper Proterozoic), Ogilvie Mountains, Yukon

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ABSTRACT

The upper Proterozoic lower Mount Harper group (informal name) or the Ogilvie Mountains, west-central Yukon, is inferred to be coeval with basal Windermere Tectonic Assemblage rocks of the North American Cordillera. A preserved synsedimentary normal fault forms the southern margin of an asymmetric, east-trending half-graben basin. The basin fill is southerly derived and consists of fault-proximal talus breccia and up to 1100 m of debris-flow conglomerates deposited in coalescing alluvial fans preserved as coarsening-upward sequences which are vertically stacked and 70 to 150 m thick. Intermediate and distal alluvial fan facies include mid-to-lower fan conglomerates and sandstones deposited by sheetfloods, debris flows and braided channel streamflows. A thick coarsening-upward basin-scale sequence in the eastern part of the study area records a change from lacustrine redbeds to fan-delta and lower alluvial fan sandstones and conglomerates. This reflects initial progradation of facies northward, but an upper fining-upward component to the basin-fill sequence preserved in intermediate and distal facies suggests onlap during late stages of basin fill.

The half-graben basin was formed, and sedimentation controlled, by the faulting at the southern margin. Comparison with strike-slip basin depositional patterns indicates significant differences, suggesting that faulting was predominantly dip-slip. Synsedimentary fault movements and minor back-stepping of the fault controlled development of both the internal alluvial fan and basin-scale sequences. Volcanism conformably postdates sedimentation in this half-graben, but north-derived coarse clastic rocks which intertongue with the volcanic rocks were deposited to the northwest, and are not directly related to lower Mount Harper group deposition. A model is proposed in which diachronous, opposed-symmetry half-grabens formed, with volcanism concentrated in the accommodation zone between half-grabens. Basins in the modern continental rift system of West Africa provide geometric and evolutionary analogues.

INTRODUCTION

Many authors have suggested continental rifting along the western margin of North America during the late Precambrian (most recently Jefferson and Parrish, 1989; Eisbacher, 1985; Young, 1985). Most studies supporting this interpretation have focused on the general stratigraphic characteristics of the Windermere Tectonic Assemblage (Tipper and others, 1981, updated in Wheeler and McFeeley 1987) and U.S. correlatives, the non-suspect upper Proterozoic stratigraphic succession in the eastern part of the North American Cordillera (Fig. 1A). Tectonic influence on sedimentation during Windermere deposition has been documented to varying degrees in both Canada and U.S.A. (Eisbacher, 1981,1985; Jefferson and Parrish, 1989; Root, 1987; Miller, 1985). However, fault control on sedimentation is generally inferred because of lack of preservation, or reactivation of, the late Proterozoic faults. This paper documents an example from the Ogilvie Mountains of the northern Canadian Cordillera, where a half-graben basin including normal faults directly related to initial Windermere sedimentation and volcanism is preserved. Detailed study of the unmetamorphosed and essentially undeformed sedimentary rocks demonstrate that faulting initiated and controlled deposition of the basin fill, a debris-flow-dominated alluvial fan complex and associated lacustrine redbeds. In conjunction with detailed studies of the overlying volcanic rocks by Roots (Roots, 1987; Roots and Moore, in review) and regional studies of the tectonic evolution of the Ogilvie Mountains (Thompson and others, 1987; Roots and Thompson, in press), the tectonically controlled sedimentation documented herein supports initiation of continental rifting of the western margin of North America at about 750 Ma (although possibly diachronous, with a range of about 730 to 780 Ma).

REGIONAL FRAMEWORK

The informally named Mount Harper group crops out in the southern Ogilvie Mountains, the northwesterly extension of the Cordilleran foreland fold and thrust belt (Figs. 1A,B). Sedimentary and volcanic strata of the Ogilvies, ranging in age from mid-Proterozoic to Jurassic, were telescoped northward during late Mesozoic -

early Tertiary deformation. Proterozoic rocks relevant to this study are generally confined to a broad, east-trending erosional inlier, termed the Coal Creek Dome by Green (1972) (Figs. 1B,C).

Figure 2 schematically illustrates the stratigraphy of the inlier. The oldest rocks consist of a thick (>4 km) succession of fine-grained siliciclastics, dolostones and cross-cutting heterolithic breccias (Wernecke-type breccias). These rocks correlate with the middle Proterozoic Wernecke Supergroup in the Wernecke mountains to the east (Thompson and Roots, 1982; Delaney, 1981; Lane in preparation). These are probably the stratigraphic equivalent of the Belt/Purcell Supergroups of the northern U.S. and British Columbia (Young and others, 1979). Wernecke Supergroup strata in the inlier are unconformably overlain by more than 2 km of dolostones (locally stromatolitic), and a less abundant basal succession of mudstones and conglomerates. Informally termed the Fifteenmile group, it probably is part of sequence B of Young and others (1979), a carbonate-dominated succession which separates the Middle Proterozoic Wernecke Supergroup (Sequence A of Young et al 1972) and the Upper Proterozoic Windermere Supergroup and equivalents (Sequence A). Sequence B includes the Mackenzie Mountain Supergroup (Aitken 1981) and the Pinguicula Group of the Wernecke Mountains (Eisbacher 1981). However, both the Pinguicula and Fifteenmile successions have not been documented in detail sufficient to suggest direct correlation with either each other or the Mackenzie Mountain Supergroup, except in the very broad sense of sequence B, which represents a time interval of several hundred million years.

Mount Harper group and Fifteenmile group sedimentary rocks comprise an unmetamorphosed, generally homoclinal succession that dips 20°-40° southwest. The Mount Harper group unconformably overlies the Fifteenmile group and is preserved along the south and west margin of the inlier (Fig. 1C). The Mount Harper group consists of three units. The oldest, the subject of this paper, is a conglomerate-rich succession (<1100 m thick), termed the lower Mount Harper group (LMHG). This unit is conformably overlain by the Mount Harper Volcanic Complex (MHVC, maximum 1200 m), a bimodal suite related to deep crustal rifting at 751 ±26/-18 Ma

(U-Pb on zircons: Roots, 1987; Roots and Parrish, 1988). The upper Mount Harper group (UMHG) is 300 to 1400 m thick, and conformably overlies and interfingers with the volcanic strata. It comprises conglomerate, sandstone, and mudstone (most are clastic dolostones, some are siliciclastic), and minor limestone. Early Cambrian trace fossils at the top of the UMHG (Mustard and others, 1988a,b) suggest that an unconformity representing a time gap of possibly 150 to 200 m.y. separates the upper map units from the lower volcanic and clastic units. The inlier rocks are unconformably overlain by archeocyathid-bearing lower to middle Cambrian dolostone.

Correlation of the pre-Cambrian part of the Mount Harper group with the Windermere Tectonic Assemblage (Tipper et al., 1981, updated in Wheeler and McFeely 1987) is warranted by the age of the volcanic rocks and similarities of tectonic and depositional history (Roots 1987, Roots and Parrish, 1988, this study).

The terms Windermere Tectonic Assemblage and Windermere Supergroup are used in this paper where the regional setting or significance of the Mount Harper group is discussed. The formations and groups which make up the former are shown on the compilation map of Tipper et al. (1981), updated in Wheeler and McFeely (1987), and briefly discussed in Gabrielse and Yorath (1989). This tectonic assemblage is defined on the basis of broadly similar interpreted depositional and tectonic settings. The Windermere Supergroup was first defined (as "Windermere Series") in the southern Canadian Cordillera (Walker 1926), but the term has been extended to include most formations and groups recognized as correlative to the type strata (reviewed in Eisbacher 1981, 1985; Young *et al.* 1982).

The terms "basal Windermere" is informal and is used in this article to refer to the varied successions of conglomerate-rich sedimentary rocks and, in some places, associated volcanic rocks, which in the Canadian Cordillera are the stratigraphically lowest part of what is uncontroversially accepted as Windermere Supergroup. This usage is well-established in the literature (e.g. Eisbacher 1981, Yeo 1981; Young 1984; Jefferson and Parrish 1989). However, in the Mackenzie Mountains of the N.W.T., a local succession of non-glacial carbonates, evaporites, redbeds and minor

conglomerates deposited during a phase of extensional faulting (the Coates Lake Group) would be included as part of the basal Windermere by some workers (Aitken 1981, Morris and Aitken 1982, Aitken pers. com. 1990). Others have argued that the Coates Lake Group should be considered separate from the Windermere Supergroup (Young *et al.* 1982, Jefferson and Parrish 1989, Jefferson pers. com. 1990).

THE LOWER MOUNT HARPER GROUP

Stratigraphic and Tectonic Boundaries

Figure 3 comprises a geological map of the lower Mount Harper group, and vertical section insets which illustrate lateral relationships of lithofacies, variations in the unit geometries, and well exposed areas of the unconformity surface. The LMHG is bounded by a basal disconformity, a conformable upper contact with the MHVC in western exposures, and a disconformable upper contact with Cambrian dolostones in eastern exposures. The southern contact is a synsedimentary high-angle fault. Original depositional pinchouts are suggested to the north and east and inferred to the west.

Basal disconformity surface and regolith. The disconformity surface which separates the Fifteenmile group from the overlying lower Mount Harper group is irregular to gently undulating, (Fig. 3, inset D). The paleorelief is typically a few metres to decimetres, rarely up to 100 metres. Paleoslopes are generally shallow, but rare steeply dipping, east-trending normal faults have locally dropped the north side a few 10's of metres (Fig. 3, inset B).

The disconformity surface is typically sharp and scoured of any regolith which was present (Figs. 4A,B). However, rare discontinuous lenses of regolith breccia are locally preserved along the contact. The most extensive example crops out north of Mount Harper, where a semicontinuous layer of breccia is preserved for about 3 km laterally (Fig. 3, map and inset A). The breccia consists of locally derived angular fragments, with interbedded silcrete and calcrete layers. A detailed study of this breccia suggests it resulted from karstification during subaerial exposure both

before and during initial deposition of the lower Mount Harper group (Mustard and Donaldson, in press).

Southern contact: late Proterozoic Harper Fault. A high-angle north-side down fault (named Harper Fault by Thompson and others, 1987) forms the southern limit of the main LMHG exposure (Fig. 3). Parallel to the Harper Fault, about 100 m south of its surface trace, is a high-angle fault now dipping 70 to 80 degrees northward. This fault downdrops both the MHVC and early Paleozoic dolostones on its south side, and is presumably related to Mesozoic-Tertiary deformation. In most of the study area the younger fault appears to have reactivated the late Proterozoic structures. However, the original Precambrian fault system is preserved and was not reactivated over a lateral distance of several kilometres where it is exposed at the southern boundary of the main LMHG exposure (Fig. 3, labelled Harper Fault).

The Harper Fault trends easterly and dips 50 to 60 degrees north (bed-tilt corrected to original dip of 70 to 80 degrees north). The fault trace is stepped on its north side with offsets visible in the main exposure (Fig. 5A,B). The fault is traceable to the west where it cuts the lowest strata of the volcanic complex, but is overstepped by most of the volcanics, suggesting fault movement ceased after initial volcanism. The minor step faults do not cut overlying beds of the LMHG, showing that faulting was also synsedimentary and formed part of a stepped fault scarp along the original southern boundary of the now-preserved LMHG. Supporting this direct evidence for synsedimentary faulting is the presence of a thick wedge of talus breccia adjacent to the fault, as well as the alluvial fan environment inferred for the LMHG conglomerate which abuts the fault (documented below).

The preserved minimum vertical offset of the Harper Fault is about 1100 metres (the maximum thickness of the LMHG north of the fault). Immediately south of the Harper Fault, the rock type consists of dark grey metasediments of the Quartet Group, the middle unit of the Wernecke Supergroup. North of the Harper Fault the Quartet Group is preserved about 3 to 4 km stratigraphically below the Mount Harper Group, overlain by 1 to 2 km of Gillespie Lake Group dolostones and a minimum of 2 km of dolostones and minor siliciclastic rocks of the Fifteenmile

Group. Assuming the sub-Mount Harper group succession preserved north of the fault is of similar thickness to that eroded south of the fault, the estimated total vertical offset of pre-Mount Harper group strata across the Harper Fault is about 4 km. This estimate is reinforced by the reverse-source stratigraphy of clast lithologies in the proximal LMHG conglomerates (described below).

Upper contact. In western exposures of the LMHG, conglomerate and sandstone of this succession are overlain by mafic volcanics of the MHVC. The contact is sharp and slightly erosive. However, two features suggest that volcanism began while LMHG sediments were still being deposited. Sandstones preserved a few metres below the volcanics contain up to 10% volcanic grains (Fig. 6A). The only possible source for these grains is the lowermost part of the volcanic complex. Supporting evidence for this conclusion is preserved in the basal volcanics immediately north of Mount Harper where mafic flows and volcanic breccias grade upward into pillowed volcanic rocks (Roots, 1987). The volcanic flows immediately overlying LMHG sandstones and mudstones have loaded and distorted the underlying sediments (Fig. 6B). The volcanics contain angular fragments of interbedded sandstones and mudstones obviously eroded from underlying beds (first documented in Roots, 1987). The fragments have convolute internal stratification, a deformation not present in the underlying sedimentary rocks. This suggests that semi-lithified sediments were incorporated during the deposition of the initial volcanic flows, implying that the time between initial volcanism and LMHG sedimentation was not significant. This evidence for essentially contemporaneous sedimentation and volcanism permits radiometric dating of the volcanism ($751 \pm 26/-18$ Ma, Roots and Parrish, 1988) to be roughly applied to the timing of sedimentation and faulting.

Eastern exposures of the LMHG are disconformably overlain by light grey dolostone of early to middle Cambrian age. Thickness changes in the MHVC show that volcanics must have covered much, if not all, of the LMHG (Roots, 1987). However, any previously existing volcanics were eroded prior to Cambrian deposition in the eastern part of the study area. The disconformity is not exposed, although it can be constrained within a few tens of metres in several places.

Northern depositional pinchout. To the north, the LMHG progressively thins from a maximum of 1100 m near the Harper Fault to less than 5 m of interbedded sandstones and pebble conglomerates about 15 km northwest of the fault. The rocks are well exposed along much of the line of section shown in Figure 3 (insets A,B). Intertonguing of the sandstone concomitant with thinning of the units reflects the original depositional geometry in this oblique section, although minor erosion during deposition of the overlying volcanics may have occurred.

Original Basin Configuration

Preservation of the original southern fault system and apparent depositional pinchout of the sedimentary rocks to the north allows estimation of the original basin configuration and size. The north-south geometry is that of a simple half graben as shown in Figure 3, inset A, although the figured section is oblique to the original half graben axis. The demonstrable width of the half graben thus is closer to 10 km than the 15 km shown.

The LMHG thins significantly eastward from greater than 600 m (Fig. 3, inset C, section 21) to less than 40 m (*ibid*, section 28) over 4 km and to less than 20 m thick at the eastern limit of semi-continuous outcrop (about 2 km east of section 28). A few small exposures on the next ridge east probably are the last remnants of the basinal deposits. This eastward thinning is apparent in all map units, suggesting that this represents an depositional feature rather than post-depositional erosion.

Any western pinchout of sediments is covered by overlying volcanic rocks or UMHG sediments. However, the most westerly exposures (southwest of Mt Harper) are a maximum of 100 m thick, a considerable thinning from the 1100 m thickness preserved near the main exposure of the Harper Fault (Fig 3, geology map), so a western pinchout can be inferred. The eastern pinchout is about 40-50 km east of the thick Harper Fault exposures. Assumption of a similar extent to the west suggests the half graben size is about 10 km minimum north-south and 80-100 km east-west (minimum of about 50 km), with a sediment fill of about 1100 m (with at least several hundred metres of added fill by overlying volcanic rocks).

FACIES OF THE LOWER MOUNT HARPER GROUP

Mapping at 1:50:000 scale by the author and Thompson and Roots (GSC open file maps refs?) has delimited four major map units based on the predominant rock type: breccia, conglomerate, sandstone, and mudstone (Fig. 3). Each map unit roughly corresponds to the major recognized facies associations, except for the conglomerate and sandstone map units. Interbedded conglomerates and sandstones included in the intermediate facies for this paper were mapped as part of the conglomerate map unit, separate from the sandstone-dominant map unit, but are interpreted together with the sandstones as lower alluvial fan and fan delta deposits. In map pattern (Fig. 3), the surface expression of the map units are geographically proximal (conglomerate and breccia), intermediate (sandstone and conglomerate) and distal (mudstone and sandstone) to the Harper Fault. One exception is breccia mantling the disconformity surface which is preserved well north of the fault and is interpreted as regolith. The control of the Harper Fault on basin formation and sedimentation is reflected by equivalence of this geographical proximal to distal relationship with an interpreted proximal to distal change in sedimentation pattern away from the fault. The facies are described and discussed in terms of this pattern.

Fault-adjacent Breccia Facies: Fault Scarp Talus

A distinctive breccia crops out adjacent to the north side of the Harper Fault. This breccia unit has a geometry of a north-tapering wedge and grades vertically and laterally (northward) to the proximal conglomerates described below (Fig. 3, inset A, Fig. 8, section 18). A detailed description of this breccia and its relationship to the disconformity surface regolith is presented in Mustard and Donaldson (in review). The breccia has a minimum thickness of 288 m immediately north of the Harper Fault and pinches out < 1200 m north of the fault. The basal contact is not exposed; the top contact with proximal conglomerates is gradational over 5 to 10 m of altered chert breccia, a possible subaerial weathering layer.

The main breccia comprises >95% medium-grey angular fragments in < 5% poorly sorted fine- to coarse-grained pale yellow orange dolowacke matrix. The

fragments range from < 1 cm to >100 m diameter (most 10 cm - 5 m). Bedding is not readily apparent, but vague layers 2 to >70m thick were defined on the basis of clusters of similar fragment sizes. The thickest layer includes several tabular megablocks with minimum long axes >100 m. These megablocks are oriented with long axes subparallel to regional LMHG bedding, and are 20 to 40 m thick. All clasts are dolostones that can confidently be assigned provenance from the upper Fifteenmile group.

The breccia of this unit is readily distinguished from the disconformity surface regolith breccias north of Mount Harper. The Harper Fault breccia lacks the pervasive alteration typical of the regolith breccias, except in the top ten metres. Restriction of the Harper Fault breccia to areas adjacent to the preserved high-angle fault, the wedge-like geometry that thins away from the fault, and the general lack of pervasive alteration, are all consistent with deposition as talus along an active fault scarp.

Coarse (Proximal) Conglomerate Facies: Upper to Mid Alluvial Fan

This major LMHG facies has a wedge-shaped geometry that tapers north from the Harper Fault. The unit thins consistently northward except for a slight thickening within 1000 m metres north of the fault, to a maximum thickness of about 1100 m (Fig. 3, inset A). The unit decreases in thickness and grades northward to the conglomerate-sandstone facies.

The basal contact of the unit is sharp and disconformable where it overlies Fifteenmile group dolostones (Fig. 4A). The basal contact, where either regolith or fault talus breccia is preserved, is gradational and interbedded, reflecting a lateral intertonguing relationship and coeval deposition of the lowest conglomerates, the fault talus and regolith produced during the final episode of subaerial weathering. In eastern outcrops the proximal conglomerates gradationally overlie and laterally intertongue with intermediate and distal conglomerates, sandstones and mudstones in a basin-scale coarsening-upward sequence (Fig. 3, inset C, Figs 17,18.). A sharp, slightly erosive upper contact with the Mount Harper Volcanic Complex is rarely exposed west of the main ridge north of the Harper Fault.

Slightly concave-upward bounding surfaces are visible from a distance on some ridge faces (Fig. 7). These intraformational contacts appear to define several roughly wedge-shaped and overlapping conglomerate units. Some are identifiable in measured vertical profiles by subtle changes in bed thickness and clast size, defining coarsening-upward megasequences (used in the sense of Heward, 1978) 80-150 m thick (Fig. 8). Many of the "wedges" also appear to contain small-scale fining/coarsening sequences a few tens of metres thick. However, when the ridges were examined in detail, the common amalgamation of bed contacts, very poor sorting, and lack of nonconglomeratic interbeds prevented definition of these smaller sequences. Many studies define subtle sequences by the detailed measurement of bed thickness and maximum clast size of all the beds in a vertical profile (for example Steel and others 1977). This proved impossible in the coarse conglomerates because insufficient bed contacts could be discerned in a single vertical section to define trends. The large-scale coarsening- and thickening-upward megasequences, although vague, were recognized by a consistent increase in boulder abundance and bed thickness, even where specific bed contacts could not always be picked confidently. In most sections the change from abundant boulder-rich, thick beds to less bouldery and "thinner" beds could be placed within about ten metres and, in spite of the uncertainty of exact placement, appeared from distant view to be relatively sharp.

The proximal facies comprises greater than 97% conglomerates plus minor sandstone and mudstone (Fig. 8). At a distance, all conglomerates are light to medium grey, reflecting the weathering colour of the abundant dolostone clasts. The matrix of the sandstone and conglomerate is pale yellowish orange on fresh surfaces, weathering somewhat darker orange. The conglomerate beds are typically clast-supported, massive, and very poorly sorted, with 80-90% pebble- to boulder-size clasts in a dolowacke matrix (classification scheme for these carbonate clastics is based on that of Folk 1959, 1974 for terrigenous carbonate detritus). The matrix shows a continuum of grain size from medium-grained sand to granules (Fig. 9A). Mud and fine-grained sand are a minor component of the matrix, generally less than

10%. Clasts are mostly subangular to subrounded and typically subspherical to spherical. The latter characteristic reflects the blocky weathering style of Fifteenmile group dolostones, the major source for the conglomerate clasts.

Ungraded, disorganized conglomerates are the most common type, forming about half of the beds in the most proximal areas, but decreasing in abundance north from the fault (Fig 9B). Almost as common, and becoming increasingly prevalent away from the fault, are beds with a cobble/boulder-rich central layer, a reverse-graded basal layer, and normally graded top, each of the latter two comprising 10 to 20% of the bed (Fig. 9C). The grading is generally poorly developed, but laterally varies from very poorly developed to well-developed in the same bed. Less common (about 15 to 20% of proximal beds) are conglomerates with either normally graded tops or reverse-graded bases, but not both (Figs. 9D,E). The normally graded beds tend to be slightly thinner and better sorted than beds showing both types of grading, and are more common farther north of the Harper Fault. Conglomerates with only reverse-graded bases are generally thick, poorly sorted, and most abundant in the proximal facies. Reverse grading is best shown by the gravel-sized clasts (coarse-tail grading).

Designation of frameworks as clast- or matrix-supported was based on defining granule- or finer-sized material as matrix. On this basis, matrix-supported conglomerates are rare (< 5%). They are typically massive, ungraded, very poorly sorted, and tend to be located in proximal areas. They contain 20 to 70% pebble- to boulder-sized clasts which randomly float in a polymodal mud-sand-granule dolowacke matrix which is generally slightly finer grained than the clast-supported conglomerate matrix. Matrix-supported conglomerate beds tend to be several metres thick (though possibly composite) and sheetlike, although bed thickness varies laterally. Several matrix-supported conglomerates grade laterally to thinner, clast-supported, ungraded conglomerates (Fig. 8 Inset C).

The boxed insets accompanying the measured sections of Figure 8 illustrate the range of bed geometries observed in the proximal facies. Most conglomerate beds are tabular, appearing to continue laterally for several tens to hundreds of metres

perpendicular and parallel to the fault, varying slightly in thickness. The vague geometry visible in Figure 7 suggests that many of the conglomerates are part of elongate, overlapping wedges. Where discernible, contacts between beds are typically nonerosive and irregular, with clasts projecting from the top of one bed into another. The thickness of recognizable beds ranges from < 20 cm to > 4 m, with a mean of 123 cm, but this value is certainly low, reflecting the difficulty in defining bedding in the proximal area, where thicker, coarser beds are common.

Exceptions to this typical bed geometry exist. In the basal part of the coarsening upward megasequences, about 10 to 20% of the thick, coarse conglomerate beds are sharply overlain by cappings of pebble-rich conglomerate a few decimetres-thick (Fig. 8, Inset B). These separate beds are laterally discontinuous, a few tens of metres in extent at most, better sorted than the underlying conglomerate and commonly vaguely stratified. The stratification is defined by internal normally graded layers, 5-15 cm thick, which overlap and merge laterally. Most of these beds appear to drape passively the irregular tops of the boulder-rich conglomerates. However, some fill broad, shallow channels, in places exhibiting well-defined cut-and-fill structures (Fig. 8, Insets A+E, Fig. 9F).

The interdependence, and vertical and lateral variations, of bed thickness (BTh) and maximum clast size (MCS, defined as the average of the ten largest clasts locally per bed) can provide a basis for distinguishing conglomerate depositional processes (reviewed in Nemec and Steel, 1984). It proved impossible to measure these parameters with enough consistency in a single vertical profile to help define vertical trends, but they were recorded wherever the bed thickness could be confidently discerned and did show great lateral variation in the immediate area. A positive linear correlation is apparent between these two features, both measured using the method of Bluck (1967). Correlation is apparent for the conglomerates whether examined in total, partitioned into proximal and intermediate facies, or separated into grading types (Fig. 10). Bed thicknesses and maximum clast sizes also decrease north from the Harper Fault (Fig. 11), although the trend is more obvious in the field because the coarsest, thickest beds are under-represented in the data due

to the scarcity of distinct bed contacts. The decrease in these parameters parallels an observed proximal-to-distal change in the grading styles, with ungraded and inversely graded conglomerates most abundant in the proximal facies, and normally graded conglomerates most abundant in more distal facies (Fig. 12). However, considerable overlap is present. Beds with a reverse-graded base and normally graded top are present in all facies. The most proximal examples are thick and very poorly sorted, with crudely developed and thin graded bases and tops. The graded parts of this lithotype become increasingly well-developed and thicker away from the fault. A similar proximal to distal trend of increasingly well-developed grading is apparent for all grading types.

Unusual conglomerate lithotypes also include rare boulder-rich conglomerate beds exhibit an open framework fabric, with cobble and boulder clasts in a fitted pattern and either no matrix (Fig. 13A), or a matrix that appears to have infiltrated after deposition. These are interbedded with relatively coarse, thick conglomerates.

Rare layers contain abundant boulders and megaboulders (defined as 10-100 metres by Sundell and Fisher, 1985). These tend to be of a single composition in a given layer. The best exposed layer (Fig. 13B) is located immediately north of the Harper Fault and contains dolostone clasts up to 20 m diameter within an unusual, very poorly sorted matrix-supported layer which does not continue north of the largest boulder (Figs. 13C,D). Dark grey mudstone (unique in the LMHG) is preserved below some boulders. Conglomerate beds above, below and north of this layer are typical clast-supported conglomerates.

Non-conglomeratic sediments are rare. The irregular unconformity surface at the base of the proximal conglomerates includes several broad gentle troughs. These commonly contain poorly to moderately sorted pebbly sandstone beds up to a few metres thick, which thin and onlap onto the rising unconformity surface. Two discontinuous oolitic sandstone layers are located a few metres above the fault proximal breccia (Fig. 8, top of section 18). The internal characteristics and geometry suggest that they formed in a ponded bench of the fault talus slope (Mustard and Donaldson, in review). Dolomitic mudstone is present as two

discontinuous layers less than ten metres thick in one vertical section (Fig. 8, section 11). Laminae in the mudstones are contorted, folded and slightly to strongly brecciated. The internal folds are consistently overturned towards the north.

Clast Provenance. All conglomerate clasts can confidently be assigned provenance from the Fifteenmile group or Wernecke Supergroup. The vertical change in clast composition roughly corresponds, but in reverse stratigraphic order, to the Fifteenmile group and upper Wernecke Supergroup successions preserved beneath the Mount Harper group.

Lower conglomerate beds contain abundant clasts identical to the disconformity surface regolith preserved north of Mount Harper. Clasts of the Fifteenmile group are not sufficiently distinctive to allow detailed study of changes upward in clast composition, but it is apparent that stromatolitic and cryptalgal dolostone clasts identical to the top unit of the upper Fifteenmile group are more common in lower conglomerate beds. A central Fifteenmile group unit consists of several hundred metres of massive dolostone with abundant grey chert as nodules and lenses, or intermixed forming sharpstone breccias. Clasts derived from this unit are most abundant in the lower 80% of the proximal facies, intermixed with stromatolitic and cryptalgal dolostone clasts.

The most distinctive clast is jasper, which generally is located only in the upper half of the proximal conglomerates. Jasper is common as clasts in the Wernecke-type breccias and as bedded jasper in the Fairchild Group, the lowest Group of the Wernecke Supergroup and the presumed source for the Wernecke-type breccia clasts (R. Lane, pers. com., 1989). The bedded jasper of the Fairchild Group is an unlikely source; it is below the Quartet Group and the Quartet Group is still partly preserved immediately south of the Harper Fault. The jasper clasts of the Wernecke-type breccias are the probable source as the breccias intrude the lowest units of the Fifteenmile Group (C. Roots, pers. com., 1988) and the top unit of the Wernecke Supergroup (Gillespie Lakes Group). Thus the first occurrence of jasper clasts in the LMHG indicates paleosource exposure at least to this stratigraphic level. Coincident with or slightly above the first occurrence of jasper clasts, clasts of orange-

weathering dolostones with alternating resistant and recessive thin beds are present. This rock type is characteristic of the Gillespie Lake Group in the Coal Creek inlier. No clasts similar to Quartet Group or Fairchild Lake Group rock types (other than jasper) were recognized.

Paleocurrents. The high sphericity of most clasts negated measurement of clast long axis orientation, a commonly used conglomerate paleotrend indicator. The only observed paleocurrent indicator is the rare imbrication of tabular clasts in the reverse-graded base of the conglomerates which display this grading pattern (Fig. 9C). Tabular clasts are rare, and the imbrication is poorly developed, so care was taken to measure the orientation of all tabular clasts within a selected interval of a reverse-graded portion without bias until an average of 50 measurements were collected. Clast measurement followed the methods of Rust (1975).

The paleocurrent data were statistically analyzed following the methods outlined by Curray (1956). The Rayleigh test of significance was applied, and only sites with values which indicate that the grouped orientations are non-random (a Rayleigh value of less than .05, as recommended by Curray) were used for paleocurrent analysis.

With these restrictions, the proximal conglomerates yielded 624 clast orientations from 15 sites (Fig. 14). Although a linear scale is commonly used to plot current roses, Nemec (1988) has pointed out that this graphically distorts the current rose, whereas a non-linear scale provides a better representation of the data. Current roses plotted with this method appear more scattered than those plotted using a linear scale, especially in roses where there is a high variance, the case for the LMHG conglomerates. The current roses show a general radial pattern, with a high circular deviation in individual sites; nevertheless, except for site F, the vector means are northerly.

Coarse Conglomerate Facies: Interpretation

Characteristics of the proximal facies strongly suggest that deposition occurred on the proximal and mid-fan areas of debris-flow dominated alluvial fans. Wedge-

shaped fan lobes coalesced laterally and vertically to form a continuous thick fan complex north of, and adjacent to, the Harper Fault.

Recent summaries of alluvial fan characteristics include Nilsen (1982) Rust and Koster (1984) and Bull (1977). Most criteria reported are present in the proximal facies of the LMHG. The slightly lensoid, tapering wedge geometry with preserved marginal normal faults and fault talus are classic features rarely recognized in ancient examples. The compositional and textural immaturity, local clast derivation, inverted clast-source stratigraphy and scarcity of non-conglomeratic lithotypes are commonly observed features. Subaerial exposure is indicated by the orange (oxidized) weathering color of the conglomerates (Nilsen, 1982, p. 62, Bull, 1972), the open framework conglomerate fabric (sieve deposits of Hooke, 1967), the high slope of the BTh. vs. MCS correlation (discussed below) and the lack of interbedded lithotypes or sedimentary structures suggestive of subaqueous deposition or reworking. The unidirectional but complex radiating paleocurrent pattern and the downfan decrease in average and maximum clast size and bed thickness are additional features common (though not unique) in alluvial fans (Nilsen, 1982, Rust and Koster, 1984).

Most of the conglomerates were deposited as debris flows. Features supporting this interpretation include the polymodal grain-size distribution, sheet-like bed geometries, lack of erosion surfaces, abundance of projecting clasts and lack of internal stratification (Bull, 1977, Nemec and Steel, 1984, Nilsen, 1982, Rust and Koster, 1984). Well-developed streamflow processes were rare, as suggested by the lack of channelized deposits and diagnostic sedimentary structures such as planar cross-stratification and parallel internal stratification.

The term debris flow is used in the sense of Lowe (1982), Nemec and Steel (1984) and Postma (1986) for sediment gravity flows showing plastic rheological behaviour. This includes cohesive debris flows, where the main internal support mechanism is matrix strength, and grain flows (cohesionless flows of Nemec and Steel, and Postma) where clast support is dominated by frictional effects (mainly dispersive pressure). In addition, a complex range of flow modification effects,

minor support mechanisms and variations in matrix strength, fluid content, etc. (reviewed in Nemec and Steel, 1984; Schultz, 1984) can result in a wide range of possible final grading, bed geometry, fabric and matrix types.

The interrelationships and proximal-to-distal changes in grading types, bed thickness, and maximum clast size are suggestive of a single depositional process undergoing downfan evolution. In the LMHG case, this process was most likely a high-concentration, gravelly cohesive debris flow, with matrix-strength and dispersive pressure as the main internal support mechanisms. The cohesive nature of the flows is supported by the MCS vs BTh data (Fig. 10); however, the high concentration of clasts in many flows suggests a significant component of dispersive pressure (Schultz, 1984). A high matrix-strength is compatible with the wide range of grain sizes in the LMHG conglomerates, despite the apparent low content of clay, a feature of some debris flows discussed by Hampton (1975) and Rodine and Johnson (1976). Reverse-grading in the basal 10-20% of some proximal beds probably reflects kinetic sieving and base-effect shearing (Enos, 1977, Lowe, 1982). Clast interactions in this zone could result in a poorly developed upflow imbrication (Enos, 1977). Flows with a higher water content, or reaching a slightly lower slope where upward pore-fluid expulsion would increase, could develop slight turbulence in the upper portions, inducing normal grading of the top of the flows. This pattern could have been enhanced by slight post-depositional or late flow reworking of the flow tops. Where combined with the basal effects discussed above, beds with reverse-graded bases, normally graded tops and a central layer of ungraded detritus (analogous to the rigid plug of Middleton and Hampton, 1976) would be deposited. In some cases several reverse-to-normally graded beds form a continuous vertical sequence with a diffuse contact between the reverse-graded base of one bed and the normally graded top of the underlying bed. These are interpreted as surging debris flows (cf. Nemec and Steel, 1984) in which the final deposit is produced by a viscous sediment flow moving downslope in successive surges. Reworking of tops of the conglomerates by rare, separate water-rich flows (possibly the sheetfloods of Bull, 1972, 1977 and Hogg, 1982) caused the draping pebbly caps. Overlapping normally

graded layers in these pebbly layers are the result of surging within the flows, an interpretation suggested for similar lithotypes by Gloppen and Steel (1981), and Larsen and Steel (1978). This is similar to the surging hyperconcentrated flows of Wells (1984), which deposit composite pebble-rich beds showing normal grading within vague to well-defined channels.

The rare megaboulder layers are interpreted as major landslide or rockfall deposits on the proximal fan slopes. The best-exposed example has an unusual amount of associated mud, both as non-gravelly mudstone beneath the megaboulders, and as a component of the unstratified, matrix-supported conglomerate south of the largest boulder. The presence of the largest boulder at the northern extreme of the flow, its flat base, muddy substrate and the lack of matrix-supported conglomerate immediately to the north suggest an unusual depositional history. Perhaps a furrow was gouged by the largest megaboulder, leading to channelization of a mud-rich debris flow dammed by the megaboulder at the north end of the furrow. The mud could have acted as a lubricant beneath the sliding megaboulders.

The open-framework conglomerates with fitted fabrics represent a type of sieve deposit. Sieve deposits form as lobate masses of permeable gravels where matrix is not deposited or is removed by rainwash or infiltrating water discharged during deposition (Hooke, 1967). Although commonly associated with streamflow processes (Bull, 1972) sieve textures can also form at the front or in levees of debris flows (Hooke, 1967). The LMHG sieve deposits are boulder-rich and lack the relatively good sorting and well-developed imbrication that is common in streamflow sieve deposits formed on lower fan areas (cf. Bull, 1972, 1977). This, and the lateral change of open-framework conglomerates to typical debris flow deposits supports deposition as debris toe or levee accumulations. This may reflect a slight change in slope, causing rapid infiltration of fine-grained detritus and water, or downslope bypass in which the coarsest material is left behind (documented in a modern alluvial fan by Blair, 1987).

Several features indicate fan accumulation in an arid or semi-arid climate. Sieve deposits are most common in this setting (Hooke, 1967; Bull, 1972, 1977). The

almost complete dominance of gravel-rich debris flows is typical of these conditions, and unlikely in areas of normal or high rainfall (Nilsen, 1982). Consistent or significant rainfall should have left much more waterlain deposits and evidence of streamflow processes.

Bth vs. MCS relationships. A positive linear correlation between maximum clast size and bed thickness primarily reflects the dependence of flow capacity and competence on the internal properties of sediment gravity flows (reviewed in Nemec and Steel, 1984). Such a relationship is not observed for fluvial conglomerates (*ibid*). Only beds for which the top and bottom contacts could be discerned with reasonable confidence were measured. This restriction probably accounts for the predominance of inverse-to-normally graded beds in the dataset, although ungraded beds are more common in proximal areas.

The correlation coefficients for the MCS vs BTh data are similar to those obtained in comparable conglomerate studies (Nemec and Steel, 1984; Gloppen and Steel, 1981; Porebski, 1984). The regression lines for all conglomerates and for the proximal facies conglomerates (Figs. 10A,B) have high slopes characteristic of subaerial alluvial fans (compare to Nemec and Steel, 1984, their Figs. 20-24). The decrease in slope between proximal and intermediate facies (Figs. 10B,C) is common (*ibid*; Gloppen and Steel, 1981), and here probably reflects a more rapid decrease in flow competence vs. capacity as fan slope decreases away from the fault. A change from subaerial to subaqueous deposition would show a similar trend (Nemec and Steel, 1984; Bluck, 1969; Porebski, 1984), but the intermediate facies conglomerates lack features supporting such an interpretation except in a few eastern exposures.

The regression lines for all the graphs intersect the y-axis (MCS) above the origin (except the line for normally graded conglomerates in Fig. 10E, based on only 11 measurements). Nemec and Steel (1984, p. 23) suggested that such intersections are consistent with, and perhaps diagnostic of, cohesive rather than cohesionless debris flows. The intercept above the origin reflects initial cohesive strength, independent of internal support factors during flow such as dispersive pressure and viscous resistance (*ibid*).

The pattern of decreasing BTh and MCS and down-fan changes in grading types is also typical of alluvial deposits. Similar trends have been observed in Devonian fan conglomerates by Porebski (1984) and Nemec and others (1984), who inferred similar proximal-distal relationships. Walker (1975) postulated a similar evolution of grading types for submarine fan conglomerates. This pattern reflects downfan changes in depositional processes. Downfan slope reduction causes a decrease in flow competence and capacity, resulting in a decrease in average MCS and BTh and the increase in the degree of internal grading and sorting. This in general reflects a decrease in matrix strength and dispersive pressure, and an increase in dewatering and settling of clasts through the matrix.

Paleocurrents. The northerly trend of paleocurrents indicates a southern source area. The general radial paleocurrent pattern is typical of alluvial fans (Nilsen, 1982, Rust and Koster, 1984), reflecting a buildup of overlapping fan lobes. The high circular deviation of imbrication at individual sites contrasts to the strongly unimodal and relatively low deviation of fluvial conglomerate imbrication. This may reflect the inefficiency of clast collision during flow, the main cause of imbrication in debris flows (Rees, 1968; Enos 1977). It probably also is partly due to the inclusion of the orientation of platy clasts from beds not consistently reverse-graded laterally in an attempt to avoid introducing field bias. This also is the probable cause of the bimodal distribution at some sites, because sudden changes in flow directions seems unlikely at the base of a single non-turbulent debris flow. Mill (1984) has demonstrated a similar poor grouping (but overall upflow dip) of tabular clasts in modern clast-supported volcanoclastic debris flows.

A wide range in the inclination of individual clasts at a given site is also evident (Fig. 15). Proximal facies imbrication includes a significant number of steeply dipping clasts. Intermediate facies imbrication shows much less scatter, with rare high dip values. This increased clustering with distance from the source may reflect downfan change from the fanhead region, where clast interaction is minimal and imbrication does not fully develop before freezing of the flows. In lower fan areas, a longer time for clast interaction allows the imbrication to develop to a

greater extent. The maximum dips of planar crossbeds in the distal facies (Fig. 15, lower graph) cluster as expected in the 10-40 degree range.

The easterly flow direction at site F (Fig. 14) is unusual, but probably not significant. This site is from a channel-like elongate lens of moderately sorted pebble-cobble conglomerate within the coarser and more poorly sorted sheet conglomerates (e.g. Fig. 8, inset A). This channel fill probably represents a fluidized flow between debris flow events in the apical part of a fan. Channelized flows in fan apical areas commonly show a complex pattern of channel directions (e.g. Hooke, 1967, Bull, 1977), reflecting the irregular fan surface.

Conglomerate-Sandstone Facies: Lower Alluvial Fan and Fan-delta

The intermediate facies of the LMHG comprises an interbedded mix of conglomerate, sandstone, and minor mudstone. Laterally the change from proximal to intermediate facies is gradual, and these two facies were differentiated on the basis of where sandstones become a consistent component of the strata (the intermediate facies). In the eastern half of the map area, the intermediate facies in turn grades vertically and laterally to a mudstone-dominated facies, the lower, "distal" part of a basin-scale coarsening upward sequence.

The intermediate facies shows slightly different characteristics in western and eastern exposures. The western outcrop, represented in Figure 16, consists of two well-defined sequences, which coarsen upward except for a capping fining-upward component 15 m thick in the top sequence. These strata overlie a thick succession of regolith breccias, described in Mustard and Donaldson (in press).

Clast-supported conglomerates are the most common rock type in western exposures of the intermediate facies, but compared to proximal conglomerates, are thinner (most 10 to 50 cm) and moderately sorted; pebbles and cobbles are generally the only gravel component. However, a few thick (75 to 250 cm) boulder-rich beds similar to the proximal conglomerates are located in the coarsest section of the coarsening-upward sequence. Conglomerates with reverse-graded bases and normally

graded tops are common, but in most cases lack a central ungraded component. Ungraded and reverse-graded beds are uncommon.

Beds normally graded throughout, or in the top half of the bed, are abundant. Where interbedded with other conglomerates, such beds tend to be tens of centimetres thick and grade from a cobble-rich base (or an ungraded cobble/pebble-rich lower half) to a small-pebble top (Fig. 16A), although some tops are matrix-supported in a medium-to-coarse-grained massive sand. However, many of these beds contain discontinuous and overlapping normally graded layers, giving a stratified appearance to the beds (Fig. 16B). Where sandstone interbeds are relatively plentiful (they nowhere exceed 15% of the total strata in the lower 120 metres of section 14), the interbedded conglomerates typically grade from a pebble to small-cobble base to a fine-grained sandstone top over 10 to 30 cm. The sandstone top is generally massive or faintly laminated and contains rare north-directed cross-laminated ripples; no mudstone cappings were observed. Separate beds of ungraded pebble to small-cobble conglomerate of similar thickness also are present.

Sandstones interbedded with the finer conglomerates are coarse- to medium-grained dolowackes. Most are normally graded, and some display granule or small-pebble bases. Almost all are massive or contain vague horizontal lamination in the upper parts of the 5 to 15 cm thick beds. The interbedded conglomerate and sandstone beds also occur as poorly defined fining-upward sequences a few metres thick, although in most places the interbedding appears to be random. Rare outsized clasts in the sandstone beds include isolated cobbles which cut several beds. Most of these clasts are near spherical or sub-spherical, and do not greatly deform the laminae of the surrounding sandstone.

The coarse conglomerate beds are vague tabular sheets traceable for tens of metres or more. Most beds have irregular bases, but only rarely have underlying beds been eroded sufficiently to produce a slightly concave-upward lower bounding surface. The thicker and coarser normally graded conglomerates show similar bed geometries. The fining-upward conglomerate-to-sandstone sequences also appear to constitute overlapping lenses a few tens of metres in lateral extent, most with

shallow and poorly defined concave-upward or irregular lower contacts (Fig. 16C). However, except where sandstone interbeds are prominent, the conglomerate beds are difficult to trace laterally, and complexly overlap with diffuse contacts.

The basal parts of many reverse-to-normally graded and normally graded beds show some imbrication of tabular clasts (but most clasts are subspherical), all indicating northerly transport (Fig. 14, sites P,Q,R,S), although with a high deviation of dip directions. Rare ripple cross-laminations also indicate northerly transport. However, three-dimensional exposures of cross-laminae are rare, so these cross-laminations were not included in the statistical analysis of the palaeocurrents.

The sandstones of the fining-upward part of the upper megasequence in Figure 16 (above 240m) are medium to fine grained and tan to light red coloured. They are 1 to 5 cm thick, slightly wavy and internally laminated. Many grade up to red mudstone a maximum of 1 cm thick (Fig. 16D). Mudstone intraclasts are common at the bases of some beds. Tabular normally graded pebble conglomerates up to 15 cm thick are rarely interbedded, and have basal contacts which load or show evidence for erosion of the underlying beds.

In eastern exposures, the conglomerate-sandstone facies also includes reverse-to-normally graded conglomerates, normally graded or ungraded conglomerates and interbedded dolowackes (Fig. 18 G,F.). These facies are similar to those described above, but form part of a distinct coarsening upward megasequence, gradationally overlying mudstone redbeds of the distal facies (Figs. 17,18). Some of the lowest conglomerates have irregular bases on fine-grained to silty red dolowacke, and show a textural inversion, with pebbles and cobbles in a matrix of red dolosiltstone (Fig. 17A). Some of the conglomerates and sandstones in this area exhibit large-scale planar cross-stratified sets, but most appear to have tabular geometries. Stratigraphically higher conglomerates are similar to those in western exposures in that both are tabular, normally graded or reverse-to-normally graded, but many grade upward to coarse- to medium-grained dolowackes (Fig. 18F), and interbedded normally graded medium-grained sandstones are common.

Planar cross-stratification also is present in the sandstones, especially where normally graded pebbly sandstones are interbedded with desiccation-cracked mudstones of the distal facies. Tabular intraclasts of the red mudstones are abundant in the planar cross-laminated beds (Fig. 18D), which thin and eventually pinchout to the north. Cross-laminated asymmetric ripples (some as climbing ripples) are located at the tops of some normally graded sandstones in this transitional unit. All of the cross-strata indicate northerly transport. Rare overlapping trough crossbeds are located in medium-grained sandstones immediately above the transition zone in section 20.

Paleocurrents from imbricated gravels indicate northerly sediment transport in western exposures (Fig. 14 sites P-S, W,X), and when combined, define a radial pattern similar to that for the proximal conglomerates. Although northerly overall (Fig. 14, sites T-V, Y), some paleocurrents from imbricated gravels in the eastern exposures show deflection toward the thickest part of the distal facies from both the east (site Y) and west (site V). This is also somewhat apparent in the most easterly proximal facies paleocurrents (sites M-O).

Conglomerate-Sandstone Facies: Interpretation

The features of this facies are compatible with the evolution of depositional processes from upper and mid alluvial fan to lower alluvial fan areas. The relatively coarse, thick, tabular conglomerates of the western exposures in most cases are similar to debris flows of the proximal areas. The slightly increased sorting, better developed grading and more apparent lenticular geometry reflect downfan changes in the debris flow processes. The lowering of fan slope, and increased time of flow result in a decrease in competence. This is reflected in the BTh vs MCS relationship (Fig 10C) which shows a lower linear regression slope relative to the proximal conglomerates. The better-developed grading of these flows may be the result of transition from the cohesive debris flows of the proximal facies to flows where clast-support is dominated by dispersive pressure and escaping pore fluid. However, matrix-strength may still be a significant component (note that the

regression line of Fig 10C still intersects the y-axis above the origin). These flows may correspond to the type that Lowe (1976) termed density-modified grain flows.

The interbedded conglomerates and sandstones show features compatible with deposition in gravelly braided channels. Miall (1977) pointed out that braided channels are common on lower alluvial fans and form deposits similar to those of proximal braided river deposystems. The rare upward-fining conglomerate-sandstone sequences a few metres thick or thinner are typical of many coarse braided stream environments (Rust and Koster, 1984; Miall, 1977, 1978; facies assemblage G_{II} of Rust, 1978). These small sequences could represent lateral migration of gravel longitudinal bars, or possibly the evolution of single large flood events in broad, shallow generally unchannelized sheets (sheetfloods in the sense of Hogg, 1982; hyperconcentrated flood flows of Smith, 1986). The lack of a regular repetition of these fining-up sequences is more compatible with, though not diagnostic, of the latter event. Cant (1984) cites this lack of small-scale sequences as a distinguishing feature of proximal gravelly braided deposits. The generally tabular to slightly lensoid and overlapping geometry of the stacked conglomerates is a common feature of proximal gravelly braided channels (Miall 1977, 1978; Hein and Walker, 1977), and results from the migration of low relief longitudinal bars. However, studies of similar gravels have revealed a significant component of planar crossbedding in the gravels, especially in pre-Mesozoic examples (Rust and Koster, 1984). This is ascribed to the common occurrence of deep channel flows. The lack of these features in the LMHG suggests that the gravels formed as superimposed bars in shallow braided channels, a feature generally indicative of a semi-arid or periglacial climate (ibid., Miall, 1977, Scott model). The rare outsized clasts may reflect an abrupt drop in competence due to increased flow width at the mouths of main channels between longitudinal bars (cf. Gloppen and Steel, 1981).

In summary, western exposures of the conglomerate-sandstone facies contain a complex mix of debris flow, sheetflood (or density modified grain flow), and braided channel deposits. The braided channel deposits lack many features common to well-developed braided rivers, such as strong and abundant clast imbrication and

openwork gravels (e.g. Rust and Koster, 1984), and are more typical of streamflow processes on alluvial fans. This corresponds to a mid-to-lower alluvial fan environment (the middle fan of Nilsen, 1982) and in terms of published vertical profile models, is similar to the Trollheim model of Miall (1978) and the G_1 facies assemblage of Rust (1978). Parallelism of the intermediate facies paleocurrent patterns to those of the proximal areas supports a model of prograding alluvial fan deposition. In contrast, braided river or braidplain successions tend to have paleocurrents oriented roughly perpendicular to those of associated alluvial fans (Rust and Koster, 1984).

The eastern exposures are in general thinner bedded, more sand-rich and show slightly better sorting. Parts of the coarsening-upward sequence where mudstone interbeds are common can be explained as slightly more distal braided channel deposition. Debris flow deposits are rare, but still present; most of the conglomerates were deposited as diffuse gravelly sheets reflecting both sheetflood events and shallow braided channels migrating across the lower fan. Bull (1972, 1977) illustrated similar braided streamflow deposits in modern alluvial and late-Cenozoic fans. Most deposition was probably related to episodic flood stage events, in which sandstones of poorly defined coarsening-upward sequences accumulated during waning flow. The rare planar crossbedded gravels may reflect slightly deeper braid channels in this area (cf. Rust and Koster, 1984).

Gradational change from the lower mudstone facies to conglomerates and sandstone is interpreted as a product of alluvial fan progradation into standing water, a coastal alluvial fan environment (Rust and Koster, 1984). The term fan-delta is also used for this type of deposystem. McPherson and others (1987, 1988) suggested the term fan-delta be restricted to deposits in which alluvial fans grade directly into standing water, with no intervening braidplain. The term braid delta is suggested for the latter case. An alternate viewpoint is given by Nemec and Steel (1988), who suggested a less restrictive definition which includes stream-dominated and sandy lower alluvial fans. Where the LMHG subaerial deposystem is interpreted to prograde into standing water (ie. the eastern half of the map area), the term fan-

delta is believed to be correct even using the narrow criteria of McPherson and others (1987, 1988). In the central part of the LMHG study area (e.g. Fig. 17), red mudstones change over a short vertical interval to conglomerates which include subaerial debris flow deposits with only rare intercalated conglomerates and sandstones possibly deposited by braided streamflow processes. This corresponds to a lower alluvial fan environment and thus the term fan-delta is correct using the strictest definition. In more easterly exposures (e.g. Fig. 18), a thick section of interbedded conglomerates and sandstones contains features characteristic of braided channels. However, poorly sorted conglomerates of probable debris flow origin also occur intercalated in this sequence and are common in the upper parts of the vertical profiles. It is clear that the depositional environment was dominated by alluvial fan processes, and the braided channels occurred on lower alluvial fan slopes, not as part of a braidplain. Thus this area also fits the fan-delta definition of McPherson and others (1987).

Features indicative of shoreline deposition are difficult to discern, especially for lake shores where tidal effects are absent and wave-energy is low. In the lower Mount Harper group, the presence of a thick sequence of laterally extensive dark red mudstones provides the only firm indication of transition to subaqueous deposition. However, the highest mudstones are commonly desiccation cracked, and a mudflat environment is also compatible with the upper part of the mudstone facies. The textural inversion of fitted conglomerate clasts with a red mudstone matrix shown in Figure 17A may represent the incorporation of mud into a flow as it entered a lake. Nemec and others (1984) and Larsen and Steel (1978) suggested such an interpretation for conglomerates showing a similar textural inversion. However, Gloppen and Steel (1981), illustrated a somewhat similar bimodal texture in what they interpreted as sieve deposits, later infiltrated by fine material (their Figure 11B). Such an interpretation is possible for the LMHG examples, but the position of this example, only a few metres above interbedded mudstone and very fine-grained sandstone redbeds of waterlain origin favours the subaqueous entrainment hypothesis.

The zone of transition from subaerial to subaqueous deposition of the conglomerates and sandstones is not easy to define. Wave and tidal features may be lacking, especially in lacustrine basins (Kleinspehn and others, 1984). Nemec and others (1984) and Nemec and Steel (1984) suggested that the appearance of abundant normally graded conglomerate beds marks a change from subaerial to subaqueous mass flows. Above the highest redbed mudstones in the eastern exposures, normally graded conglomerates are abundant, generally interbedded with normally graded sandstones, and ungraded or inverse-to-normally graded conglomerates. These normally graded conglomerates show the form of vaguely overlapping lensoid bodies, or horizontally extensive sheets. They may have been partly or wholly deposited subaqueously or as flood-generated high density sheetflood and braided flood channel deposits on the lower fan. Cross-stratification is rare, suggesting that deep channel flow typical of well-developed braided stream environments was uncommon. In places the interbedded conglomerates and sandstones strongly resemble the channel mouth bar deposits of Paleozoic fan-deltas documented by Kleinspehn and others (1984). No features indicative of beach gravels (reviewed in Bourgeois and Leithhold, 1984) were observed.

A thick interval of interbedded sandstones, mudstones and minor conglomerates separates the extensive mudstones of the basinal mudstone-sandstone facies from conglomerate-rich beds (Fig. 18, about 260 to 350 m). The interval, rich in sedimentary structures, contains features suggestive of deposition by overlapping delta lobes, formed by periodic flood events. A stacked series of fining-upward sequences a few metres thick illustrates this. Erosive-based planar crossbedded conglomerates with abundant mudstone intraclasts record the initial pulse of a flash-flood event entering the water body and quickly losing energy, depositing the coarsest debris as small foreset wedges (Fig. 18D). These foreset deposits are overlain by massive plane-bedded sandstones, many normally graded, and/or ripple and climbing-ripple-bearing sandstones, all deposited as the sediment-charged flood event waned. Lower energy floods or streamflows deposited rippled and planar-bedded sandstones between large flood deposits, probably somewhat reworking the

main fan-delta lobes. Mudstones between these packages reflect deposition during interflood low-energy periods. Many of these mudstones contain desiccation cracks, possibly a response to seasonal lowering of the lake level. All paleocurrents trends are northerly, reflecting the dominance of flood events and streamflows off the alluvial fans as a depositional control. No evidence of tidal or high-energy wave reworking of these sediments is present. Low-energy wave activity is reflected by the rare presence of symmetrical ripples oriented perpendicular to the northerly directed paleocurrents.

Somewhat similar deposits are preserved in late Pleistocene fan-deltas along the Dead Sea rift (Sneh, 1979). In the LMHG examples, the fan-delta lobes formed fining-upward packages, whereas deltaic processes in large basins generally form coarsening-upward sequences as topset beds prograde over foresets. Sneh (1979) suggested that upward-fining reflects deposition in a small lake which experienced frequent and rapid lake-level fluctuations. He attributed these fluctuations to climatic factors and frequent tectonic activity along the Dead Sea rift. Many features of the LMHG rocks suggest an arid to semi-arid climate (e.g. abundant desiccation, redbeds and oxidized conglomerate matrix, sieve deposits). Storm-triggered flood events and rapid rising of lake level would be expected. However, tectonic activity could also be a factor. Distinguishing the relative effects of the two controls on LMHG deposition is not possible.

Mudstone-Sandstone Facies: Lacustrine redbeds

The mudstone-sandstone facies, only present in the eastern part of the map area, reaches a maximum thickness of about 300 m (Fig. 18) and forms the base of the basin-scale coarsening upward sequence. The main rock type is a dark red dolomudstone and dolosiltstone with laterally continuous laminations a few mm thick in the lower part of the sequence (Fig. 18A). The mudstones coarsen and thicken upward with increasingly common fine-grained dolowacke interbeds (Fig. 18B,C,D). Silt-sized clasts (mostly transported fragments of sparry dolomite, with less abundant quartz and micritic dolostone) are coated with a dark red iron oxide

(hematite?), resulting in the red rock colour. These rocks display laterally continuous, slightly wavy to planar laminations with desiccation cracks (Fig. 18E) abundant in the upper half of the facies, but rare in the lower half. The silt-sized components of the mudstone laminae generally are normally graded, giving way upward to minor red massive dololomite. Rarely these laminae contain faint internal horizontal microlaminae or micro-crosslaminae. Rare convolute layers are generally associated with subvertical sandstone dykes a few centimetres thick. Dolowacke beds 1 to 3cm thick are rare in lower parts of the distal facies, but upward are increasingly common and coarser (very fine- to medium-grained) passing into the transitional sandstone-mudstone-conglomerate unit described in the previous section (and Fig. 18C,D,F,G). These sandstones generally are massive and normally graded, but some have planar laminated tops or cross-laminated asymmetric ripples at the top. The cross-laminae indicate a strongly defined northerly paleoflow (Fig. 14). Symmetrical wave ripples are present on the tops of some very fine-grained sandstones. Both ripple types generally display straight to slightly sinuous (rarely bifurcating) crests.

Mudstone-Sandstone Facies: Interpretation

Although discrimination of a lacustrine from marine setting is difficult in non-fossiliferous Precambrian rocks, the lower mudstones contain many features characteristic of low energy deposition in a lacustrine setting (reviewed in Fouch and Dean, 1982; Picard and High, 1981)). Desiccation cracks are rare, except in the upper part of the facies, and the mudstones are the dominant rock type over a thickness of > 200 m in some areas (eg. Fig. 18, where most of the lower covered intervals display abundant float or subcrop of mudstone), suggesting that the water body was initially semi-permanent. The mudstones are traceable for > 10 km both east and west of their thickest occurrence (Fig. 3). Exposures are discontinuous, but the unit appears to represent deposition in a single water body several hundred square kilometres in extent. The LMHG mudstones are oxidized (redbeds) and are located in a lens-shaped body in direct association with alluvial fan deposits. They

contain abundant evidence of shallow-water deposition, but lack evidence of tidal or high-energy wave effects. These features, although not individually diagnostic of a lacustrine environment, together support such an origin. No evaporites, pseudomorphs after evaporites, or primary carbonates were discovered, despite specific search for such features. This may reflect a relatively short basin lifetime, with active faulting providing abundant and continuous clastic input.

Progressive coarsening upward of the mudstone, siltstone and fine-grained sandstone redbeds, the increasing upward abundance of separate medium- to coarse-grained sandstone interbeds, and the increasing abundance upward of desiccation cracks in the redbeds, all indicate a shallowing of the basin as the alluvial fan deposits prograded. The normally graded sandstone interbeds reflect the transition of sheetflood and streamflow transportation to turbidity currents as the subaerial flows entered the lake, lost most of their energy and coarse load in the proximal fan-delta area and continued into the deeper basin. Sandy grain flows and turbulent flows were probably also initiated at the fan-delta front, either by the flood events or due to tectonic activity (cf. Postma, 1984). The normally graded siltstone and mudstone laminae represent the most distal turbidite deposits of these processes, in association with suspension deposits that accumulated in periods of low clastic input. Sparse subvertical sandstone dykes probably were injected as a result of the sudden loading of water-saturated sediments by the sandy flows, or in response to shock dewatering triggered by tectonic activity (Lowe, 1975; Hesse and Reading, 1978).

SUMMARY OF LOWER MOUNT HARPER GROUP DEPOSITION

Deposition took place in an asymmetric basin (half-graben) with dimensions of about 50 to 100 km east-west and a minimum of 10 km north-south. The main control on basin formation, subsidence and deposition was high-angle faulting at the south margin. Coarse clastic debris shed from rising fault scarps formed a talus breccia adjacent to the fault and a series of overlapping alluvial fan lobes which prograded northward. The dominant mode of deposition in the alluvial fans was debris-flow, with braided streamflow, sheetflood and downfan-evolving debris flows

increasingly important in middle and lower fan areas. In western areas, lower fan deposition was subaerial, but in the east, the fans prograded into a lacustrine setting which appears to have been localized by a paleolow on the disconformity surface. Deposition in the lake was by gravity flows and suspension settling of muds, silts and sand, all derived from the south as fan-deltas built into the lake. A schematic of the inferred environment is shown in Figure 19A.

Most of the basin fill records progradation of the alluvial fans northward, but a late-stage basin-wide transgression is apparent, with more distal facies progressively onlapping southward. Clastic deposition appears to have ceased soon after initial volcanism of the Mount Harper Volcanic Complex.

TECTONIC CONTROLS ON SEDIMENTATION

Systematic vertical changes in the coarseness or thickness of beds, clast types or depositional processes at a megasequence scale (10's to 100's of metres, cf. Heward, 1978) within alluvial fan environments may reflect the major tectonic events which control basin formation and evolution (reviewed in Nilsen, 1982, Heward, 1978, Steel and others, 1978). Large-scale climatic variations and changes in source-rock composition can also be important factors. Smaller sequences are influenced by both autocyclic and allocyclic processes and it may be difficult to discern their relative importance (Kraus and Middleton, 1987). For the LMHG, small-scale sequences were difficult to recognize. This is especially true of the proximal conglomerates, for which the absence of non-conglomeratic lithologies resulted in common bed amalgamation. However, large-scale megasequence trends were apparent where vertical profiles were measured in detail.

The abundance of redbeds and the other evidence for a semi-arid or arid paleoclimate in the proximal conglomerates and in the basal regolith (Mustard and Donaldson, in review), suggests that significant climate change during deposition was not a factor in megasequence development. The source-rocks were dominantly platformal dolostones, suggesting that changing source-rock composition was also not a major factor in megasequence formation. The half-graben basin shape, preserved

southern margin faults, and conglomerate-dominated, southward-derived fill, all support faulting as the major control on megasequence formation. The faulting that formed the basin and influenced sedimentation had a major dip-slip component, as attested by the preserved fault scarp and the thickness of the adjacent conglomerate fill. An important question is whether strike-slip motion was also a major, or even dominant, feature.

Fault-controlled basins with a major component of strike-slip movement show similar depositional patterns. Two well-documented examples are the Devonian Hornelen Basin (Norway) and the Miocene-Pliocene Ridge Basin (California), both recently summarized by Nilsen and McLaughlin (1985), as well as separately by Crowell and Link (1982, Ridge Basin) and Steel and others, (1977, Hornelen Basin). Both basins are long and narrow, with asymmetric basin fills, and are similar to the LMHG in area. Both are fault-bounded, and faulting was the principal control of basin formation and sedimentation. However, both are unusually thick (Hornelen Basin >25 km; Ridge Basin >13.5 km) for their areal extent, reflecting an overlapped stacking of depositional packages due to basin depocenter migration, a result of the strike-slip component of oblique-slip master faults. In both basins, conglomerates are only a major element of the fill at the fault margins. Axially transported finer-grained sediments form most of the fill. The strike-slip movement results in a well-defined evolution of paleocurrent trends away from the marginal faults.

Paleocurrents change from perpendicular to the fault margin in the proximal fan facies to a predominance of transport down the axis of the basin, in the opposite direction to that of depocenter migration. Volcanic rocks are absent in both basins, but syndepositional volcanism does rarely occur in strike-slip basins (Reading, 1980; Mann and others, 1983).

The LMHG shows some characteristics markedly different from those summarized above. A conglomeratic fill is dominant. Paleocurrents are consistently transverse to the basin margin, except for a slight axial trend at the lacustrine facies margins (but this swing of paleocurrents into the lacustrine basin is from both east and west). The basin fill is stacked vertically, there is no trend of lateral stacking

of megasequences or of any deflection of alluvial fan deposition into the basin. The conglomerate clast lithologies show a simple overall inversion of source stratigraphy, with no evidence of a lateral offset of the source terrane through time. These features together suggest that normal faulting with little or no strike-slip was the major basin-forming process.

The LMHG consists of a series of coarsening-upward megasequences in the proximal conglomerates, most greater than 100 metres thick. The more distal facies also coarsen upward, but at a larger, basin-fill scale and with a fining-upward component in the upper portion of the basin-fill megasequence. The thick conglomerate fill of the proximal LMHG required some mechanism to sustain high relief in the source area. Repeated reactivation of normal faults seems the most likely control. Response to continued rejuvenation of the fault was to renew supply of coarse detritus, resulting in progradation of the overlapping alluvial fans, and a single thick coarsening upward trend in relatively distal areas. Heward (1978) postulated that, if relative uplift exceeds stream dissection, active fan segments will build onto pre-existing segments with increasing slopes, causing progradation of coarse debris into the basin and coarsening upward megasequences. This process is also discussed by Hooke (1972) and Leeder and Gawthorpe (1987), who emphasize the importance of episodic listric normal fault movements in which the tectonic gradient and footwall scarp length are increased. In listric faults this movement causes relative downward rotation of the hanging wall basement, decreasing the existing alluvial fan slopes. The result is rejuvenated fan sedimentation and progradation of a new fan segment over the old alluvial fan segment, forming crude coarsening-upward sequences. A well-defined inverted stratigraphy of clast compositions is also an expected result of continued uplift and dissection of the source area (Heward, 1978). The fining upward component during the latter stages of basin fill could reflect either backstepping of the normal faults, or a lessening of fault activity, resulting in onlap of distal facies. Examples of fault backstepping are exposed at the southern margin of the basin (Fig. 5), supporting this as at least a partial cause of the final fining-upward basin-scale megasequence.

Many oblique-slip basins also contain coarsening-upward megasequences. Strike-slip motion is dominant in these basins, but the coarsening-upward megasequences result from vertical displacements associated with oblique fault movement (Steel and others, 1977, Heward, 1978, Hendrix and Ingersoll, 1987). Thus the coarsening-upward megasequences are compatible with a half-graben basin formed predominantly by normal faulting and are not diagnostic, without supporting evidence, of strike-slip movement.

Similar limited back-faulting models of basin formation have been used to interpret several comparable basin fills. A similar depositional pattern is preserved in the Devonian Solund Basin of Norway (Steel, 1976). There, a conglomerate-dominated package about 5 km thick consists of stacked coarsening-upward sequences each about 200 m thick. Paleotransport is generally normal to the basin axis and the fill shows an overall fining-upward trend (although conglomeratic throughout). The sedimentation pattern is interpreted to reflect repeated dip-slip fault movement, with possible backstepping of the faults causing the long-term fining upwards trend of the succession (*ibid*).

The lack of evidence for weathering horizons within the thick alluvial sediments of the LMHG is unusual. Caliche and silcrete layers, common in the basal disconformity surface regolith, are restricted to the top of the fault-talus breccia (Fig. 8, section 18). Yet alluvial fans, especially in semi-arid or arid climates, characteristically contain evidence of subaerial weathering horizons, although most of these fans are composed of finer material than the LMHG fans (Nilsen, 1982, Bull, 1977). The lack of these paleoweathering features in the LMHG fans may reflect rapid deposition. Rapid deposition rates (several metres/1000 years) have been postulated for other fault-controlled basins (for example Nilsen and McLaughlin, 1985).

The lack of evidence indicating deposition from the hanging-wall dip slope of the half-graben also is unusual. Many asymmetric basins receive some basin fill (in some cases most) from the side of the basin opposite the major fault (Leeder and Gawthorpe, 1987). Yet paleocurrents and grain-size trends in the LMHG indicate

derivation of sediments solely from the south, even in the most northerly exposures (Fig. 14, sites W,X). Possibly the half-graben hanging wall slope continued northward for a considerable distance (now eroded), so that north-derived sediments simply were not transported to the preserved areas. Alternatively, the basin floor may have been cut by minor synthetic and antithetic faults which diverted and localized sedimentation from the north. Such a complex hanging-wall structure is common in modern West African rift basins (Ebinger, 1989). It may also be that faulting, basin subsidence and accumulation of south-derived fill was sufficiently rapid that erosion of a gently inclined hanging-wall slope did not contribute a significant amount of sediment to the basin.

SIGNIFICANCE TO LOCAL TECTONIC EVOLUTION

Detailed description of the MHVC (Roots, 1987; Roots and Moore, in review) and regional studies of in the Ogilvie Mountains (Thompson and others, 1987; Roots and Thompson, in press) constitute the regional tectonic framework for this study. These studies provide evidence for a sequence of extensional events (episodic or protracted) that effected the ancient continental margin in NW Canada. Each event resulted in a separate, time-rock package (Thompson and others, 1987).

Roots (1987) presented detailed field, petrologic and geochemical evidence to show that the Mount Harper Volcanic Complex represents a form of continental rift volcanism. The volcanic rocks show an upward evolution from relatively primitive tholeiitic basalts with geochemical evidence for upper mantle interaction, to rhyolites and andesites with continental affinities. Roots (1987) combined his volcanic evidence with a preliminary evaluation of the associated sedimentary rocks to suggest deposition in a single half graben basin which formed as a response to extension that culminated in crustal separation along the ancient western margin of North America.

The conclusions of this study are consistent with the regional evidence, and the detailed study of the associated volcanics. The LMHG was deposited in an east-trending, north-facing half-graben. All preserved clastic detritus was derived from

the uplifted southern margin (footwall scarp); no evidence is preserved for deposition from the hanging wall margin. However, a significant change in paleotransport is apparent in the younger upper Mount Harper group succession. The depositional patterns of the UMHG sediments will be documented in a separate article detailing their stratigraphy and evolution, but features relevant to this discussion are included here. The lowest unit of the upper Mount Harper group comprises several coarsening-upward sequences (probably submarine debris apron fans) which are capped by coarse cobble and boulder-rich gravity flows. Paleotransport of these rocks is consistently southward, the opposite sense of the LMHG sediments. The UMHG conglomerates contain volcanic clasts derived from lower units of the MHVC, and also interfinger with northern deposits of the central portion of the volcanic complex. This demonstrates that initial UMHG deposition slightly postdates that of the LMHG strata. UMHG deposits are preserved north and west of the main area of LMHG strata. No LMHG rocks are preserved below the UMHG, which unconformably overlies Fifteenmile group dolostones in northern exposures, and no clasts of LMHG lithologies were noted in the UMHG conglomerates. Clearly the LMHG basin sediments did not extend into the area of proximal UMHG deposition and the UMHG basal sediments were not coeval or derived from the hanging wall of the same basin. This is inferred to reflect two slightly diachronous sub-basins that formed with opposed, but offset footwall scarps (Fig. 19B). Such a pattern, with opposed listric normal faults, is the geometry expected in propagating continental rifts, and can be observed in the East African rift system (Bosworth, 1985; Ebinger, 1989). The fact that the basal conglomeratic deposits of the UMHG sub-basin are slightly younger than the LMHG is consistent with this model, as are the thickness and areal scales of the sub-basins (*ibid.*). The regional structural mechanics of these alternating basins is complex, and somewhat in debate (Ebinger, 1989; Bosworth, 1985; Mohr, 1987; Wernicke, 1985). The concentration of volcanic rocks at the overlap zone of these opposed basins is also appropriate to a continental rift setting. It may reflect the location of a transfer fault system or accommodation zone between the two sub-basins, a common feature

of African rifts (Ebinger, 1989, Fig. 3). The accommodation zone between opposed sub-basins in East Africa contain abundant, but localized faults which serve as conduits for magma eruption (*ibid.*).

REGIONAL SIGNIFICANCE

Jefferson and Parrish (1989) review and present new evidence to establish that rift-related faulting began before Windermere sedimentation, was most active during basal Windermere deposition, and intermittently continued in a minor way during deposition of the rest of the Windermere Supergroup. Synsedimentary tectonism during deposition of basal Windermere rocks has been well documented in the northern Canadian Cordillera (for example Eisbacher, 1981, 1985; Jefferson and Parrish, 1989) and to a lesser extent in British Columbia (Root, 1987) and with possible Windermere equivalents in the U.S. (Miller 1985). Rarely, minor normal faults are preserved (for example Jefferson and Parrish, 1989, their figure 5), but most fault evidence is indirect, based on internal unconformities, and lateral changes in thickness and facies. Most of the basal Windermere strata overlie, underlie or are interbedded with preserved volcanic rocks or contain indirect evidence of broadly coeval volcanism (above authors plus Roots, 1987; Roots and Parrish, 1988; Yeo, 1986; Young, 1982; Stewart, 1972). All authors cited above ascribe the tectonism to regimes characterized by extension or transtension.

In the Mackenzie Mountains of the N.W.T., a local succession of non-glacial carbonates, evaporites, redbeds and minor conglomerates deposited during a phase of extensional faulting (the Coates Lake Group) would be included as part of the basal Windermere by some workers (Aitken 1981, 1988, Morris and Aitken 1982, Aitken pers. com. 1990), although others have argued that the Coates Lake Group should be considered separate from the Windermere Supergroup (Young *et al.* 1982, Jefferson and Parrish 1989, Jefferson pers. com. 1990). The argument on the correlation of the Coates Lake Group is relevant to this study. The presence of redbeds and abundant evidence for a hot arid climate during Coates Lake deposition support correlation of this succession with the LMHG. However, the LMHG is associated

with a major period of faulting and volcanism. Jefferson and Parrish (1989) argued that the main period of faulting and fault-related conglomerate deposition occurred after Coates Lake Group deposition at the base of and during initial Rapitan Group deposition. Conglomerates form a minor part of the Coates Lake Group, exceeding 30 m in thickness in only one place, and Jefferson and Parrish (p. 1797) suggested that source areas for the Coates Lake conglomerate were generally subdued. Yeo (1984) also suggested that the local abundance of volcanic clasts in Rapitan Group conglomerates and the presence of rare tuffs in the Rapitan Group suggested a volcanic event was associated with deposition of the Rapitan Group. Thus the main period of faulting and a possible volcanic event were associated with initial deposition of the Rapitan Group. Correlation of the LMHG with Rapitan Group by these criteria also seems possible, although paleoclimatic indicators for the two successions are contradictory.

Although indirect and direct evidence for widespread high-angle faulting is well documented for basal Windermere strata, most authors interpret the abundant conglomeratic and associated sediments to be predominately the product of glacial deposition (here taken to exclude the Coates Lake Group discussed above). Exceptions are the recent studies of Root (1987) and Bennett and McClay (in press), who re-examined the Toby Formation, the basal unit of the Windermere Supergroup in southern British Columbia. Previously interpreted to be the result of glaciomarine deposition (Aalto, 1971), the Toby Formation has been reinterpreted in different study areas by these workers to have been deposited as a direct result of extensional tectonism. However, in northern areas of Toby Formation exposure, some features (ie. isolated outsized clasts, unusual clast types, striated clasts) provide evidence that some glacial deposition took place (Root, 1987; Eisbacher, 1985).

Conclusions of this study are similar to those of Root (1987) and Bennett and McClay (in press) for deposition of basal Windermere strata in their study areas. Evidence for glacially controlled deposition in Mount Harper group strata is lacking; deposition in this area was the direct result of synsedimentary normal faulting.

This is not meant to suggest that all previous interpretations of glacial deposition for basal Windermere conglomeratic successions are suspect. Eisbacher (1981, 1985) and Yeo (1981 1986) provided convincing evidence for glaciogenic deposition in the Rapitan Group, which they considered the basal Windermere package in the Mackenzie Mountains. However, they (and Jefferson and Parrish, 1989) also documented an abundance of syndepositional tectonism, mostly related to inferred and preserved normal faults.

An important control on sedimentation clearly was the major extensional event, which affected the entire margin of the Canadian Cordillera. In some areas the sedimentary rocks, including poorly sorted conglomerates, were produced as a direct result of this event. Superimposed on this extensional event and its direct products, glaciogenic rocks are also present in some areas. The glacial deposits may also indirectly be a product of extension-related uplift (Young, 1988; 1989). The timing of the rifting event is not well-constrained, with isotopic dates ranging from about 730 to 780 Ma (reviewed in Roots and Parrish, 1988; Jefferson and Parrish, 1989). Thus the presence of glacial deposits in some areas associated with extensional faulting, and the absence in others, could reflect slightly diachronous rifting along the then western margin of North America. Another possible interpretation is that the glacial deposition was not continuous along the rifted western margin, possibly reflecting a mountainous coastline in which glaciers advanced into the rift basins only in some areas (Yeo 1984 p. 284, also suggested this possibility for early phases of Rapitan deposition).

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FIGURE CAPTIONS

Figure 1. Regional setting. A) Distribution of upper Proterozoic to lower Cambrian Windermere Tectonic Assemblage in the northern Cordillera of North America (after Tipper and others, 1982). B) Distribution of middle and upper Proterozoic to lower Cambrian strata in the Ogilvie, Wernecke and Mackenzie Mountains (after Tipper and others, 1982, Jefferson and Ruelle, 1986, Roots, 1987). C) Simplified geology of the Coal Creek inlier, Ogilvie Mountains (modified after Roots, 1987, Thompson and others, 1987).

Figure 2. Generalized stratigraphy of the Coal Creek inlier. Most units show significant lateral gradations in thickness and facies. Upper diagram shows stratigraphic relationships in the western part of the inlier before Mesozoic-Tertiary deformation.

Figure 3. Geological map of Lower Mount Harper group. Inset A. Wedge-shaped geometry of LMHG, showing vertical profiles projected on the section. The disconformity surface with the underlying Fifteenmile group was used as a horizontal datum as mapping of the disconformity surface suggests paleorelief was slight (a maximum of 50 m) along this line of section. Inset B. A small normal fault near the northwest depositional pinchout of the LMHG. The normal fault does not cut the overlying volcanics. The conglomerates immediately north of the fault are boulder-rich, massive and disorganized, reflecting their genetic relationship to the fault. Subvertical mafic dykes (cross-hatched) are interpreted as feeder dykes for the Mount Harper volcanics. Inset C. Unit geometry of eastern exposures with the location of vertical profiles projected on the section. The disconformity with the underlying Fifteenmile group was used as a horizontal datum to be consistent with inset A, except for section 20, which mapping indicates is about 125 m lower than the bases of sections 27 and 28 (ie. within a paleotopographic low which slopes upward gently east and west). Inset D. Sketch from photos of north-facing ridge on which vertical profile 28 was measured. The disconformity surface paleotopography is well-exposed, showing red mudstones (solid black) are thickest in paleolows. Thinning of map units to the east is depositional.

Figure 4. Basal disconformity A. Irregular but sharp disconformity (arrowed) with low relief between Fifteenmile group dolostones (well-bedded, medium grey) and overlying LMHG proximal conglomerates (vaguely bedded, dark grey). B. Typical disconformity surface showing unaltered dolostone of Fifteenmile group, sharp but slightly irregular disconformity surface, and coarse debris flow conglomerates of the overlying lower Mount Harper group. Jacob's staff is 1.5 m long.

Figure 5. A. Area of best exposure of the Harper Fault, looking west. **B.** Sketch of area illustrated in Figure 5A. The stepped normal fault at centre forms the southern boundary of the lower Mount Harper group. Subvertical segments of the stepped faults north of the main fault do not cut conglomerate beds above, attesting to the coeval relationship between faulting and deposition of the lower Mount Harper group. Reverse fault near south side of photo is a result of younger (probably late Mesozoic-Tertiary) deformation which reactivated segments of the late Precambrian faults. The measured section north of the fault (section 18), is shown in Figure 8.

Figure 6. Contact relationships of Mount Harper Volcanic Complex on lower Mount Harper group. A. Sand-sized volcanic clast from sandstone a few metres below the Mount Harper Volcanic Complex. Scale bar equals 0.1 mm. B. Contact of MHVC on lower Mount Harper group sandstones (dotted) and laminated siltstones (lines). The contact is loaded and deformed sedimentary clasts have been incorporated into the basalt flow (dashes). Dark clasts are pillow breccia. Reproduced with permission from Roots (PhD thesis, 1987, p. 28).

Figure 7. Overlapping wedges with slight concave-up bounding surfaces in the coarse conglomerate lithofacies, (foreshortened by telescopic lens). The main ridge face is oriented northwest and in the photo contains about 300 metres (in vertical thickness) of strata.

Figure 8. Vertical profiles through the proximal breccia (section 18) and proximal conglomerate lithofacies. Sections are placed relative to the distance of their bases north of the Harper Fault (see map view in lower centre). Inset A. Typical sheet-like, boulder-rich conglomerates with a rarely occurring cut-and-fill structure, filled with vaguely stratified and overlapping normally graded cobble-pebble

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conglomerates. Inset B. Example of thin but horizontally extensive pebble-cobble conglomerates which passively drape typical boulder-rich conglomerates. Inset C. Example of rare matrix-supported conglomerates in which thick matrix-supported conglomerate beds grade laterally to clast-supported conglomerates. Inset D. Typical crudely developed grading patterns in the coarse conglomerate lithofacies. Shown from the top are beds with an inversely graded base; inversely graded base and normally graded top; no grading; normally graded top. Inset E. Normally graded conglomerates also occur as horizontally extensive but lens-shaped bodies which consist internally of vaguely defined and complexly overlapping normally graded layers. This lithotype is similar to that shown in Inset A, but not confined to an obvious channel, and to Inset B, but generally thicker and with a concave base.

Figure 9. Coarse conglomerate lithofacies. Stratigraphic tops is towards top of each photo. A. Proximal coarse conglomerates illustrating poor sorting and vague bedding. Largest boulder (right centre) is about 1.5 m diameter. B. Ungraded, disorganized conglomerate with largest boulders concentrated in vague layers, but no obvious bed contacts. C. Proximal conglomerates with poorly defined lower reverse-grade interval and upper normal-graded interval (black bars on right side of photo illustrate the crude grading trends). A central cobble-, small boulder-rich layer of one bed is present at the same level as the 50 cm long white part of the Jacob's Staff. The boulder-rich core of a thicker bed is present at the top of the photo. D. Reverse-graded base of coarse conglomerate bed (approximate base arrowed) showing vague imbrication of tabular clasts. A relatively thin bed with a reverse-graded base and normally graded top forms the central bed in the photo and illustrates the diffuse and vague contacts between beds. The normally graded top of a thick, boulder-rich bed is shown in the lower third. E. Normal grading in proximal conglomerates. This bed is normally graded overall, but includes vague normally graded layers which complexly overlap and coalesce laterally. F. Cut-and-fill structure in coarse conglomerate facies. This rare feature is infilled with overlapping normally graded conglomerates, similar to those in E, but slightly better sorted and defined.

Figure 10. Maximum Clast Size versus Bed Thickness trends showing least-square regression lines fitted to the data. In all graphs N = number of measurements; BTh = mean bed thickness; MCS = mean maximum clast size; R = Pearsonian correlation coefficient. A. All LMHG data B. Proximal facies (coarse conglomerate lithofacies) C. Intermediate facies (conglomerate-sandstone lithofacies) D. Conglomerates with a reverse-graded base and a normally graded top. E. Other grading and support types: Gcm = ungraded; Gcmgr = reverse-graded only; Gcmgn = normally graded only; Gcs = internally stratified; Gm = matrix-supported. Note that regression lines are not plotted for the matrix-supported and stratified types because neither shows a significant correlation (and the sample size is small for both). The regression lines for the other types are shown, but the small sample sizes for each warrants caution in interpretation because a few unusual values can significantly skew the line.

Figure 11. Maximum Clast Size (A) and Bed Thickness (B) plotted against distance north of the Harper Fault. A crude decrease in both measures is apparent. These data do not include conglomerates from the eastern exposures (Inset C of figure 3) which are generally interpreted as from more distal facies, but could not be accurately placed with respect to distance north of the Harper Fault.

Figure 12. Frequency distributions of bed thickness (A) and maximum clast size (B) grouped according to grading types. Means are located by a horizontal line to the right of each distribution, with standard deviations indicated by vertical bars.

Figure 13. Unusual lithologies in the coarse conglomerate lithofacies. A. Openwork boulder bed showing a "fitted" fabric. B. Sketch from photo of megaboulder layer (located in Fig. 5B). C. Megaboulder layer looking south towards Harper Fault (large boulder in foreground is about 20 metres high). D. Looking north from smaller boulders towards largest megaboulder. An unusual matrix-supported conglomerate (arrow) occurs south of the megaboulder. Both are overlain by typical bedded bouldery, clast-supported conglomerates.

Figure 14. Summary diagram of LMHG paleocurrents. The map pattern of the LMHG map units are outlined (see Fig. 3). Paleocurrent measurement sites are shown on the map with a dot and an arrow showing the vector mean for that site.

Current roses for each site are shown above the map in approximately the same spatial grouping as they occur on the map. Roses showing the paleocurrents combined for each facies and the entire LMHG are shown in the top centre. Paleocurrent indicators consisted of conglomerate clast imbrication for both the proximal and intermediate facies, and planar cross-stratification for the distal facies. Note that the non-linear scales are different for the total combined, facies combined, and individual site roses. Circular standard deviation was calculated using the method of Krause and Geijer (1987). All measurements have been corrected for bed-tilt.

Figure 15. Inclinations of paleocurrent indicators. Histograms for the proximal and intermediate facies show inclinations of tabular clast a-b planes in conglomerates. The distal facies inclinations are the of lee surfaces of sandstone cross-lamination.

Figure 16. Vertical profile through the conglomerate-sandstone lithofacies of western exposures (section 14 of Fig. 3). A. Normally graded pebble conglomerates with poor imbrication of tabular clasts. This bed grades up to horizontally bedded granule sandstones. B. Pebble-cobble conglomerates and coarse-grained sandstones. Normal grading is common. Beds occur as horizontal sheets and less common lenses. Sandstones occur as separate beds and tops of normally graded conglomerates. Many sandstones are laterally discontinuous, truncated by overlying conglomerates. C. Sheeted conglomerates and minor sandstones. Jacob's Staff (1.5m) at bottom left. D. Medium- and fine-grained sandstones with rare small pebble conglomerate beds from near the top of the fining-upward part of the sequence.

Figure 17. Vertical profile (section 21 of Fig. 3) illustrating conglomerate-sandstone lithofacies gradationally overlying a thin portion of the mudstone-sandstone lithofacies. Sandstones are rare above 120m in this profile and the overlying conglomerates are part of the coarse conglomerate facies, occurring in several coarsening upward sequences. A. Pebble conglomerates showing textural inversion (3 cm below photo scale) in which red mudstones form the matrix to the basal pebbles. B. Planar crossbeds in pebbly conglomerate.

Figure 18. Vertical profile (section 20 of Fig. 3) through the mudstone-sandstone lithofacies, showing gradual coarsening-upward change to the conglomerate-

sandstone facies. A. Outcrop photo of basal red mudstones (dololutes).

B. Thin section of normally graded siltstone laminae from lower redbed unit.

Reduction spot (green) is 0.5 mm in diameter. Stratigraphic top is towards the top of the photo. C. Tan sandstones, increasing common as interbeds near the top of the

redbed facies. D. Planar cross-beds with abundant rip-ups of red mudstone. E.

Desiccation cracks in redbeds. F. Interbedded normally graded pebble conglomerates and medium to coarse-grained sandstones with erosional top contacts. G. Normally graded pebble-granule bases to coarse- to medium-grained dolowacke tops.

Figure 19. A. Schematic representation of LMHG depositional environment.

B. Sketch of Mount Harper group tectonic setting slightly after LMHG deposition.

Opposed, slightly diachronous half-grabens are separated by an accommodation zone in which volcanism produced flows that covered LMHG sediments, but was coeval with initial deposition of coarse clastics in the slightly younger UMHG sub-basin.

Figure 1.

Figure 2.

Figure 3.

FIGURE 4

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Figure 9 ▶ ▶ ▶ ▶

Figure 10.

Figure 11.

Figure 12.

Figure 15.

Figure 17

Figure 18

Figure 19.

CHAPTER 4

Stratigraphy and sedimentology of the upper Proterozoic - lower Cambrian upper Mount Harper group, Ogilvie Mountains, Yukon

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Abstract

In the Ogilvie Mountains, west-central Yukon, the upper Proterozoic to lower Cambrian upper Mount Harper group (informal name) contains strata equivalent to both basal Windermere Supergroup and lower Cambrian rocks in other areas of the North American Cordillera. Strata of the upper Mount Harper group are directly time-constrained: the base by a ca. 750 Ma U-Pb age from volcanic rocks which conformably underlie and intertongue with the sedimentary rocks, and the upper units by the presence of lower Cambrian trace fossils. A subtle disconformity separates lower rift-related deposits from upper marine shelf deposits, and may represent a time gap of more than 150 Ma, suggesting the lack of a direct connection between the major tectonic controls of lower Windermere deposition in this area and the directly overlying sedimentary succession. Initial deposition of the upper Mount Harper group was in the younger of two opposed half grabens, coincident with a final stage of volcanic activity concentrated in the accommodation zone between the half grabens. The basin style and evolution are analogous to propagating rift basins of the East African rift system. Evidence of glacial deposition is lacking, although the lower units contain non-glacial diamictites, lonestones, and rare pyroclastic dropstones which could be mistaken for such evidence. The disconformably overlying upper units were deposited on a marine shelf, and comprise facies representative of shoreface to deep shelf environments. Recognition of the major disconformity is a direct result of the unique age constraints available for these rocks.

Introduction

The Windermere Supergroup and equivalents (the Windermere Tectonic Assemblage of Tipper *et al.* 1981) comprise the upper Proterozoic strata of the western margin of ancestral North America. Some features of these rocks have been cited as evidence for two major events near the end of the Precambrian: supercontinent breakup (e.g. Young 1989), and one or more global glaciations

(Young 1988; Eisbacher 1981, 1985). Tectonic influence on sedimentation during Windermere deposition has been documented to varying degrees (Eisbacher 1981, 1985; Jefferson and Parrish 1989; Root 1987; Devlin 1989).

This paper presents an interpretation of the sedimentologic and tectonic evolution of Windermere Supergroup equivalents from the Ogilvie Mountains of the northern Canadian Cordillera. Here, excellent exposure and a lack of both metamorphism and complex deformation combine to permit detailed examination of the sedimentary and volcanic rocks of this important interval in the evolution of the western margin of North America. The Windermere-equivalent rocks of this area form all but the uppermost units of the Mount Harper group (informal name), a tripartite package of sedimentary and volcanic rock several kilometres thick. Early sedimentation was in diachronous, opposed-symmetry half-grabens, with coeval volcanism, dated at ca. 750 Ma, concentrated in the accommodation zone between half-grabens (Mustard in review; this study). Initial deposition of the upper Mount Harper group (documented in this paper) took place in the younger of the opposed half grabens, coincident with the final stage of volcanic activity. A subtle disconformity separates these rift-related units from significantly younger marine shelf sediments which include early Cambrian trace fossils in the uppermost 50 m. Evidence of glacial deposition is lacking, although the lowest units contain non-glacial, poorly sorted conglomerates (diamictites), limestones, and rare pyroclastic dropstones which could be mistaken for such evidence. The unique derivation of a radiometric date from actual strata formed during basal Windermere tectonism, volcanism and sedimentation, combined with discovery of Cambrian trace fossils at the top of the succession, led to recognition of a major disconformity within the upper Mount Harper group strata, and the suggestion that there is no direct temporal connection between the tectonic events and depositional environments of the rift-related Mount Harper group strata and the uppermost map units.

Informal group names applied herein reflect the ongoing nature of regional studies of the Geological Survey of Canada which have provided the framework for

the more detailed work of this study (Thompson and Roots 1982; Roots and Thompson, G.S.C. Open File Maps, in preparation). Group names will be formalized in a Geological Survey of Canada memoir, currently in preparation by R.I. Thompson and C.F. Roots of the Cordilleran Division, Geological Survey of Canada.

Regional framework

The Mount Harper group crops out in the southern Ogilvie Mountains, the northwesterly extension of the Cordilleran foreland fold and thrust belt (Figs. 1a,b). Sedimentary and volcanic strata of the Ogilvies, ranging in age from mid-Proterozoic to Jurassic, were telescoped northward during late Mesozoic - early Tertiary deformation. Proterozoic rocks relevant to this study are generally confined to a broad, east-trending erosional inlier, termed the Coal Creek Dome by Green (1972) (Figs. 1b,c), although the upper units of the UMHG are also exposed on ridges west of the inlier.

Fig. 2 schematically illustrates the stratigraphy of the inlier. The oldest rocks consist of a thick (>4 km) succession of fine-grained siliciclastic rocks, dolostones and cross-cutting heterolithic "Wernecke-type" breccias. These rocks correlate with the middle Proterozoic Wernecke Supergroup of the Wernecke Mountains to the east (Thompson and Roots 1982; Delaney 1981; Mustard *et al.* 1990; Lane 1990). These are probably the stratigraphic equivalent of the Belt/Purcell Supergroups of the northern U.S. and British Columbia (Young *et al.* 1979). Wernecke Supergroup strata in the inlier are unconformably overlain by more than 2 km of commonly stromatolitic dolostones, and a less abundant basal succession of mudstones and conglomerates. Informally termed the Fifteenmile group, it probably is part of sequence B of Young and others (1979), a carbonate-dominated succession which separates the Middle Proterozoic Wernecke Supergroup (Sequence A of Young *et al.* 1972) and the Upper Proterozoic Windermere Supergroup and equivalents (Sequence A). Sequence B includes the Mackenzie Mountain Supergroup (Aitken 1981) and the Pinguicula Group of the Wernecke Mountains (Eisbacher 1981).

However, both the Pinguicula and Fifteenmile successions have not been studied and documented in detail sufficient to suggest direct correlation with either each other or the Mackenzie Mountain Supergroup, except in the very broad sense of sequence B, which represents a time interval of several hundred million years.

The Mount Harper group unconformably overlies the Fifteenmile group and is preserved along the south and west margin of the inlier (Fig. 1c). The Mount Harper group consists of three major subdivisions. The oldest is a conglomerate-rich succession (<1100 m thick), termed the lower Mount Harper group (LMHG). The southern margin is defined by an exposed, syndepositional, high-angle normal fault. Northerly directed paleocurrents reflect progradation of subaerial alluvial fans into a subaqueous (probably lacustrine) environment, filling a half graben which formed before UMHG deposition (Mustard and Donaldson 1987). LMGH clastic sedimentation was abruptly terminated by deposition of the conformably overlying Mount Harper Volcanic Complex (MHVC, maximum 1200 m thick), a bimodal extrusive event related to deep crustal rifting (Roots and Thompson 1986; Roots 1987), and dated at $751 \pm 26/-18$ Ma (U-Pb on zircons, Roots and Parrish 1988). The upper Mount Harper group (UMHG), the subject of this paper, is a 300 to 1400 m thick succession that conformably overlies and interfingers with upper units of the volcanic rocks. The UMHG comprises doloclastic and rare siliciclastic conglomerate, sandstone, mudstone and minor limestone. The inlier rocks are overlain, probably disconformably, by archeocyathid-bearing lower to middle Cambrian dolostone. Minor thrusts and normal faults (a result of Mesozoic deformation) with maximum displacements of a few hundred metres, cut both the UMHG and the Paleozoic dolostone in the northern and western parts of the map area.

Correlation of the pre-Cambrian part of the Mount Harper group with the Windermere Tectonic Assemblage (Tipper et al., 1981, updated in Wheeler and McFeely 1987) is warranted by the age of the volcanic rocks and similarities of tectonic and depositional history (Roots 1987, Roots and Parrish, 1988, this study).

The terms Windermere Tectonic Assemblage and Windermere Supergroup are

used in this paper where the regional setting or significance of the Mount Harper group is discussed. The formations and groups which make up the former are shown on the compilation map of Tipper *et al.* (1981), updated in Wheeler and McFeely (1987), and briefly discussed in Gabrielse and Yorath (1989). This tectonic assemblage is defined on the basis of broadly similar interpreted depositional and tectonic settings. The Windermere Supergroup was first defined (as "Windermere Series") in southern British Columbia (Walker 1926), but the term has been extended to include many upper Proterozoic formations and groups along the length of the Canadian Cordillera (reviewed in Eisbacher 1981, 1985; Young *et al.* 1982). The discovery during this study of trace fossils which demonstrate an early Cambrian age for the top 50 metres of the Upper Mount Harper group (and possibly for the upper three map units) makes previous suggestions that all the Mount Harper group is part of the Windermere Supergroup (restricted to the upper Proterozoic) incorrect.

The terms "basal Windermere" is informal and is used in this article to refer to the varied successions of conglomerate-rich sedimentary rocks and, in some places, associated volcanic rocks, which are the stratigraphically lowest part of what is uncontroversially accepted as Windermere Supergroup (Rapitan Group in Mackenzie Mountains; Toby Formation in southeastern B.C.; units 1-3 of the Upper Tindor Group in Alaska and western Yukon). This usage is well-established, although the exact usage varies slightly (e.g. Eisbacher 1981, Yeo 1981; Young 1984; Jefferson and Parrish 1989). The exact meaning of the term basal Windermere is most controversial in the Mackenzie Mountains of the N.W.T. and eastern Yukon. There, a local succession of carbonates, evaporites, redbeds and minor conglomerates deposited during a phase of extensional faulting (the Coates Lake Group) would be included as part of the basal Windermere by some workers (Aitken 1981, Morris and Aitken 1982, Aitken *pers. com.* 1990). Others argue that the Coates Lake Group should be considered separate from the Windermere Supergroup (Young *et al.* 1982, Jefferson and Parrish 1989, Jefferson *pers. com.* 1990). This is discussed further as it relates to the UMHG in the final section of this article.

The upper Mount Harper group

Major stratigraphic and tectonic boundaries

Five major map units were recognized during 1:25000 mapping. The general stratigraphic relations are shown in Fig. 2c and in the slightly simplified geologic map of Fig. 3. The UMHG generally dips 20-30 degrees southwest, and overlies more steeply dipping middle Proterozoic dolostone of the Fifteenmile group with slight angular unconformity (10 to 20°), except in southeastern parts of the study area where it conformably overlies and interdigitates with the Mount Harper Volcanic Complex. The basal unconformity is slightly irregular, with several tens of metres of palcorelief. No breccia is preserved on the disconformity surface, but the upper few metres of the underlying dolostone commonly is heavily fractured, with some vertical and horizontal fractures lined or filled by both chert and dolomite. The uppermost unit of the underlying Fifteenmile group is a distinctive medium grey dolostone that contains abundant columnar and domal stromatolites, cryptalgal laminites, and silicified oolitic and oncolitic beds. This unit, typically several hundred metres thick, is progressively cut out to the north. Both the presence of a fractured and partly silicified upper surface and the progressive northward cut-out of the top UMHG unit are inferred to reflect subaerial exposure and erosion of the Fifteenmile group dolostones, with uplift initiated in the north.

No LMHG rocks are preserved between the UMHG and Fifteenmile group, and although all UMHG conglomerate clasts are of local derivation, no clasts resemble LMHG lithologies. This supports independent evidence that the LMHG was deposited in a separate, slightly older half-graben east of the UMHG basin, although slightly overlapping at the western end (documented in detail in Mustard in preparation). Volcanic clasts are common in basal conglomerates of the UMHG in map unit PH₁, but decrease in abundance northward, and are absent north of latitude 64° 49'. The only known source for these clasts is the MHVC. The decrease in volcanic clast abundance and eventual absence toward the north is interpreted as evidence for an original northern pinchout of the MHVC.

Constraints on the original depositional extent of the UMHG are limited. The most northerly exposures have been thrust northeast over Cambrian to Devonian strata; the original northern limit of the basin (if preserved) is not exposed, but all units above PH₂ thin northward from the Eagle Creek drainage, suggesting a northern pinchout of the upper units (Fig. 3). All units also thin to the east, with the PH₂ conglomerates showing marked thinning to from northeast to southeast. In addition, except in the area immediately east of Mt. Harper, the LMHG is disconformably overlain by unit CDb. The eastward-thinning of units, lack of LMHG clasts in conglomerates of the UMHG, and lack of UMHG strata above the LMHG, together suggest that the UMHG basin did not continue far to the east of present exposures of the units. High-angle faults (probably Mesozoic) define the southern limit of exposure of the UMHG. Rocks immediately south of the faults are dolostones of unit CDb, or the Ordovician to Devonian Road River Formation. UMHG units PH₁-PH₂ are absent adjacent to the southern faults, where unit PH₃ disconformably overlies poorly exposed and partly dolomitized MHVC volcanic conglomerates and breccias. This probably reflects non-deposition or erosion before PH₃ deposition. To the west, the topography is subdued and exposure is poor. However, discontinuous exposures of the upper units (PH₃-PH₆) persist almost to the Alaska border. Thus, the UMHG basin appears to have continued to the south and west in its late stages of evolution.

Map unit PH₁ - Description

The lowermost two map units of the UMHG intertongue and are separated from the upper three map units by a subtle but significant disconformity. Thus units PH₁ and PH₂ will be discussed separately from the disconformably overlying units. Unit PH₁, thickest immediately north of the main ridges of the preserved part of the MHVC (to a maximum of about 175 m), thins and intertongues northward with unit PH₂ and in most places is gradationally overlain by PH₂ (Figs. 3,4). Fault-bounded inliers of PH₁ also are present at the top of the MHVC.

Examples of measured sections through this unit are shown in Fig. 4. The base is gradational from volcanic flows, volcanic conglomerates, and tuffs of the MHVC (member C of Roots 1987). Rare volcanic rocks in this transitional interval include thin tuffs (some probably reworked) and possible flows, generally < 20 cm thick and highly altered with abundant dolomite, but with a recognizable original composition of microlaths of feldspar within a dark, glassy chloritized groundmass.

Much of unit PH_1 and all of unit PH_2 consist of mudstones, sandstones and conglomerates in which the principal component of the clastic detritus is dolomite. Examination of the conglomerates and sandstones clearly show that most of this detritus was eroded from lithified beds of dolostone. For this reason the terminology based on grain-size suggested by Folk (1959, 1974) for carbonate clastics is used for specific rock type descriptions (dololutite, dolosiltite, dolarenite or dolowacke, dolorudite). In general descriptions and interpretations, however, the terms mudstone, sandstone and conglomerate are retained.

Unit PH_1 comprises coarse, crudely bedded, poorly sorted conglomerates with less common intercalated sandstones and mudstones. Beds thicken and thin, but are roughly sheetlike and laterally traceable for tens to hundreds of metres where exposure permits (Fig. 5a). Most rocks weather either pale orange-grey or green-grey, with medium grey fresh surfaces. Most conglomerates are clast-rich (>50%) and some are partly, but randomly, clast-supported (Fig. 5b). The conglomerates are very poorly sorted and clast fabrics are random. Internal grading of clasts or matrix is generally lacking, but a few beds show a poorly defined central or upper layer rich in boulders and cobbles and vague reverse grading at the base or normal grading at the top of the bed. Contacts between beds are subtle, and both lateral and vertical bed amalgamation is suspected to be common. Bases show no evidence of erosion, but are loaded into underlying nonconglomeratic beds. Clasts commonly project from the tops of the beds. The conglomerates most commonly are matrix-supported dolorudites, 1 to slightly more than 2 m thick, with 20 to 70% granule-to-boulder sized clasts randomly suspended in a dolowacke matrix (Fig. 5c). Most

conglomerate beds are internally massive, but others range from massive to vaguely stratified, and rarely to well-stratified. Internal stratification in the conglomerates generally consists of thin, discontinuous, wavy laminae or lens of dolowacke, dolosiltite or dololutite. Rare well-stratified conglomerates are transitional to normal-graded pebbly sandstones (most are dolarenites or dolowackes, some are volcanoclastic lithic wackes) with gravel clasts both concentrated at the base and dispersed randomly in the sandstone (Figs. 5*d,e,f*). Gravel clasts are generally of high sphericity, with rare tabular and prolate clast shapes, and most clasts are subround to subangular. Volcanic clasts make up 90% of the clast lithologies in some beds close to the base of the map unit, but more typically constitute a maximum of 10% of the clasts (Fig. 5*e*). They are spotted to vesicular mafic to intermediate volcanic rocks, a rock type common in the MHVC, the only feasible source. The non-volcanic clasts are >95% dolostone, most commonly medium to light grey laminated dolostone, including cryptalgal laminates, stromatolites and oolites/oncolites. Identical rock and stromatolite types are present in the top map unit of the underlying Fifteenmile group. Rare clasts of dolostone partly replaced by chert and chalcedony are identical to silicified paleokarst regolith that is discontinuously preserved beneath the LMHG at the top of the Fifteenmile group (Mustard and Donaldson in press). These clasts probably reflect erosion of a similar regolith from the original sub-Harper group unconformity surface during initial UMHG deposition. This interpretation is supported by the more common presence of such clasts in the lowermost conglomerate beds.

Intercalated layers of thin-bedded or laminated dolowacke, dolosiltite and dololutite (a few centimetres to a few metres thick) are common; normal grading is common in the sandstones (Fig. 5*f*). Most are separate from and drape the irregular tops of the conglomerate beds. Bedding and laminae are generally slightly wavy and contorted, and loaded (but rarely eroded) by overlying conglomerate beds. Although most beds and laminae appear laterally continuous, discontinuous lens of sandstone also occur within conglomerate-rich intervals.

Interbedded mudstone and sandstone in the inliers, and where a thick gradational contact from the underlying volcanics is present, tend to be dark green-grey, characterized by a high component of volcanoclastic detritus and by rare interbeds of volcanic tuffs, flows and sills. Most mudstones in these strata are non-dolomitic.

Rare limestones are up to boulder size, but none shows evidence of non-compactional deformation of surrounding strata, except in the lower interval transitional from underlying MHVC volcanics, where a few pebbles to small boulder-sized limestones of vesicular volcanic rocks have disrupted and deformed the adjacent strata (Figs. 5g,h,i). Their composition and restriction to volcanoclastics with intercalated tuffs and flows strongly supports a pyroclastic origin.

The interdependence as well as vertical and lateral variations, of bed thickness (BTh) and maximum clast size (MCS, defined as the average of the ten largest clasts locally per bed) provide a basis for distinguishing conglomerate depositional processes (reviewed in Nemec and Steel 1984). These parameters could not be measured with enough consistency in a single vertical profile to define vertical trends, but they were recorded wherever the bed thickness could be confidently discerned, and was observed to show low variability at individual stations (method of Bluck 1967). A weak linear correlation is apparent for the PH₁ conglomerates as a whole (Fig. 6), but no statistically significant correlation is apparent for conglomerates subdivided by grading pattern or framework-support type (although this may simply reflect the small size of the dataset).

Well-defined trends or sequences, although rare in both the vertical and lateral organization of the lithofacies, do occur in a few isolated areas on a small-scale. The conglomerates are consistently poorly sorted and rich in both cobbles and boulders. The mudstones and sandstones are randomly interbedded with the conglomerates with but two exceptions: (1) Volcanoclastic mudstones and tuffs are more abundant in the lower part of most exposures, giving the impression of a crude coarsening-upward trend. However, this apparent trend is not reflected by a

progressive upward increase in grain size in either the conglomerates or interbedded finer-grained detritus, and is the result of a rapid upward increase in the abundance of conglomerates. (2) Rarely, conglomerates rich in dolostone clasts form the base of thin (< 5 m) fining-upward sequences, overlain by normally graded pebbly dolarenites or dolowackes which may be capped by fine-grained, thin bedded to laminated dolarenites, locally showing ripples that contain southerly directed internal cross-lamina.

Paleocurrent indicators are scarce (Fig. 7). Clast imbrication or other paleoflow indicators in the conglomerates were not observed. Parting lineation on some very fine-grained dolowacke bedding surfaces is oriented north-south, and rare cross-laminated ripples in nearby beds suggest that southerly paleoflow formed the lineation. Individual cross-laminated ripples (all southerly directed) were noted in the dolowackes, but most could not be sufficiently defined in three dimensions to warrant inclusion in the statistical analysis of paleocurrents.

Map unit PH₁ - Interpretation

The interbedded conglomerate-sandstone-mudstone sequence of unit PH₁ displays a generally random organization of interbedded rock types, both vertically and laterally. No facies associations suggestive of fluvial processes could be discerned, nor is a subaerial alluvial fan model consistent with the observations. Mudstone and sandstone interbeds - volcanoclastic in the lower part of the unit, doloclastic in the upper part - are laterally extensive and in some places several metres thick, and contain no desiccation or other structures indicative of subaerial exposure. Weathering horizons, common in alluvial fans (Nilsen 1982), are also absent. Deposition is thus interpreted as completely subaqueous. However, the abundance of cobbles and boulders in the conglomerates, their very poor sorting and the restriction of conglomerate clast lithologies to MHVC and upper Fifteenmile group types, all suggests local sources for the conglomeratic debris.

Map unit PH₁ is dominated by conglomerates. The irregular but sheet-like

geometry, very poor sorting, lack of clast fabric, high matrix content, presence of clasts projecting from the tops of beds, and lack of erosive basal contacts, all suggest deposition as debris flows, used here in the sense of Lowe (1982), Nemec and Steel (1984) and Postma (1986) for sediment gravity flows that show evidence of plastic behaviour. Most of the PH₁ debris flows can be further defined as cohesive debris flows, where the main internal support mechanism is matrix strength, although the high clast content of most conglomerates suggests that dispersive pressure was probably also important. Lowe (1979), proposed the term density-modified grain flow for this type of flow. A high matrix strength is indicated by the lack of internal sorting or grading of most of the beds. Most conglomerates contain a significant (>3%) proportion of mud-sized material, a source of high matrix strength (Rodine and Johnson 1976, Hampton 1975).

A cohesive debris flow origin is supported by the positive linear correlation between maximum clast size and bed thickness shown in Fig. 6. The regression line intersects the y-axis (MCS) above the origin, a relationship which Nemec and Steel (1984, p. 23) suggested might be diagnostic of cohesive debris flows, reflecting an initial cohesive strength, independent of internal support factors during flow such as dispersive pressure and viscous resistance (*ibid*). The MCS-BTH plots show a wider dispersion of points than typically seen in studies of debris flow conglomerates (reviewed in Nemec and Steel 1984). This may reflect a subaqueous environment. For example, Kessler and Moorhouse (1984) observed found similar wide dispersions for probable subaqueous debris flows in Jurassic conglomerates deposited on the west margin of the Viking Graben (Brac field) in the North Sea.

The vague, discontinuous internal stratification noted in some conglomerates may reflect surging within flows (cf. Lowe 1982). Alternatively, the lack of grading, sorting, and basal erosion of these flows makes discrimination of individual flows difficult, and apparent internal stratification may reflect the rapid amalgamation of successive flows.

Some beds have more pronounced internal stratification, showing a range

from poorly sorted, vaguely stratified conglomerates to moderately sorted, normally graded pebbly sandstones. The latter tend to exist as a cap to the massive debris flows. The range of stratification and grading types is interpreted as reflecting evolution to non-cohesive support mechanisms, possibly due to a transition from laminar to turbulent conditions in upper parts of the flows (discussed in Walker 1975, Lowe 1982). The concentration of water in the upper parts could reflect flow onto a lower slope, causing increased upward pore-fluid expulsion, or backward-streaming effects at the top of the flow in a subaqueous setting (cf. Hampton 1972, Krause and Oldershaw 1979). The latter effect would also initiate turbiditic flows of sand and mud, leading to the deposition of some of the interbedded sets of normally graded dolowackes and dololutites. The rare organization of conglomerates and sandstones into vague fining-upward sequences could represent deposition by progressively waning channelized turbulent flows (cf. Hein and Walker 1982). However, these sequences are rare and poorly developed, and non-channelized gravity flows are believed to have been the predominant depositional process.

The volcanic clasts undoubtedly are all of MHVC derivation. Roots (1987) mapped extensive volcanic conglomerates interbedded with flows, tuffs and rare sills and dykes in his Member C of the Mount Harper Volcanic Complex. This member gradationally underlies unit PH_1 , and volcanic flows of this member intertongue with the southern part of unit PH_1 . Significantly, Roots also demonstrated a major thickening of member C volcanoclastics north of an east-trending linear break a few kilometres south of the main PH_1 outcrops (south of section 17 on the location map of Fig. 4, and also shown in Fig. 3). Roots suggested that the covered break was a synvolcanic fault, and he inferred that much of the detritus in Member C conglomerates was shed from the resultant fault scarp. The gradational basal contact and intertonguing of volcanics with map unit PH_1 demonstrates that deposition of unit PH_1 was initially coincident with this late stage of Mount Harper volcanism. The debris flows containing abundant volcanic clasts

and matrix could be termed lahars, a term Smith (1986) reviewed and recommended be abandoned due to widespread misuse. Thus the fault scarp (probably one of several) that Roots (1987) suggested was a major source of Member C clasts could also have been a source for the volcanic conglomerates of unit PH₁ (Fig. 8a).

The graded sandstones and mudstones, which are in bedsets intercalated with the conglomerates, also appear to be sediment gravity flows. They probably reflect a combination of grain flow and turbidity currents, and could have been initiated by seasonal sedimentation events, backstreaming turbulence at the head of the moving debris flows as mentioned above, and as separate turbiditic flows initiated on proximal subaqueous debris slopes, and from minor slumps at the irregular and unstable head of the stationary debris-flow lobes (cf. Postma 1984). Rare cross-laminated ripples in these beds indicate a northerly source for much of this non-conglomeratic material. This is interpreted as representative of a balance between two major depositional processes (Fig. 8a): debris flows of conglomeratic material from nearby volcanic and dolostone sources, and relatively distal turbidites (although still including conglomeratic detritus in some beds) of southward-prograding subaqueous fans which were being deposited in the northern part of study area (unit PH₂, discussed below). In support of this interpretation is a lack of volcanoclastic detritus in the sandstones. All appear to have been derived from the erosion of Fifteenmile group dolostones. Exceptions are greenish-grey sandstones and mudstones in the transitional interval from MHVC volcanics to unit PH₁. These volcanoclastics are interpreted as reflecting deposition from sediment gravity flows related to the local debris flow processes described above, and suspension settling of muds during periods between flow events.

Map unit PH₂ - Description

Map Unit PH₂ is restricted to the northeastern third of the map area. The unit in general thins southward from an estimated preserved maximum thickness of about 400 m. Thicknesses measured for this unit are minima, because the top

contact is an unconformity.

The basal contact with Fifteenmile group dolostones is a sharp, angular unconformity with the Fifteenmile group having 10 to 20°s steeper dip than the overlying PH₂ rocks. Laterally to the south, PH₂ complexly grades and intertongues with the upper part of unit PH₁, and gradationally overlies unit PH₁. (Fig. 4). In these areas the lower contact of PH₂ was placed above the last observed presence of volcanic clasts in the conglomerates. Abundant brecciation, with accompanying silica and dolomitic alteration, is present at the top of unit PH₂ in a few places (Figs. 3, 4, 13), and suggests that a disconformity is located between unit PH₂ and the poorly exposed overlying PH₃ unit. This altered and brecciated layer is discontinuously exposed in small isolated outcrops south of the best-exposed example (Fig. 4, section 22) over a distance of slightly more than 5 km (Fig. 3).

Most PH₂ rocks have a greyish-orange weathering colour and a medium grey fresh colour. Distinctive coarsening and thickening-upward sequences about 75-150 metres thick are well developed in the lower part of the unit, and display a gradational upward change from dololutites to dolarenites (or dolowackes) to dolorudites, although thinner (2 to 25 m) and more subtle coarsening- and fining-upward sequences can be discerned within the major sequences (Figs. 4, 9). Conglomerates form the upper 10 to 80 metres of all sequences and increase in abundance both to the north in a given sequence and upward in the stacked sequences, defining an upward- and northward-coarsening trend for the unit as a whole. The non-conglomeratic lithofacies become increasingly dominant to the south, although in many areas only the resistant conglomerates are well-exposed.

For description, the best-developed major sequences are subdivided into three major facies: sandstone-mudstone, sandstone-conglomerate and conglomerate. These facies, although in a general way occurring in an order that reflects an overall coarsening-upward trend, also include smaller scale sequences within the major coarsening upward sequence.

Sandstone-mudstone facies:

Dolarenites and dololutites occur in continuous and parallel to slightly wavy laminae or thin beds (rarely up to 10cm thick) in the lower part of the major sequences, and less commonly in the upper part of small fining-upward sequences (Fig. 10a). A few layers display convolute deformation (Fig 10b). The most common rock types are fine- to very fine-grained dolarenites which show normal grading in which the abundance of brown dolomicrite matrix increases upward, grading upward to dolowackes and uppermost layers of silt-rich dololutite (Fig. 10c). These would be classified as AE turbidites, using the A to E nomenclature for the Bouma sequence divisions (as reviewed in Walker 1984). Less common are dolarenites which contain internal planar laminations or cross-laminations, either with or without a graded base (Fig. 10d). Following the Bouma sequence terminology, ABCE, BCE, BCDE and ACE turbidite types were all observed, with AE or BE types predominating. The ripples in these thin beds tend to be slightly discontinuous laterally, and contain internal cross-laminations that consistently dip southward (Fig. 10e). Dololutites examined in thin section contain abundant silt-sized sediment in a brown dolomicrite, show poor to fair normal grading of the silt grains, and rarely display internal planar lamination. Most form the upper parts of graded dolarenites, and appear to be the E(t) interval of a Bouma sequence rather than non-turbiditic pelagic sediments.

Sandstone-conglomerate facies:

This facies is a transitional unit in the main sequences, gradationally overlying the sandstone-mudstone facies and showing upward gradation to the conglomerate facies. It is also the upper or basal part of small (maximum of 25 m) coarsening- or thinning-upward sequences within the larger sequences. Dolarenites are similar to those of the sandstone-mudstone facies, but tend to be thicker beds (most 5 to 20 cm; some 20 to 50 cm), and range from very coarse to fine-grained (Fig. 10f,g). The thickest beds include granule- or small pebble-rich bases. Most dolarenites show normal grading with either massive, planar laminated and rarely rippled tops (A, AB, ABC types), but thin beds of the types listed in the previous

facies are also present (Fig. 10g).

The conglomerates are interbedded randomly (Fig. 11a); most are matrix-supported, but clast-rich, with 40 to 70% pebble- to boulder-sized clasts dispersed in a poorly sorted mud- to granule matrix (Fig. 11b). These would be termed disorganized conglomerates in the Walker classification of resedimented conglomerate types (Walker 1975), or diamictites as originally defined by Flint *et al.* (1960). They are in beds ranging from a few tens of centimetres to tens of metres thick, but the latter may consist of several amalgamated beds with welded contacts. The beds have non-erosive, but commonly loaded basal contacts, and slightly wavy tops. They thicken and thin laterally, but appear to be sheet-like or less commonly form elongate lens hundreds of metres long. Most are non-graded, but some show poorly developed and laterally discontinuous reverse grading at the base and/or normal grading at the top.

The clast-supported conglomerates are of two types. Some are identical to the matrix-supported types except for a higher percentage of gravel-sized clasts and the abundance of matrix (10 to 20%). These appear to be a clast-supported end-member of the disorganized conglomerates. Most are slightly better sorted than the disorganized conglomerates and typically contain a fine- to coarse-grained dolarenite (rarely dolowacke) matrix. These conglomerates commonly show poor to good normal grading, some with a nebulous reverse-graded base (Fig. 11c). The conglomerate with distinct normal grading generally grade upward to pebbly sandstone, some laminated or thin bedded. The latter conglomerates tend to occur in gently concave-upward depressions which appear to have been eroded into the underlying beds, and the conglomerates are laterally discontinuous over tens to hundreds of metres and many form the lower parts of fining-upward sequences, overlain by bedded sandstones and sandstone-mudstone sets as described above.

The upward gradation from interbedded conglomerate-sandstone facies to the main conglomerate facies is relatively uniform over a few metres to (rarely) tens of metres. Convolutely deformed layers and dewatering structures are most common

in sandstone and mudstone interbedded with conglomerate in this interval, although such structures also are present in other facies (Fig. 11d). Pebble- to cobble-sized lonestones are also common in this transition (Fig. 11e-g). These clasts, markedly outsize in terms of the immediately surrounding strata, interrupt but do not significantly deform the enclosing sandstone beds. Several lonestones commonly are located roughly within the same stratigraphic level, but many also appear to be completely isolated from equivalent-sized clasts.

Conglomerate facies:

Conglomerate and rare interbedded sandstone make up the top part of the major coarsening upward sequences and predominate in the upper two thirds of unit PH₂ in the northern part of the study area. Except in the well-defined sequences, large-scale vertical trends are not obvious, and thicker, more laterally continuous matrix-supported conglomerate (possibly several amalgamated beds) alternate with overlapping sets of clast-supported conglomerate (with convex-downward lower contacts) and less common pebbly sandstone.

The matrix-supported conglomerates are similar to those of the sandstone-conglomerate facies, with apparent bedding up to 18 m thick. However many of the very thick beds show a crude internal stratification, suggesting that they are composites of several thinner beds, but others are massive, non-graded and structureless. These conglomerates appear continuous laterally, but from a distance they can be seen to thin and pinch out on faces oblique to the paleoflow, suggesting a geometry of broad lens hundreds of metres wide (Fig. 9, top photo).

Clast-supported conglomerates are moderately to poorly sorted, with 80-90% pebble- to boulder-size clasts in a fine- to coarse-grained dolarenite or dolowacke matrix. Beds are decimetres to several metres thick, and most can be seen from a distance to be discontinuous on a scale of tens to several hundred metres or more, generally with gentle convex-downward bases, but commonly these broad shallow channelized conglomerate lenses overlap to give the appearance of thick layers (tens of metres) which continue laterally for more than a kilometre in some places (Figs.

9, 12a). The bases of these conglomerate beds are slightly eroded into the underlying rocks (Fig. 12b). The clast-supported conglomerates are generally massive; many show poor normal grading (Fig. 12c), but non-graded beds are also common, and a crude basal inverse grading exists in some beds (Fig. 12d). Beds with inverse grading at the base and normal grading at the top (both generally poorly developed) are the least common type, but account for about 15 to 20% of the conglomerates. The grading types can vary laterally in a single lens. Some conglomerate beds grade upward to pebbly sandstones. Some are continuous fining-upward sequences a few metres thick, with several pebbly sandstone beds (2 to 25cm thick) capping normally graded conglomerate.

Clasts in all conglomerates are most commonly equant and subround to subangular, although tabular clasts are present, most are oriented with apparent a-b planes subparallel to bedding, with some showing poor to fair imbrication, the latter best developed in the normally graded conglomerates. Clast compositions are > 90% medium to light grey dolostones, many cryptalgal or stromatolitic. As for unit PH₁, these can confidently be assigned provenance from the upper Fifteenmile group. Rare dolostone/chert breccias and dark grey or brown calcareous mudstone clasts are similar to rock types preserved in central or lower parts of the Fifteenmile group. The only other major clast type is partly silicified dolostone, identical to clasts observed in PH₁, and similarly interpreted to be the result of erosion of a regolith at an unconformity surface at the top of the Fifteenmile group.

Paleocurrent indicators include fair to poor imbrication of tabular clasts at the base of some conglomerate beds, ripple cross-laminae in the dolarenites, and rare parting lineation on the top surface of fine-grained dolarenite. All indicate southerly paleoflow, although a slightly radial pattern is suggested (Fig. 7). The parting lineations are oriented north-south, but closely associated cross-laminated ripples indicate that the southerly trend is the correct flow direction.

Maximum clast size data were recorded for conglomerates where bed thicknesses could be confidently measured. As for map unit PH₁, vertical trends

based solely on MCS changes are not apparent, probably reflecting the inability to confidently measure bedding in the coarsest conglomerates and the small dataset. A slight overall coarsening-upward trend of conglomerate clast size was observed in the well-developed megasequences in outcrop, although in the unit as a whole, no obvious overall vertical change in clast size is apparent. A slight increase in abundance of boulder- and cobble-sized clasts was noted from south to north. The plotting of all MCS vs BTh data for unit PH₂, either grouped (Fig. 14), or separated by grading or framework-support type, shows at best a very weak linear correlation of these variables.

Map unit PH₂ - Interpretation

Interpretation of the PH₂ features must consider the basinal setting of these deposits. The paleocurrents demonstrate that all PH₂ material was derived from the north, but the PH₂ clastics intertongue over a few tens of kilometres southward with poorly sorted PH₁ conglomerates, in part locally derived from the MHVC, probably mostly from the south. This suggests a restricted basin setting. The major control on basin formation is likely extensional faulting. A major normal fault is preserved as the south boundary of the slightly older lower Mount Harper group half graben, and faulting can be demonstrated to have directly controlled sedimentation of that succession (Mustard, in preparation). The southern faulting was active at least during the early stages of Mount Harper volcanism (*ibid*). Roots (1987) presented indirect evidence that faults were active during much of MHVC formation and were a major control on formation of the volcanic conglomerates and breccias which in part underlie and grade into the PH₁ conglomerates at their southern margin. Unit PH₂ contains an abundance of conglomerates rich in boulders and cobbles of composition identical to the Fifteenmile group preserved beneath the UMHG, as well as silicified Fifteenmile group regolith that is locally preserved on the unconformity surface below the LMHG. These observations strongly suggest a local source. The progressive northward thinning and eventual cut-out of the stromatolite-rich upper map unit of the Fifteenmile group by the sub-UMHG

unconformity is inferred to reflect uplift and erosion of the Fifteenmile group, thereby providing distinctive detritus, both in the northern part of the study area, and immediately north of the most northerly preserved conglomerates of unit PH₂. All of the above evidence suggests that fault-controlled uplift north of the present outcrop area was the primary control on PH₂ deposition.

Considering a model of sedimentation in a restricted basin setting, with active faulting as a primary control on basin formation and sedimentation, the thick coarsening upward sequences of PH₂ and the overall increasing abundance of conglomerates upward and to the north, deposition appears to have taken place predominantly in southward-prograding clastic fans. The PH₂ conglomerates only superficially resemble alluvial fan facies models (reviewed in Nilsen 1982 and Rust and Koster 1984). Direct indicators of subaerial exposure (eg. desiccation, sieve textures, local weathering crusts or profiles) are lacking, and the poorly channelized conglomerates do not show the organization, crossbedding, well-developed imbrication, and small-scale cyclicity of mid to lower fan braided stream deposits (cf. Rust and Koster 1984). In addition, the MCS vs BTh trends show a much greater dispersion than is typical of conglomerates deposited from subaerial sediment gravity flows (see review in Nemec and Steel 1984). Gravelly fan deltas in which alluvial fans build directly into water bodies also show many similar features and sequence patterns (reviewed in McPherson *et al.* 1987, 1988; Nemec and Steel 1984, 1988; Ethridge and Wescott 1984). However, in addition to the lack of subaerial indicators, unit PH₂ contains no features indicative of shoreline or littoral processes (cf. Ethridge and Wescott 1984; Kleinspehn *et al.* 1984), suggesting that deposition was at least at a sub-wavebase depth. Large-scale planar and trough crossbedding are generally an abundant structure in fan delta sandstones and finer conglomerates as part of shoreline and delta front sequences (*ibid.*, Nemec *et al.* 1984); in marked contrast, these structures are completely absent in PH₂ strata.

The repeated, large-scale coarsening-upward sequences fit well the general facies models proposed for submarine fans (reviewed in Howell and Normark 1982;

Nelson and Nilsen 1984; Walker 1985). However, there are several limits to the detail in which the PH₂ units can be interpreted using these models. The extent of outcrop and topography of the study area make it difficult to demonstrate the three-dimensional morphology or extent of individual fans. Based on the size of the largest sequences, lateral continuity of the non-conglomeratic sediments, and the limited three-dimensional exposure of the units, dimensions of the fans were probably small (<10km diameter). The paleocurrent data are somewhat suggestive of a radial pattern of deposition. Vertical stacking of the large-scale sequences could reflect lateral migration of separate fans, or fluctuations (perhaps tectonically controlled) in overall progradation of the basin fill. The latter is suggested by the increasingly conglomeratic nature of the unit upward and northward. However, the amount and nature of the exposure frustrates attempts to define lateral relationships of fans. Finally, although the most common submarine fan environment is at the base of continental slopes, it is well established that fans can form in subaqueous settings which are shallow or deep, marine or lacustrine, and in many basin types (*ibid*; Stow *et al.* 1982). The sandstones and mudstones of the megasequences show no evidence of wave reworking or tidal influence on deposition, suggesting sub-wavebase deposition, but no other features were observed which reliably demonstrate either water depth or salinity.

Reviews of submarine fan models stress the wide variety of fan types and internal features. These fan types are generally simplified into three end members: debris aprons, radial fans, and elongate fans (*ibid*). The features of unit PH₂ seem best to fit an intermediate model (perhaps reflecting an evolution) between radial (well-developed CU megasequences) and debris apron deposystems (conglomerate-rich upper and northern part of unit PH₂ with poor sequence development).

The features of the coarsening upward sequences shown in Fig. 11 correspond well to the traditional submarine fan facies models, based to a large extent on the common radial fan type. Although most submarine fan facies models build on the work of Mutti and Ricci Lucchi (1972, translated by Nilsen 1978), the

terminology used in discussions of these models and the detailed interpretations of depositional processes differ somewhat depending on the authors (compare Walker 1985 and Howell and Normark 1982, and discussions and replies of Nilsen 1980, Walker 1980, and Normark 1980, based on Walker 1978 and Normark 1978). A submarine fan model for PH_2 deposition is presented in the rather simplified terms of lower, middle and upper fan depositional processes as summarized by Walker (1985) and discussed in detail in Nelson and Nilsen (1984).

Deposition was almost exclusively by sediment gravity flow processes. The basal dololutes and dolarenites/dolowackes reflect lower (outer) fan turbidite deposition. Thin sandstone beds, generally with graded bases and rarely with rippled tops, are more common upward, reflecting a change to mid-fan areas. Rare fining-upward sequences a few metres thick with pebble-rich concave bases are interpreted to reflect channelized flow onto these regions. Small-scale (maximum of 15 m) coarsening-up and thickening-up sequences in this part of the large-scale sequence are interpreted as the product of suprafan lobes that migrated across the main fan. Non-channelized, matrix-supported, disorganized conglomerates in the conglomerate-sandstone facies are the product of individual debris flows, perhaps initiated by slumping on upper fan slopes. Convolute bedding in sandstone and mudstones interbedded with these conglomerates reflects slumping and dewatering in response to sudden loading by the debris flows. Lonestones may represent gravity winnowing processes at the front of debris flows (cf. Postma 1984a,b), probably a common feature in this setting. However, recent flume experiments suggest an alternate method in which large clasts are transported in the upper parts of highly concentrated turbidity flows and bypass the area of deposition of the lower, coarser sediment to be deposited with the finer material as outsized clasts (Postma *et al.* 1988). The conglomeratic facies which cap the megasequences were deposited in the upper fan where migrating channelized conglomerates were rapidly deposited in overlapping lenses. The conglomerates lack cross-bedding, good sorting, and generally lack well-developed normal grading, suggesting that turbulent flow was

not extensive. Most appear to fit the model of Walker (1975) for proximal resedimented conglomerates, where deposition is rapid and the clasts are supported by dispersive pressure and matrix effects rather than by turbulence. However, channelized conglomerates which grade up to normally graded pebbly sandstones may reflect a more evolved channelized flow where turbulence was significant, and waning flow was sufficiently prolonged to permit stratification to develop. Such channelized flows in some cases probably continued onto the mid fan regions, forming the normally graded conglomerates which constitute the base of some thin fining-upward sequences.

The conglomerate-rich succession which overlies the well-developed megasequences appears dominated by debris flows and high-density grain or turbidity flows. The abundance of matrix-supported, disorganized conglomerates could reflect nearby steep slopes (cf. Walker 1975). The clast-supported conglomerates in depressions attributed to high-density, gravel-rich sediment gravity flows (cf. Lowe 1976, 1982). The generally poor sorting, very crude grading, and lack of sandstone interbeds suggest a process of density-modified grain flow, a process transitional between debris flow and high-density turbidity flow, in which dispersive pressure and buoyant lift due to the high concentration of sediment are the important mechanisms of clast support (*ibid*). The slightly better sorted and graded conglomerates which commonly fill broad, shallow channels probably were deposited by traction carpet sedimentation from gravel-rich, high-density turbidity flows. This process involves both high dispersive pressure and clast collisions in the base of the flow, a highly concentrated traction carpet, and slightly turbulent suspension of gravel and sand in the top part of the flow. Deposition involves rapid and essentially *en masse* freezing of the traction carpet when flow velocity drops below the point necessary to maintain dispersive pressure. The traction carpet deposit may be inverse graded at the base if dispersive pressure and clast interactions have inhibited settling of the larger clasts. A normally graded upper part may form due to suspension settling of the slightly turbulent upper flow,

resulting in the inverse-to-normally graded bed type of Walker (1975). If suspension settling is rapid and the tops of the flows are reworked by the remaining turbiditic sandy flow, the graded-stratified conglomerate type of Walker (1975) may form. However, the finer part of this gravel-sand upper flow is likely in most cases to separate from the traction carpet and continue downslope as a high-density turbidity current to form a separate normally graded pebbly sandstone. Both Lowe (1982) and Walker (1975) noted that structures such as large-scale cross-bedding are generally absent in these conglomerates, a feature of the PH₂ conglomerates which supports this model of deposition. Many of the conglomerates occur in lenses that occupy minor depressions, and display some evidence suggesting the erosion of underlying beds. This probably reflects a slightly more turbulent and thus erosive initial flow or flow head (cf. Middleton and Hampton 1976), with the preserved conglomerates reflecting either the non-turbulent bodies of these flows, or subsequent flows which infill the channels. The conglomerates rarely occur in relatively steep-sided channels, but the channel fill is poorly sorted and graded, not the expected product of the turbulent flow needed to form the channels. In light of the debris apron environment suggested for this conglomerate facies, these conglomerates may have infilled slump scars on the steep, proximal parts of the debris aprons, or deeper channels cut by earlier turbulent flows.

The sediment gravity flow processes summarized above account for the major features of the PH₂ unit. It is generally considered that the processes and deposits of sediment gravity flows are a continuous spectrum, with high-density, gravel-rich flows evolving into low-density, sand- or mud-rich flows downslope (Middleton and Hampton 1976; Walker 1984; Lowe 1982; Nemec and Steel 1984; Walker 1975, 1984, Postma 1986). The vertical changes in lithofacies of unit PH₂ in general support an interpretation of the continued down-fan evolution of gravity flows. In common with most field studies of gravity flow deposits, it was not possible to demonstrate this evolution in any one bed (for an exception see Nemec *et al.* 1984). A deviation from downfan evolution may be the massive matrix-supported conglomerates.

Essentially *en masse* transport and deposition of the cohesive debris flows which formed these conglomerates probably inhibited all but minor evolution to other flow types at the tops and front of the flows (cf. *ibid*; Postma 1984a,b).

In summary, PH₂ deposition initially constructed well-developed coarsening upward-sequences which mimic classical models of prograding sand- and gravel-rich submarine fans. The upper conglomerate-rich parts of the overall coarsening-upward basin fill lack the well-developed cyclicity common in small radial fans. The coarseness and immaturity of the conglomerates is suggestive of a debris apron environment. Debris apron models are reviewed in Nelson and Nilsen (1982) and Nelson (1983). An example which appears analogous to the UMHG has been documented in the North Sea where upper Jurassic alluvial fans, fan-deltas, debris aprons and submarine fans are directly related to normal faults on the west side of the Viking Graben (Stow *et al.* 1982; Kessler and Moorhouse 1984). In this restricted basin, which was a half graben at the time of sedimentation (Kessler and Moorhouse 1984), complex overlapping normal faulting on the west margin resulted in deposition of overlapping gravelly fans. The Brae field of the Viking Graben was studied in detail by Stow *et al.* (1982) who interpreted the 300 to 600 m thick conglomerate-rich basin-fill, that shows an overall fining-upward trend, as a complex sediment apron along a faulted scarp margin. Fault-scarp breccias and coarse conglomerates, which were deposited at and near the base of the slope, grade basinward to complexly overlapping inner to outer fan sediments in several fining-upward fan megasequences representative of a shallow marine, but generally sub-wave base, setting. The main control on fan development was interpreted as tectonic, with periodic faulting initiating the deposition of fan megasequences.

Because the exposed part of unit PH₂ does not include the original northern basin margin, any original faults or base-of-slope breccias could not be identified. However, the coeval and slightly older MHVC and LMHG rocks are demonstrably related either directly (Mustard submitted; Mustard and Donaldson 1987), or indirectly (Roots 1987), to extensional faulting and half-graben formation. A

similar tectonic control is strongly inferred for PH₂ deposition on the basis of this association, the locally derived and immature nature of the conglomerates, and the restricted basin setting implied by the southward intertonguing with PH₁ sediments. Other possible first-order controls on sedimentation include changes in source rocks, climatic changes, and major sea-level fluctuations (Stow *et al.* 1985). Source rock changes can be discounted; all detritus was derived from the Fifteenmile group dolostones. There is no direct evidence to suggest the nature of the overall climate, or whether changes in climate took place during deposition. Eustatic sea-level fluctuations other than the rapid and major fluctuations caused by glaciation probably would be too small and too gradual to be significant compared to the rates of tectonically induced uplift and subsidence generally associated with active margins (*ibid.*).

A major glaciation could certainly influence the depositional regime, even on an active margin, both by direct glacial transport and deposition and also by major sea-level fluctuations in response to large volumes of water being locked up in major ice sheets during glacial periods, and released during warm interglacials. This possibility is relevant to PH₂ deposition, because possibly coeval lower Windermere Supergroup coarse clastics have been interpreted as glacially derived, and are also believed to be associated with active tectonism (summarized in Young 1988; and Eisbacher 1985). This Windermere glaciation is correlated with widely accepted major Late Precambrian glacial events (reviewed in Hambry and Harland 1985; but with non-glacial alternative interpretations presented in Schermerhorn 1974). Of the many features commonly cited as evidence for direct or indirect glacial deposition (exotic clasts, faceted and multiply striated clasts, glacially modified substrates, glaciotectonic deformation etc., reviewed in Boulton and Deynoux 1981), only the presence of abundant poorly sorted, matrix-supported conglomerates (diamictites) and limestones could be cited as possible evidence for glacial deposition of unit PH₂. However, the diamictites contain only locally derived clasts and in the context of their facies association, they best fit an origin

as non-glacial debris flows. The limestones are in direct association with abundant gravity flow conglomerates of submarine fan sequences and show none of the features commonly associated with a dropstone origin (eg. Thomas and Connell 1985). Thus there is no compelling evidence for a direct glacial influence on PH₂ deposition, although an indirect influence cannot be ruled out. The onset of a major glaciation could cause a rapid and significant sea-level fall, which could have resulted in the basin-scale progradational sequence of unit PH₂. However, as discussed previously, basin-margin faulting is the most likely primary control on PH₂ sedimentation, and this control alone can account for the features of unit PH₂.

The fault-controlled megasequences and basin-fill pattern of the Viking Grabens' Brae field described as a possible analogue show fining-upward megasequence trends, in contrast to the coarsening-upward trends of unit PH₂. However, conglomerate-rich coarsening upward sequences are common on the margins of fault-controlled basins, although most examples are of alluvial fan or fan-delta deposits (reviewed in Nilsen 1982). The best-documented examples are from the Devonian Hornelen basin of Norway (Steel 1976; Gloppen and Steel 1981) and the Miocene-Pliocene Ridge Basin of California (Crowell and Link 1982), both recently summarized and compared by Nilsen and McLaughlin (1985). In both basins, the basin formation and sedimentation patterns are the result of major oblique-slip faulting at the margins. However, both are unusually thick (Hornelen Basin >25 km; Ridge Basin >13.5 km) for their areal extent, reflecting an overlapped stacking of depositional packages due to basin depocenter migration, a result of the strike-slip component of oblique-slip master faults. Volcanic rocks are absent in both basins, but syndepositional volcanism does rarely take place in strike-slip basins (Reading 1980; Mann *et al.* 1983). Strike-slip motion is dominant in these basins, but the coarsening-upward megasequences in these and other strike-slip basins in general reflect vertical displacements associated with oblique fault movement (Steel *et al.* 1977; Heward 1978; Hendrix and Ingersoll 1987). Thus the coarsening-upward megasequences are also compatible with basins formed

predominantly by normal faulting, and without supporting evidence, are not diagnostic of strike-slip movement.

There is little direct evidence in unit PH₂ to choose between strike-slip or normal faulting at the northern margin. However, several lines of evidence suggest that normal faulting was predominant. The paleocurrent patterns of unit PH₂ and the interdigitated dolomitic sandstones of unit PH₁ are essentially southerly, perpendicular to the known and presumed east-west faults. This is not the trend common to strike-slip basins where the strike-slip movement results in a well-defined evolution of paleocurrent trends away from the marginal faults, changing from perpendicular to the fault margin in the proximal facies to a predominance of transport down the axis of the basin for most of the basin fill. In addition, the lack of LMHG clasts in the UMHG conglomerates, suggests geographically separate basins.

The LMHG lithofacies are more completely exposed than the UMHG strata; a separate study of these rocks has documented deposition in a half-graben basin, with basin formation and sedimentation controlled by normal faults that are partly preserved at the southern margin (Mustard in preparation). The preserved part of the Mount Harper Volcanic Complex separates the western edge of LMHG half graben from the most easterly exposures of units PH₁ and PH₂. Roots (1987) presented detailed field, petrologic and geochemical evidence to show that the MHVC is best interpreted as a product of continental rift volcanism. The volcanic rocks show an evolution upward from relatively primitive tholeiitic basalts which have provided geochemical evidence for upper mantle interaction, to rhyolites and andesites that show affinities characteristic of continental crust. Roots also mapped faults within the volcanic complex which were probably active during volcanism. The faults are both parallel and slightly oblique to the trend of the marginal faulting on the south side of the LMHG half graben.

Given the evidence for normal faulting, half graben sedimentation, rift-related volcanism and synvolcanic faulting in the underlying and coeval volcanic

and sedimentary rocks, deposition of units PH_1 and PH_2 is interpreted to have been in a half graben basin slightly younger than the LMHG half graben and with a footwall scarp opposed to, but offset to the west from, the footwall faults of the LMHG (Fig. 8C). Such a pattern, with opposed listric normal faults, is the geometry expected for propagating continental rifts, and can be observed in the East African rift system (Bosworth 1985; Ebinger 1989). The fact that the basal conglomeratic deposits of the UMHG sub-basin are slightly younger than the LMHG is consistent with this model. The concentration of volcanic rocks at the overlap zone of these opposed basins is also appropriate to a continental rift setting, and may reflect the locus of a transfer fault system or accommodation zone between the two sub-basins, a common feature of African rifts (cf. Ebinger, 1989, Fig. 3). The accommodation zone between opposed sub-basins in East Africa contains abundant but localized faults which serve as conduits for magma eruption (*ibid.*).

Post-depositional uplift resulted in exposure, alteration, and the creation of a disconformity between PH_2 and coeval to younger sedimentary and volcanic rocks and the overlying UMHG map units. This uplift and the resultant disconformity may correspond to the break-up unconformity generally associated with the late stages of continental rifting (Bally 1981). However, the overlying units PH_3 - PH_5 are clearly much younger than the underlying Mount Harper group rocks; trace fossils in the top 50m of unit PH_5 attest to an early Cambrian age (Mustard *et al.* 1988a), and the contacts between the upper units are gradational except locally, suggesting that all UMHG strata above the disconformity are approximately dated by these fossils. Thus a time gap of about 150-200 Ma could exist between the events which caused deposition of the upper three units of the Mount Harper group and the underlying rift-related rocks.

Map units PH_3 , PH_4 , PH_5 - Description

The uppermost three map units of the UMHG have gradational contacts, vertically and to some extent laterally, suggesting that they represent different parts of the continuous evolution of a single depositional environment. The lowest of

these units, PH₃, is a recessive-weathering mudstone preserved on relatively gentle grass-covered slopes, with outcrops restricted to gullies which cut these slopes (Figs. 15a,b). The basal contact is not exposed, but the silicified breccia preserved at the top of the underlying PH₂ unit in the northern half of the map area suggests a disconformity. In the southern half of the map area, unit PH₃ directly overlies volcanic conglomerate and breccia of the MHVC (member C of Roots, 1987). The volcanic conglomerates are also poorly exposed, and the only place where both PH₃ and the conglomerates are exposed close to the contact has several metres of brecciated crystalline dolostone between them, again suggesting that a disconformity is present. The upper contact is generally gradational over a few tens of metres to unit PH₄, or to unit PH₅ where PH₄ is not present.

Map unit PH₃ is not present at the northern extreme of the UMHG outcrop area (Figs. 3, 16). Measured thicknesses of this unit are up to 900 m, but the thickest section measurements (Fig. 16, section 25) may be due to repetition by minor thrusts. A general thickness of about 200-300 m is apparent where the possibility of structural complications can be discounted.

The mudstones are thinly laminated to massive; fresh surfaces are medium to dark grey, and weather yellow-brown to medium-grey. Clay-rich in the lower part and generally non-calcareous, the mudstones gradually coarsen upward to silt-rich mudstone that becomes increasingly dolomitic in the top third of the unit. A strong pencil cleavage obscures original sedimentary structures in most areas, frustrating attempts to examine bedding surfaces. The laminae are faint, but appear to be generally straight, continuous and parallel. No cross-laminae or other paleocurrent indicators were observed. Thick laminae and thin beds of greyish-orange dolosiltite to very fine-grained dolarenite or dolowacke are increasingly common upward in the top third of the unit, forming a gradational change to unit PH₄ (taken where dolarenite makes up >50% of the strata). These dolostones are internally massive, but some show subtle normal grading (generally only apparent in thin section). Cross-laminae and other paleocurrent indicators are generally absent, but flutes and

cross-laminae can be seen in the dolarenite beds at the gradational change to unit PH₄ and indicate southerly paleoflow (Fig. 7; included in the PH₄ rose diagrams).

Unit PH₄ consists of three major facies: lenticular bodies dominated by dolarenite; calcilutite which caps the dolarenite lenses in a few localities, and interbedded dolarenite, dolosiltite, and dololutite which are laterally at the same stratigraphic interval as the dolarenite lenses. The entire unit reaches a maximum thickness of 230 m, but typically is < 150 m thick (Fig. 16).

The discontinuous sand-rich lenses are generally a maximum of 50 m thick, but rare thicker examples (up to 80 m) are present (Figs. 15a, 16, section 16). The lenses rarely persist laterally for more than a few kilometres; the large-scale three-dimensional geometry could not be defined. The dolarenite of the sand-rich lenses is orange-grey on both weathered and fresh surfaces. The prevalent grain size ranges from fine-grained sand to coarse silt (the latter technically are dolosiltites, but the distinction in the field proved difficult, so the term dolarenite was used unless a silt size was obvious). Fine- to medium-grained dolarenites make up a maximum of 10% of most lenses, and are most common in the upper part, suggesting a subtle coarsening upward trend. The bases of the lens are gradational from PH₃ interbedded mudstones and silty or very fine-grained dolarenites. The lower dolosiltites interbedded with the dolarenites in some areas are a distinctive moderate red rather than the typical orange-grey colour.

The dolarenites, moderately to well sorted, are composed of >97% dolosparite clasts and <3% quartz or chert clasts. A matrix of silt-size dolosparite or rarely dolomicrite makes up a maximum of 10% of the dolarenite beds. The cement is a fine- to medium-crystalline dolomite. Slight neomorphic aggradation of the dolosparite clasts has altered original grain boundaries in many cases, but the equivalent size of the dolosparites and the rare quartz grains demonstrate that the original grain size has not been significantly modified post-depositionally.

The dolarenites typically form continuous, parallel, straight to slightly wavy thin beds or thick laminae with sharp and non-erosive contacts. Grading is not

apparent in outcrop, but weak normal grading is generally observable in thin section. Some beds are rippled; most ripples are isolated lens of medium-grained dolarenite enclosed by finer-grained dolarenite. The ripples are asymmetric, with well-developed internal cross-laminae which without exception indicate southerly transport. Rare continuous, asymmetric, non-climbing ripple forms also contain internal cross-laminae which reflect southward paleoflow (Fig. 7). Rare bed-surface exposures of sinuous to linguoid ripples were observed in upper parts of some lens.

Hummocky cross stratification (HCS), noted in three of the PH₄ lens, consists of planar laminae which grade upward to undulating hummocks and subtle swales, overlain in turn by more planar laminae or thin beds. The domes typically show about 8-10 cm relief and 1-2 metres wavelength (Figs. 15c,d). In a few outcrops the three-dimensional circular dome-and-depression morphology could be confirmed. The HCS generally shows no evidence of erosion into the underlying planar beds. This unusual type of HCS ("PHF" type in the sequence code proposed by Walker *et al.* 1982) is present in very fine-grained dolarenites as single sets which in the best exposure (Fig. 16, section 16) are repeated upward at 3-5 metre intervals for a total of about 20 metres, separated by planar-bedded or laminated very fine-grained dolarenites and rare dolosiltites or dolomitic mudstones. Rare large-scale undulating bedforms (Fig. 15c) show a more definitive low-angle truncation of laminae, and some appear to be overlapping sets with wavelengths of several metres or more (most are larger than the lateral outcrop extent). The wide and shallow forms of these structures, and their isolated presence in the planar-stratified very fine-grained sandstones suggest an origin as swaley cross stratification rather than as slightly similar looking angle-of-repose trough crossbedding (cf. Walker 1982, p.23).

Where the distinctive PH₄ lens are not present, map unit PH₃ grades vertically to interbedded thin beds of very fine-grained dolarenite with increasingly rare recessive interbeds of dolosiltite and dololutite (Fig. 15f). The dolarenite interbeds contain either sharp or loaded bases, some with flutes, and internally

range from massive and non-graded, very subtly normally graded or finely laminated in the lower part, with commonly a laminated upper interval and rarely a ripple cross-laminated top (Bouma turbidite sequence types AB, BC, ABC). Both the flutes and cross-laminae indicate southerly paleoflow (Fig. 7). Rare interbeds up to 20 cm thick of flat-pebble conglomerates are also present (Fig. 15e). These beds have slightly wavy but non-erosive bases and consist of tabular intraclasts (up to 10 cm maximum length) of laminated dololite and very fine-grained to silty dolarenite which are similar to the dolostones of the enclosing beds (and the finer lithofacies of the laterally equivalent PH₄ sand-rich lenses). The tabular clasts are oriented subparallel to bedding or imbricated, the latter indicating southerly paleoflow. The upper contact of unit PH₄ is gradational over a few tens of metres to PH₅ quartz- and chert-rich lithic wackes or arenites, and is placed where siliciclastic sandstones or siltstones make up >10% of the unit. A sharp, slightly wavy and erosive top contact is present in the few places where chert-pebble conglomerates of map unit PH₅ overlie unit PH₄.

Dark grey laminated calcilutite is present in a few places overlying the normal PH₄ dolarenites. The contact with the dolarenites is interbedded over a few metres to tens of metres. The calcilutite is present only at the top of the thickest dolarenite exposures (Fig. 16, sections 16, 17, 25), and appears to be roughly confined to these areas laterally. The calcilutites are laminated, with straight to slightly wavy, parallel, continuous laminae and consists of a brown micrite, appearing massive in thin section with very rare (<2%) silt-sized quartz grains either randomly distributed or in discontinuous wispy laminae. Dark grey carbonate concretions constitute up to 10% of some intervals. Rare downward-terminating cracks show polygonal or triangular bedding-parallel patterns and are infilled by laminated mudstone identical to the host rock; these cracks are of probable syneresis origin. No paleocurrent indicators were observed in this facies.

Map unit PH₅ marks a change from the predominantly carbonate clastics of the underlying Mount Harper group sedimentary rocks to a mixed siliciclastic-

carbonate lithofacies. Most of this unit consists of siltstones and very-fine-grained to fine-grained sandstones. Unit PH₅ thickens and becomes finer-grained to the southwest and west from < 30 metres in the northeast to > 280 metres at the most westerly exposure measured. The basal contact in most places is gradational over several metres to a few tens of metres from either unit PH₄ or unit PH₃. The contact is placed where the siliciclastic arenites make up >10% of the succession. The upper contact with the CDb dolostones is rarely exposed, but is sharp, parallel and non-erosive where exposed, with no brecciation, deformation or alteration of the underlying rocks. However, the dramatic lithologic change suggests that the contact represents at least a minor disconformity, and thus the measured thicknesses of unit PH₅ are minimal depositional thicknesses.

Except in the northeastern part of the study area, unit PH₅ consists of laminated to thin-bedded siltstones, sandstones and mudstones, both siliciclastic and doloclastic, with the former most common and increasingly abundant upward in most areas. The medium grey siliciclastic rocks generally weather pale brown, but in the thick section in the western part of the study area, reddish brown weathered surfaces are common. These strata consist of laminated to thin-bedded (most 1-3 cm thick), silty mudstone, siltstones and very fine- to fine-grained litharenites, and rare lithic wackes with 15-20% silt-clay matrix. Framework grains are generally >90% quartz/chert and <10% dolosparite, although in basal parts of the unit transitional from PH₄ dolarenites, dolosparite makes up 10-50% of some lithic wackes and arenites. Most quartz grains are monocrystalline and clear, with straight extinction, but polycrystalline grains are also present. The chert is generally fine-grained and of indeterminate origin, but up to 20% of the sand grains in most of the arenites consist of abundant sericite in a cherty groundmass, probably the result of silicification of an originally volcanic rock. The quartz-chert arenites and wackes increase in abundance, grain size, and bed thickness upward, generally in a single subtle trend in a measured section. At the most westerly section (Fig. 16, section 34), the unit consists of several coarsening- and fining-upward sequences are 50 to 100

metres thick. Grain size and bed thickness decrease to the west and southwest, corresponding to a general increase in the thickness of the unit. The siliciclastic units constitute thick laminae and thin beds which are straight to slightly wavy, parallel and continuous. Rare layers a few cm thick display convolute lamination, probably a product of syndimentary deformation. Rare small-scale cross-lamination indicates paleoflow ranging from northerly to westerly (Fig. 7). The bases are generally non-erosive, but show rare microloading. Subtle normal grading was recognized only in thin section. Rare medium-grained lithic wackes form 2 to 5 cm thick beds which are randomly located in the upper parts of the unit. These beds show vague normal grading, contain rare rip-ups of the underlying laminae, and display both basal load casts and flame structures that are consistently deformed towards the north (Fig. 17a). In the turbidite sequence terminology (cf. Walker 1985) the most common internal sequences of individual thin beds (where discernable) are classified as ABE BE ABCE, with rare BCE types, although normal grading in the fine sands and silts is generally very subtle and/or microscopic.

Orange-grey dolowacke or dolarenite beds and laminae are intercalated with the siliciclastic beds. The dolostones generally decrease in abundance upward from 20 to 40% of the unit in the lower half to <5% (or absent) in the upper half. However the dolostones also increase in abundance to the west and near the western boundary of the study area, unit PH₆ contains up to 70% dolarenite and dolowacke beds in the upper 80 metres. The dolostones are similar to those of unit PH₄, very fine-grained to fine-grained dolarenites in thick laminae or thin beds. Beds and laminae are continuous, parallel and straight to slightly wavy. Cross-laminae in asymmetric ripples in some beds consistently indicate southerly paleocurrents for the dolostones (Fig. 7).

In the southwestern part of the map area, a black siliciclastic mudstone <10m thick is present at the top of unit PH₆ in several widely separated areas (Fig. 16, sections 16, 26, 34), abruptly overlain by light grey dolostones of unit CD_b. The mudstone is very finely laminated, slightly fissile, and consists of >75%

cryptocrystalline clay with up to 25% fine silt-sized quartz and sericite as discontinuous interlaminae.

Northeastern exposures of the upper units are significantly different. A basal subunit of chert-pebble conglomerates and chert-rich lithic arenites in unit PH₆ occurs locally in discontinuous, lenses a few hundred metres long and up to 30 metres thick (Fig. 16, section 24). These conglomeratic lenses show a sharp, slightly wavy and eroded basal contact with the underlying PH₄ dolarenites. The upper contacts appear sharp to gradational, over a few metres, with interbedded lithic wackes and dolarenites typical of unit PH₆ in this area, or rarely is overlain by a few tens of metres of thin dolarenite beds of unit PH₄. In either case, these sands grade upward to the trace-fossil-bearing PH₆ siltstones and fine-grained sandstones described below. The conglomerate lenses consist of 15 to 75 cm thick beds of chert-pebble conglomerate, displaying a grey-green weathering and fresh colour. The conglomerates are composed of > 90% granule- to large pebble-sized clasts, tightly packed in a medium- to coarse-grained chert-rich lithic wacke or litharenite matrix (Fig. 17b). These moderate- to well-sorted conglomerates are in vertically repetitive sheets traceable for several tens of metres laterally, have slightly erosive bases, and commonly grade upward to coarse- to medium-grained chert-rich litharenite beds a few centimetres thick. The pebbles are subround to round and more than 60% are tabular. The tabular clasts tend to be oriented subparallel to bedding; some are poorly imbricated. The clasts, > 70% chert, are mostly light green-grey, but include medium to dark-grey chert and light grey laminated chert which may be silicified dolostone. About 20-30% of the clasts are white quartz. The least abundant clasts (< 5%) are orange-grey dolarenite identical to dolarenites of the underlying PH₄ unit, the probable source of these clasts. Thin section examination of the pebbles and sands reveals that up to 50% of the clasts are a random chert-sericite mix (Fig. 17c), almost certainly silicified volcanic rocks; 20-30% of the clasts are clear, monocrystalline quartz showing straight extinction, features compatible with an volcanic source (Folk 1974); the rest of the clasts are quartz and chert of

indeterminate provenance, rare potassic feldspar, and dolarenite.

The conglomerates and interbedded sandstones are gradationally overlain by up to 10 metres of medium- to very coarse-grained, moderate- to well-sorted, chert-rich lithic arenites. These arenites are present as 1 to 4 cm thick, slightly wavy, continuous thin beds with fair normal grading, and as trough-crossbedded sets up to 3 m thick. The crossbedding displays overlapping trough bases about 1 m long, with 10-30 cm of trough relief preserved. The individual troughs consistently cut down to the north where relationships could be determined. The imbricated clasts of the conglomerates show a complex pattern of paleocurrents. Although an overall northerly trend was observed, in the measured sets a high variance is typical, some appear bimodal and in one area beds closely related vertically contain imbricated clasts which indicate roughly opposed paleocurrents (Fig. 7 stations B,C,D).

Trace fossils were discovered in unit PH₆, but despite extensive search were found only in the top 50 metres of the unit in the northeastern part of the study area. Here the vertically coarsening and thickening upward sequence in unit PH₃ is as described for other areas, but the overlying PH₄ is thinner and lacks HCS. These planar-bedded (rarely rippled) dolarenites abruptly give way upward to a thin interbedded succession of dolarenites and siliciclastic sandstones of unit PH₅ (Figs. 18, 19a). Trace fossils are common in this thin PH₄-PH₅ transitional sequence. They are preserved in hyporelief on the bases of beds of fine- to medium-grained sandstones (generally siliciclastic), most commonly in the basal part of the unit where it is transitional from underlying dolarenites of unit PH₄ (Fig 19b,c). Some of these beds consist of complexly amalgamated sets of trough crossbeds, forming cosets up to 60 cm thick (Fig. 19d). The lowermost and most common trace fossil is the simple horizontal feeding trace *Planolites*. The complex trilobite traces *Cruziana* and *Rusophycus* (Figs. 19e,f,g) also are common, slightly higher in any section than the first occurrence of *Planolites*, but below the first occurrence of the rare vertical burrow, *Skolithos* (Fig. 19h) and the U-shaped vertical burrow, *Arenicolites*. Except for the thick layers of amalgamated trough crossbeds, most beds are massive, planar

to slightly wavy, with rare cross-laminated ripples on top. The abundance of trace fossils on the soles of some beds suggests that bioturbation may have obscured internal structures.

The top 10-20 metres of unit PH₅ in these trace-fossil-bearing successions consists of laminated, very fine-grained dolowacke or dolosiltstone and dololutite with rare very fine-grained siliciclastic siltstone or lithic wacke as interbeds. Some of the laminae are wavy and appear to have formed as microbial mats, locally associated with laterally linked domal stromatolites with < 10 cm synoptic relief. Desiccation cracks and trace fossils (*Skolithos* and *Arenicolites*) are rare in this facies. The upper contact with the overlying CDb dolostones appears sharp and essentially parallel here as elsewhere, although it is commonly recessive-weathering and covered.

Map units PH₃, PH₄, PH₅ - Description

These units are here interpreted as having accumulated on a storm-dominated marine shelf (Fig. 20). The lateral association of facies reflects a consistent northeastward shallowing of the basin, with the overall vertical sequences suggesting a general regression. The northeastern part of the study area is discussed separately because the unique presence of trace fossils and differences in structures and facies associations suggest that an inner shelf to shoreface interpretation for units PH₄ and PH₅ is appropriate, rather than the middle to deep shelf interpretation suggested for most of the study area.

The strong cleavage, poor exposure, lack of sedimentary structures and lack of fossils hinders a detailed interpretation of unit PH₃. The finely laminated mudstones were deposited in a quiet-water, basinal setting, below storm wave base. The upward change to shelf sands of unit PH₄ is suggestive of a deep shelf setting. The general coarsening-upward nature and increasing presence of thin beds of dolostone suggests a regressive sequence. The interbedded dolostones in the upper part of the unit all appear to have been deposited as turbidites.

The dolarenites common in the upper part of unit PH₃ and making up the

bulk of unit PH₄ are interpreted in terms of facies models commonly applied to non-carbonate rocks. Most models of shallow marine carbonate facies reflect the strong intrabasinal control of organisms on sediment production and initial depositional processes (eg. reviews of Enos 1983; Wilson and Jordan 1983; James 1984).

Precambrian shallow marine carbonates commonly show abundant evidence of stromatolitic and cryptalgal sequences. However, the UMHG dolarenites are quite different. With a few minor exceptions, stromatolites, oncolites, cryptalgal laminates, oolites or other algal-related lithotypes are absent. Neomorphic alteration of the original textures is generally slight, and the original size and shape of the dolarenite sand grains can generally be discerned. The grains are crystalline dolomite, but broken and obviously transported, with a later dolomite cement. They are almost certainly terrigenous material, with the paleocurrents and changes in facies suggesting a northern source (discussed below). The sandstones are identical to, but better-sorted than, the sandstones of unit PH₂ which disconformably underlie the upper units in the northeastern part of the study area, and these older clastic rocks may have been partly eroded to provide the dolomitic sand. Thus these terrigenous clastic sediments are interpreted in terms of noncarbonate facies models.

Unit PH₄ is best explained with reference to depositional models for storm-dominated shelf sands. Recent reviews of shelf sand depositional processes include Tillman *et al.* (1985), Walker (1985), and Harms *et al.* (1982). The dolarenite lenses show none of the internal crossbedding of shoreface bars or ridges (*ibid*). The predominance of planar stratification and very fine-grained sand size suggests that deposition was below fair weather wave base. However, there seems to be a consensus that the presence of hummocky cross bedding indicates proximity to storm wave base (*ibid*). The great variability in bedding sequences of HCS probably reflects variations in sediment type, grain size, water depth and formation processes (*ibid*; and Dott Jr. and Bourgeois 1982 1983; Walker *et al.* 1983). The best exposed HCS beds show a vertical sequence of gradation from planar to hummocky to planar bedding with little or no evidence of scouring. Walker *et al.* (1983) described

identical HCS beds and proposed a turbidity current origin, although modified and possibly triggered by a major storm event. The lower planar stratification could be caused by upper plane-bed flow, oscillatory wave motion or some combination of these processes; a progressively decreasing rate of deposition and possibly storm wave effects would form the classic hummock and swale structures, in turn overlain by planar stratification which could be primary or reflect reworking by storm waves, probably immediately after deposition. The lack of small-scale ripples in the strata immediately above the HCS may reflect reworking. The generally non-rippled, planar-stratified very fine-grained sandstones and siltstones were probably deposited by suspension settling with little traction load, suggested by the small grain size, lack of parting lineation, and the isolated, nonclimbing form of the rare current ripples (cf. Harms *et al* 1982, ch. 3).

Several processes could transport large amounts of very fine-grained sand and silt essentially in suspension to areas below normal wave base. Reviewed in Walker (1985), these include rip currents, incremental storm flows, storm surge ebb currents, wind-forced currents and density (turbidity) currents (storm-generated or due to slumping on nearshore sand bodies). However, the rare HCS beds and medium-grained current ripples and graded beds are best explained as the result of density currents, probably storm-generated. The paleocurrents recorded by the ripples in these coarser bedforms support this interpretation. All indicate generally southerly flow, away from the shallow-water facies to the north (and northeast) and parallel to the paleocurrents of the sandstones by turbidity currents in the interbedded sandstone-siltstone-mudstone facies immediately below and laterally equivalent to the sand-rich lens. Other processes of moving medium-grained sand to areas below fairweather wave base should primarily indicate deposition by geostrophic flows oriented roughly parallel to shoreline (*ibid*, Tillman 1985).

The interbedded very fine-grained dolarenites, dolosiltites and dololutes present in many areas, and laterally equivalent to the dolarenite lenses, are interpreted as a slightly deeper facies in which sandstones were emplaced solely by

turbidity currents. The best examples are in the southern part of the study area, directly south of a thick and HCS-bearing dolarenite lens (Fig. 16, section 15), suggesting that they represent a continuation of storm-induced turbidity currents from depths near storm wave base to slightly deeper parts of the shelf, where sandy turbidites were deposited. Parallelism of the paleocurrents deduced from the sole marks and cross-laminae in these turbidites with those of the sand-rich areas supports this interpretation. Several Phanerozoic shelf sequences show a similar lateral facies transition (eg. Hamblin and Walker 1979; Walker 1983; summarized in Walker 1984b). The rare interbedded intraclastic conglomerates also are best interpreted as sediment gravity flows. The clasts all appear to be intrabasinal ripups from shallower-water facies. A depositional process of rare-event (hurricane?), storm-generated high density turbidites which transferred large masses of ripups from shoreface or shallow shelf areas to the deeper shelf is envisioned for these beds.

The calcilutites which cap some dolarenite lenses (eg. sections 16 and 17, Fig. 16) are enigmatic. They lack fossils, current structures or other possibly diagnostic evidence. Their isolated presence only in association with the some of the thickest dolarenite lenses suggests deposition in an area sheltered from normal shelf processes. Although the dolarenite lenses coarsen slightly upward, as is typical of regressive sequences, they nowhere show the high-energy structures (such as crossbedding) or facies associations typical of barrier island and shoreface sands (as reviewed in Reinson 1985 and McCubbin 1982). However, the laterally equivalent upper PH₄-PH₅ facies of the northeastern part of the study area contain both trace fossils and sedimentary structures indicative of shoreface deposition. The lack of these features and facies association with the deeper shelf sands suggests that the calcilutite was deposited in a protected deeper water environment, but a more detailed interpretation is not warranted from the available data.

Except in the northeastern part of the study area, discussed separately below, unit PH₅ reflects deposition by low-density turbidity currents below storm wave

base, probably in a mid- to deep-shelf setting, "distal" in the sense of the facies association with the trace-fossil part of unit PH₅. A basin-slope is a possible setting. However, basin slopes are generally sites of instability, with slumps and slides commonly generating episodic relatively thick, poorly sorted sediment gravity flow deposits and large-scale deformation or erosional structures (reviewed in Cook *et al.* 1982). However, although the PH₅ turbidites are consistently thin and fine-grained, the rare small-scale deformation structures commonly can be directly related to overlying sandy turbidites. No large-scale slump, slide or soft-sediment deformation structures were observed. It seems likely, even given the intermittent and poor exposure in western parts of the study area, that these features are not present.

A detailed interpretation of the subtle large-scale vertical sequences observed in the western exposures is not attempted. However, none of the sequences shows any change upward to more "proximal" fan facies, and major fan or delta facies associations are not present in the shallow-water facies preserved to the northeast; thus such models are not applicable to these strata.

The paleocurrent patterns show an interesting change from southward for the doloclastic rocks to westerly for the siliciclastic rocks in the most westerly exposures. Assuming that the paleocurrents (admittedly small in number) accurately reflect transport away from rather than parallel to the shoreline, as argued for the PH₄ turbidites, the simplest explanation is the mixing of two different sources: dolomitic detritus derived from the north and siliciclastic debris from the east. This fits well with the paleocurrent patterns and with the proximal vs. distal facies associations of the underlying and laterally equivalent units; it also agrees with the argument advanced below that the provenance of the siliciclastics was part of the Mount Harper Volcanic Complex that was exposed to the east.

The thinner, coarser, trace-fossil-bearing, northeastern exposures of the upper units in general are interpreted as a regressive offshore-shoreface-foreshore sequence. The interpretation presented below is based on the models reviewed in McCubbin (1981) and Reinson (1985). The best exposed example is illustrated in

Fig. 18. In this vertical sequence, the upward change from silty mudstones with rare sandstone turbidites (map unit PH₃) to planar bedded dolarenites is interpreted as a change from a sub-wave-base shelf to a lower shoreface environment. The planar bedding and rare ripples of the lowest dolarenites (shown as map unit PH₄) reflect low-energy depositional processes of the lower shoreface. The trough crossbedded sets, which appear to be slightly channelized in some cases, probably represent upper shoreface bar or shallow tidal inlet deposits. The intercalated planar-bedded sandstones with rare ripples and rare thin trough-crossbedded sets probably are upper shoreface or foreshore deposits, dominated by wave surge. The siltstone-mudstone-sandstone facies at the top of this sequence, with rare desiccation cracks, probably reflects a backshore lagoonal or tidal-flat environment; the few medium-grained dolarenite beds may have been deposited by rare storm washover processes. Reinson (1985) emphasized that the shoreface environment involves several complex and rapidly changing processes, subject to complicated and hybrid, cyclic transgressive and regressive events. In the present study, well-exposed areas of this facies association are limited to small, widely separated areas, one of which is illustrated in Figs. 18 and 19a. Thus the local lateral variations and three-dimensional aspects of these facies are obscured and the depositional environment is interpreted only in the general sense given above.

The types and distribution patterns of the trace fossils in general supports the suggested shoreface interpretation. Specific trace fossils tend to be grouped in similar environments, and thus trace-fossil assemblages broadly indicate depositional facies. The interpretations given here are based on the recent review articles by Frey and Pemberton (1985) and Ekdale *et al.* (1984). The limited number of ichnogenera identified in the study area are subdivided into two widely recognized ichnofacies, coincidentally both named after a representative ichnogenus present in the UMHG. The U-shaped (*Arenicolites*) and simple straight vertical burrows (*Skolithos*) characterize the *Skolithos* ichnofacies; the resting and grazing traces (*Cruziana*, *Rusophycus* and *Planolites*) typify the *Cruziana* ichnofacies. Both

ichnofacies are broadly restricted to shallow shelf environments, but slight variations in local conditions (energy, sediment type and supply, etc) can strongly effect habitats. The *Skolithos* ichnofacies is most common in shallow, high-energy sandy environments such as the foreshore and upper shoreface. The presence of *Skolithos* in dolarenites of interpreted tidal flat environment might reflect intermittent high-energy events (storm washovers for example). The *Cruziana* ichnofacies is generally associated with lower shoreface or shallow shelf sands below normal wave base (but are also found in both shallower and deeper shelf environments). Its presence within the UMHG in planar bedded sandstones of an interpreted shoreface environment is thus not unusual. The shallow-water environment generally cited for both ichnofacies explains the absence of these trace fossils from the rest of the study area. Except for the northeastern trace-fossil-bearing part of the study area, the facies associations of the upper three map units suggest that deposition was generally below storm wave base, possibly deep or middle shelf, and thus in water deeper than normally attributed to these trace fossil assemblages. Thus the areal restriction of these fossils probably reflects environmental control rather than any time significance. Given the paucity of fossil sites and the laterally limited exposure, a more detailed interpretation based on these ichnogenera is not justified. Of importance for this study (in addition to their time-stratigraphic significance) is the support their presence lends to the inner marine shelf interpretation independently suggested for the rocks in which they occur.

The few elongate and discontinuous sheets of chert-pebble conglomerate and associated trough cross-bedded sandstones that are present as broad lenses within the shoreface dolarenites constitute an overall fining-upward sequence, but with a complexly amalgamated pattern of smaller fining-upward conglomerate-sandstone beds. In terms of the interpretation of the enclosing and immediately overlying facies discussed above, these channelized conglomerates appear have been deposited in a shoreface environment. In their review of beach and shoreface gravel

deposition, Bourgeois and Leithold (1984) noted that both beach and shoreface gravels commonly show tight packing and a high percent of discoid clasts, as is observed in the PH₂ conglomerates. However, most beach conglomerates show better sorting and internal organization, and a more consistent imbrication than the UMHG chert-pebble conglomerates (*ibid.*). These sheeted conglomerates and sandstones were more likely deposited in upper to lower shoreface environments as a response to high-energy nearshore currents (mainly waves, longshore currents, and rip currents). The high variance and complex paleocurrents indicated by the gravel imbrication may reflect that several currents were involved (eg. Fig. 7, stations B,C,D,I). The overlying trough-crossbedded lithic arenites and planar-bedded dolarenites are interpreted as similar to facies in areas where the conglomerates are not present, ie. shoreface bars or tidal inlet deposits.

Evidence of how the siliciclastic gravels and sands were transported to the shoreface is not preserved. However, there is little doubt that the provenance of this detritus, principally felsic volcanic clasts, was the Mount Harper Volcanic Complex. Roots (1987) defined an upper MHVC unit (his member D) of massive silicic flows, tuffs and quartz-porphyry dykes. The flows are described as light pinkish-grey or green and cherty, with strong sericite replacement of plagioclase (*ibid.*, p. 94). These compositions and alterations are common in the chert-pebble conglomerates. This felsic unit is partly preserved in the southern part of the MHVC, but in the northern part only quartz-porphyry plugs and dykes remain, suggesting that originally overlying felsic volcanics have been eroded. There is also indirect evidence that the volcanic edifice was at least partly exposed prior to deposition of the Cambrian (CDB) carbonates. At the most southerly exposure of the MHVC, gently dipping CDB carbonates directly overlie slightly more steeply dipping volcanics of the MHVC (Fig. 3). Roots (1987) interpreted this contact as a thrust, but in light of the younger-over-older relationship, and the evidence for a major disconformity which separates the MHVC and UMHG units PH₁ and PH₂ from the overlying UMHG units and CDB in other areas, this contact more likely is an

angular unconformity caused by exposure and perhaps slight tilting of the volcanics before CDb deposition. The lack of PH₃, PH₄ or PH₅ strata at this contact is most easily explained by exposure of the volcanic edifice during at least PH₅ deposition.

Summary of upper Mount Harper group deposition

The disconformity between the lowermost two map units of the UMHG and the upper units separates strata deposited in two very different environments. Map units PH₁ and PH₂ were deposited in a restricted basin at a time of active faulting and volcanism. The best explanation for the primary control on basin formation and clastic deposition is normal faulting. In the context of the depositional models proposed for the coeval or slightly younger volcanics (MHVC) and conglomeratic LMHG, a model of offset and opposed half grabens with volcanism concentrated in the accommodation zone is proposed.

The significantly younger PH₃-PH₆ map units were deposited in an environment that was relatively stable tectonically. The generally regressive sequence is typical of marine shelf deposition. The shallowest part of the basin presently preserved is in the northeastern part of the study area. Here deposition was generally in a shoreface environment. Water depth increased to the west and southwest, as suggested by the finer grain size, thinner bedding and lack of trace fossils. The mixed dolomitic clastic and siliciclastic strata and the complex paleocurrent patterns suggest two different sediment sources. Clastic input from the north was from a dolostone source terrane, possibly exposed PH₁ and PH₂ strata. The siliciclastics were probably eroded from felsic volcanics of the MHVC, at that time exposed to the east and south. Platformal carbonates of the overlying CDb map unit appear to be separated by, at most, a minor hiatus.

Spr. alations on regional correlations and relevance to models of Windermere evolution

The internal UMHG disconformity is subtle and generally is at the base of a thick, recessive, and poorly exposed interval. The presence of a platformal marine

succession directly overlying rift-related volcanics and sedimentary rocks would not be an unusual sequence if the UMHG succession was interpreted in terms of the "rift-drift" models of passive margin evolution (Bally 1981). A minor unconformity separating the lower rift-succession and upper platformal succession is also compatible with such models. It was only with the combination of radiometric dating of MHVC volcanic rocks (Roots 1987; Roots and Parrish 1988), and the subsequent discovery of Cambrian trace fossils near the top of the UMHG, that it became apparent that at least one major intra-UMHG unconformity was likely to be present. Subsequent specific examination of all outcrops near the major map unit contacts eventually resulted in the discovery of several widely separated small exposures of brecciated and highly altered rocks below unit PH₃ (top of unit PH₂ in the north, top of MHVC in the south).

The amount of time represented by the intra-UMHG disconformity cannot be accurately estimated, but a recent review of Precambrian-Cambrian boundary age-data (Conway Morris 1988) demonstrates that, contrary to the 560-570 Ma previously accepted by many, new data support age estimates as young as 530 Ma or as old as 600 Ma (reviewed with citations in Conway Morris 1988). Relevant to Windermere studies is a recent date for the Mistaken Point Formation in Newfoundland of 565 ± 3 Ma (U-Pb from zircons), from a tuff layer within strata that contain spectacular Ediacaran fauna (Benus 1988). Ediacaran fauna have been recovered from the upper Windermere Supergroup in several areas (eg. Narbonne and Hofmann 1987; Hofmann *et al.* 1983, 1985). The Ediacaran fauna in the Canadian Cordillera, as elsewhere in the world, invariably are present at lower stratigraphic levels than the first irrefutable Cambrian trace fossils. The unusually young age suggested for this fauna in Newfoundland supports younger age estimates for the Precambrian-Cambrian boundary, but in light of the uncertainty about the age of this boundary, the time gap represented by the intra-UMHG disconformity cannot be defined more closely than about 150-200 Ma.

Such a major time gap probably does not occur, however, in most other parts

of the Windermere Assemblage. Elsewhere, Windermere successions generally are thicker than the Mount Harper group, contain evidence of several shallowing upward sequences above the basal conglomerate-rich strata and below the Cambrian (Gabrielse 1972; Eisbacher 1981, 1985, Aitken 1989), and at several localities contain Ediacaran fossils (eg. Narbonne and Hofmann 1987; Hofmann *et al.* 1983, 1985).

One succession to which evidence from the Mount Harper group may be directly applicable is the upper Tindir Group, which straddles the Alaska-Yukon border less than 50 km northwest of the most westerly UMHG outcrops examined in this study. The units defined in the Upper Tindir Group, although complexly varying in the several separate areas of upper Tindir Group exposure, show some gross similarities to the UMHG stratigraphy and include both direct and indirect evidence of a volcanic event and synsedimentary faulting. Undated basal tholeiitic volcanic rocks are geochemically similar to those of the MHVC (Roots 1987). Clastics overlying the volcanics (unit 2 of Young 1982) are in many ways similar to those of the UMHG PH₁ unit, especially in the transitional mudstone-rich interval which forms the gradational contact between PH₁ and the volcanic complex. The upper Tindir Group unit 2 is a coarsening-upward sequence (<200m to >700 m thick) which comprises abundant mudstone, less common conglomerates (volcanic and dolostone-rich) and orange-weathering diamictite with a dolomite-rich matrix (Young 1982). One difference is that the UMHG mudstones of the similar interval are greenish-grey, whereas the upper Tindir Group mudstones are generally red (although grey and green mudstones are also present) and in a few places are sufficiently iron-rich to be classified as "iron-formation" (Young 1982, p. 768). A thick unit consisting predominantly of crudely stratified diamictites occurs locally (unit 3 of Young 1982). Young (p.772) considered this unit to be allochthonous, probably roughly coeval with unit 2 deposition, and possibly related to synsedimentary faulting. These clastics are interpreted to be the product of glacial deposition by Young (1982), although he generally attributes final deposition to sediment gravity flow processes. Evidence for glaciation includes limestones which

show evidence of a dropstone origin, clasts that show multiple striae and facets clasts, and extrabasinal clasts.

The lower units of the upper Tindir Group (units 1-3 of Young 1982) are overlain by complex and laterally diverse facies of fine-grained siliciclastics and carbonate clastics, plus rare conglomerates, all somewhat similar to the deeper water facies of the PH_3 - PH_6 units of the UMHG. The upper units also contain black limestones, which are much more abundant and extensive, but appear to be similar to the black limestones (calcilutites) that in some places occur at the top of UMHG unit PH_4 . A diverse biota of microfossils has been recovered from the black limestones and siliceous shales of the uppermost Tindir Group units (Allison and Awramik 1989; Allison 1987). However, there is disagreement on whether the microfossils are restricted to Cambrian or younger rocks or could be pre-Cambrian in age (Allison and Awramik 1989). Because of the proximity and gross similarity of the UMHG to the upper Tindir group, it is suggested that the Cambrian trace fossils of the UMHG support (although tenuously) a Cambrian interpretation of the Tindir microfossils. A feature of the Tindir Group relevant to interpretation of the Mount Harper group is the presence in many places of overlying archeocyathid-bearing dolostone and limestone (Jones Ridge or Funnel Creek Limestone), the probable equivalent of the CDb unit of the Mount Harper area (from which archeocyathids have also been recovered near the base and within the study area by R. I. Thompson of the Geological Survey of Canada). A sharp contact at the base of the Alaskan carbonates was interpreted as a disconformity by Young (1982), but Allison and Awramik (1989) have argued that the regional geologic evidence is ambiguous and that the similarity of microfossils above and below the contact are indicative of little or no depositional hiatus. This supports the suggestion that the contact of the upper Harper group with unit CDb is at most a minor disconformity.

Constraints on the initial depositional age of the Windermere Tectonic Assemblage consist solely of age determinations from intrusive igneous rocks which crosscut strata that underlie the Windermere units (reviewed in Roots and Parrish

1988; Jefferson and Parrish 1989). These ages demonstrate that a widespread, slightly diachronous igneous event took place on the then western margin of North America, approximately bracketed at 730-780 Ma. However, none of these igneous bodies can be shown to cut or be coeval with the lowest Windermere strata, and thus the ages for these igneous rocks provide only maximum ages for initial Windermere deposition.

Synsedimentary tectonism during deposition of basal Windermere rocks has been well documented in the northern Canadian Cordillera (for example Eisbacher 1981, 1985; Yeo 1984; Jefferson and Parrish 1989) and to a lesser extent in British Columbia (Root 1987; Bennett and McClay in press). In addition, most of the basal Windermere strata overlie, underlie, or are interbedded with preserved volcanic rocks or contain indirect evidence of broadly coeval volcanism (see above authors plus Roots and Moore in review; Roots and Parrish 1988; Yeo 1984; Young 1982; Stewart 1972). All authors cited above have ascribed the tectonism to extensional or transtensional regimes. The inference that the volcanic rocks are coeval subaerial equivalents of the dated igneous rocks, and thus that the major period of extension and basal Windermere deposition is related to the 730-780 Ma igneous event, is directly demonstrated only in the case of the Mount Harper group. One possible exception is a value of 762 ± 44 Ma obtained by Sm - Nd isotopic analysis of volcanic rocks from the Huckleberry Formation of northeastern Washington, which overlie conglomerate-rich basal Windermere rocks equivalent to the Toby Formation of southeastern B.C. (Devlin *et al.* 1988). However, the authors have cited this value as preliminary, based on "essentially a two-point isochron" (*ibid.* p. 1907) and they suggested that open-system behaviour with respect to the Sm - Nd system had likely taken place (*ibid.* p. 1908). Additional isotopic analyses are necessary to demonstrate that this value represents the isotopic age of the volcanic rocks.

The Toby Formation of southern B.C. (with equivalents in northern U.S.A.), is a thick package of poorly sorted conglomerates and related clastics at the base of the Windermere Supergroup. Although previously interpreted as glacially derived

(Aalto 1971, Eisbacher 1981), the Toby Formation has recently been independently re-examined in detail in two areas (Root 1987, Bennett and McClay in press). Both authors rejected the possibility of a glacial interpretation, and documented abundant evidence (including synsedimentary normal faults) to show that sedimentation was the direct result of syndepositional extensional faulting in their study areas. However, in other parts of the Toby Formation, some features (lonestones, non-local clast types, striated clasts) do suggest that glacial deposition occurred within these areas (Root, 1987; Eisbacher, 1981).

Evidence also exists for glaciogenic deposition in the northern Canadian Cordillera. Eisbacher (1981, 1985) and Yeo (1981) documented glacially derived deposition in the Rapitan Group, which they considered to be the basal Windermere package in the Mackenzie and Wernecke Mountains of the western N.W.T. and eastern Yukon. They (and subsequently Jefferson and Parrish 1989) documented an abundance of syndepositional tectonism, mostly related to inferred and preserved normal faults. The most abundant and widespread evidence for glacial deposition in the Rapitan Group is provided by the diamictite-rich Shezal Formation, which in addition to displaying lonestones of convincing dropstone origin, also contains abundant striated and faceted clasts, and in one place overlies a striated pavement (Eisbacher 1981). The Shezal Formation also contains igneous and gneissic clasts of probable non-local origin (Eisbacher 1981; Yeo 1981, 1984). In most places the Shezal Formation either unconformably overlies older rocks or overlies the Sayunei Formation, the lowest unit of the Rapitan Group. The Sayunei Formation is dominated by laminated siltstone and sandstone, but in some places also contains diamictites, lonestones, striated clasts and possible "till pellets". Both Eisbacher (1985) and Yeo (1981, 1984) interpreted the Sayunei Formation as also having been deposited in a glacial deposystem. However, good evidence for faulting and fault-related sedimentation comes from the Sayunei Formation. Although a glacial influence on the Sayunei Formation depositional environment is difficult to dispute, deposition of some of the conglomerates and associated sedimentary rocks due to the

syndimentary faulting also seems likely. Yeo (1984, pp. 37,38, plates 1d-f) identified paleoscarps at the base of the Rapitan Group and at least one associated "talus breccia wedge" (*ibid*, p. 37). Jefferson and Parrish (1989, Fig. 5 and pp. 1786, 1798) also illustrated preserved syndimentary faults and adjacent "fanglomerates", up to 200 m thick, and in gradational contact with overlying Sayunei Formation.

Occurring locally below the Rapitan Group in the Mackenzie Mountains, a succession of non-glacial carbonates, evaporites, redbeds and minor conglomerates (the Coates Lake Group) deposited during a phase of extensional faulting, has been included as part of the basal Windermere by some workers (Aitken 1981, Morris and Aitken 1982, Aitken pers. com. 1990). Others have argued that the Coates Lake Group should be considered separate from the Windermere Supergroup (Young *et al.* 1982, Jefferson and Parrish 1989, Jefferson pers. com. 1990). The controversy about correlation of the Coates Lake Group is relevant to this study. The redbeds and abundant evidence for a hot arid climate during Coates Lake deposition allow tentative correlation of this succession with at least the lower Mount Harper group. However, the LMHG is associated with the major period of faulting and volcanism in the Ogilvie Mountains and, although there is some evidence for arid and temperate paleoclimate at the base of the LMHG (Mustard and Donaldson in press), the paleoclimatic evidence for most of the rift-related part of the Mount Harper group is ambiguous (redbeds and semi-arid alluvial fans in the LMHG do not unequivocally indicate a hot climate; paleoclimatic evidence for the rift-related rocks of the UMHG is lacking). Jefferson and Parrish (1989) argued that the main period of faulting and fault-related fanglomerate deposition occurred after Coates Lake Group deposition, either before or during the time of initial Rapitan Group deposition. Conglomerates form only a minor part of the Coates Lake Group, exceeding 30 m in thickness in only one place, and Jefferson and Parrish (p. 1797) suggested that Coates Lake conglomerate source areas were generally subdued. Yeo (1984, 1986) interpreted the local abundance of volcanic clasts in Rapitan Group conglomerates and the presence of rare tuffs in the Rapitan Group as evidence of a

volcanic event associated with deposition of the Rapitan Group. The evidence for major faulting and thick associated conglomerates in the Mount Harper group, the lack of evaporites (abundant in the Coates Lake Group) and the evidence for associated volcanism (absent in the Coates Lake Group, although volcanics are present unconformably beneath the Coates Lake Group), all support broad correlation with the basal Rapitan Group. However, the case for either interpretation is not conclusive on the basis of the available evidence.

Two upper Proterozoic successions in the western U.S.A are commonly correlated with the Windermere Tectonic Assemblage (Miller 1985, 1988; Christie-Blick *et al.* 1980). The Kingston Peak Formation of eastern California is a thick succession with abundant diamictites, interpreted by Miller (1985a) to be the result of glaciomarine deposition. Abrupt thickness changes and sub-Kingston Peak faults are cited by Miller as evidence of both pre- and synsedimentary tectonism, with intercalated volcanic rocks indicating that an igneous event was coeval with the sedimentation. Miller (1985a) based her glacial interpretation on the abundance of diamictites, presence of limestones, facies associations of the diamictites, and the presence of other upper Proterozoic successions interpreted to be both glaciogenic and correlative with the Kingston Peak Formation.

The uppermost diamictite-bearing member of the Kingston Peak Formation (Wildrose Member) contains clasts of non-local provenance, in addition to the above-cited evidence for glaciation. However, Miller (1985b) demonstrated that an unconformity separates this member from the rest of the Kingston Peak Formation. Walker *et al.* (1986, 1987), also recognized an unconformity within the Kingston Peak Formation in a different area, and suggested that late Precambrian folding and normal faulting affected only the lower Kingston Peak Formation and also rejected a glaciogenic interpretation for diamictites deposited during this event in their study area. Their interpretation of an intra-Kingston Peak unconformity is disputed by Troxel *et al.* (1987), and Miller (1985a) clearly did not consider the unconformity within the Kingston Peak Formation unconformity to represent either

a major time gap or a change in depositional environments.

Miller (1985a) cited a possible range for the age of the Kingston Peak as "between about 1400 and 570 m.y old" (the younger age is an estimate of the Precambrian-Cambrian boundary), although a 1200 Ma maximum age is also suggested (Miller 1985b). Thus, although similar interpretations of extensional faulting, syntectonic and synsedimentary volcanism and glaciogenic deposition suggest broad correlation with the basal Windermere (Miller 1985a, 1988), the large range of age constraints on Kingston Peak deposition remains a problem.

Other major outcrops of upper Proterozoic diamictites in the western U.S.A. are located in Utah and Idaho. Correlation of the many separate successions is complicated by their lithologic heterogeneity, but glaciogenic interpretations have been suggested for the diamictite-bearing units by several authors (reviewed in Crittenden *et al.* 1983). The Mineral Fork Formation of Utah has been studied in detail and contains convincing evidence for a glaciogenic origin, including a basal unconformity surface that displays features characteristic of glacial erosion (Christie-Blick 1983). Microfossils have been recovered from the Mineral Fork Formation; Knoll *et al.* (1981) suggested that these microfossils are Vendian (650 Ma to Precambrian-Cambrian boundary age). Age constraints other than those provided by the microfossils are given as 900 Ma to Cambrian by Christie-Blick (1983). If the microfossil data are correct, the undoubted glaciogenic Mineral Fork Formation is considerably younger than deposits related to the basal Windermere tectonic event.

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Figure captions

FIG. 1. Regional setting. (a) Distribution of upper Proterozoic to lower Cambrian Windermere Tectonic Assemblage in the northern Cordillera of North America (after Tipper *et al.* 1982). (b) Distribution of middle and upper Proterozoic to lower Cambrian strata in the Ogilvie, Wernecke and Mackenzie Mountains (after Tipper *et al.* 1981, Jefferson and Ruelle 1986, Roots 1987). (c) Simplified geology of the Coal Creek inlier, Ogilvie Mountains (modified after Roots 1987, Thompson *et al.* 1987).

FIG. 2. (a) Generalized stratigraphy of the Coal Creek inlier. Most units show significant lateral gradations in thickness and facies. (b) Schematic representation of the stratigraphic relationships in the western part of the inlier before Mesozoic-Tertiary deformation. (c) General stratigraphic relationships of the upper Mount Harper group map units and enclosing stratigraphy.

FIG. 3. Geologic map of upper Mount Harper group. The outlined area is enlarged in the top right to show the main trace fossil collection sites, as well as the more complex geology in this area of abundant minor thrust faults.

FIG. 4. Measured sections for map units PH₁ and PH₂. The locality map (top left) is a simplified version of the Figure 3 geology map. Sections are drawn with reference to a horizontal datum at the top of the Fifteenmile group for PH₂ sections, and the top of the MHVC for PH₁ sections. However, both the Fifteenmile group and MHVC upper surfaces display paleotopographic relief. The amount of separation of the sections reflects the horizontal distance between section bases, projected onto a north-trending vertical plane which intersects the base of section 17.

FIG. 5. Features of map unit PH₁. Stratigraphic top is towards the top in all photos. (a) Conglomerate-rich outcrop of unit PH₁ (about 100 m vertical extent). Beds laterally thicken and thin considerably, and some can be seen to pinch out, but most beds can be traced horizontally for hundreds of metres. (b) Poorly sorted clast-rich conglomerates which vary randomly between matrix- and clast-supported, both laterally in a single bed and vertically in a succession of beds. Bedding can be discerned due to slight size segregation of clasts and rare non-conglomeratic

interbeds, but the precise location of bed contacts in many places is not obvious. (c) Matrix-supported conglomerate displaying poor sorting and mix of dolostone clasts (light-coloured) and volcanic clasts plus a few clasts of chert (both dark grey in photo). Green noncalcareous mudstone layers less than 3 cm thick mark the top (base of photo reference letter) and bottom (bottom right corner of photo) of this conglomerate bed. Top of scale card is in centimetres. (d) Stratified bases and tops of several matrix-supported conglomerate beds show upward gradation to pebbly sandstones. Many of these stratified layers are laterally discontinuous and appear to grade laterally as well as vertically into the massive conglomerates. Total thickness of strata in photo is about 60 cm. (e) Normally graded conglomerate with a sand-rich but massive upper part. Clasts are a mix of dolostones (light grey) and volcanic rocks (dark grey). (f) Normally graded beds of pebbly dolarenite/dolowacke with laminated to thin-bedded upper parts (AB Bouma sequences). These well-graded beds do not contain volcanic detritus, and appear to be laterally continuous and separate from the poorly sorted, volcanic-clast-bearing conglomerates. Rare cross-laminated ripples at the top of these beds indicate southerly paleoflow. Scale in centimetres. (g) Lower part of a PH_1 unit (section 26 in Fig. 4). Conglomerates contain >90% volcanic clasts and are intercalated with dark green-grey, non-calcareous mudstones and sparse volcanic flows and tuffs (none of the latter are visible in this photo). Rare lonestones, such as the large cobble to the left of the 35cm-long hammer, are all vesicular volcanic rocks, most of which have pierced and deformed the surrounding strata (probably reflecting pyroclastic deposition). (h) Vesicular, chlorite-spotted, volcanic pebble lonestone (pyroclastic bomb) in green-grey non-calcareous mudstone, from the gradational succession between the MHVC and the overlying map unit PH_1 . The two photos are of mutually perpendicular polished surfaces through the cobble. In both, deformation indicative of an impact origin is apparent, including rucking (arrowed), where the mudstone has been deformed by upward folding against the side of the clasts (cf. Thomas and Connell 1985). Small normal faults below and adjacent to the lonestone do not cut laminae

above the lonestone, suggesting that these also are synsedimentary features. A second lonestone which also displays impact deformation structures at its margins is visible in the upper part of the left photo. Scale in centimetres.

FIG. 6. Maximum clast size versus bed thickness trend for map unit PH_1 conglomerates, showing least-square regression line. N = number of measurements; BTh = bed thickness; MCS = maximum clast size; R = correlation coefficient.

FIG. 7. UMHG paleocurrents, with summary rose diagrams for the map units at the upper left. Individual rose diagrams are patterned as for the summary roses. The geologic contacts of the UMHG map units are outlined, but not patterned (see Fig. 3 for the detailed geology). Paleocurrent measurement sites are indicated on the map by a dot, an arrow showing the vector mean for that site, and a reference letter corresponding to the appropriate current rose. Where possible, current roses are shown in approximately the same spatial grouping as their distribution on the map. Circular standard deviation was calculated by means of the method of Krause and Geijer (1987). Roses were constructed using a non-linear scale as suggested by Nemec (1988). All measurements have been corrected for the effects of bedding tilt.

FIG. 8. Schematic diagrams illustrating depositional models for units PH_1 and PH_2 .

(a) Unit PH_1 deposition coincided with a late stage of MHVC volcanism.

Synvolcanic faults (only one shown for simplicity) formed fault scarps, initiating generally northward deposition in debris aprons. Early stages of normal faulting north of the volcanic complex formed the northern margin of the UMHG half graben (the faults in the volcanic complex are interpreted as antithetic faults in the overall half graben basin). Detritus derived from uplifted Fifteenmile group dolostones was transported southward, intermixing with the volcanic detritus of the PH_1 debris aprons. (b) Most deposition of unit PH_2 was post-volcanic and controlled by normal faulting at the north end of an east-trending half graben. Subaqueous debris aprons and radial fans prograded southward, both intermixing and covering PH_1 detritus rich in volcanic clasts. (c) The ca. 750 Ma Harper group basins formed as offset half grabens with deposition of the lower Mount Harper group in a slightly

older, north-facing half graben. Volcanism was concentrated at the accommodation zone between opposed half grabens. This model of propagating continental rifting closely parallels observed basin styles in the western arm of the East African rift system (reviewed by Ebinger 1989).

FIG. 9. Stratigraphic section through unit PH₂ megasequences (section 19 of Fig. 4), measured on the exposure shown between triangles on the upper photo (northeast to the right in photo). The lowermost coarsening upward megasequence (85 metres thick) is shown in greater detail, with facies divisions and interpretations (discussed in text). The outcrop of this megasequence is shown in the lower photo (oriented with east to the left). Symbols are the same as used in Figure 4.

FIG. 10. Mudstone-sandstone facies of unit PH₂. Stratigraphic top is toward the top in all photos. (a) Persistent strata of laminated to thin-bedded dololutes and dolarenites. (b) Convolutely deformed layer of laminated dolarenite and dololuite with south-dipping cross-laminae at the bottom of the layer. Scale in centimetres. (c) Photomicrograph of AE turbidite showing normal-graded basal fine-grained dolarenite (with abrupt and loaded lower contact on dololuite) grading upward to dolowacke and dolosiltite. About 5 mm of strata visible in photo. (d) Photomicrograph of BE turbidite showing internally laminated very fine-grained dolarenite which grades upward to silty dolowacke. About 7 mm of strata visible in photo. (e) South-dipping cross-lamina in ripples of BCE turbidites. Pen is about 14 cm long. (f) Normally graded dolarenite with granule base and laminated top (AB turbidite). Diameter of lens cap is about 6 cm. (g) Laminated dolarenites with rare granules at base and a pebble lonestone in top right of vertical section. White segment of measuring rod is 10 cm long.

FIG. 11. Sandstone-conglomerate facies of unit PH₂. Stratigraphic top towards top in all photos. (a) Interbedded resistant conglomerates and recessive sandstones. Jacob's Staff is 1.5 m long. (b) Clast-rich matrix-supported conglomerate. Staff is divided into 10 cm segments. (c) Normally graded clast-supported conglomerate showing slight erosion of underlying dolarenite. Staff is divided into 10 cm

segments. (d) Deformed dolarenite laminae and thin beds are common between conglomerate beds and probably reflect sudden loading by the gravel sediment gravity flows. Pen is about 14 cm long. (e) Normally graded small pebble and granule conglomerate which grade to laminated dolarenite. A cobble lonestone is present at the top right of the photo. Scale (top right corner) is in centimetres. (f) Lonestones commonly occur at about the same stratigraphic level and in some places laterally are at the same level as matrix-supported conglomerates. (g) Lonestone (6 cm diameter) in dolarenite beds. Piercement of beds appears to be related to compaction, and shows no evidence of the impact deformation structures common in glacial dropstones (cf. Thomas and Connell 1985). Increased abundance of granule clasts on left (south) side of the lonestone and onlap of well-sorted dolarenite on the north side of the lonestone most likely are a result of obstacle-controlled scour-and-fill deposition (here indicating southerly paleoflow).

FIG. 12. Conglomerate-sandstone facies of unit PH₂. Stratigraphic top is towards top in all photos. (a) Overlapping lenses of conglomerate, each about 1-1.5 metres in maximum thickness, and extending laterally for several hundred metres. In many exposures, bed amalgamation has resulted in the appearance of laterally continuous conglomerate sheets tens of metres thick. (b) Several conglomerate beds; the lowest thins laterally over a short distance and fills a concave-upward depression on the underlying matrix-supported conglomerate (rubble-covered in this photo). Jacob's Staff (lower left centre of photo) is 1.5 m in long.

(c) Normally graded beds of cobble-pebble conglomerate. A thin pebbly sandstone layer caps the central conglomerate bed, just above the 35 cm long hammer (handle parallel to bedding), defining the contact with an overlying conglomerate bed (inversely graded, although this is not easily seen in the photo). (d) Boulder-rich conglomerate beds commonly are not graded, or show only crude grading, making distinction of bed contacts difficult. In this photo a crude inversely graded base is apparent between the large boulder and the top of the Jacob's Staff (subdivided into 10 cm segments). The largest boulders in these beds tend to be concentrated in the

upper or central parts of the beds.

FIG. 13. Disconformity breccia at the top of unit PH₂. (a) The original rock type of this breccia (located in Fig. 4, section 22) has been obscured by intense dolomitization, brecciation and multiple silicification events. White and dark grey chert (and rare dolomite) veinlets, fracture-fills and vug-fills occur in complex cross-cutting relationships, attesting to a complex history of exposure and alteration of the top of unit PH₂. (b) Photomicrograph of vug fill in the breccia, showing radiating fibrous chalcedony at margins and central breccia of previously formed quartz and chert cements and void fills. Maximum dimension of chalcedony clast right of centre is 1 mm.

FIG. 14. Maximum clast size versus bed thickness trend for conglomerates of map unit PH₂. A best-fit regression line is fitted to the data, but only a poor correlation of the clast size and bedding thickness is apparent ($R = 0.32$). N = number of measurements; BTh = bed thickness; MCS = maximum clast size; R = correlation coefficient.

FIG. 15. Map units PH₃, PH₄ and PH₅. Stratigraphic top is toward top in photos unless otherwise indicated. (a) Looking west at exposure of uppermost UMHG units where they disconformably overlie volcanic rocks of the MHVC (section 16 of Fig. 16 was measured on the ridge containing the arrowed PH₄ lens. Unit PH₃ is poorly exposed in the grassy lower slopes; Unit PH₄ is visible as light-coloured lenses in central parts of the slopes, overlain by dark and slightly more recessive exposures of unit PH₅. Light grey dolostones of Paleozoic CDb unit form a distinctive resistant cap to the UMHG strata. (b) Looking northwest at slope containing all UMHG units (section 25 of Figs. 4 and 16). Volcanic rocks of MHVC are exposed in creek below the PH₁ conglomerates in this photo; Unit PH₂ is thin in this slope, and only the resistant conglomerate beds are visible in photo. Unit PH₃ occurs as abundant float and rare outcrop in the central grassy slopes, with an apparent thickness of over 900 metres, probably reflecting repetition by minor thrusts (complex folding and brittle deformation is evident in creek exposures west of the section). Unit PH₄ constitutes

thin, discontinuous, light-coloured dolarenite lenses. Unit PH₅ gradationally overlies unit PH₄ (or PH₃ where the former is absent); trace fossils are located in the top 50 m of this unit, below the resistant light grey CDb dolostone visible in top right corner of photo. (c) Hummocky cross stratification showing low relief domes (arrowed) repeated laterally in a succession dominated by horizontally bedded, very fine-grained dolarenite. Low-angle truncation visible in dolarenites (above star in upper right of photo) is part of a larger scale HCS bedform (swaley bedding?). Jacob's Staff is 1.5 m long. (d) HCS bedset (example arrowed at left in c), showing non-erosive base and low-relief dome which gives way gradationally upward to horizontal bedding. This type of HCS is termed a "PHF" form according to the sequence terminology of Walker *et al.* (1982). Jacob's Staff is subdivided into 10 cm segments. (e) Flat-pebble conglomerate within unit PH₄ dolarenite, in which dolosiltite intraclasts display both a well-developed imbrication (indicating southerly paleoflow) and reverse grading. (f) Intercalated resistant, very fine-grained dolarenite thin beds, and recessive dolosiltite and dololutite laminae and beds. Several dolarenite beds display flutes on their bases that indicate southerly paleoflow. Most are massive and show subtle normal grading, and some display wavy to rippled upper surfaces (the ripples also indicate southerly paleoflow). Stratigraphic tops is to right in photo. Lower part of scale card in cm.

FIG. 16. Measured sections through map units PH₃, PH₄, and PH₅. The locality map in lower right is a simplified version of Figure 3 geology map. Sections are drawn with horizontal datum taken as base of the overlying CDb unit. Amount of separation of sections reflects horizontal distance between section bases projected into a north-trending vertical plane which intersects the base of section 26. However, section 34 is from area about 9 km west of area where other sections were measured.

FIG. 17. Features of unit PH₅. Stratigraphic top towards top in all photos.

(a) Laminated to thin-bedded PH₅ sandstones and siltstones. All sandstones are very fine grained, except the light-coloured lithic wacke above the deformed layer, which

is a fine to medium grained sandstone. Flame structures are deformed toward the north, suggesting a northerly paleoslope and implying northerly paleoflow for the overlying wacke. (b) Chert-pebble conglomerates of unit PH₅. Larger, generally tabular chert pebbles grade upward to chert-rich granules and small pebbles. The tabular clasts show poor imbrication or are sub-parallel to the bedding. (c) Photomicrograph of PH₅ sandstones (matrix to chert-pebble conglomerate) showing abundance of clasts containing sericite floating in a chert groundmass (probably silicified volcanics). Rare potassium feldspar clast visible near right side of photo is about 0.5 mm in apparent length.

FIG. 18. Measured section through trace-fossil-bearing strata in northeastern part of study area (section 33 of Fig. 16). Lowest occurrence of each ichnogenus is shown; most are abundant above their lowest occurrence in this section, except that *Planolites*, *Cruziana* and *Rusophycus* do not occur in the upper 10 metres, where the vertical burrows are present. Throughout study area, the first occurrence of *Planolites* is generally at a lower stratigraphic level than the other traces, but *Cruziana* and *Rusophycus* tend to occur within a few metres of each other, and neither is consistently lower in first occurrence. The distinction between units PH₄ and PH₅ in these northeastern areas is based on lowest occurrence of >50% siliciclastic sandstone, but in most places the dolarenites, siliciclastic sandstones and chert-pebble conglomerates are intercalated within a few metres above the last PH₃ mudstones and dolarenites (which also grade subtly upward to the two top units).

FIG. 19. Features from the trace-fossil-bearing section of Figure 18. All outcrop photos have stratigraphic tops towards tops of the photos. Unless indicated, the trace fossil photos are convex hyporelief views. (a) Outcrop (about 180 metres thick) illustrated by the stratigraphic section shown in Figure 18. Dark recessive mudstones and sandstones in lower part of gully are the upper part of unit PH₃, grading over a short interval to more resistant sandstones of units PH₄ and PH₅. The light-grey cliff at top is unit CD_b, except for the lowest outcrops, partly scree-covered, which are the uppermost siltstones, mudstones and sandstones of the

UMHG, containing vertical burrows, rare stromatolites, cryptalgal laminates and desiccation cracks. (b) Interbedded dolarenites and siliciclastic sandstones of PH₄-PH₅ (corresponding to the 70-105 m interval of Fig. 18).

(c) Resistant siliciclastic sandstones interbedded with slightly recessive dolarenites. The trace-fossils are most common on bases of the siliciclastics. The lowest resistant, slightly concave-based and laterally discontinuous bed is the trough-crossbedded lithic arenite, about 60 cm thick, shown in the following photo. (d) Trough cross-bed cosets in lithic arenite, probably reflecting deposition as shoreface bars.

(e) Abundant overlapping *Cruziana* trace fossils, with a single *Rusophycus* trace in lower centre of the photo. (f) Well-preserved partial *Rusophycus* trace illustrating scratch marks on lobes. (g) *Rusophycus* trace fossils which are more compact than the *Rusophycus* shown in (f), and show lobe separation. (h) View of face

perpendicular to bedding, containing the simple vertical burrows *Skolithos*; collected from outcrop about 10 m below unit CDb and about 200 m southwest of section 33.

FIG. 20. Schematic illustration of depositional models envisioned for upper units of UMHG. The basin is shown at a late stage of PH₄ deposition, with PH₅ siliciclastics being introduced from an exposed part of the MHVC. Paleocurrent indicators suggest that the dolarenites and dolosiltites derived from the north, possibly from exposed parts of the disconformably underlying PH₂ and/or Fifteenmile group dolostones. Both clast compositions and paleocurrent indicators of the PH₅ siliciclastic rocks suggest derivation from the MHVC, exposed to east and south in the eastern part of study area. The depositional environment is envisioned as a marine shelf, with shoreface and shallow shelf deposition in the northeastern part of the study area, and middle to outer shelf deposition to the southwest. Post-Devonian faulting to the south, and poor exposure to the west, limit speculation on nature of the basin in these directions, but the presence of correlative basinal mudstones and sandstones of the Hyland Group to the south, and upper Tindir Group sedimentary rocks to the west, suggests that the UMHG basin deepened to the south (and west?).

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5

Figure 6.

Figure 7.

Figure 8.

3

Figure 10

Figure 11

FIGURE 12

FIGURE 13

Figure 14

Figure 16.

Figure 17

Figure 18.

Figure 20.

CHAPTER 5

Summary

In the Ogilvie Mountains, west-central Yukon, the upper Proterozoic to lower Cambrian upper Mount Harper group (informal name) contains strata equivalent to both basal Windermere Supergroup and lower Cambrian rocks of other areas in the North American Cordillera. Strata of the upper Mount Harper group are directly time-constrained: the base by a ca. 750 Ma U-Pb age from volcanic rocks which conformably underlie and intertongue with the sedimentary rocks, and upper units by the presence of lower Cambrian trace fossils.

Breccias at the base of the lower Mount Harper group are of two different, but in part coeval, origins. A normal fault that was active during late Proterozoic time forms the southern boundary of the lower Mount Harper group, and is genetically related to a wedge of paleotalus breccia that thins rapidly northward from the fault. Another breccia layer is preserved on a disconformity surface that separates lower Mount Harper group strata from a thick succession of underlying dolostones (Fifteenmile group). This disconformity breccia contains silcretes and calcretes that provide evidence of several episodes of subaerial exposure. Rare debris flows are interbedded with this breccia, indicating initial deposition of sediments of the lower Mount Harper group coincided with the final episodes of silcretization and calcretization. The presence and types of silcretes and calcretes suggest that the climate at the onset of Windermere deposition in this area was temperate to equatorial, and probably semi-arid to arid.

Distinctive breccias interpreted as paleokarst are coincident with, although physically separate from, the fault talus breccia. Extensional faulting was common during initial Windermere deposition, and breccias in other basal Windermere strata have generally been interpreted to be the products of this faulting. However, the coeval presence of fault talus breccia and paleokarst breccia documented in this study allows that some breccias previously interpreted as fault-induced may be the products of subaerial weathering. The discrimination of fault-talus breccia from subaerial exposure breccias requires a combination of detailed field study and

petrographic examination. Faulting tends to coincide with subaerial weathering in many settings, regardless of age. Failure to recognize the co-existence of breccia types can lead to misinterpretations, or to interpretations which fail to fully assess all paleoclimatic and paleotectonic indicators.

A syndimentary normal fault forms the southern margin of an asymmetric, east-trending half-graben basin which contains the lower Mount Harper group. All preserved clastic detritus appears to have been derived from the uplifted southern margin (footwall scarp); evidence for deposition from the hanging wall margin is lacking. The basin fill consists of fault-proximal talus breccia and up to 1100 m of conglomerates, most of which were deposited from cohesive debris flows in coalescing alluvial fans. Intermediate and distal facies include mid-to-lower fan conglomerates and sandstones deposited by sheetfloods, distal debris flows and braided channel streamflows. A basin-scale coarsening-upward sequence in fault-distal areas records the change from lacustrine redbeds to fan-delta and lower alluvial fan sandstones and conglomerates. This reflects overall northward progradation of facies during most of the time of basin evolution, but an upper fining-upward component to the uppermost part of the basin-scale sequence preserved in intermediate and distal facies suggests onlap during late stages of basin fill. Clastic deposition appears to have ended soon after volcanism was initiated, resulting in the overlying Mount Harper Volcanic Complex (ca. 750 Ma).

The LMHG half-graben basin was formed, and sedimentation controlled, by the southern margin faulting. Comparison with strike-slip basin depositional patterns indicates significant differences, suggesting that faulting was predominantly dip-slip. Syndimentary fault movements and minor back-stepping of the fault provided the control for development of vertically stacked coarsening-upward sequences 50 to 150 m thick. Volcanism conformably postdated LMHG sedimentation, but northward-derived coarse clastic rocks (UMHG) intertongue with the volcanic rocks, and are not directly related to LMHG deposition. Synvolcanic

faults formed fault scarps in the volcanic complex, initiating generally northward deposition in debris aprons (PH₁). Early stages of normal faulting north of the volcanic complex formed the northern margin of the UMHG half graben, and shed detritus derived from uplifted Fifteenmile group dolostones southward, intermixing with volcanic detritus of the debris aprons. Most deposition was post-volcanic, controlled by inferred normal faulting at the north end of an east-trending south-facing half graben. Subaqueous debris aprons and radial fans (PH₂) prograded southward, both intermixing and covering PH₁ volcanic-rich detritus. Evidence of glacial deposition is lacking, although the presence of non-glacial, poorly sorted conglomerates (diamictites), lonestones, and rare pyroclasts could be mistaken for such evidence.

Given the evidence for normal faulting, half graben sedimentation, rift-related volcanism and synvolcanic faulting, deposition of units PH₁ and PH₂ is interpreted to have occurred in a half graben basin slightly younger than the LMHG half graben and with a footwall scarp opposed, but offset to the west, from footwall faults of the LMHG. Such a pattern, with opposed listric normal faults, is the geometry expected for propagating continental rifts, and can be observed in the west arm of the East African rift system (Bosworth 1985; Ebinger 1989). The fact that basal conglomeratic deposits of the UMHG sub-basin are slightly younger than the LMHG is consistent with this model. The concentration of volcanic rocks at the overlap zone of these opposed basins is also appropriate to a continental rift setting, and may represent the locus of a transfer fault system or accommodation zone between the two sub-basins, a common feature of African rifts (cf. Ebinger, 1989, Fig. 3). The accommodation zone between opposed sub-basins in East Africa contains abundant but localized faults which serve as conduits for magma eruption (*ibid.*).

The rift-related clastics and volcanics of the lower Mount Harper group, Mount Harper Volcanic Complex, and the lower two units (PH₁ and PH₂) of the upper Mount Harper group, are separated by a subtle disconformity from an overlying

shallow-water succession (PH₃-PH₅) of marine-shelf mudstones, sandstones and rare conglomerates. These upper units contain early Cambrian trace fossils in the uppermost 50 m of the shallow shelf facies. The intra-UMHG disconformity represents a major time gap (> 150 Ma, possibly > 200 Ma) indicating the lack of a direct temporal connection between the rift-related deposition and the immediately overlying sedimentary rocks in this study area. The significantly younger PH₃-PH₅ map units were deposited in an environment that tectonically was relatively stable. The generally regressive sequence is typical of marine shelf deposition. The shallowest preserved part of the basin is in the northeastern part of the study area, where deposition was generally in a shoreface environment. Water depth increased to the west and southwest, as suggested by the finer grain size, thinner bedding and lack of trace fossils in that direction. The mixed doloclastic and siliciclastic strata, and the complex paleocurrent patterns, suggest two major sediment sources. Clastic input from the north was from a dolostone source terrane, possibly exposed PH₁ and PH₂ strata. The siliciclastics probably were eroded from felsic volcanics of the MHVC, exposed to the east and south. Marine shelf carbonates of the overlying CDb map unit appear to be separated from the UMHG by, at most, a minor hiatus.

Combined

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APPENDICES

APPENDIX I

DETAILED DESCRIPTIONS

OF

MEASURED SECTIONS

Thirty stratigraphic sections were measured for this study. These comprise 14 from the lower Mount Harper group and 16 from the upper Mount Harper group. A summary of section data and locations is given in Tables A1-3 and A1-4. Figures A1-1 and A1-2 show the locations of the sections. All sections were measured using a Jacob's staff. The section graphic logs in this appendix have a 1 cm = 10 m vertical scale, or a 1 cm = 20 m scale for some of the longer sections (LMHG sections 10, 12, 27; UMHG sections 17, 25, 26). The exception is section 33 of the UMHG, shown at a scale of 1 cm = 5 m to permit the accurate location of the lowest occurrence of trace fossil ichnogenera.

The lithofacies code used during mapping and section measurements is provided in Table A1-1. The summary descriptions of lithofacies give the codes of all the lithofacies occurring in the interval in order of abundance. For example, **Gcmgr Gcmgn** indicates the first lithofacies is the more common type present. Codes in parentheses are used to indicate rare (<5%) occurrences of a lithofacies. A hyphen (*e.g.* **Gcm-Gcs**) is used to indicate that a lithofacies does not clearly fit either code. Table A1-2 presents lithologic and sedimentary structure symbols for the graphic logs.

Conglomerate-bearing graphic logs of the lower Mount Harper group include a graphic representation of maximum clast size data to the left of the lithology logs. Collection methods and tabulation of this data is given in Appendix II. Paleocurrent data summarized as current roses on the graphic logs are detailed in Appendix III.

Lower Mount Harper group conglomerate and interbedded sandstone descriptions generally do not include colours. Conglomerates often appear light to medium grey at a distance, reflecting the weathering colour of the predominantly carbonate clasts. The matrix of the conglomerates and sandstones associated with the conglomerates are consistently greyish orange to moderate yellowish brown weathering with a pale yellowish orange (rarely yellowish brown or grey brown) fresh surface. Mudstones and fine-grained sandstones of map unit PHc are consistently moderate red weathering, dusky to dark red fresh ("redbeds"). Colour

terms are from the GSA colour chart (GSA Rock-Color Chart Committee, 1986). 215
 Exceptions to these colours are given in the descriptions.

Collected lithology samples are listed in the right columns of the description pages. Samples from measured sections were labelled with consecutive numbers starting at 1 for the lowest sample in a section. Each of the actual samples are also labelled with the section number and MS (measured section), but only the last number is given in the sample column. For example, the lowest sample in measured section 10 is labelled MS-10-1. The letters TS appear below the number if a thin section was made for the sample.

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Gravel, (G):

Gm matrix supported
 Gc clast supported
 G-m massive (<10% stratified)
 G-s stratified
 G--gn normally graded
 G--gr reverse graded
 G--grgn reverse graded base
 normally graded top
 G--bx gravel-sized breccia

Sandstone, (S):

pS pebbly (>10% gravel)
 Sm massive
 Sh horizontal lamination
 Sr rippled
 St trough crossbedded
 Sp planar crossbedded
 S-gn normally graded
 S-gr reverse graded

Fine-grained, (F): Mudstone, minor very fine-grained sandstone

Fl laminated
 Fm massive (<10% laminations)

**TABLE A1-1. Lithofacies code used for mapping and section measurement
 (modified from Miall, 1978, and Rust, 1978).**

	Conglomerate (dolomitic) clast-supported		Desiccation cracks
	Conglomerate (dolomitic) matrix-supported		Clast imbrication
	Sandstone (dolomitic)		Asymmetric ripples
	Siltstone (dolomitic)		Planar Crossbedding
	Mudstone (dolomitic)		Trough Crossbedding
	Breccia (dolomitic)		Flute Casts
	Extrusive Volcanic Rock		Stromatolitic
	Dyke		Hummocky Cross-stratification
	Dolostone (crystalline)		cherty or silicified
	Limestone mudstone		carbonate concretions
	Covered interval		synsedimentary folding
			lonestones
			trace fossil locality

Grain Size Scale

Paleocurrent Roses

TABLE A1-2. Legend for measured sections

MEASURED SECTION	BASE OF SECTION		TOTAL THICKNESS (metres)	MAP UNIT THICKNESS (metres)				
	LATITUDE	LONGITUDE		PHa	PHb	PHc	PHd	PHe
6	64 39' 49"N	139 47' 02"W	132	-	132	-	-	-
7	64 39' 41"N	139 46' 46"W	134	-	134	-	-	-
8	64 39' 40"N	139 46' 31"W	172	-	172	-	-	-
9	64 39' 37"N	139 46' 08"W	196	-	196	-	-	-
10	64 39' 21"N	139 46' 16"W	775	-	775	-	-	-
11	64 39' 18"N	139 46' 08"W	546	-	546	-	-	-
12	64 39' 37"N	139 44' 30"W	406	-	406	-	-	-
13	64 34' 15"N	139 45' 34"W	415	-	415	-	-	-
14	64 40' 57"N	139 51' 35"W	251	48	180	-	23	-
18	64 38' 55"N	139 45' 00"W	337	288	49	-	-	-
20	64 41' 08"N	139 07' 30"W	612	-	122	288	202	-
21	64 39' 47"N	139 23' 48"W	421	-	409	12	-	-
27	64 41' 00"N	139 12' 58"W	445	-	92	248	70	35
28	64 41' 35"N	139 03' 10"W	140	-	38	46	8	48
30	64 42' 53"N	139 59' 07"W	12	-	12	-	-	-

TABLE A1-3. Summary of lower Mount Harper group measured section locations and thicknesses.

MEASURED SECTION	BASE OF SECTION		TOTAL THICKNESS (metres)	MAP UNIT THICKNESS (metres)					
	LATITUDE	LONGITUDE		PH1	PH2	PH3	PH4	PH5a	PH5b
15	64 40' 03"N	140 07' 00"W	313	-	-	105	69	-	139
16	64 41' 19"N	140 06' 26"W	270	-	-	>100	140	-	130
17	64 44' 30"N	140 02' 11"W	729	200	-	229	229	-	-
19A	64 50' 20"N	140 04' 35"W	235	-	235	-	-	-	-
19B	64 50' 20"N	140 04' 40"W	296	-	296	-	-	-	-
22	64 53' 04"N	140 09' 26"W	590	-	305	-	-	78	40
23	64 48' 42"N	140 02' 30"W	280	90	190	-	-	-	-
24	64 46' 54"N	140 04' 11"W	132	-	-	-	82	30	20
25	64 46' 50"N	140 08' 15"W	1395	145	140	910	68	36	96
26	64 45' 16"N	140 09' 26"W	1312	132	363	210	43	-	564
29	64 43' 38"N	140 00' 30"W	123	123	-	-	-	-	-
31	64 42' 30"N	140 00' 00"W	80	80	-	-	-	-	-
32	64 41' 16"N	139 58' 32"W	83	83	-	-	-	-	-
33	64 47' 43"N	140 07' 53"W	115	-	-	>150	15	-	33
34	64 45' 32"N	140 17' 45"W	323	-	-	-	22	-	>301

TABLE A1-4. Summary of upper Mount Harper group measured section locations and thicknesses.

Figure A1-2.

LEGEND - MEASURED SECTIONS

	Conglomerate, clast-sup
	Conglomerate, matrix-sup
	Sandstone
	Siltstone
	Mudstone
	Breccia
	Extrusive Volcanic Rock
	Dyke
	Dolostone (crystalline)
	Limestone mudstone
	Covered interval
	Desiccation cracks
	Clast imbrication
	Asymmetric ripples
	Planar Crossbedding
	Trough Crossbedding
	Flute Casts
	Stromatolitic
	HCS Hummocky Cross-strat
	cherty or silicified
	carbonate concretions
	syndimentary folding
	lonestones
	trace fossil locality

Paleocurrent Roses

LOWER

MOUNT

HARPER

GROUP

SECTIONS

MS-6

1 2 3

Metres
above
base

MS-6 DESCRIPTION

SAM
PLE

Section located near the west end of low WNW trending ridge which parallels main LHG conglomerate ridge to south (see Figure A2-1). Lat. 64°39'49"N, Long. 139°47'02"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map 116B/12 (Mount Harper). Best seen in RCAF airphoto A13135-146.

Total Thickness = 132 m

- 132 Top of ridge - no outcrop in slope dipping to southwest
- 80-132 Gcmgn, Gcmgrgn, Gcm as below but fair gn top 20-40 cm defines 1.5-2m beds in top 30m of section, no obvious gr bases in most, poor gr in basal 20 cm where present, <20% beds not graded, appear thick (up to 5 m) but subtle cobble-boulder rich zones suggest multiple beds with cryptic contacts; generally 80-90% clasts (rare 60-70%) in poorly sorted, massive med- to cse-grained Sm matrix; clasts >50% pebbles, 20-30% cobbles, 20-30% boulders; generally high sphericity, sub-ang to sub-rd; < 30% tabular clasts sub// bedding or poor imbrication; beds appear to thin slightly laterally, some die out over 30-50m, appear to be overlapping, non-erosive sheets 30->100m wide; clast lithologies: all PFu; lam (algal) dolostones > massive med crystalline dolostone > black chert/dolostone > white chert
- 56-80 Gcmgrgn, Gcmgn, Gcmgr as at 40m but now 80-90% gravel and >50% cobbles-boulders; boulders rarely >1m, many 30-60cm dia, beds generally 80-150 cm thick with gr bases and/or gn tops <20 cm thick and ungraded cobble-boulder rich core; one possible 5m bed; contacts non-erosive, straight to slightly wavy (loaded?); projecting clasts common; beds appear laterally continuous (sheet-like), but contacts are commonly vague, welded; 30-40% tabular clasts sub// beds or poorly imbricated (S dip) bedding: 113/42 SE, ave of 2
- 52-56 covered
- 43-52 Gcm as below but poorly exposed; contacts not obvious but very poor clast size differences suggest about 1m thick beds.
- 42.5-43 pSt coarse-grained, <5% pebbles; 30cm thick, lenticular, erosive, convex-based, flat-topped wedge; cosets of overlapping trough x-beds <10cm thick, <30cm wide bedding: 110/46 SW, ave of 3
- 30-42.5 Gcm(grgn) 70-90% gran-cob>bldr in med- cse-grained Sm matrix; very poorly sorted; clasts generally subang-subrd, equant, rare tabular clasts sub// beds or poorly imbricated (S dip), rare poor gr bases, comfair gn tops, boulder-cobble rich core (>60% of bed), beds about 70-130 cm thick with indistinct welded contacts; laterally continuous(?); clast lithologies: PFu algal laminated dolostones > massive dolostones > cherts (some PHa?)
- 14-24 Gmm recessive; 30-50% pebble-cobble clasts in a med-cse Sm matrix; very poor sorting, no contacts (all 1 bed?); all roundness and sphericity types
- 2-4 Gmm recessive, badly weathered exposure; appears same as outcrop above
- 0 covered, unconformity surface not exposed
- 27 to -50 Dolostone (PFu): slightly resistant, light gray weathering, medium gray finely laminated mudstone; lams slightly wavy, parallel, continuous; probably algal, top map unit of PFu; no regolith or alteration bedding: 112/47 SW; ave of 7

MS-7

Metres
above
base

MS-7 DESCRIPTION

SAM
PLE

Section located near the west end of low WNW trending ridge which parallels main LHG conglomerate ridge to south, but east of MS-6 (see Figure A2-1). Lat. 64°39'41"N, Long. 139°41'46"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map 116B/12 (mount Harper). Best seen in RCAF airphoto A13135-146.

Total Thickness = 134 m

134 Top of ridge - no outcrop on slope dipping to southwest

100-134 Gcm(gn) 70-90% clasts in poorly sorted med- to very cse-grained Sm matrix but one 1m bed has abundant voids between clasts (open framework); clasts poorly sorted, pebbles = cobbles, <20% small boulders; generally no grading, rare gn top 10-20cm; very poor sorting; beds about 1m thick, separated by matrix-rich (20-30%) pebbly layers 10-30cm thick which are massive, poorly sorted, not graded, distinct from Gcm beds; contacts non-erosive, slight loading of Gcm into pebbly layers; clasts: high sphericity, subang to subrd, <30% tabular clasts sub// bedding or poor imbrication in basal 20cm; clast types: all PFu, 60-70% light gray massive crystalline dolostone, 20-30% interbedded white or blk chert/dolostone, chert/dolostone bx, blk or white chert

bedding: 139/51 SW ave. of 8 in top 20m

90-100 Gcm(gr) as above but rare gr basal 10-20 cm and separate pebbly horizons now rare;
bedding: 142/50 SW ave. of 2

75-90 Gcm coarser than below or above; boulder-rich (30-40%; 50-60% at 80-85m), non-graded, very poor sorting, no bed contacts but boulder concentrations suggest beds about 1.5 to 2.5 m thick; clast lithologies: all PFu; chert/dolst bx > mass/lam dolst > white or blk chert

37.5-90 Gcmgrgn Gcmgr Gcmgn Gcm 80-90% peb-bldr clasts in poorly sorted cse-grained Sm matrix; very poor sorting but cob/bldr rich central layers common with <20 cm thick poor gr base, and/or gn tops which define 40cm - 3m thick beds (most 70-130cm thick), contacts slightly loaded but non-erosive, projecting clasts common; clasts mod-high sphericity, sub-ang to sub-rd, clast lithologies: all PFu, blk chert/dolst bx > blk chert-altered dolst > mass dolst, gray lam dolst, blk or white chert

10-37.5 Gmm(bx?) <60% granule to bldr clasts in fine- cse-grained Sm matrix, very poor sorting; intense alteration/replacement by white crystalline dolomite appears to be transported rubble breccia of PFu clasts but intense alteration has destroyed much of original textures, clast shapes etc.

6-10 Gcmgr poor exposure; 80-90% peb/ccb in cse-grained Sm matrix; poorly sorted, no fabric, basal 10-15 cm poor gr; no internal contacts (1 bed?); clasts sub-ang to sub-rd

0-6 Gcs-pSh Fl overlapping convex-based erosive sequences 1-1.5 m thick; Gcs in 10-30cm thick beds, > 70% granule to small pebble clasts (< 3cm) in cse-grained faintly lam Sh matrix; mod sorted, peb > 20% tabular, sub// beds, no imbric; Gcs grades to med- to cse-grained pSh with <20% small pebbles conc at base; pSh 1-4 cm thick; slight erosion of pSh by Gcs above; rare discont calc Fl in 3-10 cm thick layers, <10m laterally, eroded by Gcs-pSh;

bedding: 098/54 SW, ave of 4

0 to -25 Dolostone (PFu): slightly resistant, light gray weathering, medium gray, finely laminated algal mudstone (60% of o/c); lams slightly wavy, parallel, continuous; 10-20% rip-up breccia of algal lams; domal stromatolites (LLH) common in on 40 cm bed, but poor exposure; top stromatolitic unit of PFu
bedding: 111/50 SW, ave of 4

0 unconformity surface: Fair exposure laterally shows irregular paleorelief with broad shallow trough at MS-7. Slope rises sharply to west (33m measured relief over 50m laterally), then dips to same level by MS-6 base (120m west). Slope rises gently to east (about 10m over 110m laterally then dips gently further east into another broad trough (base of MS-8). Unconformity surface sharp, no breccia preserved, no unusual alteration or fracturing of PFu beneath unconformity.

unconformity surface attitude: 119/38 SW, ave of 6 between MS-6 and MS-7

6
TS

5
TS

4
3
2a2b
TS

1
TS

MS-8

1 1 1 1

Metres
above
base

MS-3 DESCRIPTION

SAM
PLE

Section located near centre of low WNW trending ridge paralleling main LHG cgl ridge to south (see Figure A2-1). Lat. 64°39'40"N, Long. 139°46'31"W in NTS map 116B-116C(E half) (Dawson), Yukon; 1:50000 map 116 B/12 (Mt. Harper). Best seen in RCAF airphoto A13135-146.
Total Thickness = 172 m

- 172 Top of ridge - no outcrop in slope dipping to southwest
- 151-172 Gcmgr Gcmgrgn 80-90% peb to bldr clasts in poorly sorted med- cse-grained Sm matrix; very poorly sorted but cob-bldr rich central layers common with <20cm thick poor gr base and less common gn top define 70cm-2.5m thick beds, some central layers boulder rich (up to 1.6m dia) with open framework "fitted" look; contacts al wavy but non-erosive; beds appear cont. >50m laterally; projecting clasts common; clasts generally equant, sub-rd, <25% tabular clasts sub// beds or poor imbric in basal gr horizon; clast lithologies: all PFu, blk chert/dolst bx = blk chert-altered dolst > lam gray dolst = massive gray dolst > blk or white chert (pebbles)
bedding: 133/51 SW, 1 measure
- 102.5-151 Gcm Gcmgr Gcs 2-5m thick Gcm layers, rare gr bases and welded contacts suggest layers are composites of 1-2m thick beds; 80-90% peb-bldr clasts in med- to cse-grained Sm matrix; very poorly sorted; rare <20cm thick poor gr base, contacts welded, non-erosive, projecting clasts common; clasts generally equant, sub-ang to sub-rd, <25% tabular clasts sub// beds or poor imbric. clast lithologies: all PFu; blk chert/dolst bx > blk chert-altered dolst > massive gray dolst > lam gray dolst, blk or white chert; rare (ave 5m spacing) 20->50cm thick Gcs interbeds of 60-70% pebbles in cse-grained Sm matrix (rare Sh); mod-poor sorting; pebbles 30-40% cherts, >40% tabular (sub// beds); poor 5-10cm gn zones define vague stratification; Gcs thickens/thins laterally, infills irregular tops of Gcm beds, loaded by Gcm above
- 73-102.5 Gcmgr Gcmgrgn Gcm 85-95% peb-bldr clasts in poorly sorted med- cse-grained Sm matrix; very poorly sorted but cob-bldr rich central layers common with <20cm thick poor gr base and/or less common gn top; beds 40cm-1.5m thick beds, <15% 10-40cm thick pebbly Gcm(rare Gcs) interbeds as below; bed contacts loaded but non-erosive, projecting clasts common; clasts generally equant, sub-ang to sub-rd, <25% tabular clasts (most pebble size) sub// beds or poor imbric. clast types: all PFu, blk chert/dolst bx > blk chert-altered dolst > massive gray dolst > lam gray dolst, blk or white chert
bedding: 112/51 SW, ave of 4
- 58-73 Gcm as below but no pebbly interbeds or gr bases
- 50-58 covered
- 2.5-50 Gcm Gcmgr 80-95% peb-bldr clasts in poorly sorted cse-grained Sm matrix; very poorly sorted, rare <20cm thick poor gr base, most non-graded 70cm - 4 m thick beds (most < 2m), common separate 15-30cm thick, pebble-rich, al better sorted beds, but drape and infill between projecting clasts of irregular tops of cob-blder rich beds; contacts loaded but non-erosive, welded where no pebbly horizon; projecting clasts common; clasts generally equant, sub-ang to sub-rd, <25% tabular clasts sub// beds or poor imbric. clast lithologies: all PFu; massive gray dolst > blk chert/dolst bx > blk or white chert > blk or white chert-altered dolst > lam gray dolst,
bedding: 115/45 SW, 1 measure
- 0-2.5 Gcs-pShgn F1 unconf surface trough fill, < 50m wide, 2.5m thick; Gcs in 20-50cm thick beds, >80% gran-small peb clasts (< 3cm) in cse-grained lam Sh matrix; mod. sorted, peb >60% tabular, sub// beds; Gcs grades to 3-6cm thick cse- to fine-grained pShgn; slight erosion of pShgn by Gcs above; top 20cm is calc F1, wavy cont lams, eroded, loaded by Gcm above
bedding: 127/51 SW ave. of 10
- 0 unconformity surface exposed 50 m to west; surface undulating - broad troughs 30-50m width, 10m max relief, no bx or alteration of PFu below
- 3 to dolostone (PFu) slightly resistant, light gray weathering, medium gray finely laminated algal mudstone
- 20 (50-60% of o/c); lams slightly wavy, parallel, continuous; 10-20% rip-up bx of algal lams; domal stromatolites (LLH) in some beds but poorly exposed; top unit of PFu
bedding: 108/36 SW ave. of 10

6
5

4
TS

3

2

1
TS

MS-9

Metres
above
base

MS-9 DESCRIPTION

SAM
PLE

Section base located at Lat. 64°39'37"N, Long. 139°46'08"W, NTS map 116B-116C(E half) (Dawson). Yukon; 1:50000 map 116B/12 (Mt Harper) (see Fig. A2-1). RCAF airphoto A13135-146. Total Thickness = 196 m

Top of ridge - no outcrop in slope dipping to southwest
164- Gcmgrgn Gcmgr Gcm 75-85% peb-bldr clasts in poorly sorted, cse-grained Sm matrix; very poorly sorted but cob-bldr rich central layers common with <40cm thick poor gr base and/or <20cm gn top which defines 80cm-2m thick beds (very rarely 2-3m), contacts loaded but non-erosive, <50% Gcm beds with very poor gr bases or non-graded; projecting clasts common; clasts generally equant, sub-ang to sub-rd,

bedding: 100/45 SW, 1 measure

162- pSh/Gcs discont. 50 cm layer thins and pinches out 10m to east; pSh is med- very cse-grained with <20% small pebbles; 1cm lams in approx 5cm wavy sets which cut sets below; possible thin trough x-beds; poor gn in lams and sets as whole; 1 small pebble Gcs bed 10-15cm thick, poor gn with cse-grained Sh matrix grades to top 10cm pSh; unit eroded by Gcmgr bed above; similar pSh/Gcs lenses very rarely exposed in cliff face off section, all < 10m wide and eroded by Gcmgr beds above

bedding: 100/51 SW, ave. of 2

2
TS

70.5- Gcm Gcmgr Gcm/Gcs as below but < 50% gr bases above 60m; beds generally 1-2m thick, defined by gr bases or cobble-boulder rich horizons; pebbly interbeds now rare and appear generally massive
162

68.5- approx 2m of pervasive dolomite alteration of Gcm - abundant <1cm thick white, medium crystalline dolomite veinlets, subvertical, crosscut matrix and clasts; clast margins and matrix also slightly altered by light gray finely crystalline dolomite
70.5

1b
1a

0-68.5 Gcmgr Gcm Gcs 80-90% peb-bldr clasts in med- cse-grained Sm matrix; very poorly sorted; 0.7-2m thick beds (most 1-1.5m), 50-70% have 10-20cm thick gr bases, non-graded Gcm beds have welded contacts; contacts non-erosive, projecting clasts common; clasts generally equant, sub-ang to sub-rd, <20% tabular clasts, sub// beds or poor imbric. in gr bases; clast lithologies: all Pfu, chert/dolst bx > lam sandy dolostone = chert replaced dolst. lam algal dolostone = white and dark chert rare (ave 5m spacing) 10-20cm thick Gcs interbeds of 60-70% pebbles in cse-grained Sm matrix (rare Sh); mod-poor sorting; pebbles >40% tabular (sub// beds defines poor stratification); possible very poor gn; Gcs thickens/thins laterally, infills irregular tops of Gcm beds, loaded by Gcm above
bedding 098/52 SW, ave. of 2

0 unconformity exposed 75m W; surface sharp but irregular; unconf is about 85m higher 75m W of MS-8 (not exposed between); possible steep paleoslope or fault between base MS-9 and exposed unconf conglomerate beds of LHG not displaced by possible fault (ie. faulting pre-Harper deposition)

-10 to dolostone (PFu) exposed 50m W of section base; slightly resistant, light gray weathering, medium gray finely laminated algal mudstone; lams slightly wavy, parallel, continuous; rare subvertical dewatering dykes up to 30cm wide and traceable > 20m vertically; domal stromatolites (LLH?) poorly exposed but present; top unit of PFu
-20

bedding: 114/40 SW, ave. of 4

MS-10

Metres
above
base

MS-10 DESCRIPTION

SAMP
LE

Section base located in creek near the west end of WSW trending main LHG conglomerate ridge (see Figure A2-1). Lat. 64°39'21"N, 139°46'16"W in NTS map sheet 1168-116C(E half) (Dawson), Yukon; 1:50000 map 1168/12 (Mount Harper). Best seen in RCAF airphoto A13135-146. Total Thickness = 775 m

- 765- Gcm-Gcsgn Gcmgrgn Gcmgr top 10m has dark red matrix of abundant jasper but also hematitic
775 sands/muds; generally pebble-cobble rich beds in med- cse-grained Sm or Shgn matrix; mod to poor sorting with fair gn layers which appear to lense out laterally; possible sl concave bases, may be overlapping, sl erosive lense; some "pockets" of pShgn infill between projecting cobbles-boulders at top of Gcmgr beds; cobble-boulder zones of Gcmgrgn and Gcmgr beds generally matrix-poor or open framework; definitely better sorting and more stratified, finer conglomerates over last 125m; but many boulder-rich beds too
bedding: 110/45 SW, 1 measure
- 710 Dyke dark green weathering, dark gray fresh, medium crystalline mafic dyke; about 10m thick with <10cm chilled margins; subvert; conglomerate beds sharply cut, no deformation
dyke orientation: 140/70 SW (approx.)
- 650- Gcmgrgn Gcm-Gcs from 675m Gcm-Gcs beds increasingly common, up to 50% of beds by 775m;
775 Gcmgrgn as below, generally less boulders and slightly thinner (1-1.5m), but some beds anomalously coarse with >70% boulders in central zone (1.5-2m thick beds), fitted open framework look and little or no matrix (some matrix definitely filtered down from bed above); Gcm-Gcs now 80% clasts (pebbles and rare cobbles) in 20% cse-grained to granule matrix; beds 20-120cm thick (most <70cm); cont for >20m laterally; consist of multiple poor gn zones or slight size segregation giving poorly stratified look; poorly sorted but better than Gcmgrgn beds; contacts with Gcmgrgn beds diffuse, vague; appear generally non-erosive, slightly wavy; PGI jasper and dolost increasingly abundant upward, >30% of clasts by 770m, but concentrated in pebble-granule size range, rarely cobbles or boulders; rest of clasts are PFu types as below
- 500- Gcmgrgn Gcmgr (Gcm-Gcs) >90% peb-bldr clasts in poorly sorted cse-grained to granule-sized
650 Sm matrix; very poorly sorted with cobble-boulder rich central layers (matrix-poor, some possible open framework); boulders now >60% of bed, most <50cm dia, but 20% 50-100cm dia; <20cm thick poor gr base and less common gn top which defines beds 1-2m thick beds, beds laterally cont. > 50m; contacts slightly wavy, loaded but non-erosive, projecting clasts common; clasts generally equant, >80% sub-rd, <20% tabular clasts mostly pebble size, sub// beds or very poor imbric in gr bases; clast lithologies: >90% PFu; blk chert/dolst bx > blk chert-altered dolst > massive gray dolst > lam gray dolst, blk or white chert; <10% PGI jasper and lam dolostone; boulders all PFu; most chert/dolst bx or chert-altered dolst
Thin pebble-rich Gcm-Gcs now rare (<10%), generally occurs above separate Gcmgr bed; >80% pebbles in med- cse-grained Sm matrix; very poor discont gn zones suggests slight stratification; poorly sorted but better than coarser conglomerates; <40cm thick and thicken and thin laterally, discont. over 10-50m; appear to infill between projecting boulders on Gcmgr top surfaces
- 420- Gcmgrgn >90% of beds, rest Gcmgr or rare Gcm-Gcs as below; central cores now >60% boulders
500 (most <50cm dia, 10-20% 50-75cm dia); cobbles/boulders subrd, equant; >95% PFu lithologies; definite coarsening upward sequence over last 150m; beds now 1-2m thick consistently and laterally continuous sheets for >50m; now up to 5% PGI dolostone clasts, <3% PGI jasper;

section continued on following page

MetresAboveBase

section continued on previous page

SAMPLE

365- Gcmgrgn now >80% of beds; Gcmgr and Gcm-Gcs rarer than below; typical bed has 20-30cm gr
420 base of >85% pebbles in cse-grained Sm matrix; 100-150cm thick, non-graded central core of
50% boulders (most 25-50cm dia), 30% cobbles, 20% pebbles, <5% Sm matrix; top 20-30 cm poor
gn from pebbles/cobbles to small pebbles/granules with indistinct (welded) non-erosive
contact with gr base of Gcmgrgn bed above; definite slight coarsening up sequence over last
100m;

320- Gcmgrgn Gcmgr Gcm-Gcs >70% cob/bldr-rich beds 70cm-2m thick, as described at 200m; beds
365 appear to be laterally continuous (>50m) non-erosive sheets; <30% 50cm or thinner beds of
Gcm-Gcs lenses every 3-6m vertically, generally traceable <10m laterally;
rare PGI laminated dolostone clast and jasper (<3%)

bedding: 130/45 SW, 1 measure

290 ** first occurrence of PGI Jasper clasts; all PFu lithologies below this **

168- Gcmgr Gcmgrgn Gcs-Gcm >90% 1-1.5m thick Gcmgr or Gcmgrgn beds, similar to below, very poor
320 sorting, with poorly defined 10-30cm gr bases and less common (<30%) 10-20cm thick gn tops
most of bed is cob/bldr rich, non-graded, massive; beds thicken/thin but cont laterally;
contacts irregular but non-erosive; projecting clasts common: <10% Gcs-Gcm lenses as below
in 30-75cm max thickness beds; gn and gr zones throughout but commonly well-defined gn
base; appear to infill irregular lows/troughs in surface of Gcmgr bed below (one 30
exposure trends 234°); large clasts of Gcm beds above commonly project down into Gcs bed;
no good imbrication; clast types (all beds): all PFu; chert/dolst bx > massive lite grey
dolst > white or dark chert > lam dolst

93-168 covered

78-93 Gcmgn Gcmgr Gcs-Gcm 70cm-2m thick Gcmgr or Gcmgn beds, similar to below, but coarser with
more large bldrs (50-90 cm dia); very poor sorting, with poorly defined, laterally discont
gr and gn and non-graded layers in same bed (surges?); beds thicken/thin but cont.
laterally; contacts irregular but non-erosive;
<10% Gcs-Gcm in <30m long lenses with flat tops, concave (but non-erosive) bases which
pinch-out laterally from max 45cm thickness; granule-pebble size clasts; poor sorting but
segregation in pebble-rich and granule-rich layers (5-10cm thick) with poor gn and/or gr in
many gives stratified look; lenses irregular spacing vertically;

33-78 covered

0-33 Gcmgn Gcmgrgn Gcmgr >50% Gcmgn beds: 85-95% peb-bldr clasts in poorly sorted med- cse-
grained Sm matrix; poorly sorted but better than lower sections; <25% small bldrs (gn
<50cm dia) all at base of beds; modal clast size large pebble, rare equant outsized clasts
(largest 1.6m) cut beds; fair to good gn defines 40cm-120cm thick beds, some thick beds are
multiple gn layers which coalesce laterally (surge deposits?); main contacts loaded but
non-erosive, beds laterally cont >20m but thicken/thin; clasts generally equant, sub-ang to
sub-rd, 20-40% tab clasts sub// beds or poor imbric. clast types: all PFu
Gcmgrgn Gcmgr beds: as above but thicker (1-1.5m) coarser with more and larger bldrs conc
in central core or at top if no gn; very cse-grained Sm matrix; grading less well-developed
with basal 20-50cm gr, massive blder-cob central core (some "fitted" looking and matrix-
poor) and 10-30cm poor gn top if present; very poor imbric of tab clasts in gr bases only;

bedding: 120/45 SW, ave. of 4

0 Base of section in creek at about 1180m elevation. Is roughly on line with MS-9 but about
100m stratigraphically higher (see Figure A2-1). Section measured approx south up main NW
trending ridge of map unit PHb.

5
4
TS

3

2a
2b
TS

1

MS-12

1. L.W.

Metres
above
base

MS-12 DESCRIPTION

SAM
PLE

Section on N face of peak (elev 1770m) at intersection of N trending ridge of PFu (MS-4), low WNW trending ridge of LHG sections MS-6,7,8,9; and SW trending ridge of MS-13 (see Figure A2-1). Lat. 64°39'37"N, Long. 139°44'30"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map sheet 116B/12 (Mount Harper). Best seen in RCAF airphoto A13135-146.
Total Thickness = 406 m
top of peak - end of section -

350-406 Gcmgr Gcmgrgn Gcm 80-90% peb-bldr clasts in poorly sorted med- cse-grained Sm matrix; >60% Gcmgr, <25-30% Gcmgrgn, <10% Gcm; all very poorly sorted but cob-bldr rich central or upper layers common with <20cm thick poor gr base and/or gn top defines beds 70cm-2m thick beds, contact non-erosive, sl wavy, projecting clasts common; clasts generally equant, sub-rd >> sub-ang, <20% tabular clasts sub// beds or random; clast lithologies: >97% PFu types, <3% PGI jasper and dolst

bedding: 144/35 SW, 1 measure

290-350 Gcmgr Gcmgrgn as below but now >80% Gcmgr, rest Gcmgrgn; slight coarsening up sequence from 150m; still <3% PGI jasper or dolst

150-290 Gcmgrgn Gcmgr Gcm 80-90% peb-bldr clasts in poorly sorted cse-grained Sm matrix; very poorly sorted but cob-bldr rich central layers common with <20cm thick poor gr base and/or gn top which defines beds 70cm-2.5m thick beds; >50% Gcmgrgn, 30-40% Gcmgr, generally thicker (1.5-2.5m) and coarser than Gcmgrgn beds with an irregular, boulder-rich tops; Gcm beds rare and as below; contacts loaded but non-erosive, projecting clasts common; clasts generally equant, sub-rd > sub-ang, 20-30% tabular clasts sub// beds or random; clast lithologies: >97% PFu: >60% lam to thin bedded gray dolst, >20% chert/dolst bx and chert-altered dolst, <20% dk or white chert; <3% PGI jasper and dolst

140 Gcm as below but sudden decrease in PGI jasper and dolst (<3%); slightly coarser and thicker beds than below 140m with more boulders and most beds 1.5-2m thick

100-120 >80% Gcm <20% Gcmgr; contacts very subtle; rare slight segregation of pebble-rich zones vs. cobble-boulder rich zones suggests 1-2m bed thickness; clasts now 10-20% jasper and 5-10% PGI dolst (increasing % upward); rest PFu types

bedding: 138/34SW, ave of 2

90 ** jasper clasts first occurrence, 3-5% of clasts, all sizes including boulders (unusual)

6-100 Gcmgr Gcm 80-90% peb-bldr clasts in poorly sorted med- cse-grained Sm matrix; very poorly sorted with very poor <20 cm thick pebble-cobble bases, rest non-graded peb-cob-bldr top; beds 75cm-1.5m thick but contacts very indistinct, non-erosive, projecting clasts common; <30% Gcm in 1-3m thick beds with no obv grading, contacts welded; clasts generally equant, sub-ang to sub-rd, 25-30% tabular clasts sub// beds or random; clast lithologies: <10% orange wthr lam sandy dolst (PF1?, not PGI); rest PFu types; 30-40% chert/dolst bx and chert-altered dolst; 30-35% lam or thin bedded gray dolst; <30% dark or white chert;

covered

bedding: 096/34 SW, ave of 2 from Fl lams

1.5-6 Fl vfg calc set and siltst in thin, norm graded lams; blk chert nodules <3% but to east unit thickens to >3m and strongly replaced by discont black chert layers (silcrete?)

0-1.5 unconformity not exposed but to east is sharp, sl undulatory, no breccia

Dolostone light gy wth, med gy finely lam algal mudst; lams wavy (some contorted), parallel, cont; 10-20% rip-up bx of algal lams; domal stroms not present; top unit of PFu

-1 to >-10

2
TS

1
TS

MS-13

metres

Metres
above
base

MS-13 DESCRIPTION

241 | Sam
ple

Section located along south trending ridge crest which separates valley of sections 6-11 from bowl of south Harper fault and MS-18 (see Figure A2-1). Lat. 64°34'15"N, Long. 139°45'34"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map 116B/12 (Mount Harper). Best seen in RCAF airphoto A13135-146.

Total Thickness = 415 m

- 412 PHV dk gy to rust brn wthr; med grn gy fresh, massive, aphanitic, appears bedded in ridge to west; contact not exposed, creek separates last cgl from first volcanics
- 406- Gcmgrgn Gcm poor exposure in southwest dipping slope from top of cgl ridge to PHV ridge; appears same Gcmgrgn as below 405m but beds 50-70cm thick?
- 410 bedding: 149/35 SW, ave of 2
- 406 dyke mafic dyke cuts all sequence, about 2-3m thick; orientation: 115/subvertical
- 400- Gcmgrgn Gcmgn blder-rich thick beds as 330-400m but gr bases thickening up to 50% of some beds;
- 406 beds 1.5-1.75m thick; poor imbric of tab clasts in gr bases; gn tops thin (<15cm) and no imbric; 10-15% cse-grained sand to granule matrix; one 1m thick Gcm bed with 15-25cm thick gn (poss gr-gn) cycles; mod sorting with cobbles <10cm dia at base grade to small pebbles/ granule top; bed 80-99% pebbles, no imbric; beds appear sheet-like but some definite pinch-outs visible in slope suggest beds >100m lateral sheets; Gcsgn lenses now elongate sheets <50m laterally
- 360- Gcmgrgn Gcmgn as below but <20% thick, bldr-rich beds; 70-80% 75-150cm (most 90-130cm) thick with 30-60cm thick fair gr base (poss poor imbric of tab clasts) and 10-40cm thick gn top; central horizon massive peb-cob-small bldr in granule, cse-grained Sm matrix; rare outsized bldrs >50cm dia (1 2.5m dia blder cuts 1.3m bed!); clasts >70% subrd and mod-high sphericity; cob/bldr clasts >90% subrd and equant; <30% tab clasts sub// beds or poor imbric in gr bases (ntherly paleocurrents); clast lith: 50-60% gy dolst (mass>thin bd>lam), 20-30% dolst-chert bx > cherty dolst, <10% chert (gy>>white), <10% dk gy lat siltst (PFI?) <5% orange, lam dolst (PGI?); no jasper above 350m
- 330- Gcmgrgn (Gcmgn) 30-35% thick bedded (1.5-2.5m) Gcmgrgn with bldr-rich central horizons including 20% 75-150cm dia bldrs, very poor sorting with 20-50cm thick gr bases, gn tops; 50-60% 75-150cm thick Gcmgrgn with sm blder- cob-rich central horizons and rare oversized bldrs (all high sphericity); slightly better sorted and better grading then thicker, coarser beds; <10% Gcsgn lenses, less distinct then 269-330m and many >50m laterally, some appear to merge laterally to gn tops of Gcmgrgn beds
- 300- Gcmgrgn (Gcmgn) >90% Gcmgrgn in progressively coarser and slightly thicker beds above 300m; by 300m several beds up to 2.5m thick with 2m thick blder - cobble central horizons, but most beds <1.5m thick; beds laterally cont sheets, slightly thicken-thin laterally; <10% Gcsgn lenses, similar to 271-300m types; clast lithologies: 40-50% gy dolst (thin bd>mass>lam); 30-30% dolst-chert bx.> cherty dolst, 10-15% chert (gy>white), <5% orange lam dolst (PGI?), <3% jasper
- 330 bedding: 149/37 SW, ave. of 3
- 271- Gcmgrgn Gcmgn >70% Gcmgrgn as below but thinner beds than below 270m, most 70-125cm thick with cobble- med blder cores; <30% Gcsgn lenses as at 369m but <50cm thick (most <30cm) and <20m long; generally only one gn cycle and all small pebbles in med- cse-grained Sm matrix
- 300 bedding: 131/38 SW, ave of 5 tops of Gcsgn beds)
- 269- Gcmgn discont lense, max 2m thick, pinches out over 25-30m laterally; concave, al erosive base, straight top; 4 10-15cm thick beds, mod sorted, normally graded, med pebble base, small pebble top in med-cse-grained Sh matrix; higher cycles progressively smaller pebbles overall; top 20cm non-graded small pebbles in cse-grained Sm matrix; pebbles >80% subrd; >60% mod-high sphericity, <40% tabular - sub// bedding, no imbric; pebble lithologies: 50-60% med gy dolst (lam>mass>thin bd), 10% dolst-chert, 5-10% chert (gy>white>blk), 10% jasper, <5% red siltst(?), 5-10% orange lam dolst (PGI?)
- 271
- 265 mafic dyke about 1.5m thick; orientation: 170/70 E, 1 measure
- 245 first jasper clasts above 150m; 2-55 of Gcmgrgn bed including 50cm dia boulder
- 200- Gcmgrgn as at 175m; but clast sizes generally increasing slightly and gr-gn bases/tops thinner (20-40cm) and less well-defined than below 200m; boulder: >50cm dia now 5-10% of beds, random, all PFu dolostone
- 240

section continued on following page

7
TS

section continued on previous page

Sample

- 200 approx level of well-exposed megaclast horizon in slope to south, no evidence of horizon in section outcrop but most clasts are similar PFu dolostones
- 175 Gcmgrgn as below but gradational change over last 10m from subtle coarsening up sequence above 80m; beds now 60-70% pebbles and small cobbles; <5% boulders (generally 30-50cm dia); beds still generally 1-2m thick and still rare outsized boulders (largest = 3m dia) 6
- 104-175 Gcmgrgn similar to 80-104m but gr bases and gn tops thicker (20-60cm), more matrix-rich (20-30%) and some bases/tops very poorly graded, 30% of bases/tops non-graded, matrix-rich pebble-cobble horizons bordering matrix-poor (<10%) cobble- boulder-rich central horizons; beds 75cm to 2m thick (most <150cm); matrix very poorly sorted, granule to med-grained Sm; boulders generally <50cm dia but rare random 50->100cm dia; contacts non-erosive, straight to sl wavy; projecting clasts common; beds laterally cont for >40m, thicken-thin slightly; clasts generally equant, sub-ang to sub-rd, <25% tabular clasts sub// beds no imbrication; clast lithologies: >99% PFu; 40-50% med gy cryptalgal lam and massive dolst, 20-30% cherty dolst and dolst/chert bx; 20-30% chert, lite gy > white > black; <1% jasper, no PGI dolst
- 81-104 Gcmgrgn 80-90% peb-bldr clasts in poorly sorted granule to cse-grained Sm matrix; very poorly sorted but cob-bldr rich central layers common with 20-30cm thick poor gr base and gn top which defines 1-2m thick beds, boulders all <1m dia, gen <50cm but def coarsening up; contacts non-erosive, sl wavy; beds laterally cont for >30m, thicken-thin slightly; clasts generally equant, sub-ang to sub-rd, <25% tabular clasts sub// beds or poor imbric clast lithologies: 50-60% med gy lam or mass dolst; 20-30% dolst-chert interbeds > dolst-chert bx; <5% chert; <3% jasper; <3% orange lam dolst (PGI?) 5 TS
- 80 ** first occurrence of jasper clasts; all PFu lithologies below this
- 71-80 Gcm as at 6-65m but no obv. grading; poor cser central horizons suggest 1.5-2m thick beds bedding: 163/20 SW; ave of 2
- 60-64.75 Gcmgrgn 85-95% peb- sm bldr clasts in cse-grained Sm matrix, poorly sorted, beds 75-100 cm thick with 10-20cm poor gr base, gn top; clasts subrd>subang, gen equant, 25% tabular; clast lith: all PFu; 70-80% cryptalgal lam dolst as in Gcm(bx) below; 10-15% dolst-chert interbedded and bx; <5% chert
- 52-60 Gcm(bx) 90-95% angular clasts, all med gy PFu cryptalgal lam dolst in cse-grained Sm matrix; clasts gen 30-150cm dia., med-high sphericity; rare tab clasts sub// bedding; top 5-10cm poor gn and gradational to Gcm above
- 43-52 Gmm Gcmgrgn 50-60% peb-bldr clasts in granule to cse-grained Sm matrix; very poor sorting; beds irregular, 1-6m thick and some laterally change to Gcm beds; boulders random in beds, no central cobble-boulder horizons; contacts indistinct, non-erosive, wavy; no fabric, rare poor gr bases, gn tops 4 TS 3 2 TS
- 10-43 Gcm Gcmgrgn Gmm as below but extremely poor sorting, bedding very indistinct; 10-15% large boulders (to 5m dia, most 1-2m) in poorly defined cobble- boulder-rich central or upper horizons of 2-5m thick beds; graded bases or tops rare (<20%); <50% 20-60cm thick irregular Gmm interbeds or bases/tops of Gcm beds, generally pebble- cobble-rich with 20-40% granule- cse-grained Sm matrix; clast lithologies: all PFu; dolst-chert bx, interbedded dolst-chert >stromatolitic and crptalgal lam dolst > massive dolst bedding: 150/40 SW; 1 measure 1 TS
- 0-10 Gcm Gcmgrgn 80-90% peb-bldr clasts in med- very cse-grained Sm matrix; very poor sorting, rare very poor thin (<30cm) gr bases and gn tops, most beds 1 to >2.5m thick, non-graded with welded contacts; clasts generally subrd to subang; equant plus <30% tabular clast, no imbrication
- 0 base of section at first outcrop SW of lowest point in saddle, elevation about 1525 m

MS-18

Metres
above
base

MS-18 DESCRIPTION

247
Sample

	Section located in south-facing bowl containing south Harper fault and south of ridge of MS-12, MS-13 (see Figure A2-1). Lat. 64°38'55"N, Long. 139°45'00"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map 116B/12 (Mount Harper). Best seen in RCAF airphoto A13135-146. Total Thickness = 337 m	
	top of section, scattered outcrop above to base MS-13 all Gcm types	
318-337	Gcm Gcmgrgn >90% gran-bldr clast in cse-grained Sm matrix; poor sort; 60-70% cob-bldr (much > below 311m); massive, beds 2-4.3m thick; no grading or poor 10-25cm gr base/gn top; bed contacts obscure/welded, appear non-erosive; clasts >70% subrd-rd, equant; <30% tab clasts random, no imbric; clast lith: 30-40% chert (dk gy>>white), 20-30% gy lam dolst, 20-30% chert-dolst, <15% chert-dolst bx	
307.4-313	Gcmgrgn-pShgn 70-90% gran-sm bldr clasts in med- cse-grained Sm matrix; mod-poor sorting; 1.5-2.2m thick beds with bldr-cob central horizon and good 10-25cm gr base, 10-40cm gn top grades into discont (<20m) pShgn beds between Gcm beds; beds sl concave base, straight top, lenticular but cont >30m; clasts 70-80% subrd-rd, >70% equant, <30% tab (tab sub// beds or poor imbric in gr base); clast lith: 60-70% chert (white/lite gy>blk), 30-40% PFu dolst	PM-10e
	contact sharp, sl wavy, sl erosive	
305.4-307.4	pSh pSp buff wthr, lite gy fsh, oolitic, med- to very cse-grained, <10% pisolitic with spherical grains up to 1cm dia; well sorted, faint horis lams, laterally cont unit >30m, top 15cm very cse oolites/pisolites with planar xbeds, tangential base, sharp top (northerly paleocurrents) bedding: 030/33 NW, ave of 5	10a 10b 10c
301.7-305.4	Gcmgrgn >90% granule to small bldr clasts in cse-grained Sm matrix; poorly sorted; 1.5 & 2.2m thick beds, bldr-cob rich central horizon, fair 10-30cm gr base/gn top; poor imbric in gr base (nthrly paleocurrents); clasts 50% subang, 50% subrd-rd; clast lith: 50-60% gy dolst (chert-dolst>lam), 25-30% chert (lite gy/white> dk gy), 5-10% blk lam wackest; basal contact slightly gradational, erosive	
300-301.7	pSh buff wthr, med gray fsh, oolitic, med- to cse-grained with 5-15% white chert peb conc at base of mass 30-50cm thick beds, poor internal lams/thin bds, wavy to convolute, sub//, cont beds>discont	5 TS
295.3-300	Gcmgrgn Gcmgr >80% gran-cob in med- to cse-grained Sm matrix, mod sorted, 40-120cm beds (thicken/csen up) with 0-20cm good basal gr/ top gn, beds laterally cont >20m, contacts sharp non-erosive, sl wavy; 20-30% tab clasts, fair imbric in gr bases (ntherly); clast lith: 25-30% chert (gy>>white), 20-25% blk lam calc wackest, 15-20% chert-dolst, 10-15% gy lam dolst, 5% gy mass dolst	
	contact obscure (welded?)	
295-295.3	Gmgn 50-60% gran-peb (<6cm dia) in med- to cse-grained Sh matrix; mod sorted (bimodal), poor cse tail grading, clast >50% tab, sub// bed or poor imbric; clast lith: >70-75% chert (gy>>white), 15-20% dk gy lam calc wackest, 10% gy lam chert-dolst, <5% med gy mass dolst	
	contact sharp, sl wavy, nonerosive	
288-295	Gmm Gcm poorly exposed, 60-70% clasts in 30-40% Sm matrix; clasts 75% ang-subang, 25% subrd; 60-70% equant, rest tabular; beds massive, no grading; clast lith: 60-70% med to lite gy thin bedded dolst, 10-20% lite gy lam dolst, 10% chert (blk/gy>white)	
	contact obscure - gradational?	
275-288	Gmmbx Gmmbx strongly altered rubble breccia with 50-70% clasts in med gray wthr pale yellow fsh Sm matrix; clasts >75-80% ang-subang, 20-25% subrd (but strong clast margin alteration?); matrix clay-granule sizes with 30-40% angular chert grains, 60-70% orange dol clay(?) alteration(?); clast lith: 60-70% chert (dk gy>>white), 20-30% lam-thin bd gy dolst, <10% dolst/chert bx	4 TS
	contact gradational	
239-275	Gmmbx rubble breccia of angular, tabular clasts 1cm to >5m dia; massive, very poorly sorted, no grading, clasts >60-70% chert-dolst, 20-30% med gy lam-thin bedded dolst, <10% dolst/chert bx, <5% blk or white chert	
	contact gradational over 1m	
184-239	Gmmbx rubble breccia consisting of megablocks of PFu interbedded chert-dolst; block in section traceable >90m laterally; to east is another block with internal bedding at high angle to this block; blocks slightly broken and rotated, smaller bx fragments in fractures; block dimensions minimum only - none exposed in all directions in slope	
178-184	Gmmbx rubble breccia of >90% med gy wthr/fsh angular, tabular blocks 1cm to >5m dia (most 2-3m), random, massive; small clasts (<25cm?) coated with isopachous fibrous dolomite cement (<5% rock) and voids infilled with pale yellow orange wthr, med gy fsh vfg Sm matrix (<5% rock) or sparry dolomite (<3% rock); clast lithologies all PFu: 50-60% lam gy dolst, 40-50% dolst/chert bx	

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section continued on previous page

- 160- **Gcmbx** one block traceable >80m laterally; broken into large, sl rotated fragments; rare small bx clasts
178 between megafragments; block is PFu interbedded, finely xtall dolost and white/lite gy chert
- 136- **Gcmbx** rubble breccia of >90% med gy wthr/fsh angular blocks 1cm to >5m dia (most 2-5m), random,
160 massive; small clasts (<25cm?) coated with isopachous fibrous dolomite cement (<5% rock) and voids
infilled with pale yellow orange wthr, med gy fsh vfg 3m matrix (<5% rock) or sparry dolomite (<3%
rock); clast lithologies all PFu: 60-70% lam gy dolst, 30-40% dolst/chert bx and chert-altered dolst
- 129.5- **dyke** recessive dark brown-green wthr, dark gray-green fsh; med xtall, mafic, contacts covered
136
- 129- **Gcmbx** 50cm bed rubble breccia with small clasts (2-50cm LA - all tab), all lam, gray PFu dolst; no
129.5 grading, very poor sorting, clasts random; 10-15% pale yellow orange vfg 3m matrix
120- **Gcmbx** >1m dia clasts of angular bx, clasts are PFu dolst/chert bx and chert-alter dolst; <3% pale
129 yellow orange fg 3m matrix; sudden change in bx lithology but no obvious contact at 120m
106- **Gcmbx** large blocks with >70% crackle breccia of med gy lam PFu dolost as at 97.5m; clasts angular,
120 most tabular; all slightly rotated with isopachous fibrous dolomite cement coating most clasts and pale
yellow orange sparry infill of central voids; <3% pale yellow orange vfg 3m matrix
- 103.5- **F1 Sh** siltst, vfg sandst; fine lams, sl wavy, cont, sub//, rarely contorted
106 bedding: 135/33 NE, ave of 6, inconsistent, probably rotated block
- 97.5- **Gcmbx** >80% crackle breccia of med gy lam PFu dolost; clasts 1->20cm dia; angular, most tabular; all
103.5 slightly rotated with isopachous fibrous dolomite cement coating most clasts and coarse xtall sparry infill
of central voids; <3% pale yellow orange vfg 3m matrix, most on edges of outcrop in discont horizons
- 46.5- covered grassy slope; >20% float; float >80% Gcmbx, <20% Gcm-Gmm, all with lower Harper Gp
97.5 clastic matrix
- 39-46.5 **Gcmbx** rubble breccia with megaclasts of PFu med gy dolost/chert bx; largest block about 7.5m x 10m
- 0-39 covered grassy slope; >10% float; float >70% Gcmbx, <30% Gcm-Gmm, all with lower Harper Gp
clastic matrix
- 0 base of section elevation 1150m; approximate location of south Harper fault in grass-covered slope at
base of bowl. Section measured north up slope. Dip unknown, thickness to first outcrops is minimum
thickness (zero dip).

Sam
ple

3 TS

2 TS

1 TS

MS-20

Metres
above
base

M5-20 DESCRIPTION

Sam
ple

Section located in south-flowing creek cutting east trending ridge north of Seela Pass and on west-facing slope of ridge (see Figure A2-1). Lat. 64°41'08"N, Long. 139°07'30"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map sheet 116B/11. Best seen in RCAF airphoto A13230-155. Total Thickness = 612 m

- 612+ dolostone (CDB) lite gray wthr/fsh finely crystalline dolostone; very faint thin beds; 10-20% random vugs <1cm dia filled or lined with white or clear quartz crystals; bedding: 104/20 SW, ave of 4
- disconformity contact not exposed
- 605- covered - <50% subcrop or poor outcrop, similar to 590-605m
- 612
- 590- Sh pSh 70-80% med-grained lam Sh in 0.5-2cm thick beds; similar to 526-541m but lams wavy; 20-30% vfg to silty recessive Sh in 3-5cm thick layers; <10% 2-10cm thick pShgn beds with <10% small pebbles near base of med-grained sandstone
- 605 bedding 074/22 SE, ave of 4
- 541- covered- <25% subcrop and poor outcrop of Sh as at 541m but all fine- to very fine-grained; lams more wavy upward, cryptalgal looking in some places; could be non-dolomitized equivalent of unit PHe
- 590
- 526- Sh pShgn >90% med- fine-grained lam to thin-bedded Sh; strata sl wavy, cont; possible vague ripples; poss faint trough x-lams in lower 2m; <10% vfg/silty recessive Sh in 10-15cm thick interbeds (internally finely laminated); rare poor desiccation cracks; <5% pShgn in <3cm thick beds with rare granules-small pebbles at base and normal grading from med- to fine-grained Sh; rare Fe-minerals (pyrite?) as irregular elongate blebs <0.5cm dia conc at bed contacts
- 541 bedding: 093/20 S, ave of 3
- 513- covered
- 526
- 480- pShgn Gcsgn Gmagn >50% cse-grained sandstone in 2-20cm thick beds with <10% small pebbles conc at base and slight normal grading, horison lams throughout; <30% Gcsgn as below but beds gen <50cm thick (one 1m thick bed) and commonly grade to pShgn beds; <20% Gmagn as below; basal contacts of all beds very slightly erosive; top contacts sharp or gradational; beds laterally cont >10m but poorly exposed
- 513 bedding: 085/23 SE, 1 measure
- ** gradational change to sandstone-dominated unit (PHd)
- 450- Gcmgn Gcsgn Gmagn pShgn slight fining up trend from 450m; 50-60% Gcmgn/Gcsgn as from 420-450m but beds <50cm thick; 20-30% Gmagn with 30-50% pebbles in cse-grained Sh matrix; pebbles conc in lower 60% of 10-50cm thick beds with fair overall normal grading; 20-30% pShgn; better sorting than Gmagn and 10-20% pebbles all in basal 20% of 10-30cm thick beds; all beds appear cont but lateral exposure poor
- 480
- 420- Gcmgn Gcsgn pShgn most beds poor to fair gn and conglomerates generally grade into pShgn; beds laterally cont >50m (sheets?); cobble-rich bases of beds now common but laterally change over 10's m to pebble-rich Gcmgn or Gcsgn; coarser bed 30-60cm thick; very rare gr bases to coarse, thick Gcmgn beds; bed base sl wavy, erosive; tops grade to pShg or sharp to Gc bed above

continued on next page

Metres
above
base

continued on previous page

		Sample
358-420	Gcm(gn) Gcs(gn) Shgn pShgn pSp 70-80% med gy wthr/fsh Gcm Gcs: 80-90% granule to small cobble clasts (>80% pebble) in cse-grained Sm or Sh matrix; beds 10-70cm thick (most 15-25cm) with sharp, sl erosive bases and sharp to sl gradational tops to Shgn beds; beds cont >30m laterally; Gcs stratification defined by size segregation into vague internal beds, alignment of tab clasts // bedding and rare discont Sh lenses; rare poor discont gn horizons (surges?); top 2-5cm commonly gn into pShgn beds; clasts >80% subrd-rd, <20% subang; 30-40% tabular; 60-70% equant; clast lith: 50-60% PFu med gy dolst (lam = massive/thick bedded); 20-30% PFu chert (med gy > lite gy > blk/white); ~10% black calc Fl (PFi?); <5% PFu dolst/chert bx; no jasper unlike <358m where >30% jasper in many beds; 20-30% Shgn pShgn; cse- med-grained in 2-10cm thick beds (internally lam), commonly with 10-20% small pebbles at base; thick beds cont >20m laterally; thin beds commonly laterally discont lenses <10m and commonly are gradational tops of Gcm Gcs beds	15bT S 15a TS 14 TS
358	beds thicken and coarsen upward from 358m ** sharp change to conglomerate dominated unit (PHb); no dark red colour above 358m	
300-358	Shr pShgn Gcs(p) pSp pSt 30-40% fine- to med-grained, 1-3cm thick laterally cont beds of Sh; 20% rippled with symmetrical or sl asymmetrical (to NW) ripples (<.25cm high, 3-5cm wavelength), crests straight to sl undulatory and <10% branching; <30% med- to cse-grained pShgn in <5cm thick beds, rarely with Fl tops (commonly desiccation cracked), beds laterally cont, sub//; 20-25% Gcs or Gcsp in 10-50cm thick beds with 80-90% granule/pebble clasts (including 10-20% jasper clasts) in 10-20% cse-grained Sh matrix; med sorted, poor gn in some parts of beds but not cont; beds lenticular over 20-50m with erosive, sl concave bases and straight tops which commonly grade into pSp or pShgn; some Gcs have faint planar x-beds (N or NW paleocurrents); 10-20% med- v cse-grained pSp in 10-30cm thick lenticular beds (20-50m) which thin/thicken laterally and gen erode beds below; all x-beds N or NW paleocurrents; rare pSt in 5m interval of overlapping/crosscutting trough xbeds; in cse-grained sand; troughs <8cm high, 40cm length but all eroded by troughs above; no good 3D but appear NW directed	13 TS 12 TS 11 TS
290-300	Shr pShgn Gcmgn pSp/Gcsp Fl as below but 20-25% Gcmgn in 5-30cm thick beds with small pebble granule bases grading up to cse- med grained pSh or pSp; pSp/Gcsp beds up to 30cm thick and grade up to med-grained Sh in top 25% of bed; Fl now rare (<5%); dark red colour <30% of beds ** gradational contact from Fl-rich unit (PHc) to sandstone/small pebble cgl dominated unit (PHd)	
280-290	Sh(r) pShgn Fl pSp/Gcsp Fl now <15% and dark red colour <50%, most beds pale yellow orange; now 10% pSp beds with pebble-rich Gcsp thick layer (20-25cm) which thins and changes laterally to pSp then pShgn then lam Sh before pinching out (total 20-50m), beds are sl concave based and erosive on Sh or Fl below; rest of o/c 40-50% fine- med-grained Sh (with rare ripples, some climbing, some symmetrical and stright-crested, all xlams N or NW oriented), and 20-25% granule- cse-grained pShgn in thin beds laterally cont // with non or very slightly erosive bases and straight tops	10a TS 10b TS
258-280	Sh(r) Fl pSp pShgn coarsening up cycle (continuation of megacycle from 7m) with dark red Fl decreasing from >30% at 258m to <10% at 296m; 40-70% fine- med-grained pale-yellow orange Sh in 0.5-3cm beds (cont, // sl wavy laterally) with fine wavy lams, rarely with xlam ripples (ripples gen straight to sl undulatory, cont crests with rare bifurcations); Fl silty to vfg sand, finely lam in //, cont lams with rare ripples; desiccation cracks (polygonal, 2->10cm across) increasingly common above 275m; 5% pSp in 3-20cm beds with planar crossbeds 1-2cm wide (tangential bases, sharp tops, northerly paleocurrents); x-beds normally graded with base granule-rich and abund 0.5-2cm long tabular rip-ups of dark red Fl, grades up x-bed slopes to med-grained top; beds laterally discont over about 20-60m, sl erosive, loaded base, straight tops; beds thicken/thin laterally; xbeds best developed in thicker (>10cm) portions; thinner layers cse-grained pShgn, bedding: 091/24 S; ave of 15 (258-280m; very consistent)	9 8 7 TS 6
232-258	covered - abundant Sh Fl float	
223-232	Sh Fl pShgn >50% interlam fine- to med-grained Sh > silty Fl; Sh mod sorted in 0.5-1cm lams; slightly wavy, //, gen cont but <20% discont, lenticular; Fl lams <0.5cm thick, wavy, //, cont to >20% lenticular; 30-35% <5cm thick Fl layers with no Sh interlams; rare desiccation cracks in Fl; rare cross-lam ripples in float; <10% pShgn beds as below	
200-223	covered - <10% outcrop/subcrop in creek, all dark red Sh Fl as below	

continued on following page

1 2 3

Metres
above
base

continued on previous page

Sam
ple

165-200	covered - <10% outcrop/subcrop in creek, all dark red Sh Fl as below	
145-155	Sh(r) Fl pShgn as below but rare poorly exposed cross-laminated ripples in Sh lams (northerly paleocurrents - not measured); 10-15% pShgn with rare beds to 10cm thick (<3% of total)	
132-145	covered	
111-132	Sh Fl pShgn >80% dark red fine-grained Sh and silty Fl, slightly wavy lams gen cont but common dewatering structures (clastic dykes gen <2cm wide, subvertical and with med- to cse-grained Sm infill); common desiccation cracks on surface of Fl, infilled by sandstone; 15-20% pale yellow orange wthr, lite gray fsh, pShgn; normally graded with granule to cse-grained bases grade to med-grained tops in thin beds 1-3cm thick; gray-grn reduction spots in dark red Sh Fl common	5
79.5-111	covered	
71-79.5	Sh Fl pShgn as below but fine- med-grained Sh/Shgn now > Fl (silty mudstone and vfg sandst) and 10% granule based pShgn	
63-71	covered, abundant Fl float	
57-63	Fl Sh as below	
45-57	covered, abundant Fl float	
40-45	Fl Shgn >80% pale red wthr, dark red mudstone/siltstone, laminated with sl wavy, gen //, cont lams and sharp contacts; Fl in 1-5cm thick layers with <20% cse- med-grained normally graded Sh, slightly loaded bases, rare granule-rich bases; tops gradational into Fl; common dewatering disruption with vertical clastic dykes <1.5cm thick and disrupted/mixed beds; poss rare desiccation cracks; <5% lite grn gray reduction spots up to 5cm dia (most 1-4cm)	4b TS 4a
9.5-40	covered, dark red Fl float	
6.5-9.5	pShgn Fl Gcs(gn) >40% 3-10cm thick beds granule- to med-grained pShgn; massive base grades to lam top, rare discont nodules of pyrite/marcasite, elongate, // beds; beds cont, sub// sl wavy; tops straight, sharp with 1-10cm thick lam Fl between beds; Fl silt-rich with wavy lams; rare desiccation cracks; Fl more common and changes from green-gray fresh colour to dark red above 7m; Gcs in two 20-30cm thick beds; small peb to granule clasts in cse-grained Sh matrix; poss poor gn; poss poor imbric of tab clasts (NW paleocurrent); clasts 40-50% med gray chert, 50-60% PFu dolostone; contacts sharp, straight; beds appear cont but poorly exposed laterally	3 2 TS 1 TS
0	unconformity defineable within 20m in creek, exposed on ridges to east and west; sharp with no regolith preserved; unconformity surface topography appears to be broad troughs and hills of <100m relief over >2km laterally; troughs trending roughly north-south?	
0 to -20	dolostone slightly resistant, light gray weathering, medium gray, medium crystalline; finely laminated to thin bedded; lams slightly wavy, parallel, continuous (some cryptalgal?); 20-30% nodular/discont bedded med gray chert, up to 50% of some beds; top unit of PFu	

bedding: 091/36 S, ave of 5

bedding: 085/37 S, ave of 4

base of section on west side of nth-trending creek valley nth of Seela Pass; first o/c is about 15m above creek and about 150-200m north of main redbed outcrop (site of John Park paleomag sampling, 1985)

MS-2I

Metres
above
base

MS-21 DESCRIPTION

Sam
ple

Section located on SW trending ridge crest east of Fifteenmile River where the river changes from south to southeast flowing (see Figure A2-1). Lat. 64°39'47"N, Long. 139°23'48"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map sheet 116B/11. Best seen in RCAF airphoto A13139-16.

Total Thickness = 421 m

- 421 end of section at southwest end of ridge; covered to southwest past this point down slope into Fifteenmile River valley. Contact with CDB estimated to be in valley bottom; estimated >100m stratigraphically above end of section
- 350-421 **Gcmgrgn** no other bed types above 350m; two distinct types of **Gcmgrgn** randomly interbedded; increasing abundant (to >25% at top) 70->100cm thick **Gcmgrgn** with boulder-rich central layers; rest of beds 30-70cm thick with cobble-rich central layers and rare boulders; all beds appear laterally continuous with contacts subtle, non-erosive, straight to sl wavy with common projecting clasts; clast lithologies: 30-40% PFu lite-med gy dolst (lam > bedded > mass); 15-20% jasper; 10% orange wthr lam dolst (PGI); 5-10% chert (med gy > lite gy); 5-10% PFu chert-dolst interbedded or bx; <5% dark red Sh (PFI or PHc?); <5% dark gy calc mudst (PFL?)
bedding: 125/21 SW, ave of 4
- very subtle continuous coarsening up trend above 250m; above 340m is increase in number of thick (60->100cm) beds with boulder-rich central horizons to >25% by top of section; rest of beds have cobble-rich central horizons with rare boulders and are thinner (most <70cm)
- 250-350 **Gcmgrgn Gcmgn Gcsgrgn** >80% **Gcmgrgn** with cobble/boulder rich central horizon; 10% **Gcmgn**, similar to **Gcmgrgn** but no gr base; <10% **Gcsgrgn** in slightly thinner bed (most <50cm thick) and with boulders rare and slightly better sorting; imbrication of tabular clasts common in gr bases and rarely throughout bed, but no good 3D exposures of clasts to measure (2D exposures indicate northerly paleocurrents)

150-250 **Gcmgrgn Gcsgrgn Gcm-Gcsgrgn** described on following page

continued on next page

I L W

<u>Metres above base</u>	continued on previous page	<u>Sam ple</u>
150- 250	<p>Gcmgrgn Gcmgrgn Gcm-Gcmgn as below but now >70% Gcmgrgn; poorly sorted, most beds >60cm thick; <20% Gcmgrgn in thinner beds (30-70cm) with stratification suggested by slight clast size segregation and rare discont laminae in upper gn horizon; <10% Gcmgn; rare Gcagn; beds 30-125cm thick, most 50-80cm; contacts commonly subtle, welded, straight to sl wavy, non-erosive; beds appear to be laterally cont sheets; imbrication of tabular clast common in gr bases but not sufficiently 3D exposed to measure (all indicate northerly paleocurrents); clast lithologies: 50-60% PFu lite to med gray dolst (lam > bedded > mass); 10-15% dk gy calc mudst (PFi?); 10-15% orange wthr lam dolst (PGI) 10% dark red Sh (PFI or PHc?); <5% jasper; <5 chert (dk gy > lite gy); <5% chert/dolst bx (PFu)</p> <p>bedding: 117/26 SW, ave of 3</p>	
115- 150	<p>Gcmgrgn Gcmgrgn Gcmgn 80-90% granules to boulders in cse-grained Sm (rarely Sh) matrix; >80% 50-100cm thick beds with cobble-boulder rich central horizon and fair-poor gr base and fair-good gn top; rest have cobble-boulder rich lower 60-80% and gn top; poor sorting; rare vague size-segregated layering within beds suggest internally stratified (surges?); beds appear laterally cont >40m but thicken/thin slightly; contacts appear nonerosive; rare outlasted boulders up to 85cm dia in beds <1m thick; most matrix is pale-yellow orange wthr, med gy fsh, but <5% of beds have dark red wthr/fsh cse-grained Sm matrix; common fair to good imbric of tabular clast in gr bases or throughout (but 3D exposure sufficient for measuring is rare)</p> <p>bedding: 113/28 SW, ave of 4</p> <p>upward coarsening and bed thickening trend from about 115m to about 150m; above 150m no consistent trends in clast size or bed thickness to 250m; coarsening up again above 250m</p>	
75- 115	<p>Gcmgrgn Gcmgrgn Gcs-Gcmgn similar to 34-75m but fining and bed thinning upwards from 75m; beds <75cm thick and most 15-35cm by 100m; boulders rare, absent in beds <50cm thick; <20% cobbles; Gcs slightly more abundant than Gcm but no Sh interbeds; >95% of beds have fair-poor gr basal 10-20%</p> <p>upward fining and bed thinning trend from about 75m to 115m; change from coarsening up to fining up at about 75m is gradational, continuous</p>	
34- 75	<p>Gcm-Gcmgrgn Gcs-Gcmgn Sh >90% Gcm>Gcs with fair gr bases and gn tops; upward coarsening-thickening beds with >10% boulders (most 50-100 cm dia) in central horizons by 60m; beds 15-110cm thick; rare Gcmgn or Gcagn; internally stratified look from crude size segregation layers within beds (surges?); fair imbric of tab clasts in gr bases of Gcmgrgn and throughout Gcs beds (N or NW paleocurrents); <1% Sh in discont lenses eroded by cgl beds; clast lith: 50-60% med gy dolst (lam > thin bed > mass); 15-20% dolst-chert bx or interbedded; 10-15% orange wthr lam dolst (PGI?); 10% dark red lam Sh/FI (PHc); 5% jasper (PGI); <10% gy chert; <5% dk gy lam calc mudst (PFI?)</p> <p>bedding: 126/32 SW, ave of 5</p> <p>consistent upward coarsening and bed thickening trend from base to 75m</p>	
12-34	<p>Gcs-Gcmgn Gcs-Gcmgrgn Sh(gn) 85-90% granules to sm cobbles in cse-grained Sm; mod sorted in beds 15-50cm thick; >60% fair gn throughout, <40% basal 10-20% gr with rest gn; beds laterally cont >30m, bases sharp, sl erosive on Sh, tops sharp straight, clasts >75% subrd, <25% subang, 70% equant, 30% tab with tab clasts sub// beds or poor/fair imbric (N to W paleocurrents); rare possible open framework with red Sm infiltrated matrix; some Gcs beds possible trough x-bedded, troughs NW-SE oriented; <10% Sh (<1% above 34m) med- cse-grained, 3-8cm thick beds rarely gn to dark red FI top, laterally discont over about 30m (lenses or eroded by Gcs beds); clast lith: 50-60% med gy dolst (mass > lam/bedded); 20% orange wthr lam dolst (PGI?); 10% jasper; 10% dark red fg Sh (rip-ups of PHc?)</p> <p>bedding: 139/27 SW, ave of 3</p>	3 2
0-12	<p>interbedded contact over 20m; Gcs/Gcm erosive into Sh FI beds abundant rip-ups Sh/FI in Gcs/Gcm Sh FI >80% dark red wthr/fsh, fine- very fine-grained lam Sh and coarse silt mudstone; lams straight, cont, //, no ripples or other sed structures; <20% grn-gy wthr fresh-colour Sh; spotty & laterally changes to dark red Sh (map unit PHc)</p> <p>disconformity recessive, sharp, no regolith; defined within 2m</p>	1
0 to -20	<p>Dolostone (PFu) slightly resistant, light gray weathering, medium gray, laminated mudstone; lams slightly wavy (cryptalgae?); 20-25% blk chert nodules or layers // beds and up to 60cm thick</p> <p>bedding: 118/42 SW, ave of 4</p>

**Major
Unconformities**

ME-37 DESCRIPTION

261

Section located on north face of west trending ridge about 8km south of Mt Gibbon (see Figure A2-1).
Map sheet 110B/11. East seen in RCAP airphoto A131B-106.
Total thickness = 445 m

445+	dolomite (CDB) lite gray wthr. med gray finely crystalline, lam dolst with rare dolst bk layers covered - all CDB float - contact estimated from lowest CDB outcrop (>40m east of section)	2
422-423	Grimm/Gem 1.9m thick Grimm bed with 70-80% pebble, small cobble clasts in coarse-grained 3m matrix. Gem. 4m non-sorted, massive, med poorly sorted, top 50cm fair, en throughout to coarse-grained 3m top; beds not well exposed laterally, may be lenticular; basal contact straight to wavy, gray lam dolst (rarely crystalline); 10-15% lite gray mass dolst (mass > lam); 30-50% lite covered, mixed float of PHb and CDB	3
360-418	contact not exposed - base of PHb unit on PHe	4
348-360	dolomite 80% lite gy wthr. med gy very finely crystalline massive dolomite; beds 2-15cm thick (most thick in layers 3-12m); straight; 40% intercalated dk gy lam dol mudstone (sl xaline); lam <0.0cm thick in layers 3-12m; abundant white qtz and pink dolomite infilling discont pods of broken areas	5
280-348	contact not exposed - base of PHe unit on PHb	6
248-280	covered, mixed float of units from above	7
218-243	Grimm/Gem 75-85% pebbles/cobbles in med- to coarse-grained 3m matrix; borderline matrix- w/ clast-supported, support type varies randomly; poorly sorted, no grading, bedding indistinct, rare poor en below 20cm; 20-40% pebbles at 280m (largest 20cm); clasts all pebbles below 20cm and coarse to up to 20% high sphericity; tab clast sub// beds or poor imbrication (northerly paleocurrents); clast crystalline; 10-20% lite gy matrix; 30-40% dark red; 10% white > white > lite gy; 30-40% lite gy lam dolst (some, contact covered, PHb contact on PHe)	8
180-218	dolomite 80% lite gy wthr. med gy very finely crystalline massive dolomite; beds 2-15cm thick (most thick in layers 3-12m); straight; 40% intercalated dk gy lam dol mudstone (sl xaline); lam <0.0cm thick in layers 3-12m; abundant white qtz and pink dolomite infilling discont pods of broken areas	9
120-180	covered, abundant dark red P1 float	10
91-120	P1 Shgn 80-90% dark red silt to vfg sandy P1 lam in wavy, // cont, desiccation cracks more common than below 120m; 30-40% fine to med sand; 2-3cm thick beds slightly erode into P1; Shgn beds straight, //, cont, generally non-erosive but 2-3cm thick beds slightly erode into P1; Shgn beds commonly pale green gray sh, but change laterally to dark red; <5% lite gy in gy reduction spots 1-4cm dia in dark red P1 and rare discont 3m gy lay bedding: 090/25 S, ave of 3	11
85-91	covered, abundant dark red P1 float	12
61-66	P1 Shgn as below	13
33-48	P1 Shgn Grimm >80% dark red lam mudst > vfg Sh; lam //; cont; rare desiccation cracks; <5% gray med gray Grimm in 10-20cm thick beds; poorly sorted with 70-80% granular pebbles in coarse-grained 3m matrix; fair en with top 10% of coarse-grained shgn; clasts gen sub//, >60% tab; tab clasts sub// beds chert; 10-15% pale yellow orange Sh; (ripples PHe?); Grimm bedding: 090/25 SW, ave of 3	14
0-33	covered, abundant PHe float (most dark red P1)	15
0	dolomite not exposed but change in float from Pfu to PHe and slight bench in slope	16
65 to 75	dolomite (PHe) slightly resistant, med-dark gray weathering, medium gray finely laminated, algal of beds; top unit of Pfu	17

MS-28

Unconformity surface on north-facing slope of MS-28 bridge.

Metres
above
base

MS-22 DESCRIPTION

Sam
ple

Section located on east trending ridge north of Seala Pass at east margin of map sheet 116B/11 (see Figure A2-1). Lat. 64°41'35"N, Long. 139°03'10"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map sheet 116B/11. Best seen in RCAF airphoto A13230-155.

Total Thickness = 140 m

140+	dolostone (CDB) lite gy, finely xtal, mass dolst; 20-30% vugs (<0.5 cm dia), open or white qtz infill	7
140	disconformity contact not exposed	
138-9	Sm subcrop; as at 116-127m but 10% random small pebbles (most blk/dk gy chert)	
130-	Gcm (Gmm) 50% subcrop; 70-80% peb-cob in cse-grained Sm matrix; borderline Gcm-Gmm, >80%	6
138	Gcm with random Gmm layers; bedding not apparent; mod-poor sorting, no grading; clasts ang-subrd (most subrd), all shapes, >30% tabular; clast lithologies: 60-70% blk/dk gy chert (lam > mass); 20% lite gy mass fine xtal dolst; 10-15% lite gy lam dolst; <5% white/lite gy chert	
	covered, contact not exposed	
116-	Sm Gcm poor subcrop (5% outcrop), pale yel orange wthr, lite gy cse-grained, mass to very faintly thin	5
127	bedded; one Gcm bed about 50cm thick similar to outcrop at 130-138m	
	covered, contact not exposed	
9a-	dolostone pale yel orange wthr, lite gy very fine xtal lam dolst; lams sl wavy, cont, //; 10-15% irregular	4
115	lite gy/white chert veinlets conc in top 1m of unit bedding: 073/10 SE, ave of 2	
	contact sharp, non-erosive, map unit PHe on PHb	
	ridge crest: change from steep north-facing slope to shallow sth-facing slope with poor outcrop exposure	
70-98	Gms (Gmgn) 40-50% pebbles to cobbles in cse-grained Sm/Sh matrix; poorly sorted, very rare poor discont gn horis. ns suggest beds 30-60cm thick but generally bedding not apparent; poor vague lams in matrix, sub// tab elasts and slight gravel segregation (gravel-rich vs gravel-poor "horizons") gives stratified appearance; clast lithologies: all PFu; 50-60% blk/gy chert (lam > mass >); 20-30% lite gy mass fine xtal dolst; 10-20% lite gy lam dolst	
	contact gradational, PHb on PHd, all part of coarsening upward cycle from 1m to 108m	
47-70	Gmm-pShgn lite bn gy 40-60% con- small bldrs in cse-grained Sh matrix; 30-50cm thick beds, beds overlapping, lenticular with concave bases, 30->50cm long, straight tops, sl erosive on beds below; mod sorting with basal cob-peb rich (rare small blders) with poor gn to cse-grained, lam/thin bedded Sh with rare planer x-beds and ripples (all paleocurrents northerly); gravel clasts sub-ang to rd (most subrd), equant with <20% tab clasts (sub // beds); clast lithologies: all PFu types; 40-50% blk/dk gy mass chert > med gy lam chert; 20-30% kite gy mass fine xtal dolst; <20% med gy lam dolst (rarely cryptalgal); <5% silicified oolitic dolst; <5% white chert (mass>>lam)	3
	contact not seen, gradational and interbedded to east as part of coarsening-up sequence	
22-47	covered, Fl float: outcrop to east Fl>Sh coarsening up to Shgn Sp Sr >Sr (intertonguing contact with map unit PHd to east)	
1-22	Fl Shgn (Srgn) dark red lam Fl; clay-rich base, increasingly silty to vfg sand up; lams 0.5cm thick, //, cont, straight to sl wavy; rare desiccation cracks; <3% lite grn gy Fl changes laterally to dark red; Shgn/Srgn rare at base but increases up to 20% by 22m; Sh is fine-grained with rare cse-grained bases; rare xlam ripples (discont, starved), most beds 1-2cm thick, // cont, straight; sl loading/erosion of Fl bedding: 091/23 S, ave of 6	2
0-1	Gmgn 40-50% gran to small peb in cse-grained Sm matrix; mod-poor sorting; poor gn at top; clasts subang>subrd; most tab (random); clasts all PFu of unit below; <5% white chert veinlets sub// bed	1
0	disconformity sharp no bx or regolith; paleotopography apparent with PHc thickening to east and west of section as infill of paleolows on disconformity surface	
0 to -10	cherty dolostone (PFu) slightly resistant, lite gray weathering, med gray, finely laminated, finely xtal dolostone; lams slightly wavy, parallel, continuous; dolost contains up to 50% lite-med gy tabular, lam, chert fragments up to 10cm long, random or sub// bedding; >20% lite=dk gray chert as bed// nodules or massive beds up to 2m thick; top map unit of PFu	
	bedding: 075/20 SE, ave of 4	

4

MI 1700001 - RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

MS-30

Metres
above
base

MS-30 DESCRIPTION

Sam
ple

Section located near NW pinch-out of lower Harper group, about 800m east of west edge of 1:50000 map B/12. Lat. 64°42'53"N, Long. 139°59'07"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map sheet 116B/12 (Mount Harper). Best seen in RCAF airphoto A13140-202.

Total Thickness = 12 m

12+	volcanics unit PHV; dk rust brn wthr, dk grn gy fsh; massive, aphanitic mafic volcanic

contact sharp, sl wavy, top Gcm bed very orange wthr compared to others but no other alteration | 3 |
| 0-12 | Gcm Gcmgrn Gcmgr 80-90% granule to small boulder clasts in cse-grained Sm matrix; very poor sorting, about 50% nongraded with obscure, welded contacts; rest cobble-small bldr central or upper horison with thin (<10cm) poor gr base and less common gn top; beds 50cm-2m thick; contacts sl wavy/irregular (loaded?) with common projecting clasts; clasts subang >subrd; equant; <5% tabular (random); clast lithologies all PFu | 2 |
| 0 | disconformity sharp but wavy with about 3-5m relief over about 20m laterally; abundant fracturing of top 10cm of PFu but no preserved breccia/regolith on disconformity surface;
about 300m NW of section is preserved minor normal fault which displaces LHG/PFu contact (displacement about 75-100m, north-side down) but doesn't displace PHV/LHG contact. | |
| 0 to
-30 | dolostone (PFu) slightly resistant, light gray weathering, medium gray finely laminated mudstone, possibly cryptalgal; lams slightly wavy, parallel, continuous; about 20m below contact lithology changes to include about 30% dk gy chert as nodules, discont lenses and discont interbeds; top unit of PFu bedding: 137/36 SW, ave of 5 | 1 |
| -20 | dyke dark brown gray wthr, med gray green fresh, med crystalline, mafic, subvert to steeply north-dipping; intrudes PFu and LHG; contact with PHV not exposed | |

UPPER
MOUNT
HARPER
GROUP
SECTIONS

MS-15

Mudstone Number Name	Section located on east-facing slope about 12 km due west of Mt. Harper. (see Figure A2-2). Map 116C/9. Best seen in R.C. NP photo A1323-47. Total thickness = 215 m	SAM DLS
313	SED like GY med. striae dolomites, no textures preserved on fish surf; w/str surf cas sand text	10
305- 313	covered abundant flow F1 dk GY siliceous mudstones, al fine, very finely lam; wispy discont lam of sub-sand, qtz grains in thick cryptocrystalline clay	15 TS
240- 305	240 (F1) subtle coarsening/thickening upward trend; siliceous lam rare in top 50m; >70% brown-grey beds; <30% dark orange-grey (G dolomite) (rare G-striae) in 1-2 cm thick thin bedded both types; ripple in dolomite are linguoidal or complex interference wave ripple; rare 3-D xlam in sub-sand; <10% siliceous mudstone; dolomite very rare and not well exposed; xlam appear northerly on 3-D surface (no 3-D exposures)	14 TS
205- 235	240 F1 >80% brown-GY w/str, light olive GY lithic arenite (G-striae); vfg to lg thick beds; <20% dark orange-grey (G dolomite) (rare G-striae) in 1-2 cm thick thin bedded rich, some dolomite; <3% cas lithic arenite in 2-8 cm thick beds with poor normal grading; possible poor incipient ripples and xlam	13
184- 191	240 F1 GY med. striae dolomites, no textures preserved on fish surf; w/str surf cas sand text lower half, graded up to GY med. striae dolomites; 240 F1 bedded with 8% dolomite in this bed with loaded bases and thickening/thinning laterally; w/str is med sorted. 50% dolomite, 50% quartz first occurrence of mixed dolomite/quartz lithic w/str marks gradational change to unit PHS	13 137S 117S 10
174- 177	GMS med-dark GY tabular shapstone all of >200% clasts in orange-grey med-dark dolomite matrix; >80% clasts are tabular med GY lam calc w/str, <1-2 cm long, med 2-8 cm thick; clasts random, no grading, slight trend to tabular lone axes sub// bed; rare clasts collitic or massive calc w/str.	9 7
146- 174	240 F1 similar to 105-130m but very slight coarsening/thickening upward trend; now 10% med- to fine- grained dolomite in 1-1.5 cm thick beds, some with poor flutes at base, most load vfg Sh and silty F1 lam; xlam at top of some Sh thin beds	13
105- 120	covered fls of Sh F1 as below	6 TS
105- 105.5	240 F1 GY-orange w/str, lite olive GY sh; >80% fine-vfg dolomite, med/wall-sorted, lam-thin beds cont; // straight to wavy, rare plan ripples at top (w/str, cont, al wavy) and flutes on base (all southerly); med-dark GY sh (vfg?) grains; <20% vfg to cas silty F1 as recessive lam in 1-3 cm thick beds, loaded and fluted by Sh beds;	4 TS
60-80	240 med-dark GY tabular shapstone all of >200% clasts in orange-grey med-dark dolomite matrix; >80% clasts are tabular med GY lam calc w/str, <1-2 cm long, med 2-8 cm thick; clasts random, no grading, slight trend to tabular lone axes sub// bed; rare clasts collitic or massive calc w/str.	4 TS
0-1	covered but common F1 floor/subcrop in gully	3
0 to -2.5 -3.5 to -5.0	F1 dark GY non-calc mudstone, med fine, massive, al. silty; lam not seen; moderately sharp, slightly wavy, generally covered beds yellowish grey, rubble class-sub bc of angular xlam dolomite; no fabric; common (10-20%) chert veins <1 cm thick, random through bed, appear highly altered; original texture lost F1Y volcanic med GY are mag. volcanic/dolomite with <25% calc bc clasts up to 20 cm dia, bc random, no bedding, highly articulated and chloritized vol groundmass; no structures	2 TS TS

MS-16

Mudstone
Altoza
RMS

ME-18 DESCRIPTION

Section located on west-facing slope about 1.5 km west of Mt. Meade and 2 km north of ME-15 (see Figure A3-23). Loc. 84°41'10" N, 140°00'20" W in NTS map sheet 140B-116C(E NW) (D. Meade).
Figure A3-23: 1:50000 map 140C/E. Best seen in RCAP airphoto A3233-47.
Total thickness = 270 m

CRSs like δ^2 dolomite: fine-medium scale, lam to crinoid-bis; > 10% like δ^2 -white chert as repli dolost + bx incli
Contact not exposed, probably discontinuity

FI subcrop dk δ^2 wthr/fsh siliciclastic mudstones; very thin laminae; al fissile

covered, contact not seen

200-
255

SH (FI) 25% outcrop, rest subcrop or float; > 50% brown-grey, fine- to med-grained siliciclastic
litharenite in thin beds 1-4cm thick; < 40% lg to coarse-litharenite in thick laminae; rare orange-grey vfg
dolomite; no ripple or lamination seen; no trace fossils despite extensive search
to straight; no ripple or lamination seen; no trace fossils despite extensive search

137-
200

SH FI > 70% coarsening and increasing up brownish-grey wthr/fsh vfg to lg litharenite and siltst;
qts-chert rich with < 30% dolomite grains; chert may be silicified vfg; thick laminae al wavy, cont, sub//;
rarely discont, sub//; laminae with rare xlam starved ripple (south/southwest paleocurrents);

127-
137

FI SH dk δ^2 lvs siltst; lam al wavy, cont. //; 5-10% dk δ^2 lvs muds, rarely bluish-grey colour
(phosphatic); < 10% vfg lg lat wackest thin beds; massive, cont. //

SH FI 80% grey-orange lam, vfg dolomite intercalated with med δ^2 fine- to med-grained lat packet: 1-
4cm thick thin beds, //; cont; grad change in upper 2m to > 50% lat FI Sh above

98-
114

SH FI Gcm > 40% yellow-grey vfg-fg dolomite as below but some is calcareous (lat packets) with
x-lam starved ripples; 25-30% lam coe dolomite and δ^2 lat mudstone; four 20-100cm thick Gcm beds of
> 50% flat-pebble δ^2 lvs muds clasts in lat wackest marks; all clasts tab, ang to subang, 1-10cm long
and 1-2cm thick; //; bedding is fine-grained but non-erosive on Sh below;

86-98

SH FI as below but grey-red colour increasing (40-50% of beds) and 20% lam dolomite sets 2-10cm
thick intercalated with Sh; rare starved xlam ripples of med-grained lvs δ^2 dolomite; laminae 1-1.2cm
thick and < 10cm long; all southerly paleodip

SH FI > 80% δ^2 -orange wthr, like olive δ^2 fsh, vfg dolomite; lam/thin bedded, beds cont. //, straight to
sh wavy; rare hummocky cross-strata as domes 2-3cm tall and about 1m diameter, repeated sets of
HCS every 1-2m over 10m interval, separated by flat thin beds of Sh.

48-60

SH FI full-brn wthr, like olive δ^2 fsh, vfg dolomite (5% qts clasts), < 10% red wthr-colour and
dolomite; beds straight to al wavy, //; cont; bases sharp no loading or erosion; no obv bedding

22-48

FI SH alternating sets (decimetre scale) grey-red wthr/fsh and pale yellow brown wthr, lvs δ^2 grn fsh
dolomite and vfg dolomite; red colour increasingly common up to > 50% by 40m, appears to be
a gradual change to red and grey flows, not regular; top 5m is like δ^2 vfg dolomite; lam with 15 wavy cont
at wavy fine laminae to rare thin beds 1-1.2cm thick; thicker and coarser (to vfg dolomite) in top 2m as
gradational change to non-red dolomite above; very rare small, discont xlam; southerly paleocurrents
but none measured

20-22

FI SH grey-orange wthr, like olive δ^2 vfg to coe-silt dolomite; lam al wavy, cont, sub// with rare
wavy discont laminae vfg qts-rich dolomite (< 5% of unit)

0-20

Dolomite FI SH orange-brown wthr, med δ^2 fine xlam dolomite (some al siltst); 20% I.H. stroms and
stroms; rare chert/dolost bx (Gcm) with loaded bases on med and sub-med folds in FI overlain to
FI; appears to red and grey flows, not regular; top 5m is like δ^2 vfg dolomite; lam with 15 wavy cont
laminae and rare thin starved ripples of lg dolomite; paleocurrents al southerly; bedding: 032/26 NW ave of 4
covered grassy slope; float and subcrop of dk δ^2 PHS mudstone rarely exposed

0-20
-100

11

TS

10

PM

24

24

9

TS

8

TS

7

TS

6

TS

3

TS

1

TS

1

AD

1

A3

MS-17A

Metres
above
base

ME-17 DESCRIPTION

272 Sam
ple

Section located along north-trending ridge north of north Harper fault and PHV main ridge NW of Mt Harper (see Figure A2-2). Base of section at Lat. 64°44'30"N, Long. 140°02'11"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map 116C/9. Best seen in RCAF airphoto A13233-47. Total Thickness = 729 m

subvertical fault north side down, may dip steeply to north (normal fault); south of fault is MHVC but about 3m thick unit of grey-orange Gmm similar to base of section defines base of PH1/PH2; suggests dip-slip offset is about 1000 m here

- 615- FI dk gy calc mudstone (limestone); thin lams cont, //, sl wavy; mudstone is calc micrite, 729 microcrystalline with <30% brown mud (clay?) in TS; no signif. neomorphism; 10% carb concretions, elliptical, up to 60cm long axis, // to bedding; rare polygonal cracks infilled by same lam mudstone; poss syneresis: (not subaerial mudcracks), rare cse dolomite xtals and chert (replacing dolomite) in cracks bedding: subhorizontal to <5° SW
- 580- Sh FI Gcmbr >80% grey-orange fine-med lam/thin bd dolarenite as below with rare xiams at top of 615 thin beds; <20% dk gy lam calc mudstone as below and above; one 1m thick Gcmbr (flat peb cgl) all clasts tabular, med gy calc packst/wackst, sub// bed to poor imbric (southerly paleoflow), base sharp loaded, no erosion; massive, no grading
- 562- FI dk gy limestone mudstone; fine lams, cont, //, sl wavy to straight, rare carb concretions up to 60cm 21a 580 dia (most 3-20 cm), elong // bedding, poss sl cser than mudst surrounding 21b 20
- 532- Sh FI Gcmbr >70% vfg-med dolarenite as below; <30% FI: mod red and lite grn non-calc mudst in 5- 562 20cm thick sets of thin lams; in top 5 m rare dk gy calc mudst interbeds 1-5cm thick as gradational change to calc mudst above; three 10-40cm thick med gy flat peb cgl (Gcmbr) of 80-90% tab clasts calc wackst, tab clasts 1-8cm long axes, sub// bed, loaded base, not graded, no good imbric bedding: 083/18 S ave of 6
- 515- Sh (FI) as below but coarsening/thickening up slightly; now 20% fine-med dolarenite thin beds (1-4cm) 18 532 as resistant interbeds in sets up to 40cm thick; >80% vfg dolarenite and rare dolosiltite; contacts sharp, nonerosive, no loading; rare sl wavy thin beds with dome/swaley morphology of poor HCS (possibly swaley type), rare xlam ripples at top of fg Sh thin beds 17
- 500- Sh (FI) >80% gy-orange lam vfg to cse-silt dolarenite, <20% lam to thin bd fg dolarenite; both straight, 515 cont //, massive, no obv grading, no xiams bedding: 110/11 SW ave of 6
- 480- FI Sh FI as below but now interbedded vfg dolarenite thin beds, same as overlying unit PH4, 500 increasingly common up as gradational contact to PH4

FI as below, all non-calc mudstone; one 20cm thick set of convolute lams (synsed slump?)

16

section relationships
(faulting removed)

MS-17B

310-480	F1 as below but all dark gy mudstone, no dolarenite interbeds; <50% poor outcrop or subcrop; >50% scree of F1	
290-310	F1 Sh >80% dark gy non-calc mudstone; silty, fine-lam; lams straight, //, cont; strong pencil cleavage; <20% grey-orange vfg dolarenite thin beds to thick lams bedding: 109/13 SW ave of 2	15
260-271	covered: disconformity suggested by bx below and from other sections to north Bx lite grey wthr, med grey mosaic/crackle breccia of fine-med crystalline dolostone; altered to >90% crystalline dolomite, frags up to 50cm size, ang-sub ang but appear <u>in situ</u> , poss sl rotated, clast edge alter'n cause pseudorounded look; <10% irregular chert; orig text lost except rare poss micritic intraclasts(?); common subvert/horiz white chert veinlets 1-3mm wide. Poss subaerial exposure altered? covered: most float is volcanic; top 50m is pale orange brown wthr, fine-med pSh dolowackest (PH2?)	14 13 12
	*** description above here is for MS-17A covered: prob sub-vert, east-trending fault drops nth side 100-200m; section restarted about 200m to east (MS-17B), across fault; MS-17A PH1 congl similar but thick covered interval with abund PHV mafic volc float suggests intertonguing of PHV and PH1 between MS-17A and MS-17B MS-17B DESCRIPTION	11 10 volc
155-200	Gms F1/Sh(gn) Gmm(Gcm) >80% Gms: 50-80% grn-bldrs in med-v cse dolowackest; poor sort, matrix crudely bedded/lam defined by sl segregation of v cse + med sands in discont lenses (<2m), poor gn in some lenses; beds 1-2m thick but contacts vague; appear lat cont, sl wavy, loaded bases but non-erosive; projecting clasts common; clasts in Gms >80% Pf as below, but <20% volcanics: grn-gy vesicular or massive, mafic, aphanitic. volc. No volc clasts in Gmm(Gcm) F1/Sh more common than below 150m and thicker (up to 1.5m sets); most is dolosilt/vfg dolowackest, cont, subb// lam to thin beds; <30% fine-med Shgn dolowackest in 1-2cm thin beds; <10% peb, rare cob random lonestones, no dropst struc; Gmm as below but rare (<10%)	8 9
102-155	Gmm(Gcm) Gms pSh(gn) 70-80% Gmm(Gcm) as below; >75% matrix-sup, 20-30% bldrs (to 1m dia), many in centre of beds but no grading; very poor sorting; most massive but rare beds have discont internal lams/thin beds; beds 1-2.5m thick defined by 10-30cm Shgn interbeds, but may be composite; clasts subang-subrd, mod-high sphericity, 30% tabular (random fabric); clasts all PF: >50% med-lite gy lam dolst (some cryptalgal/strom/oncolitic) > irreg white chert/dolst (PHa?) > dk gy lam lat wackest/mudst > blk chert; no volcanics; Shgn silt-med dolowacke, lam/thin bd; most lat cont >20m but thicken/thin greatly and strongly loaded by Gmm; good parting lineation on dolosiltite bed surfaces bedding: 141/52 SW ave of 5 covered, abundant grn-gy vesicular mafic volc flt; prob PHV intertongue (fault unlikely)	
65-68	Gms pShgn 60-70% peb-bldrs in med-v cse dolowackest; mod-poor sorting, no grading, but irregular discont, sl wavy lams in matrix, pShgn alt vfg-fg and med-cse lams/thin beds .5-2cm thick of dolowackest; good gn; <10% peb in thin beds at base or throughout; rare peb-cob (to 20cm) lonestone pierce beds but no dropstone struc. some shelter fills on sth side of lonestones bedding: 129/32 SW ave of 5	7B 7A 6
0-47	Gmm(Gcm) pSh(gn) F1 30-70% peb-bldrs in med-v cse dolowackest; v poor sorting, mass, no grading; >80% matrix-sup to borderline clast-sup (<30%); beds 1-3m thick def by irreg discont peb-rich lenses 3-5cm thick, < 1m long (but repeated laterally at same level); Gmm beds sheet-like >100m laterally, poss vague concave-bases suggest channelized on 500m scale?; clast mod-high spher, subrd-subang, 30-40% tabular (random or sub// beds); bldrs <30%, many conc in centres of beds (but no grading), some outsized (up to 2m dia); clasts >95% PF: med to lite gy lam dolst (many cryptalgal/strom) >> white chert > blk chert > oolitic/oncolitic dolst > blk dolst; 5% silicified dolst, poss PHa unit; Sh med-v cse dolowackest with <10% random peb lonestones (no dropstone struc); <15cm thick, irregular but semicont laterally >20m; loaded by Gmm; faint lams/thin beds, rare xlam ripples (sth paleoflow) F1 silt-vfg dolowackest/siltite, lams cont, sub//, sl wavy; good parting lineation on some surfaces (nth-sth) contact not exposed bedding: 093/32 S ave of 4	5 4 3 2 1
0 0 to -10	PHV volcanic green grey aphanitic mafic volcanic

MS-22

MS-23

Maxima
above
base

ME-22 DESCRIPTION

Section located along southeast trending ridge, 500m above NE side of UMHG exposure, two ridges SE of MS-19 ridge (see figure A3-3). Lat. 54° 48' 32" Long. 140° 05' 30" W in NTS map sheet 116C-116C(E half) (Dawson), Yukon; 1:50000 map 116C/16. Best seen in RCAP airphoto A13233-49.

Total thickness = 280 m

subvertical normal fault, north trending; drops west side about 200m; UMHG across fault is poorly exposed repeat of section on east side and not measured

covered: common float and subcrop of Gmm as below

Gmm Gmm gray orange with, like G7 fab; 80-90% peb-bldr clasts in fine-ess dolowacke matrix; very poorly sorted, massive, no obvious bedding, no grading, random fabric; clasts subang-subbrd, mod sphericity (30% tabular, random to sub//bed); no vol. clasts; all PF types; 28-40% like G7 lam dolst (some with small subang-subbrd clasts); mod G7 dolst, 20% chert/dolst breccia and G7 chert; 10% dk G7 lam lat mudstone (some stroms)

snow-covered

Gmm(Gmm) Gmm similar to below, 80% Gmm(Gmm) with 70-80% peb-bldr, 40% Gmm with 80-90% peb-bldr in subang-subbrd matrix; no grading, random fabric; clasts subang-subbrd, mod sphericity; 28-40% like G7 lam dolst (some with small subang-subbrd clasts); mod G7 dolst, 20% chert/dolst breccia and G7 chert; 10% dk G7 lam lat mudstone (some stroms)

PH2/PH3 contact taken as gradational change where volcanic clasts no longer present in conglomerates

Gmm as below but 20% large boulders (1-2m dia), all PF's strom/cryptalgal dolst

covered: Gmm/Gmm as below in unaccessible cliff

Gmm(Gmm) Gmm F1 decreasing F1 and increasing clast content; now 70% Gmm(Gmm), similar to Gmm(Gmm) below but 70-80% clasts; crude segregation of cob-bldr in central layer suggests bedding is 1-2m thick; 1-2m thick, at stratified look in some faulted by slight cleavage; clasts subang-subbrd, mod sphericity; 28-40% like G7 lam dolst (some with small subang-subbrd clasts); mod G7 dolst, 20% chert/dolst breccia and G7 chert; 10% dk G7 lam lat mudstone (some stroms)

Gmm(Gmm) Gmm F1 G7 orange with, mod G7 fab; 70% Gmm(Gmm); 80-70% peb-bldr in fine-ess dolowacke matrix; poorly sorted, massive, no grading, random fabric; clasts subang-subbrd, mod sphericity; 28-40% like G7 lam dolst (some with small subang-subbrd clasts); mod G7 dolst, 20% chert/dolst breccia and G7 chert; 10% dk G7 lam lat mudstone (some stroms)

snow-covered: patchy exposures of Gmm(Gmm) and F1 as above but Gmm beds <1 m thick and less common;

unconformity: not exposed, appears in ridge PF is about 15 degrees steeper than UMHG
PFs dolowacke, like G7 fine xtal dolst; very cryptalgal laminated and LHR stroms in top 5m 8-50% mod G7 chert mudstone, discont lenses and complete bedding 008/33 NW (estimated from wavy lam)

MS-24

Metres
above
base

M3-24 DESCRIPTION

283 Sam
ple

Section located along north face of north-trending spur of NE divide separating Eagle Creek headwaters from NW trending straight valleys of main PH2 exposure (see Figure A2-2). Base of section at Lat. 64°46'54"N, Long. 140°04'11"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map 116C/16. Best seen in RCAF airphoto A13233-49.

Total Thickness = 132 m

>135	PH4, PH5a repeat of section below but rare poorly preserved horis trace fossils (<u>Planolites</u>) in top 20m of upper PH4 dolostones	
135	thrust: not exposed but can see in ridge to SE, repeats PH4	
115-132	Sh dark yellow-orange weathering colour, yellow-grey fresh; cse silt to very fine-grained dolarenite; very well-sorted, laminated in thin lams, sub// to sl wavy, continuous; very similar to PH4 below chert-peg clgs but contains rare desiccation cracks and intraclasts of orange-grey dolosiltite (rip-ups); very rare and poorly preserved vertical burrows (<u>Skolithos</u> ?); rare wavy lams may be cryptalgal covered, contact not exposed	9 TS JAD A33
101-112	St pshgn pale yell-brn wthr, brn gy fsh; med- v cse lithic arenite, mod-well sorted; 1-4cm thin beds with fair gn, sl wavy cont; 50% overlapping trough xbeds about 1m long and 10-30cm high but erosive, lower part of trough only; troughs cut down to north (northerly paleocurrents)	8 TS
82-101	Gcmgn pshgn dark gy grn wthr, grn gy fsh, >90% gran-peg in med-cse lithic wacke; mod-well sorted in beds 15-75cm thick; overlapping concave-based lenses 50-100cm long; bases erosive, tops grade to cse-med litharenite; rare composite "surge" beds total 1-2m thick w welded contacts; clasts >60% tab, most subrd-rd, sub// bed or poor imbric; clast lith: >60% chert, polychert and lam (silicif dolst?) 20% white qts (straight ext, volc?), 10-15% chert-sericite mix (silicified volc?), <5% orange-gy dolst PH4 ripups; pshgn <25% of beds; mod yell-brn cse-v cse lithic arenite; top of Gcmgn or sep beds 1-5cm thin beds in 2-20cm thick sets; mod sorted; clasts 50% chert-sericite mix (silicified volc?); 30% "clean" qts; 10% polyqts; 10% dolospar' rare brn-red Fe micrite (matrix?)	7 TS 6 TS 5 TS 4 TS
52	contact: sharp, wavy, erosive with 3-5m relief over 100m laterally bedding: 124/27 SW ave of 3	
65-82	Sh Fl >75% vfg yellow-orange weathering lam dolarenite as below; <25% med gy dolosiltite; recessive, sl fissile, mostly cse-silt sized, lam in sets 5-10cm thick; lams //, cont, straight	
6-65	Sh dark yellow-orange weathering colour, yellow-grey fresh; cse silt to very fine-grained dolarenite; very well-sorted, laminated in thin lams, sub// to sl wavy, continuous; monotonous with no ripples of other structures; possibly subtle gn in thin section; <3% qts (TS); rare faint HCS in three layers evenly spaced between 30 and 50m above base; HCS as subtle domes-swales with 3 - 5 cm total relief and 1 - 1.5 m wavelength; above 50m are very rare starved ripples <1cm high and <5cm long of fg dolarenite; internal xlams indicate southerly paleocurrents but no 3D exposures so not measured bedding: 128/22 SW ave of 5	3 TS
	contact appears sharp, non-erosive	
0-6	Sh(gn) FL gy-orange wthr, yell-brn fsh vfg to cse silt dolarenite; thin lams cont, //, subtle gn, very well sorted; <2% qts grains; lams occur in 60-100cm sets; <40% intercalated med red wthr/fsh dolosiltite (<10% hematitic micrite? coating dolospar grains gives red colour); very fine lams in 30-60cm sets; rare 2cm thin beds of fg normally graded dolarenite	2 TS 1 TS
-25	thrust not exposed but can be placed within 25 m and is exposed 500 m NW and cont for about 4 km	
-30 to -40	Cdb dolostone, lite-med grey med xtalline, poorly exposed but some internal folding observed	

MS-25

Metres
above
base

M2-25 DESCRIPTION

Sam
ple

Section located on south-facing slope of east-trending ridge north of Eagle Creek headwaters (see Figure A2-2). Lat. 64°46'50"N, Long. 140°08'15"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map 116C/16. Best seen in RCAF airphoto A13231-167.
Total Thickness = 1395 m

>1395	CDb dolostone: lite gy finely crystalline lam dolostone contact not exposed; appears sharp, probable disconformity	14
1375- 1395	Sh abund float, 30% subcrop, 30% outcrop: 70% orange-gy fg dolet lams/thin beds; 30% brn-gy qtz-rich litharenite lams/thin beds (>60% qtz, 20% chert, 20% chert-sericite mix [silicified volc?]); all sub//, cont, straight to sl wavy; trace fossils in top 50m but most from subcrop or float, most on litharenite bases: <u>Planolites</u> > <u>Crusiana</u> , <u>Rusophycus</u> , rare <u>Arenicolites</u> , <u>Skolithos</u> in top 15m in dolarenite but with qtz-rich fill bedding 083/40 N ave of 4	13 TS 1988 8a,b 9a-c
1340- 1375	Gcmgs subcrop and outcrop: dk grn-gy wthr, grn-gy fsh >90% gran-cob in cse chert-rich lithic wacke; mod sorted and fair gn in 20-79cm thick beds with peb-cob bases and granule-small peb tops; beds sl concave-based, prob <100m overlapping lenses? (poor lateral exposure); clasts subrd-rd and common tabular clasts sub// beds or fair imbric (northerly paleocurrents); clasts > 60% med-lite grn chert (silicified volc?) + lite gy chert; <20% gy-orange dolarenite (ripups PH4); 10-20% med red lam chert; rare med gy lam carb (PH4?) bedding: 086/32 N ave of 2 covered, float of Sh Fl as at 1290	
1263- 1290	Sh Fl float, subcrop and rare poor outcrop: 70-80% orange-grey vfg to silty dolarenite lams to thin beds; >20% vfg qtz-rich lithic arenite lams, dolarenite less common up contact not exposed, conformable, gradational	
1250- 1263	F1 Sh 60% dk gy lam limestone mudstone as below in 1-3cm sets, intercalated with orange gy vfg dolarenite as below, lam to 1.5cm thien beds, all sub//, cont, sl wavy; 5% carbonate concretions elongate // bedding and up to 10cm long, 7cm thick; same as concretions in MS-17 lat mudstone covered no float	12 TS
1210- 1215 1195- 1210	F1 dk gy limestone mudstone, thin lams sub//, cont, sl wavy; rarely broken and poss "teepee" structure with white calcite infill between tabular mudst clasts <1cm thick and 2-5cm long Sh gy-orange wthr, yell-gy fsh fg dolarenite; lams sl wavy, cont, //; well-sorted sand is >97% dolospar clasts, <3% qtz, <3% dolomitic matrix; <3% white calcite veinlets sub// lams and discont <1m bedding: 051/39 NW ave of 5 contact not exposed, conformable and gradational	11 10 TS
1150- 1195	F1 Sh subcrop; same as below but Sh thin beds now 20-30% probably represents gradational contact to PH4 above	
45C- 1150	abundant float and subcrop of F1 Sh as below; no outcrop but definitely all PH3 in slope; orange-grey Sh very slightly increasingly common up; poor exposure in gully 500m to west is internally folded, possibly a minor thrust repeats PH3 within the grassy slope? would account for unusual thickness of unit

Metres section continued on previous page
above
base

Sam
pls

abundant float and subcrop of Fl Sh as below

- 285- Fl Sh abundant float, <10% subcrop/outcrop; dark grey noncalcareous mudstone (slightly dolomitic in upper third); thin laminae, //, cont, sl wavy to straight; Sh: grey-orange vfg dolowacke to dolosiltite, lams to rare thin beds as individual beds and sets up to 40cm thick; increasingly common up but <20% of unit in general 9
- 450
- PH3/PH2 contact covered; probable disconformity as at MS-23 and MS-17
- 265- Gmm as below but 1 bldr 7.5m dia (subpherical, rd PFu), rest <50cm; >10% white chert + euhedral qtz crystals in vugs to 10cm dia + abund random stringers: poss subaerial expos surf (silcrete alter'n)?
- 285 abundant Gcm float
- 248- Gcm(gr) resistant ribs in grassy slope; yellowish grey wthr, med gy fish, 85-95% peb-bldr in cse dolarenite matrix; mod-poor sorting; poor gr bases suggest 1-1.5m beds with welded contacts; laterally cont >50m; clasts mod-high sphericity, subrd; 100% PF types: gy mass dolst > gy lam dolst (some cryptalgal) > gy oolitic dolst > dark gy lam let mudstone (PF1?), rare blk chert; 3-5% white chert alteration as rims and infill to clasts, definite late secondary silicification; in thin section all cement is chert as fibrous chacedony, spherulites and equant blocky qst pore fill (silcrete?)
- 252
- 171- covered: rare Sh Fl float suggests coarsening upward sequence as in MS-19
- 248
- 149- Gmm all yellow-orange wthr; med grey fish here and above; 40-50% peb-bldrs in med-cse dolowacke matrix; massive, poorly sorted; ungraded beds 70cm-2m thick; >30m laterally; clasts <20% bldrs, subrd, mod-high sphericity; clasts >90% PFu, <10% mafic volc. most lam grey dolst (some cryptalgal/strom), <30% mass grey dolst>blk chert>chert/dolst bx;
- 171 gradational change to yellow-orange PFu-rich Gmm of map unit PH2
- 128- Gmm Fl Sh grey green wthr/fish Gmm as below in 20-80cm beds, most peb-cob rich, bldrs rare; clasts >70% mafic volc;
- 145 Fl and Sh as below
- covered - abundant Fl Sh float
- 100- Gmm Fl Shgn volc tuff/flow 60-70% peb-bldr clasts in fine-med dolowacke matrix; massive, random fabric; beds not obvious; clasts 70-90% mafic volc, 10-30% PFu; Fl laminated dolomudstone; lams //, cont, straight; rare Shgn of fine-grained dolowacke (poss volcanoclastic-rich); one 50cm thick mafic volc with reworked top and grades to Fl, poss tuff?
- 123 bedding: 040/15 NW 1 measure
- 62-100 Gmm Fl volc flows/tuffs Gmm as below, random mafic volc clasts (<15% PFu clast), slight fining-up trend; Fl dolowacke/mudst but greenish (volcanoclastic) look; lams cont, sub//, sl wavy; volc flows of plag microlathes and glassy groundmass poss sl reworked tops grade to Fl suggest may be tuffs
- bedding: 012/24 NW ave of 4
- 61 volcanic flow 1.2 m grn-gy, highly altered (dol and hem) aphanitic, glass and random plag microlathes
- 51.5-61 Gmm as below; 60-70% peb-bldr clasts, >95% volc but 1 PFu bldr 3m dia; massive, no bedding
- 39-51.5 Fl Gmm >70% grey grn dololomite/siltite; lams //, cont, sl wavy; interbd 20-50cm Gmm of 60-70% peb-cob clasts (volc, <10% PFu) in gy grn dolowacke matrix; beds cont, sharp, loaded, nonerosive bases
- 0-39 Gmm Gms 20-70% peb-bldr clasts in med grey grn fine-cse dolowackestone; massive, dark grey brn wthr; very poorly sorted, ungraded, random fabric except rare irregular discont lams in some beds (Gms); beds 20cm - 2.5m thick (most 50-120cm), laterally sheetlike >100m; sharp, sl loaded, nonerosive bases; >80% volcanic clasts in most beds and volcanoclastic rich matrix; all others PFu or rare Pha types and rare beds have PFu clasts up to 90%; <10% discont, pebbly, matrix-rich beds 20-50cm thick with a mud-rich, vaguely lam, between boulder-rich beds; clasts mod-high sphericity; subang-subrd
- 0 gradational change to interbedded agglomerates and conglomerates; rare volc flows/tuffs
- 0 to PHV volcanics tan wthr, green grey mafic volcanic (andesite?): hypocrySTALLINE, >70% microcrystalline
- 10 plag microlathes with <10% phenocrysts (feldspar, olivine?) now altered to dolomite; strong carbonate alteration of groundmass and phenocrysts 1

MS-26

<u>Metres above base</u>	<u>ME-26 DESCRIPTION</u> Section located on nth-facing slope of east-trending ridge (site of guides airstrip and storage cabin) at headwaters of Eagle Creek (see Figure A2-2). Lat. 64°45'16"N, Long. 140°09'26"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map 116C/16. Best seen in RCAF airphoto A13231-167. Total Thickness = 1312 m	<u>Sam ple</u>
>1312	CDB lite gy fine xtall dolostone; thin bedded: oolite + intraclast beds common: rare dololutite intrabeds contact not exposed; probable disconformity bedding: 102/32 SW ave of 4	12
1291-	F1 broken subcrop of dark grey-brown finely laminated siliciclastic mudstone	11
1292	Sh orange-grey weathering, dark grey fresh, finely crystalline (fine-grained) dolarenite, laminated to	
1280-	thin-bedded, //, cont, straight to sl wavy beds; crackle-brecciated layers up to 10cm thick with white	10
1291	dolomite infill; this could be an unusual facies of unit CDB bedding: 100/29 SW 1 measure	
	covered, abundant float Sh as below	
1020- 1220	Sh Shgm 50% outcrop > subcrop; 50% extensive float; all med grey siliciclastic qts-rich lithic wacke; lams to 1cm thick beds; >90% very fine-grained to fine-grained in //. cont lams; <10% 2-4 cm thin beds of medium- to coarse-grained, qts-rich lithic wacke; poor normal grading; beds thicken thin slightly laterally and load fg Sh, rare microflame structures and very rare xiams at top of graded beds indicate northerly paleocurrents; no trace fossils despite extensive search	
1010- 1040	minor thrust fault saddle with broken bedding and some vertical beds in 30 m interval of subcrop; can see thrust to NW in repeating PH5 and CDB; estimate 100-200m of repeated section	
900- 1000	F1 Sh as below

Metres above base	section continued on previous page	Sam pls
760- 900	Fl Sh as below but with very subtle coarsening-up in quartz wacke lams, 50% vfg to fg by 900m, rest is siltstone; poor gn in many lams, <5% orange-grey dolarenite lams/thin beds bedding: 094/19 SW ave of 6	9
748- 760	Fl Sh gradational change over 10m to <10% fg orange-grey dolarenite as below in 1-2cm thick thin beds or lam sets; >90% med-dk gy silt-vfg quartz wacke lams; lams //, cont straight	8
703- 748	Sh grey-orange fine-grained dolarenite, lam to thin bedded, sl coarsening/thickening up trend; lams sl wavy, cont., rare xlam ripples (cont, sl wavy) and very rare swaley or HCS strata; <15% vfg-cse silt dolarenite as recessive lam sets 10-40cm thick, less common up (<5% in top third); contacts st to sl concave, nonerosive, very rare poor groove marks at base of fine-grained Sh; one 10cm thick flat-peb cgl (Gmm) of tabular Sh clasts <3cm long axes (ripups) in identical matrix tab bedding: 096/34 SW ave of 5	7a 7b 7c
495- 703	covered; abundant float 60% blk noncalc Fl, 40% pale yellow brown vfg Sh(gn) dolowackest	
494- 495	Gmm 75cm thick bed similar to Gmm at 240m float of Fl, Sh and Gmm	
468- 470	Gmm single 2m bed 50-70% peb-cob in fine dolowacke; similar to Gmm at 240m; clasts all PF	
259- 468	covered; rare float and outcrop in creek 500m to east is PH3 dark gy finely lam mudstone	
240- 259	10-20% outcrop; abundant subcrop and float suggest ribs Gcm separated by Sh Gcm Gmm grey orange wthr, med grey fsh; 80-90% clasts in fine-granule dolopackst/wackest; poorly sorted, massive, ungraded beds 75-120cm thick, laterally cont >20m; clasts random fabric, med-high sphericity, subrd, 100% PF, no volc clasts; types: med gy lam dolst > med gy mass dolst > chert > chert/dolst bx; prob interbeds Sh not exposed	6
132- 240	covered rare float Fl/Sh (all dolowackestone/siltstone suggesting part of PH2 coarsening-up sequence) PH2/PH1 gradational contact not exposed	
36-132	Gmm Gcm(30%) Fl(15%) alternating volc-clast and PF-clast rich Gmm/Gcm similar to below; >80% of beds volc-clast rich, brown wthr, med grey fsh; 70-80% peb-bldr clasts but <20% bldrs; poorly sorted 20cm - 2m thick beds (most 50-120cm), no grading, beds sharp-based, non-erosive but load Fl, laterally cont >30m; volc clasts all lite-med green aphanitic mafic volc, vesicular and black spotted (chlorite-altered phenocrysts?); PF-rich Gmm/Gcm orange-brn wthr; med gy fresh; similar to below; Fl 20-100cm thick sets of lam grey green mudstone to vfg wacke; sl dolomitic; lams sl wavy, cont, sub//, drape projecting clasts of Gmm/Gcm and loaded from above bedding: 116/28 SW ave of 4	5
0-81	Gmm Gms Fl >40% (increasingly common up) grey orange wthr, med grey Gmm/Gms with 50-80% peb-bldr clasts in grey-green fine-med dolowacke matrix (poss volcanoclastic also); very poorly sorted, generally massive (rarely poor discont Fl lenses suggest Gms); beds 10-170 cm thick (most 30-70cm), some composite beds in 5-7m sets; clasts med-high sphericity, subrd-subang; clast 90-90% PF types: lam gy dolst >> mass gy dolst > gy-blk chert; <50% Gmm (decreasing up) of 70-90% peb-bldr clasts (60 to >90% volcanic) in green grey fine-grained wacke (dolowacke) matrix; very poorly sorted, beds 20-120cm; clasts med-high sphericity, subrd-subang; <40% PF clasts (generally <15%); most conglomerates sheet-like >50m laterally, rarely sl concave based lenses thin over 30-30m laterally; bases sharp, sl loaded into Fl; projecting clast common at top; Fl 10-15% of unit in 5-50cm thick sets of lam green grey mudstone (volcanoclastic?), lams sl wavy, sub//, cont, loaded by Gmm/Gms beds above and drape clasts of Gmm/Gms below; no pyroclastic bombs or volcanic flows/tuffs seen bedding: 085/23 SE ave of 3	4 3 2
0 0 to -65 m	PH1/PHV gradational contact taken as first Gmm bed with <90% volc clasts Gmm Gcm Fl + volc flows/tuffs PHV-PH1 transition: volc agglomerates and rare mafic flows/tuffs; pyroclastic bombs up to 30 cm dia in several Fl beds; Gcm/Gmm 10-80cm beds repetitively interbedded with 5-150cm of lam Fl; brown wthr Gmm/Gcm 60-80% peb-bldr clasts (all volc) in grey green volcanoclastic wacke matrix; carb alter'n common; Fl is grey green volcanoclastic mudstone to vfg wacke (rare Shgn); rare mafic volc flows or tuffs up to 25cm thick bedding: 085/23 SE ave of 3	1

MS-29

Metres
above
base

MS-29 DESCRIPTION

Sam
ple

Section located at southeast end of upper Harper group exposure, cut by North Harper Fault of Roots (1986) (see Fig. A2-2). Section on north-trending grassy spur north of PHV cliff, measured from nth to sth. Lat. 64°43'38"N, Long. 140°00'30"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:80000 map 116C/9. Best seen in RCAF airphoto A13140-202.
Total Thickness = 122.5 m

est 200 Mount Harper Volcanic Complex (PHV) >200 m high cliffs of med green mafic volcanics
base estimate, no float in grassy slopes below PHV

covered grassy slope - no float fault clear in cliffs to northeast and can be located within 50m in slope by projection

121-122.5 Gmm single 1.5m bed, same as Gmm at 50-92m but no volc clasts

covered; abundant float and 5% subcrop Gmm as below and Shgn in <5cm thick beds with granule bases grading to laminated fine-med dolowacke tops

97-100 Gmm Sh as at 38-50m

50-92 Gmm: grey orange wthr, med grey fsh; 30-50% peb-bldrs in vfg-granule dolowacke matrix; very poorly sorted (diamictite), massive, ungraded, random fabric; no beds discerned (prob composites with welded contacts); clasts mod-high sphericity, subrd, 85-90% PF, 10-15% volc (green-grey, massive, vesicular); PF: med grey lam dolst (some cryptalgal + strom) >> dark grey lam dolst, med grey mass dolst > dark grey chert

38-50 Gcm Sh(r) Gmm Gcm >80% peb-bldrs in med-grained dolowacke matrix; clast >90% PF, <10% volc; Gmm <80% clasts but similar to Gcm; >20% sm bldrs; beds 50-70cm thick, non-erosive, loaded base; Sh vfg-fg dolowacke/arenite; lam-thin bedded; lams wavy // with abundant xlam ripples and draped lams; all paleocurrents southerly

bedding: 199/12 NW ave of 4

10-19 FI/Sh Gcmgn Gmm gy orange wthr, med gy fsh; lam dolosilt > fg dolowacke, cont, // lams; 25% Gcmgn: 80-90% peb(-cob) in cse dolowacke; 20-25cm thick, fair gn, mod sorted; bases non-erosive, loaded into FI; clasts <80% PF, <20% volc; one 20cm thick peb-cob Gmm as below
0-10 Gmm 2 beds 70,100cm thick; gy orange wthr, med gy fsh; 30-40% peb-bldr clasts in fine-cse dolowacke matrix; very poor sorting, no grading, random fabric; clasts 10% volc as below, 90% PF: med grey lam dolst (many cryptalgal and stromatolitic) >> med grey mass dolst > dark grey lam dolst
0 contact not exposed, possibly disconformity?
0 to PHV agglomerate/breccia dk red brown wthr, dk gy grn agglomerate/rubble breccia? >90% mass mafic
-10 volc clasts in dark green volcanoclastic matrix, mod-poor sorted with no beds or fabric; clast peb-sm bldr, angular, mod-high sphericity; rare discont white qts lenses sub// bed, up to 1m long, 5cm thick

3

2

1

MS-31

מהרה

Metres
above
base

MS-31 DESCRIPTION

Sam
ple

Section located at east side (on east-facing cliffs) of small isolated UMHG inlier (Baldie Inlier of Roots, 1986) at top of MHVC, near north end of main volcanic ridge (see Figure A2-2). Lat. 64°42'30"N, Long. 140°00'00"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map 116C/9. Best seen in RCAF airphoto A13140-202.
Total Thickness = 80 m

> 80	PHV volcanic agglomerate, similar to agglomerate at base of section, fault repeated	
80	Thrust cuts section out to south, northwesterly directed, fault gouge and bx common	
78-80	Sm med grey fg limestone wackestone, massive, no bedding or structures	7
66-78	Gmm(gn) Fl >60% Gmm in 20-50cm thick beds of 30-60% peb-cob in vfg-fg wacke: poor normal grading; beds appear laterally cont >20m, bases non-erosive, sl load Fl; clasts 100% PHV vesicular mafic volcanic; Fl laminated, dark grn grey (volcaniclastic?) mudstone in 5-20 cm thick sets bedding: 140/28 SW 1 measure	6
54-66	Gmm Shgn >90% Gmm as below; vague 1-2m bedding and rare Shgn beds bedding: 125/23 SW 1 measure	
53-54	Shgn mod brn wthr, lite brn fsh; granule base grade to med wacke tops; 1-3cm thin beds, straight, cont, //; sl loaded bases, massive internally	5
33-53	Gmm as below but no Fl Sh interbeds; brn red wthr, grey brown fsh; rare boulders up to 1.5m dia, both PF and PHV types;	
27.5-33	Sh Gmm Fl Sh dark red brn wthr, grey red fsh; lam vfg-fg wacke, not dolomitic; lams cont, sub//, sl wavy, rare med-grained wacke thin beds, discont, 1-1.5cm thick; <3% peb-cob limestones or lags, both PHV and PF types, no dropstone structures; Fl and Gmm as below bedding: 132/21 SW ave of 4	4
13-27.5	Gmm as below but greyish red wthr, no Fl interbeds; beds appear to be welded composites 1.5-2m thick but very vague	3
0-13	Gmm Fl >60% Gmm: dk brn gy wthr; gy grn fsh; 60-70% peb-bldr clasts in fine-cse wacke; 20-100 cm beds thicken and coarser up; massive, poorly sorted; laterally cont >30m, bases sl wavy, non-erosive; clasts subang-subrd, high spher; 60-70% PHV volcs, 30-40% PF, most med gy lam dolst (some cryptalgal/strom); <40% Fl as 10-20cm thick sets of lite grn gy lam mudstone; nondolomitic, prob volcaniclastic; lams sub//, cont, sl wavy; loaded by Gmm above; <3% peb-small cob limestones in Fl cut lams but no dropstone structures bedding: 155/21 SW 1 measure	2
0	contact gradational; picked where Gmm non-volc clasts consistently present (>3%)	
0 to -10	PHV agglomerate dk brn gy wthr, dk gy grn fsh; 65-75% peb-bldr volc clasts in fine-cse volc wacke; poorly sorted subang-subrd clasts all mafic volc; massive, random fabric; no grading or obv bedding	1

MS-32

Metres
above
base

MS-32 DESCRIPTION

Sam
ple

Section through inlier at top of MHVC (Snowcap Inlier of Roots, 1986). Located on Figure A2-2. Lat. 64°41'16"N, Long. 139°58'32"W in NTS map sheet 116B-116C(E half) (Dawson), Yukon; 1:50000 map 116B/12. Best seen in RCAF airphoto A13233-47. Total Thickness = 83 m

- >83 Subvertical fault, SE side down about 40m; conglomerates/mudstones continue above fault for 30-40m (to top of ridge, no upper contact to PH1), but identical to conglomerates/mudstones below and may be fault repeat (not measured).
- 62-83 Gmm FI same as at 10-32m except Gmm clasts 100% volcanic in most beds; 5% PF clasts in top 3m; Gmm beds 1-3m thick, load FI but non-erosive; 5% of FI lams discont, lenticular and synsed slump folded
- 57.5-58 Sh(gn) gy orange wthr, med gy fsh; fg lst wackest, thin bedded (2-4cm), cont, //, sl wavy; poor gn in some with med-grained bases and vaguely lam tops
- 46-55 Gmm FI Gmm as below in 2.5-3.5m thick beds, interbedded with FI lst mudst as below in 20-50cm sets
- 32-46 Gmm dk red brn wthr, dk gy grn fsh; 60-70% peb-cob clasts in med-cse wacke; very poorly sorted, massive, no grading, random clast fabric, appears to be one bed?; clasts subang-subrd, high sphericity; >90% volcanic: gy grn, vesicular, mafic volc with 10% dark chlorite spots (replacing ?); <10% PF dolst
- 10-32 Gmm FI >60% Gmm: dk red brn wthr, dk gy grn fsh; 60-70% peb-cobs in med-cse wacke; poorly sorted, beds massive, no grading, 30cm - 3.5m thick with sharp loaded, non-erosive bases; clasts 85-95% gy grn vesicular mafic (andesite?) volc (100% in some lower beds); 5-15% (more common up) PF dolst clasts; clasts high sphericity, subrd-subang; FI dk gy lst mudstone; lam to 3cm thick, massive thin beds; rare limestones, all volcanic, possible pyroclastic (but no good dropstone structures)
- 0-8 Sh grey orange wthr, dk grey fsh; fine-med lst wackest; thin beds 1-5cm, massive, no grading, cont, sl wavy, sub// bedding: 148/11 SW ave of 4
- 0 contact sharp
- 0 to -20 PHV agglomerates, FI >60% dark gy grn agglomerates: 60-60% peb-bldrs in cse wacke; poorly sorted, massive, no grading; clasts all volcanic; beds 50-100cm thick, cont >20m, sharp, loaded, non-erosive bases; clasts high spher, subang-subrd; FI lite grn gy, lam mudstone, non-calc, poss tuff or reworked tuff; lams cont, wavy, some convolute slump-folded lams bedding: horizontal to <5% sth dip

4

3

2

1

MS-33

Metres
above
base

MS-23 DESCRIPTION

Sam
ple

	Section located in NE facing bowl of NW trending ridge separating the Eagle Creek drainage area from the NW drainage basin of main PH2 outcrops (see Fig. A2-2). Lat. 64°41'08"N, Long. 139°07'30"W in NTS map sheet 116B-116C, 1:50000 map 116C/16. Best seen in RCAF airphoto A13233-49. Total Thickness = 115 m	
>115	Cdb lite grey, sacrosic finely xtalline dolostone, faint sl wavy, //, cont lams contact covered (1m): appears sharp, probable a disconformity bedding: 166/17 SW ave of 3	
108-	Sh Fl orange-gy vfg dolowacke and lite olive-gy fg lithic wacke (qts-rich), both thin beds to thick lams	9 TS
114	in sets 5-25cm thick; //, cont, sl wavy; brn-gy sl dolomitic lam mudstone/siltstone in 10-30cm thick sets (most subcrop or float), small LLH stroms in one mudstone, "egg carton" geometry/size; rare U-shaped worm burrows in fg dolowacke at, no sprays suggest <u>Arenicolites</u> type covered, float of Sh Fl as above (but may be from above)	8 7 7 5
100.5-	St Sh similar to 82.5-90m interval with silic med-cse lithic wacke, trough crossbedded in 50-70cm thick sets with planer thin-bedded top 10-30cm; <30% grey-orange fine-med dolarenite interbeds, 1-2 cm thin beds in sets up to 50cm thick; trace fossils at base of St beds include <u>Planolites</u> , <u>Cruisiana</u> and trilobite resting trace <u>Rusophycus</u> (first occurs at 100.5m, common at 102m)	4a 1988 12
104	Sh (pShgn) brown wthr, lite olive gy fine- to medium-grained dolarenite/litharenite (qts/chert grains <50% but common in TS), 1-2 cm thin beds, //, cont, sl wavy, rarely disrupted (boturb?); recessive wthr vs siliciclastics; one pShgn bed 20cm thick, gran-med lithic wacke with gran qts at base grades up to dolospar-rich upper Sh; base loads and sl erodes Sh below, laterally thins, may be lens one 20cm lam dolosiltite layer at 90.5m; no trace fossils seen	a-e
82.5-90	St Sh med gy wthr, lite gy med-cse silic lithic wacke; >60% overlapping trough xbeds <50cm long, 10cm high (all are preserved bases of larger troughs eroded by above xbeds); rare ripups orange-gy fg dolarenite in bases of troughs, xbeds oriented east-west, can't define paleoflow; <40% planer-bedded, 1-4cm beds, cont, //, sl wavy, poor gn in some; <5% vfg/silty wacke interbeds in St, <20cm thick and laterally discont < 20m (eroded by St above); Trace fossils common on bases St, rare on bases Sh; most common + lowest is horis worm trace <u>Planolites</u> , also abund trilobite trace <u>Cruisiana</u> , no other types contact sharp, sl wavy, sl erosive	4 TS
75.3-	Sh orange-grey fine-med dolarenite with 20cm of lam dolosiltite at top, Sh thin bedded, sl wavy, cont,	
82.5	//; can trace orange-grey Sh for >100m laterally Gmgn gy-grn >60% gran-sm pebs in med-cse lithic wacke; mod sorted, poor gn, most clasts subrd,	3 TS
75-75.3	subequant, no imbric, base sl wavy, loaded into Sh	
73-75	Sh (Fl) mod brn-orange vfg dolarenite/siltite; lam/thin-beds, rare desiccation cracks, intraclast ripups	
72.8-73	Gmgn mod brn, >60% granules in cse dolowacke, poor gn, base loads Sh,	
69-72.8	Sh mod brn wthr, orange gy fine-med dolarenite, thin bed, sl wavy, cont, //, no traces, no grading	
69	contact sharp, slightly wavy	
36-69	Fl (Sh) >98% dk gy non-calc mudstone as below, very rare vfg dolarenite thin beds	
26-36	Fl Sh as below with 20% vfg to silty dolarenite thin beds or lams within dk gy non-calc mudstone	
20-26	Sh orange-grey dolosiltite - vfg dolarenite in lams or thin beds .5-1.5 cm thick; sharp, non-erosive bases, tops, straight, //, cont; no internal lams; rare very sl normal grading bedding: 143/26 SW ave of 3	2
0-20	Fl Sh dark grey wthr/fsh siliciclastic (very sl dolomitic) mudstone; very finely laminated, slightly fissile, strong pencil cleavage in some intervals; <5% orange-grey wthr/fsh vfg-silty dolowacke thin beds 1-3cm thick section measured from first continuous outcrop of PHS base not seen, rare outcrop PHS exposed in creek >50m below	1

MS-34

SECRET

Notes
about
base

Section located in east-facing cirque north of base of study area (see Figure A2-2).
Lat. 64°45'33" N, Long. 140°17'48" W in NTS map sheet 116B-116C, Yukon; 1:50,000 map 116C/16. Best
seen in RCAF airphoto A1338-88.

CDs like grey fine vitall dolerite with <40% tabular but frage of same lith <2cm long in poorly defined beds

contact not exposed; probable discontinuity

F1 Sh gradational change from orange-grey fine-medium-grained dolowacke thin beds to dark grey
laminated limestone mudstone, poorly exposed subcrop/outcrop/floor

Sh (Gmm) similar to 265-285 Gmm rare and only 10cm thick with very small (granule to 2cm)
intracrustal ripple; most 5m fine to coarse-grained dolowacke thin beds

very slight fining-up sequence 285-300 m

Sh F1 Gmm as 245-265 but with rare orange-grey with/with flat-pab cgl; 40-60% tabular, angular,
bedded dolowacke intracrustal (ripples) in medium-grained dolowacke; moderately sorted with clasts sub-
bedding, but no imbrication; beds 10-30cm thick with slightly bedded sharp base and at wavy sharp
top

Sh F1 > 70% orange-grey, fine-coarse dolerite thin beds; most 1-2cm thick, <20% 2-10cm thick beds
with loaded but non-erective base, no obvious grading; <30% med grey siliclastic siltstone/vfg lithic
arenite, laminated to thin-bedded

subtle coarsening-upward sequence 245-275 m and increase in dolerite vs. siliclastic

Sh F1 > 60% pale brown with, medium grey fresh colour, laminated vfg to silty siliclastic
siltstone, // to al wavy with sharp non-erective contacts; top 10 m interbedded with med grey siliclastic
siltstone, // to al wavy with sharp non-erective contacts; top 10 m interbedded with med grey siliclastic
siltstone (no 3D so not measured); no indicators in siliclastic

subtle fining-upward sequence to 245 m

Sh F1 poor outcrop of orange-grey with, med gy fine-grained dolowacke, thin-bedded

F1 med grey-brown weathering, med grey, fresh colour, siliclastic siltstone to vfg qtz wacke; laminated
and rare 1 cm thick thin beds; all continuous, // straight to slightly wavy; no xilams or ripples

overall fining-upward sequence from 80 m to minimum of 160 m

gradational change over 5-10 m from dolerite to siliclastic siltstone

Sh F1 grey-orange weathered-fresh colour vfg to silty dolerite; 1-2 cm thick thin beds are planar,
cont. // to al wavy with sharp non-erective contacts; top 10 m interbedded with med grey siliclastic
siltstone, // to thin-bedded in 1-2cm beds, increasingly common up

gradational change over 5 m from siliclastic siltstone/vfg wacke to dolerite

overall coarsening-up sequence from 55 m to about 85 m reflects increased abund of fg dolerite up

Sh Sh med grey siliclastic siltstone and vfg wacke; laminated and rare 1 cm thin-beds, all continuous,
// straight to very slightly wavy; no xilams or ripples

overall fining-up sequence from 20 m to about 55 m

Sh F1 med grey siliclastic 75% vfg wacke and 20% siltstone; laminated and 1 cm thin beds, all
continuous, // straight to very slightly wavy; <5% fine to medium-grained wacke thin beds; 2 cm
thick beds; // straight to normal grading; no dolerite, fine 20cm thick layer of convoluted laminations
(synsed slump);

Sh moderate brown weathering, medium grey fresh colour, siliclastic very fine to medium-grained
wacke/arenite; >75% 1-2 cm thick thin beds, <20% thick lams, <5% 2-4 cm thick thin beds; most
continuous, // slightly wavy to straight, rare small cross-laminated ripples all indicate northwesterly
palaeocurrents

section started at base of continuous o/s in gully, >20m of PHS poorly and discontinuously exposed
below base; >100 m of PHS mudstone very poorly exposed in creek below PHS

bedding: 048/24 NW ave of 6

bedding: 048/24 NW ave of 6

bedding: 048/24 NW ave of 6

bedding: 048/24 NW ave of 6

bedding: 048/24 NW ave of 6

bedding: 048/24 NW ave of 6

bedding: 048/24 NW ave of 6

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bedding: 048/24 NW ave of 6

bedding: 048/24 NW ave of 6

bedding: 048/24 NW ave of 6

APPENDIX II

CLAST SIZE

VERSUS

BED THICKNESS:

STUDY METHODS

AND

DATA SUMMARY

The conglomerates of the lower Mount Harper group show many characteristics that suggest deposition by sediment gravity flow (documented in chapter II). Early recognition of this probable origin prompted a study of the relationship between clast size vs. bed thickness in these conglomerates. In response to Bluck's (1967) proposal that these features are not independent, many studies (reviewed in Nemec and Steel, 1984) demonstrated a linear correlation between bed thickness and maximum particle size which reflects the competence of the depositing flow at the point of measurement. This correlation is not observed with other processes of conglomerate deposition (fluvial, glacial, etc.). Thus data on clast size and bed thickness is useful for inferring the depositional modes of conglomerates, and in some cases supports more specific interpretations (subaerial vs. subaqueous deposition for example). Data were also collected from the upper Mount Harper group, although subsequent analysis has shown that bed thickness and clast size show a weak or no correlation. This is interpreted to reflect subaqueous deposition and a mixing of several gravity flow and non-gravity flow depositional processes.

Methods

Maximum clast sizes (MCS) for individual beds were measured as suggested by Bluck (1967). The MCS value for a bed is taken as the average of the diameters (generally apparent diameters in the Mount Harper group) of the ten largest clasts within that bed, measured to the nearest centimetre. The area of the bed examined for the largest clasts varied due to accessibility and time available, and generally was a few tens of metres. Any clasts that appeared abnormally large compared to other clasts or bed thickness were not included in the ten averaged, as recommended by Bluck (1967). These oversized clasts (some much larger than the bed that contained the other clasts) are considered exceptions to the hypothesis that clast size is related to flow competence in sediment gravity flows. The most likely explanation for their unusual size is rolling or sliding, either as bedload during the flow, or after the main flow was deposited. Bed thickness varies laterally for many

beds and where possible was measured from the same area of the majority of clast measurements. Bed thickness was measured to the nearest five centimetres. Beds which showed extreme lateral thickness variations were not measured. Neither were beds from which the top or bottom contacts of the bed could not be discerned with reasonable confidence. This later restriction probably accounts for the predominance of Gcmgrgn bedtypes (Table A2-1) in the dataset, because the graded bases and tops make contacts more apparent than for other bed types.

Statistical Analysis

All data were collated, analyzed and graphed using the spreadsheet program LOTUS 1-2-3 (1985, LOTUS Development Corp.). Data for the lower Mount Harper group were grouped (Fig. A2-1) and separated into subsets of interpreted proximal and intermediate facies (Fig. A2-2) and also of lithotypes based on framework-support and internal grading characteristics (Figs. A2-3 to A2-5). These data are summarized in Table A2-1 and detailed in Table A2-2. Best-fit linear regression lines are shown for graphs which have Pearsonian Coefficient (R) values greater than 0.65. Upper Mount Harper group data are given in Table A2-3. Data for units PH1 and PH2 are combined in Figure A2-6. Because the units differ only in the presence of volcanic clasts in map unit PH1. Separation by individual units and major grading or framework-support types is shown graphically (Figs. A2-7 to A2-11), but, as for the major data grouping, a statistical correlation between bed thickness and maximum clast size is weak or not apparent (discussed in chapter 4).

BLUCK, B. J. 1967. Deposition of some Upper Old Red Sandstone in the Clyde area: a study in the significance of bedding. *Scottish Journal of Geology*, 3: 139-167.

MARSAL, D. 1987. *Statistics for Geoscientists*. Pergamon Press, Oxford, 176 p.

NEMEC, W. and STEEL, R. J. 1984. Alluvial and coastal conglomerates: their significant features and some comments on gravelly mass-flow deposits. *In* *Sedimentology of gravels and conglomerates*, Edited by E.H. Koster and R.J. Steel, Canadian Society of Petroleum Geology, Memoir 10, pp. 1-31.

Figure A2-1. lower Mount Harper group

Bed Thickness vs Maximum Clast Size

Total combined facies and lithotype data.

Figure A2-2: lower Mount Harper group conglomerates
Proximal and Intermediate Facies

A

B

Figure A2-3. lower Mount Harper group
Bed Thickness vs. Maximum Clast Size

A

B

Figure A2-4. lower Mount Harper group
Bed Thickness vs. Maximum Clast Size

A

B

Figure A2-5. lower Mount Harper group
 Bed Thickness vs. Maximum Clast Size

Figure A2-6. upper Mount Harper group

Bed Thickness vs. Maximum Clast Size

A

B

Figure A2-7. upper Mount Harper group

Bed Thickness vs. Maximum Clast Size

A

B

Figure A2-8. upper Mount Harper group
Bed Thickness vs. Maximum Clast Size

LOWER MOUNT HARPER GROUP CONGLOMERATES: MAXIMUM CLAST SIZE VERSUS BED THICKNESS DATA

		MEAN CLAST SIZE (MCS)	MEAN BED THICK (BTh)	BTh MCS	# OF SITES	LINEAR REGRESSION STATISTICS				
						Constant (Y inter -cept)	95% Confid Limit	R Value	X Coeff. (slope)	Std Err of X Coeff.
TOTAL LMHG		31	106	3.37	182	1.97	21	0.78	0.28	0.07
L	Gcmgrgn	29	97	3.34	104	3.97	14	0.80	0.26	0.02
I	Gcmgr	37	132	3.57	21	population not statistically significant				
T	Gcmgn	18	51	2.83	11					
H	Gcm (no grading)	51	165	3.24	22					
O	Gcs	8	44	5.50	9					
L										
O	All Matrix-Supported	14	59	4.21	12					
G										
Y	All Clast-Supported	31	103	3.32	170	2.11	21	0.78	0.28	0.02
F	Proximal	37	123	3.32	130	3.63		0.72	0.27	0.02
A	(Upper to mid fan)									
C										
I	Intermediate	12	44	3.75	52	4.18		0.68	0.17	0.03
E	(Lower fan/braidplain)									
S										

Table A2-2:

Lower Mount Harper group conglomerates: maximum clast size versus bed thickness. Data summarized by clast support and internal grading type.

Gcm: Clast-supported, massive, no grading; N = 22

MEASURED SECTION	BED BASE (m)	BED TOP (m)	LITHO- FACIES CODE	BED THICK- NESS (cm)	MAXIMUM CLAST SIZE (cm)	LARGEST CLAST (cm)
MS-6	32	33.2	Gcm	120	26	NA
MS-6	39.5	40.8	Gcm	130	24	32
MS-6	62	67	Gcm	100	49	98
MS-6	94	95	Gcm	100	31	57
MS-6	120	121.75	Gcm	175	39	54
MS-7	0	1.75	Gcm/Gmm	175	22	37
MS-7	92	94.3	Gcm	230	38	69
MS-7	109.5	111.15	Gcm	165	36	82
MS-8	31	33	Gcm	200	44	85
MS-10	80.7	81.3	(Gcs-)Gcm	60	34	93
MS-10	773.4	774.5	Gcm	110	56	67
MS-12	100.5	101.3	Gcm	80	29	44
MS-13	12.2	13.5	Gcm	130	63	198
MS-13	22	26.5	Gcm	450	179	250
MS-13	38.5	41.5	Gcm	300	192	320
MS-14	1	3.3	Gcm	230	88	140
MS-14	48	50.3	Gcm	230	97	255
MS-18	318	322.3	Gcm	430	32	40
MS-20	399	399.5	Gcm-Gcs	50	11	14
MS-20	420	420.6	Gcm-Gcs	60	12	17
MS-20	442	442.5	Gcm	50	17	24
MS-20	443	443.6	Gcm-Gcs	60	9	11
LITHOTYPE MEAN:				165	51	90

Gcmgrgn: Clast-supported, massive, reverse-graded base,
normally graded top; N = 104

MEASURED SECTION	BED BASE (m)	BED TOP (m)	LITHO- FACIES CODE	BED THICK- NESS (cm)	MAXIMUM CLAST SIZE (cm)	LARGEST CLAST (cm)
MS-7	55	56.25	Gcmgr-gn	125	59	100
MS-9	186	189	Gcmgr-gn	300	90	119
MS-10	1.7	2.8	Gcmgr-gn	110	33	56
MS-10	83	85	Gcmgr-gn	200	88	150
MS-10	222.8	223.8	Gcmgr-gn	100	23	38
MS-10	301.6	303.2	Gcmgr-gn	160	53	83
MS-10	382.5	384.1	Gcmgr-gn	160	43	71
MS-10	432.6	434	Gcmgr-gn	140	41	64
MS-10	591	592.6	Gcmgr-gn	160	74	104
MS-10	631.5	633.2	Gcmgr-gn	170	41	79
MS-10	740	741	Gcmgr-gn	100	31	49
MS-11	40	41	Gcmgr-gn	100	36	59
MS-11	278	279.5	Gcmgr-gn	150	37	77
MS-11	411	412.6	Gcmgr-gn	160	49	85
MS-11	415.5	416.9	Gcmgr-gn	140	54	83
MS-11	449.75	451.85	Gcmgr-gn	210	54	77
MS-11	451.85	454.65	Gcmgr-gn	280	60	104
MS-11	481.5	483.5	Gcmgr-gn	200	74	200
MS-11	514	515	Gcmgr-gn	100	31	74
MS-11	515	516	Gcmgr-gn	100	29	47
MS-12	126	127	Gcmgr-gn	100	31	39
MS-12	148	149.8	Gcmgr-gn	180	43	81
MS-12	211	211.8	Gcmgr-gn	80	40	57
MS-12	290.3	291.1	Gcmgr-gn	80	14	16
MS-13	62	63.25	Gcmgr-gn	125	28	44
MS-13	80	81.7	Gcmgr-gn	170	51	79
MS-13	106	106.95	Gcmgr-gn	95	39	88
MS-13	115	115.9	Gcmgr-gn	90	29	44
MS-13	167	168.9	Gcmgr-gn	190	42	61
MS-13	170	172	Gcmgr-gn	200	67	125
MS-13	172	173.3	Gcmgr-gn	130	33	50
MS-13	275	276	Gcmgr-gn	100	34	62
MS-13	331	333.5	Gcmgr-gn	250	86	200
MS-13	359.5	361	Gcmgr-gn	150	75	146
MS-13	361	362	Gcmgr-gn	100	20	27
MS-13	362	363.7	Gcmgr-gn	170	53	81

(continued on next page)

MEASURED SECTION	BED BASE (m)	BED TOP (m)	LITHO- FACIES CODE	BED THICK- NESS (cm)	MAXIMUM CLAST SIZE (cm)	LARGEST CLAST (cm)
MS-13	401	402.3	Gcmgr-gn	130	35	50
MS-13	402.3	403.8	Gcmgr-gn	150	41	56
MS-13	403.8	404.8	Gcmgr-gn	100	20	28
MS-13	410	410.7	Gcmgr-gn	70	19	26
MS-14	125.35	125.6	Gcmgr-gn	25	11	18
MS-14	125.6	125.75	Gcmgr-gn	15	5	8
MS-14	125.75	125.85	Gcmgr-gn	10	5	7
MS-14	135	135.55	Gcmgr-gn	55	19	30
MS-14	135.55	136.07	Gcmgr-gn	52	14	26
MS-14	136.07	136.6	Gcmgr-gn	53	15	37
MS-14	136.6	136.87	Gcmgr-gn	27	12	22
MS-14	136.87	137.16	Gcmgr-gn	29	10	22
MS-14	147.5	148.05	Gcmgr-gn	55	16	24
MS-14	148.05	148.57	Gcmgr-gn	52	20	39
MS-14	148.57	149.1	Gcmgr-gn	53	13	19
MS-14	149.1	149.37	Gcmgr-gn	27	11	15
MS-14	181.3	181.6	Gcmgr-gn	30	10	12
MS-14	181.6	182.8	Gcmgr-gn	120	39	57
MS-14	182.8	184	Gcmgr-gn	120	44	51
MS-14	204.5	204.76	Gcmgr-gn	26	9	14
MS-14	205.52	205.85	Gcmgr-gn	33	14	26
MS-14	205.85	206.35	Gcmgr-gn	50	22	34
MS-14	232	232.3	Gcmgr-gn	30	6	10
MS-14	232.3	232.45	Gcmgr-gn	15	6	8
MS-14	232.45	232.53	Gcmgr-gn	8	3	6
MS-14	232.53	232.78	Gcmgr-gn	25	7	9
MS-14	232.78	232.99	Gcmgr-gn	21	4	7
MS-14	243	243.15	Gcmgr-gn	15	2	3
MS-14	249	249.4	Gcmgr-gn	40	4	5
MS-14	250.3	250.75	Gcmgr-gn	45	5	8
MS-18	296.1	296.5	Gcmgr-gn	40	8	11
MS-18	296.5	296.9	Gcmgr-gn	40	8	19
MS-18	297.8	298.8	Gcmgr-gn	100	15	22
MS-18	298.8	300	Gcmgr-gn	120	13	18
MS-18	301.7	303.2	Gcmgr-gn	150	25	44
MS-18	303.2	305.4	Gcmgr-gn	220	14	23

(continued on next page)

MEASURED SECTION	BED BASE (m)	BED TOP (m)	LITHO- FACIES CODE	BED THICK- NESS (cm)	MAXIMUM CLAST SIZE (cm)	LARGEST CLAST (cm)
MS-18	307.4	308.9	Gcmgr-gn	150	41	-
MS-18	308.9	309.8	Gcmgr-gn	90	16	-
MS-18	309.8	311.3	Gcmgr-gn	150	18	-
MS-18	311.3	313.1	Gcmgr-gn	180	36	-
MS-21	14	14.2	Gcmgr-gn	20	5	7
MS-21	14.2	14.65	Gcmgr-gn	45	6	7
MS-21	20.5	20.7	Gcmgr-gn	20	7	9
MS-21	20.7	21.15	Gcmgr-gn	45	13	16
MS-21	34	34.7	Gcmgr-gn	70	15	17
MS-21	37	37.75	Gcmgr-gn	75	35	40
MS-21	59	59.8	Gcmgr-gn	80	29	40
MS-21	60.5	61.5	Gcmgr-gn	100	32	42
MS-21	94	94.3	Gcmgr-gn	30	14	22
MS-21	127	128	Gcmgr-gn	100	41	53
MS-21	140	140.9	Gcmgr-gn	90	57	86
MS-21	142	142.65	Gcmgr-gn	65	22	41
MS-21	181	181.35	Gcmgr-gn	35	14	20
MS-21	182	182.7	Gcmgr-gn	70	32	54
MS-21	211	211.9	Gcmgr-gn	90	23	31
MS-21	227	227.6	Gcmgr-gn	60	29	33
MS-21	242	242.7	Gcmgr-gn	70	29	45
MS-21	254	254.6	Gcmgr-gn	60	26	31
MS-21	279.4	280.05	Gcmgr-gn	65	23	31
MS-21	301	301.55	Gcmgr-gn	55	24	29
MS-21	322	322.6	Gcmgr-gn	60	22	27
MS-21	336	336.6	Gcmgr-gn	60	32	48
MS-21	337	337.6	Gcmgr-gn	60	54	94
MS-21	360	360.85	Gcmgr-gn	85	41	49
MS-21	400	400.65	Gcmgr-gn	65	21	30
MS-30	2	3.5	Gcmgr-gn	150	30	46
MS-30	5	5.8	Gcmgr-gn	80	19	33
MS-30	7.5	9	Gcmgr-gn	150	20	30
LITHOTYPE MEAN:				97	29	46

Table A2-2 (continued)

Gcmgr: Clast-supported, massive, reverse-graded; N = 21

MEASURED SECTION	BED BASE (m)	BED TOP (m)	LITHO- FACIES CODE	BED THICK- NESS(cm)	MAXIMUM CLAST SIZE(cm)	LARGEST CLAST
MS-6	60.5	61.9	Gcmgr	140	38	60
MS-7	122	123	Gcmgr	100	38	62
MS-8	3	4.1	Gcmgr	110	32	95
MS-8	78	79.5	Gcmgr	150	61	94
MS-8	169.5	171.5	Gcmgr	200	88	160
MS-9	7	8.3	Gcmgr	130	27	36
MS-9	85.5	87	Gcmgr	150	35	80
MS-10	18	21	Gcmgr	300	70	93
MS-10	216	217.3	Gcmgr	130	22	37
MS-10	229	230.6	Gcmgr	160	46	75
MS-10	479	480.5	Gcmgr	150	42	76
MS-11	10	11.3	Gcmgr	130	26	45
MS-11	145	146.4	Gcmgr	140	46	61
MS-11	221	222	Gcmgr	100	35	55
MS-12	7	8.1	Gcmgr	110	30	50
MS-12	288	290.3	Gcmgr	230	57	100
MS-14	125.2	125.35	Gcmgr	15	6	10
MS-14	149.37	149.66	Gcmgr	29	26	39
MS-14	180	181.3	Gcmgr	130	31	67
MS-18	295.3	296.1	Gcmgr	80	21	42
MS-18	296.9	297.8	Gcmgr	90	9	17
LITHOTYPE MEAN:				132	37	64

Gcmgn: Clast-supported, massive, normally graded; N = 11

MEASURED SECTION	BED BASE (m)	BED TOP (m)	LITHO- FACIES CODE	BED THICK- NESS(cm)	MAXIMUM CLAST SIZE(cm)	LARGEST CLAST
MS-7	38	38.4	Gcmgn	40	7	10
MS-7	38.4	38.9	Gcmgn	50	14	16
MS-10	0.75	1.7	Gcmgn	95	27	46
MS-10	7.5	7.9	Gcmgn	40	9	15
MS-10	8.3	9	Gcmgn	70	32	61
MS-11	350	350.6	Gcmgn	60	19	30
MS-13	409	409.35	Gcmgn	35	14	22
MS-14	126	126.2	Gcmgn	20	9	12
MS-20	374	374.3	Gcmgn	30	5	6
MS-21	99	99.7	Gcmgn	70	39	57
MS-30	0	0.5	Gcmgn	50	20	29
LITHOTYPE MEAN:				51	18	28

Gcs: Clast-supported, stratified, all grading types; N = 9

MEASURED SECTION	BED BASE (m)	BED TOP (m)	LITHO- FACIES CODE	BED THICK- NESS (cm)	MAXIMUM CLAST SIZE (cm)	LARGEST CLAST (cm)
MS-10	81.3	81.75	Gcs-Gcm	45	5	7
MS-10	303.2	303.7	Gcs-Gcm	50	13	19
MS-10	741.5	742	cs-Gcmgn	50	13	20
MS-20	360	360.2	Gcs-Gcm	20	5	8
MS-20	364	364.22	Gcsgn	22	5	6
MS-20	380	380.45	Gcsgn	45	7	9
MS-20	385	385.35	Gcsgn	35	9	7
MS-20	473	473.3	Gcsgn-pSh	30	8	11
MS-20	504	505	Gcs	100	10	13
LITHOTYPE MEAN:				44	8	12

Gm: matrix-supported, all grading types; N = 12

MEASURED SECTION	BED BASE (m)	BED TOP (m)	LITHO- FACIES CODE	BED THICK- NESS (cm)	MAXIMUM CLAST SIZE (cm)	LARGEST CLAST (cm)
MS-13	43	44.1	Gmmgr-gn	110	27	42
MS-14	3.3	4.3	Gmm	100	41	130
MS-18	295	295.3	Gmsgn	30	5	7
MS-27	248.5	248.9	Gmmgn	40	6	7
MS-27	418	419.9	Gmmgn	190	20	24
MS-27	420.9	421.2	Gmmgn	30	5	7
MS-28	46.5	46.8	Gmmgn	30	17	24
MS-28	52.9	53.1	Gmmgn	20	11	17
MS-28	53.1	53.5	Gmmgn	40	8	17
MS-28	68.5	69.1	Gmmgn	60	8	10
MS-28	69.1	69.3	Gmmgn	20	6	9
MS-28	102	102.4	Gms	40	12	17
LITHOTYPE MEAN:				59	14	26

Table A2-3.

UPPER MOUNT HARPER GROUP CONGLOMERATES
SUMMARY OF MAXIMUM CLAST SIZE AND BED THICKNESS DATA

MAP UNIT	MEAN MAXIMUM CLAST SIZE (cm)	MEAN BED THICK- NESS (cm)	MEAN BTh MEAN MCS	SAMPLE SIZE	LINEAR REGRESSION		STATISTICS X
					CONSTANT (y inter- cept)	R VALUE	
ALL PH1	20	90	4.5	31	8.8	0.67	0.13
ALL PH2	22	110	5.0	42	17.3	0.32	0.039
PH1-PH2: combine matrix-supported	20	115	5.8	36	13	0.52	0.63
PH1-PH2: combine clast-supported	22	90	4.1	37	16.4	0.35	0.64
PH1-PH2: combine	21	102	4.9	73	15.2	0.42	0.58

Table A2-4. Upper Mount Harper Group: Bed Thickness and Maximum Clast Size Data

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MAP UNIT PH1 - ALL GRADING AND FRAMEWORK-SUPPORT TYPES N = 31

MEASURED SECTION	BED BASE (m)	BED TOP (m)	LITHOFACIES CODE	BED THICK- NESS (cm)	MAXIMUM CLAST SIZE (cm)	LARGEST CLAST (cm)
MS-17	1	2.8	Gmm	180	44	78
MS-17	33	34.5	Gmm-Gcm	150	26	50
MS-17	37	38.5	Gmm	150	33	71
MS-17	103	104.5	Gmm	150	35	78
MS-17	155	156.7	Gmm	170	34	48
MS-23	35	36.1	Gcm	110	32	63
MS-23	37.1	38.45	Gcm	135	37	56
MS-23	38.45	39.8	Gcm	135	24	36
MS-23	41.4	43.4	Gmm	200	22	42
MS-25	9	10.2	Gmm	120	23	38
MS-25	14.3	15.1	Gmm	80	22	48
MS-25	25	25.6	Gmm	60	17	33
MS-25	28.1	29.4	Gmm	130	23	48
MS-25	49	49.3	Gmm	30	19	23
MS-25	80.55	81	Gmm	45	12	19
MS-25	131	131.5	Gmm	50	10	14
MS-26	6	6.6	Gmm	60	20	30
MS-26	13	13.6	Gcmgr	60	18	31
MS-26	34.2	34.7	Gmm	50	27	45
MS-26	35	35.5	Gmmgr	50	21	31
MS-26	47.5	48	Gmm	50	24	37
MS-26	53.5	53.9	Gmm	40	20	30
MS-26	63	64.7	Gmm	170	14	28
MS-26	79.5	80.25	Gmm	75	14	20
MS-26	121	121.4	Gmm	40	7	10
MS-26	123.5	124.1	Gmm	60	11	16
MS-29	44.3	45	Gcm	70	21	34
MS-31	1.5	2	Gmm	50	7	9
MS-31	3.1	3.6	Gmm	50	7	10
MS-31	10.5	11	Gmm	50	6	8
MS-32	10.2	10.5	Gmm	30	7	12
MAP UNIT MEAN VALUES				90	20	38

Table A2-4 (continued)

MAP UNIT PH2 - ALL GRADING AND FRAMEWORK-SUPPORT TYPES N=42 322

MEASURED SECTION	BED BASE (m)	BED TOP (m)	LITHOFACIES CODE	BED THICK- NESS (cm)	MAXIMUM CLAST SIZE (cm)	LARGEST CLAST (cm)
MS-19A	49	50.5	Gcm(gn)	150	23	28
MS-19A	109	112.0	Gmm	300	28	46
MS-19A	137	137.7	Gcmgn	70	17	24
MS-19A	140	141.8	Gcmgn	180	22	40
MS-19A	141.2	143.4	Gcmgn	120	22	26
MS-19A	182.0	186.0	Gmm	400	26	41
MS-19A	194.0	194.6	Gcmgr-gn	60	22	26
MS-19A	197.4	197.6	Gcmgr-gn	20	12	15
MS-19A	199.5	200.25	Gcmgn	75	18	46
MS-19A	202.5	203.1	Gcmgr-gn	60	16	22
MS-19A	225.5	227.5	Gcm(gr)	200	15	18
MS-19A	257.1	258.2	Gcm(gn)	110	11	16
MS-19A	258.5	259.25	Gcm(gn)	75	21	32
MS-19A	283.0	285.0	Gmm	200	18	35
MS-19A	289.5	290.5	Gcmgn	100	14	15
MS-19B	43	45.5	Gmm	250	53	-
MS-19B	82	82.2	Gcmgn	20	10.5	-
MS-19B	82.5	82.75	Gcmgn	25	6.5	-
MS-19B	85.5	86.25	Gcmgn	75	33	-
MS-19B	113	113.5	Gcm	50	20	30
MS-19B	122	122.25	Gcm	25	14	30
MS-19B	123	123.25	Gcm(gn)	25	10	13
MS-19B	123.3	123.9	Gmm/Gcm	60	14	19
MS-19B	139	140.5	Gcm(gn)	150	37	45
MS-19B	144	144.5	Gcm(gn)	50	40	-
MS-19B	154.52	155.52	Gcm	100	28	47
MS-19B	156.52	157	Gcm	48	37	60
MS-19B	190	193	Gmm	300	15	22
MS-19B	193	193.5	Gcmgn	50	13	17
MS-19B	193	194	Gcmgr-gn	100	15	19
MS-19B	194	195	Gcmgn	100	30	50
MS-19B	195	196.6	Gcm	160	23	33
MS-19B	217.5	218.2	Gcm	70	12	17
MS-19B	232	234.3	Gcm(gn)	230	27	33
MS-22	86	87	Gcm/Gmm	100	25	34
MS-22	87.3	88.3	Gcmgn	100	44	80
MS-22	103	103.8	Gcm/Gmm	80	23	37
MS-22	125	125.65	Gcm	65	25	44
MS-22	125.6	127	Gmm	140	32	40
MS-23	110	110.5	Gms	50	21	32
PM-51			Gmm/Gcm	110	12.9	18
PM-57			Gmm/Gcm	41	7	12
MAP UNIT MEAN VALUES				110	22	38

Table A2-4 (continued)

OTHER MAP UNITS - ALL GRADING AND FRAMEWORK-SUPPORT TYPES

MAP UNIT	MEASURED SECTION	BED BASE (m)	BED TOP (m)	LITHOFACIES CODE	BED THICK -NESS (cm)	MAXIMUM CLAST SIZE (cm)	LARGEST CLAST (cm)
PH4	MS-15	189	189.75	Gcmgn(bx)	75	18	26
PH4	MS-15	198	199	Gmmgr	100	17	29
PH4	MS-15	199.5	199.7	Gmmgn	20	8	11
PH4	MS-22	445	446.6	Gcm	160	36	52
PH5A	MS-24	83	83.3	Gcmgn	30	8	10
PH5A	MS-24	93.35	93.6	Gcmgn	25	6	9

APPENDIX III

PALEOCURRENT DATA: METHODS OF COLLECTION AND ANALYSIS

A summary of the paleocurrent data and trend statistics for the lower Mount Harper group is given in Table A3-1. Data are given for individual sites, grouped by interpreted facies. Table A3-2 presents a summary of data for the upper Mount Harper group with data for individual sites grouped by map units. The paleocurrent data also are shown as current roses that correspond to individual sites located on 1:50,000 geology maps in figure B1 (LMHG) and figure B2 (UMHG) (both back-pocket inserts) and as figure 14 and figure 7 in chapters 3 and 4 respectively. The current roses were plotted using a non-linear frequency scale (shown on the figures). Although a linear scale is the commonly used method, Nemec (1988) has pointed out that this graphically distorts the current rose, and use of a non-linear scale provides a more accurate representation of the data.

Collection Methods

Paleocurrent data were collected from all map units of the Mount Harper group except unit PH3 of the UMHG in which no sedimentary structures indicating paleocurrents were observed. All measurements have been corrected for bed-tilt; fold-plunge corrections were not necessary. The bedding attitude used for each correction is a mean of several measurements, generally 4-6 measurements per collection site, taken where possible from the beds that contain the paleocurrent indicators.

The most common paleocurrent indicator measured was clast imbrication in conglomerates. The carbonate matrix of the conglomerates weathers recessively with respect to the clasts, providing an abundance of clasts which protrude sufficiently to allow the tabular clasts to be distinguished, although generally not the specific orientation of the a- or b-axis. Clast measurement was of the dip direction of the a-b plane of tabular clasts that show apparent long axes greater than 1 cm (generally greater than 3 cm), a method suggested by Rust (1975). Where possible, fifty clasts were measured at each site, but the scarcity of tabular clasts (most clasts are sub-spherical) necessitated less measurements at some sites.

Imbrication measurements at each site generally were restricted to a single bed and as small an area within that bed as possible.

Planar crossbedding, crosslamination and rare trough crossbedding were measured only where three-dimensional orientation of the structures could be determined. The scarcity of well-exposed cross-strata meant that the total number of measurements at any site seldom exceeded twenty, and measurements from immediately adjacent beds or lamina were combined in some cases where a strong unidirectional trend was apparent.

Rare unidirectional indicators include flutes from bed soles within map units PH4 and PH5 of the UMHG, and bed surface expressions of asymmetric ripple crests in map unit PH4. Map unit PH2 of the UMHG contains three sites where parting lineation was observed. In each case the total number of measurements represents a combination from several bed surfaces exposed within a few metres of stratigraphy. Although parting lineation does not give a unidirectional sense of current flow, exposed ripple crosslamination from nearby lamina allowed the sense of direction to be inferred for these paleocurrent indicators, and the current roses drafted using these measurements reflect this inference.

Two-dimensional exposures of planar paleocurrent indicators were noted, but not used for the final paleocurrent maps or statistical analysis. This is also the case for three-dimensional exposures of paleocurrents where less than five measurements were possible. Where five to ten paleocurrent measurements were possible at a site, the measurements have been plotted on the paleocurrent maps as individual arrows rather than rose diagrams and statistical measures were not computed, but these data were added to other paleocurrent data for the combined map unit roses.

Statistical Analysis

Trend analysis of the paleocurrent data in general follows the methods outlined by Curray (1956) and recommended by most authors discussing paleocurrent analysis (eg. Potter and Pettijohn, 1977, Miall, 1984). This involved

calculation of vector mean and magnitude and testing for significance against randomness. The Rayleigh test of significance was used, and all sites have values which indicate that the grouped orientations are non-random (ie. a Rayleigh value of less than .05, the cut-off value recommended by Curray). The formulae for these calculations are given in Curray (1956). Circular standard deviation and circular variance were calculated using the method of Krause and Geijer (1987).

All statistical calculations and the corrections for bed-tilt were done using computer templates developed by the author for the spreadsheet software programme LOTUS 1-2-3. These computer templates are detailed in Mustard (1989).

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PROXIMAL FACIES CONGLOMERATES

N = 624

STATION LOCATION			OBSERVATIONS PER 30 DEGREE INTERVAL																Vect Rayleigh			
MAP OR REF SECTION	METRES	MAP UNIT LITHOLOGY	0-30	31-60	61-90	91-120	121-150	151-180	181-210	211-240	241-270	271-300	301-330	331-360	# Vect Obs	Mag (%)	Signif. t-test	Circ Dev	Circ Var			
A MS-7	39-40.3	PHb Gcmgr	2	5	5	2	1	2	0	1	2	0	3	3	26	38	9	1.9E-02	63	3967		
B MS-7	133-133.4	PHb Gcm(gn)	8	5	3	0	1	3	1	1	0	7	11	11	51	344	56	8.8E-08	53	2817		
C MS-8	80-80.5	PHb Gcmgr	3	3	1	0	1	1	3	0	0	3	3	7	25	342	44	7.1E-03	60	3612		
D MS-8	169.5-171.5	PHb Gcmgr	2	3	0	6	0	0	1	0	1	1	6	11	31	358	53	1.7E-04	55	3052		
E MS-10	18-21	PHb Gcmgr	4	4	8	2	0	2	4	1	0	1	1	3	30	67	39	9.4E-03	63	3946		
F MS-11	39.5-40	PHb Gcmgn	6	1	3	11	12	1	1	4	4	0	5	2	50	110	26	3.3E-02	70	4834		
G PM87	centre map	PHb Gcmgr(gn)	7	0	1	0	0	0	0	1	0	1	2	8	20	351	82	1.7E-06	34	1148		
H MS-11	545-545.9	PHb Gcmgr(gn)	9	7	5	6	3	3	3	0	0	5	4	6	51	34	37	9.4E-04	64	4110		
I MS-13	402.3-403.8	PHb Gcmgr(gn)	9	8	6	6	7	5	1	0	1	1	4	2	50	69	46	2.8E-05	59	3524		
J MS-13	403.8-404.8	PHb Gcmgr(gn)	5	7	11	11	3	1	1	0	1	1	3	6	50	59	55	2.6E-07	54	2908		
K MS-18	296.1-297.9	PHb Gcmgr(gn)	10	4	2	1	0	2	1	1	0	2	6	21	50	353	71	1.1E-11	43	1846		
L MS-18	307.4-308.7	PHb Gcmgrgn	12	15	1	2	1	1	2	1	0	0	4	11	50	17	65	7.4E-10	48	2259		
M MS-21	33.5-34	PHb Gcmgr(gn)	3	9	6	4	4	0	1	0	0	5	10	8	50	16	46	2.2E-05	59	3491		
N MS-21	122-122.7	PHb Gcmgr(gn)	7	11	6	7	3	0	0	0	0	0	0	6	40	54	73	7.0E-10	42	1744		
O MS-21	142-142.7	PHb Gcmgr(gn)	6	4	9	9	8	0	0	0	1	1	5	7	50	59	51	2.1E-06	56	3166		
TOTAL			93	86	67	67	44	21	19	10	10	28	67	112	624	33	40	2.2E-36	62	3898		
PERCENT			15	14	11	11	7	3	3	2	2	4	11	18								

Table A3-1. Summary of lower Mount Harper group paleocurrent data.

$N = 505$

STATION LOCATION				PALEO-CURRENT	OBSERVATIONS PER 30 DEGREE INTERVAL																Vect Rayleigh Circ			
MAP OR REF SECTION	OR METRES	MAP UNIT	LITHOLOGY	TYPE	0-30	31-60	61-90	91-120	121-150	151-180	181-210	211-240	241-270	271-300	301-330	331-360	Obs	Vect mag (%)	Signif-icance	Sed Dev	Circ Var			
P MS-14	126-126.3	PHd	Gcmgrgn	imbrication	10	15	19	1	2	0	0	0	0	0	0	3	50	53	85	1.7E-16	30	907		
Q MS-14	138-138.3	PHd	Gcmgrgn	imbrication	20	12	4	0	3	0	1	0	0	1	3	6	50	25	76	2.9E-13	39	1521		
R MS-14	154-154.5	PHd	Gcmgrgn	imbrication	6	2	0	4	5	3	3	1	4	7	10	9	54	322	31	5.8E-03	67	4514		
S MS-14	204-204.25	PHd	Gcm-pShgn	imbrication	10	7	7	1	2	1	0	0	1	2	9	10	50	12	62	4.4E-09	49	2445		
T MS-27	260	PHlb	Gmm/Gcm(ga)	imbrication	7	9	5	5	2	1	4	4	3	1	5	5	51	33	28	2.0E-02	69	4723		
U MS-27	273	PHlb	Gmm/Gcm(ga)	imbrication	13	5	7	2	2	1	1	0	0	1	6	12	50	15	62	4.6E-09	50	2451		
V PM44	E edge map	PHld	Gcmgrgn	imbrication	7	6	20	11	4	0	1	1	0	0	0	0	50	77	80	9.0E-15	35	1224		
W PM81a	NW end LH	PHlb	Gcm(gn)	imbrication	2	2	1	0	0	0	0	0	1	5	23	16	50	327	88	1.6E-17	27	723		
X PM81b	NW end LH	PHlb	Gcmga	imbrication	15	1	0	0	0	0	0	0	1	0	7	27	51	349	92	1.2E-19	21	428		
Y PM42	E end map	PHld	Gcmgrgn	imbrication	3	1	2	1	4	1	3	11	9	9	1	4	49	256	42	1.7E-04	61	3765		
TOTAL					93	60	65	25	24	7	13	17	19	26	64	92	505	14	58	1.7E-56	52	2720		
PERCENT					18	12	13	5	5	1	3	3	4	5	13	18								

DISTAL FACIES

85 = 22

STATION LOCATION			OBSERVATIONS PER 30 DEGREE INTERVAL													Vect Rayleigh Circ				
MAP OR REF SECTION	MAP UNIT LITHOLOGY	CURRENT TYPE	0-30	31- 60	61- 90	91- 120	121- 150	151- 180	181- 210	211- 240	241- 270	271- 300	301- 330	331- 360	#	Vect Mag (%)	Signif- icance	Std Dev	Circ Var	
Z MS-20	271-271.1	PHc pSp	0	0	0	0	0	0	0	0	0	0	9	10	19	332	99	9.3E-09	4	17
AA MS-20	272-272.5	PHc pSp/Gesp	0	0	0	0	0	0	0	0	0	0	14	6	20	323	98	4.4E-09	7	52
BB MS-20	275-303.25	PHc pSp/Gesp	1	0	0	0	0	0	0	0	0	4	9	3	17	319	92	5.6E-07	21	456
CC MS-28	0-20	PHc FI/SN(r)	14	0	0	0	0	0	0	0	0	0	0	1	15	4	99	4.1E-07	2	4
DD MS-28	20-30	PHc Sp	11	0	0	0	0	0	0	0	0	0	0	14	25	358	98	4.2E-11	9	73
TOTAL			26	0	0	0	0	0	0	0	0	4	32	34	96	340	93	2.1E-36	21	422
PERCENT			27	0	0	0	0	0	0	0	0	4	33	35						

Table A3-1 (cont.). Summary of lower Mount Harper group paleocurrent data.

TOTAL LOWER MOUNT HARPER GROUP PALEOCURRENTS N = 1225

	OBSERVATIONS PER 30 DEGREE INTERVAL																	Vect Rayleigh Circ				
	31- 61- 91- 121- 151 181- 211- 241- 271- 301- 331-	# Vect	Mag	Signif-	Circ																	
	0-30 31- 60 61- 90 91- 120 121- 150 151 180 181- 210 211- 240 241- 270 271- 300 301- 330 331- 360	Obs	can	(%)	icance	Dev	Var															
PROXIMAL	93 86 67 67 44 21 19 10 10 28 67 112	624	30	42	2.2E-36	62	3898															
INTERMEDIATE	93 60 65 25 24 7 13 17 19 26 64 92	505	12	47	1.7E-56	59	2720															
DISTAL	26 0 0 0 0 0 0 0 0 4 32 34	96	340	93	2.1E-36	21	422															
TOTAL	212 146 132 92 68 28 32 27 29 58 163 238	1225	13	49	1.0E-269	57	3898															
PERCENT	17 12 11 8 6 2 3 2 2 5 13 19																					

PERCENT OF EACH FACIES/INTERVAL IN COMBINED ROSE

PROXIMAL	44	59	51	73	65	75	59	37	34	48	41	47
INTERMEDIATE	44	41	49	27	35	25	41	63	66	45	39	39
DISTAL	12	0	0	0	0	0	0	0	0	7	20	14

Table A3-1 (cont.). Summary of lower Mount Harper group paleocurrent data.

MAP UNIT PH5/PH5A SILICICLASTICS: Sandstones and Siltstones only

N = 80

STATION LOCATION			OBSERVATIONS PER 30 DEGREE INTERVAL												Vect		Circ			
MAP OR REF SECTION METRES	MAP UNIT	PALEO- CURRENT TYPE	31- 0-30	61- 60	91- 90	121- 120	151- 150	181- 180	211- 210	241- 240	271- 270	301- 300	331- 330	360	# of Obs	Vect Mag (%)	Rayleigh Signif	Std Dev	Circ Var	
A MS-22 485-495	PH5A	troughs	3	0	0	0	0	0	0	0	0	0	0	9	12	347	99	1.7E-09	2	4
D MS-24 100-104	PH5A	troughs	0	7	5	0	0	0	0	0	0	0	0	0	12	55	82	3.1E-04	33	1120
E MS-34 0-20	PH5	crosslams	0	0	0	0	0	0	0	0	0	16	4	0	20	291	99	3.1E-09	2	4
F PM-74 N of MS26	PH5	crosslams	4	2	0	0	0	0	0	0	0	0	0	0	6	30	99	2.5E-03	2	4
G PM102 W edge map	PH5	grooves?	0	0	0	0	0	0	0	0	0	25	5	0	30	292	99	1.9E-13	2	4
TOTAL PER 30 DEGREE INTERVAL			7	9	5	0	0	0	0	0	0	41	9	9	80	347	51	7.4E-10	56	3161
PERCENT			9	11	6	0	0	0	0	0	0	51	11	11	100					

MAP UNIT PH5/PH5A SILICICLASTICS: Chert-pebble conglomerates

N = 190

STATION LOCATION			PALEO- CURRENT		OBSERVATIONS PER 30 DEGREE INTERVAL																# of		Vect		Circ	
MAP OR REF SECTION METRES	MAP UNIT	TYPE	31- 0-30	61- 60	91- 90	121- 120	151- 150	181- 180	211- 210	241- 240	271- 270	301- 300	331- 330	360- 360	Obs	Vect Mean	Mag (%)	Rayleigh Signif	Std Dev	Circ Var						
B MS-24 82.5	PH5A	imbrication	1	0	0	4	3	3	6	4	8	9	5	7	50	262	39	5.2E-04	63	3976						
C MS-24 98	PH5A	imbrication	1	1	6	13	16	10	0	0	1	0	2	0	50	125	74	1.1E-12	41	1640						
H PM-88-10 200m E MS25	PH5A	imbrication	23	4	4	3	1	0	0	0	0	0	0	5	40	26	84	4.4E-13	31	965						
I PM71 500m W MS24	PH5A	imbricat	0	0	1	2	2	1	5	32	6	1	0	0	50	219	82	2.8E-15	34	1129						
TOTAL PER 30 DEGREE INTERVAL			25	5	11	22	22	14	11	36	15	10	7	12	190	180	13	3.6E-02	75	5687						
PERCENT			13	3	6	12	12	7	6	19	8	5	4	6	100											

Table A3-2. Summary of paleocurrent data for the upper Mount Harper group.

MAP UNIT PH5/PH5A: CARBONATE CLASTICS N = 97

STATION LOCATION		PALEO- CURRENT		OBSERVATIONS PER 30 DEGREE INTERVAL												# of		Vect		Circ	
MAP OR REF SECTION METRES	MAP UNIT TYPE	31- 0-30	61- 60	91- 120	121- 150	151- 180	181- 210	211- 240	241- 270	271- 300	301- 330	331- 360	Obs	Mean	Mag (%)	Rayleigh Signif	Sid	Circ Dev Var			
J MS-15 250-275	PH5(4) crosslams	0	0	0	0	4	27	17	0	0	0	0	48	205	96	6.1E-20	14	190			
K MS-26 710-725	PH5 crosslams	0	0	0	0	0	2	8	0	0	0	0	10	215	99	5.1E-05	2	4			
L PM-31 N OF MS15	PH5(4) flutes	0	0	0	0	19	1	0	0	0	0	0	20	138	99	1.5E-04	2	4			
M PM-75 Cres. Mtn	PH5 crosslams	0	0	2	7	0	0	0	0	0	0	0	9	98	98	3.7E-09	8	57			
TOTAL PER 30 DEGREE INTERVAL		0	0	2	7	19	5	29	25	0	0	0	87	171	58	2.9E-13	52	2740			
PERCENT		0	0	2	8	22	6	33	29	0	0	0	100								

MAP UNIT PH4 N = 167

STATION LOCATION		OBSERVATIONS PER 30 DEGREE INTERVAL												Vect			Circ					
MAP OR	OR	MAP	CURRENT													#	Vect	Mag	Rayleigh	Sid	Circ	
REF SECTION	METRES	UNIT	TYPE	0-30	31-60	61-90	91-120	121-150	151-180	181-210	211-240	241-270	271-300	301-330	331-360	Obs	Mean	(%)	Signif	Dev	Var	
N MS-15	107-150	PH4	flutes	0	1	1	6	23	10	2	2	0	0	0	0	45	145	87	1.2E-15	28	788	
O MS-17	PM82	PH4	crosslams	0	0	0	7	9	9	1	1	2	0	0	0	29	150	82	4.1E-09	33	1120	
P PM-88-1	200m N MS16	PH4	crosslams	0	0	0	0	0	0	3	11	0	1	0	0	15	222	96	1.1E-04	14	209	
Q MS-16	65-100m	PH4	crosslams	0	0	0	0	7	3	2	4	2	1	0	0	19	184	66	2.5E-04	47	2176	
R MS-17	PM83	PH4	crosslams	0	0	0	0	6	5	3	0	1	0	0	0	15	163	83	3.2E-05	32	1053	
S PM-67	w traces	PH4(S)	crosslams	1	0	2	3	0	0	0	0	0	0	0	0	6	111	79	2.3E-02	36	1319	
T PM-88-4	500m N MS16	PH4	crosslams	0	0	0	0	0	5	2	5	1	0	0	0	13	201	88	4.2E-05	27	719	
U PM-88-4.5	"	PH4	ling ripples	0	0	0	0	0	0	1	16	8	0	0	0	25	235	98	3.7E-11	7	56	
DEGREE INTERVAL				1	1	3	16	45	32	14	39	14	2	0	0	167	176	68	1.1E-34	45	2022	
PERCENT				1	1	2	10	27	19	8	23	8	1	0	0	100						

Table A3-2 (cont). Summary of paleocurrent data for the upper Mount Harper group.

MAP UNIT PH2/PH1

N = 244

STATION LOCATION		PALEO- CURRENT TYPE	OBSERVATIONS PER 30 DEGREE INTERVAL												Vect		Circ			
MAP OR REF SECTION	MAP UNIT		31- 0-30	61- 60	91- 90	121- 120	151- 150	181- 180	211- 210	241- 240	271- 270	301- 300	331- 330	360	# of Obs	Vect Mean	Mag (%)	Rayleigh Signif	Std Dev	Circ Var
V	MS-29 , 42-43m	PH1 crosslams	0	0	1	0	0	1	5	4	3	0	0	0	14	206	76	3.0E-04	39	1507
W	MS-17 38.5	PH2(1) part lin	0	0	0	0	0	0	8	18	0	0	0	0	26	216	99	9.6E-12	2	4
X	MS-17 102	PH2(1) part lin	0	0	0	0	0	0	11	14	0	0	0	0	25	209	99	2.0E-11	2	4
Y	MS-19A 148	PH2 crosslams	0	0	0	0	6	4	2	0	0	0	0	0	12	155	94	2.4E-05	18	323
Z	MS-19A 218-222	PH2 crosslams	0	0	2	0	4	0	6	0	1	0	0	0	13	157	65	4.1E-03	47	2249
a	MS-19B 200-205	PH2 crosslams	0	0	0	3	6	4	0	0	0	0	0	0	13	135	88	4.3E-05	27	721
b	MS-19B 292-292.75	PH2 imbrication	0	0	0	0	2	8	12	6	0	9	6	6	49	235	46	3.1E-05	59	3511
c	PM-52 S of MS22	PH2 part lin	0	0	0	0	0	0	18	13	0	0	0	0	31	238	70	2.2E-07	44	1917
d	PM-55 S of MS22	PH2 crosslams	0	0	4	20	1	0	0	0	0	0	0	0	25	102	98	3.1E-11	8	57
e	PM-61 S of MS19	PH2 imbrication	0	1	0	0	2	0	7	4	7	5	1	0	27	239	67	5.6E-06	46	2116
f	PM-62 S of MS19	PH2 crosslams	0	0	0	4	5	0	0	0	0	0	0	0	9	119	98	1.8E-04	8	57
TOTAL PER 30 DEGREE INTERVAL			0	1	7	27	26	17	69	59	11	14	7	6	244	193	54	1.0E-31	55	2974
PERCENT			0	0	3	11	11	7	28	24	5	6	3	2	100					

Table A3-2 (cont). Summary of paleocurrent data for the upper Mount Harper group.

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

140° 00'

55'

50'

45'

40'

35'

64° 45'

FIGURE B1

MAP 1

GEOLOGY

LOWER MOUNT HARRISON

YUKON TERRITORY

(SEE MAP 2 FOR LOCATION)

Scale 1:50,000

metres 1000 0 1000 2000

64° 40'

FIGURE B1

MAP 1

GEOLOGY

LOWER MOUNT HARPER GROUP

YUKON TERRITORY

(SEE MAP 2 FOR LEGEND)

Scale 1:50,000

1:250,000

MAP 2

1:50,000

NATIONAL TOPOGRAPHIC SYSTEM REFERENCE

MAP 1

25'

20'

15'

10'

05'

139° 00'

64° 45'

DAWSON
CITY
DAWSON

MAP 2

C/16	B/13	B/14
C/9	B/12	B/11
C/8	B/5	B/6

MAP 1

100,000
1:50,000
NATIONAL TOPOGRAPHIC SYSTEM REFERENCE

64° 40'

COOLVILLE

Pf₁

Pf₁

Pf₁

COIL

SECTION

40'

35'

30'

25'

20'

15'

Pf₂

Pf₁

Pf₂

64° 40'

COLEVILLE

COLEVILLE

64° 35'

25'

20'

15'

10'

05'

139° 00'

YUKON TERRITORY

metres 1000 0 1000 2000 3000 4000 metres

1:250,000

155,00

WATSON TELETYPE SYSTEM REFERENCE

PH

PMS

Grey brown lithic wacke or arenite, very fine-grained to silty, thin bedded to laminated; intercalated with dark brown to orange grey dolowacke or dolarenite, very fine-grained to silty, laminated to thin bedded, rare ripples in both; rare coarse-grained to granule lithic wacke "grit"; rare Early Cambrian trace fossils in upper 50 m (only in northeast exposures)

64° 55'

65° 00'

65° 00'

13	B/14
12	B/11
15	B/6

MAP 1

ACE

64° 55'

Dark grey brown weathering, dark greenish grey chert pebble conglomerate, clast-supported, tabular green grey chert clasts, fines upward to light brown grey medium- to coarse-grained lithic arenite, generally trough crossbedded, both as discontinuous, lenticular units interbedded with, or overlying P114.

Contact sharp, erosive P115a on P114, gradational P115 on P114 or P113

P114 Grey orange weathering, yellow brown dolarenite, dolowacke and dolostillite, silt- to medium-grained, thin bedded, rare hummocky cross-stratification and ripples, discontinuous unit, rare dolowacke intraclast breccia beds; rare laminated black limestone mudstone at top of thick dolarenite lenticels

Contact gradational

P113 Black laminated mudstone, rarely shale; noncalcareous at base, increasingly dolomitic up; dark brown to grey orange, laminated to thin bedded dolostillite increasing common upward

Disconformity: contact generally obscured, overlies breccia of P112 in north, altered to brecciated P111 or P112 in central map area, brecciated, altered P11V in south.

P112A Light brown grey rubble breccia or fractured silicified and/or dolomitized P112, P111 or P11V lithology

P112 Yellow orange weathering, light to medium grey fresh, laminated to thick bedded, dolorudite, dolarenite, dolowacke, dolostillite; coarsening-upward cycles <150 m thick common, conglomerates pebble to boulder sizes; 100% Fifteenmile Grp. clast types.

Contact gradational with P111, sharp angular unconformity (10-20°) where overlies Fifteenmile Grp

P111 Dark green grey or orange grey conglomerate; matrix- and clast-supported, pebble to rare small boulder sizes, mixed volcanic (Mt Harper Volc. Complex) and dolostone (Fifteenmile Grp.) clasts and matrix; less common interbedded dolowacke, dolostillite, epiclastic sandstone, mudstone, rare tuff (with pyroclastic bombs), volcanic flows.

Contact gradational (10's to 100's of metres) where overlies Mount Harper Volcanic Complex; sharp angular unconformity (10-20°) where overlies Fifteenmile Group.

MOUNT HARPER VOLCANIC COMPLEX

P11V Undivided

Contact sharp, conformable on Lower Mount Harper Group; angular unconformity where overlies Fifteenmile Group.

LOWER MOUNT HARPER GROUP

Light grey weathering, medium grey, very finely crystalline dolostone, laminated, very fine grained. Only occurs as rare, discontinuous lenses near top of L111G in east part of map sheet

Contact sharp, conformable

Pale yellowish orange weathering, grey-orange to medium grey dolowacke, fine- to very coarse-grained, thin to medium bedded, generally fining up from, or interbedded with, pebble to small cobble dolomitic conglomerate, clast- and matrix-supported, thin- to medium-bedded.

64° 50'

coarse grained, thin to medium bedded, generally lining up from, or interbedded with, pebble to small cobble dolomitic conglomerate, clast- and matrix-supported, thin- to medium-bedded.

Contact gradational

Basal unit in east half of LMHG. Moderate to dusky red (maroon) dolowacke/mudstone "redbeds", generally dolomitic, but high chert content, coarsens up from mudstone to coarse-grained wackestone, laminated to thin bedded; abundant desiccation cracks, common ripples, rare planar and trough crossbeds

Disconformably overlies Fifteenmile Group

Pale yellow-orange weathering, grey-orange to medium grey dolomitic conglomerate; generally clast-supported, pebble to boulder sizes (coarsest to south), medium to thick bedded, complex grading or massive; very rare dolomitic mudstone and medium- to coarse-grained dolowacke discontinuous interbeds (increasingly common N.W. of Coal Creek).

Contact gradational where overlies PHc or Pha, disconformity where overlies Fifteenmile Group

P1a

Medium to light grey breccia, generally rubble packbreccia, unaltered Fifteenmile Group breccia at south contact of LMHG, adjacent to main fault; east of Mt. Harper is complexly altered with multiple chalcedony and carbonate cements, rare silcrete and/or calcrete

Disconformity: up to 50 m preserved paleorelief, rare preserved pre-Harper Group, high angle normal faults. Contact sharp except gradational where P1a is preserved east of Mt. Harper

MIDDLE TO LATE PROTEROZOIC (?)

FIFTEENMILE GROUP

Pfu

UPPER FIFTEENMILE GROUP - undivided: medium to light grey, finely crystalline dolostone, laminated to thin bedded, commonly stromatolitic in top 200 m, common chert, dolostone breccia, rare siltstone, shale and fine grained quartzite.

Contact gradational

LOWER FIFTEENMILE GROUP - undivided: Medium grey, finely crystalline dolostone and dolostone breccia, rarely stromatolitic; dark grey shale, pebbly mudstone; dark to medium grey stromatolitic limestone; rare quartz sandstone.

Unconformity: sharp, angular (>10°)

MIDDLE PROTEROZOIC

WERNECKE SUPERGROUP

GILLESPIE LAKES GROUP: Moderate orange brown weathering, medium grey to grey brown, dolostone and argillaceous or silty dolostone, laminated to thick bedded, rare maroon weathering argillite.

Contact gradational

Pq

QUARTET GROUP: Dark grey to black intercalated siliciclastic mudstone, siltstone, sandstone, laminated to rare thick beds.

Disconformity, up to 50 m preserved paleorelief, rare preserved pre-Harpur Group high angle normal faults. Contact sharp except gradational where P14a is preserved east of Mt. Harpur.

MIDDLE TO LATE PROTEROZOIC (?)

FIFTEENMILE GROUP

UPPER FIFTEENMILE GROUP - undivided: medium to light grey, finely crystalline dolostone, laminated to thin bedded, commonly stromatolitic in top 200 m, common chert, dolostone breccia, rare siltstone, shale and fine grained quartzite.

Contact gradational

LOWER FIFTEENMILE GROUP - undivided: Medium grey, finely crystalline dolostone and dolostone breccia, rarely stromatolitic; dark grey shale, pebbly mudstone; dark to medium grey stromatolitic limestone; rare quartz sandstone.

Unconformity: sharp, angular (>10°)

MIDDLE PROTEROZOIC

WERNECKE SUPERGROUP

GILLESPIE LAKES GROUP: Moderate orange brown weathering, medium grey to grey brown, dolostone and argillaceous or silty dolostone, laminated to thick bedded, rare maroon weathering argillite.

Contact gradational

QUARTET GROUP: Dark grey to black intercalated siliciclastic mudstone, siltstone, sandstone, laminated to rare thick beds.

Geological boundary (defined, approximate, inferred)

Gradational geological boundary

Bedding, tops known (horizontal, inclined, vertical)

Foliation (horizontal, inclined, vertical)

Fault (defined, approximate, inferred)

Thrust fault (teeth in direction of dip; defined, approximate, inferred)

Anticline (defined, approximate; arrow indicates plunge)

Syncline (defined, approximate; arrow indicates plunge)

Fossil locality

END

1|5|0|4|9|1

FIN