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GEOLOGICAL SURVEY OF CANADA  
BULLETIN 492

**RIFT-RELATED VOLCANISM, SEDIMENTATION,  
AND TECTONIC SETTING OF THE  
MOUNT HARPER GROUP, OGILVIE MOUNTAINS,  
YUKON TERRITORY**

P.S. Mustard and C.F. Roots



1997



Natural Resources Canada  
Ressources naturelles Canada

Canada

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Catalogue No. M42-492E  
ISBN 0-660-16790-5

Available in Canada from  
Geological Survey of Canada offices:

601 Booth Street  
Ottawa, Ontario K1A 0E8

3303-33rd Street N.W.,  
Calgary, Alberta T2L 2A7

101-605 Robson Street  
Vancouver, B.C. V6B 5J3

or from

Canada Communication Group – Publishing  
Ottawa, Ontario K1A 0S9

A deposit copy of this publication is also available for reference  
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Price subject to change without notice

#### **Cover illustration**

View west towards Mount Harper (peak in centre). Bedded conglomerates of the lower Mount Harper Group are exposed in the foreground cliffs, overlain in the distance by pillowed lava flows of the Mount Harper volcanic complex. Light coloured strata north (right in photo) of Mount Harper are mostly southwest-dipping dolostone of the Fifteenmile group, unconformably overlain by a few hundred metres of lower Mount Harper Group sedimentary rocks at the base of Mount Harper. GSC 1995-091

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*Original manuscript received: 1994-01*  
*Final version approved for publication: 1994-08*

## Preface

The Ogilvie Mountains of west-central Yukon consist of well-exposed Precambrian to Triassic strata that formed on the shelf and adjacent basin of an ancient continental margin. Within the shelf strata are several profound unconformities, each representing a period of time when the stable sedimentary environment was disrupted by tectonic upheaval. One of these periods, near the end of the Precambrian era, was a continental rift event now represented by the Windermere Tectonic Assemblage, whose rocks are exposed in a thin belt along the spine of the Cordillera from Alaska to Mexico. The Mount Harper Group is one of the best exposed and most complete sedimentary and volcanic successions related to initial Windermere rifting.

This bulletin presents a detailed account of the sedimentology, volcanology and tectonic setting of the Mount Harper Group. It is one product of the larger Ogilvie Mountains Project, a bedrock mapping effort by staff of the Cordilleran Division of the Geological Survey of Canada and graduate students directly supported by the GSC. The detailed studies summarized in this publication provide foundation geological data fundamental for a better understanding of the evolution of the northern Cordillera.

Elkanah A. Babcock  
Assistant Deputy Minister  
Geological Survey of Canada

## Préface

Les monts Ogilvie dans le centre ouest du Yukon se composent de couches précambriennes à triasiques bien exposées formées sur la plate-forme continentale et le bassin adjacent d'une ancienne marge continentale. Dans les couches de la plate-forme continentale on observe plusieurs discordances profondes, chacune représentant un période pendant laquelle le milieu sédimentaire stable a été perturbé par un soulèvement tectonique. L'une de ces périodes, proche de la fin du Précambrien, a été marquée par un épisode de distension continentale maintenant représentée par l'Assemblage tectonique de Windermere dont les roches affleurent dans une mince ceinture longeant l'épine de la Cordillère de l'Alaska au Mexique. Le Groupe de Mount Harper est l'une des successions sédimentaires et volcaniques les mieux exposées et les plus complètes associées au rifting initial de Windermere.

Le présent bulletin donne un compte rendu détaillé de la sédimentologie, de la volcanologie et du cadre tectonique du Groupe de Mount Harper. C'est l'un des produits du vaste projet portant sur les monts Ogilvie, projet de cartographie du substratum rocheux réalisé par le personnel de la Division de la Cordillère de la Commission géologique du Canada et des étudiants diplômés financés directement par la CGC. Les études détaillées qui sont résumées dans la présente publication contiennent des données géologiques fondamentales pour approfondir l'évolution de la Cordillère septentrionale.

Elkanah A. Babcock  
Sous-ministre adjoint  
Commission géologique du Canada

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# RIFT-RELATED VOLCANISM, SEDIMENTATION, AND TECTONIC SETTING OF THE MOUNT HARPER GROUP, OGILVIE MOUNTAINS, YUKON TERRITORY

---

## *Abstract*

*The ca. 750 Ma Mount Harper Group contains volcanic and coarse clastic rocks corresponding to the basal Windermere Tectonic Assemblage in the Canadian Cordillera. The lower Mount Harper Group is a tapering wedge of alluvial fan conglomerate and sandstone derived from the uplifted south side of a Proterozoic normal fault (Harper Fault) and preserved in a west-trending half graben which formed during initial extension. The Mount Harper volcanic complex oversteps the Harper Fault and is a subaqueous-to-emergent basaltic shield capped by rhyodacitic and andesitic flood flows. The upper Mount Harper Group comprises coarsening-upward cycles of interbedded mudstone and sandstone with locally derived volcanic conglomerate, deposited in submarine debris apron and fan complexes. The upper Mount Harper Group formed in a half-graben, of opposing symmetry, and offset with respect to the lower Mount Harper Group half-graben. This is similar to the continental rift geometry of some modern rift systems. Volcanism occurred mainly in the accommodation zone between the two subbasins, probably reflecting a concentration of faults in a transfer fault system of the propagating rifting event. In comparison with other volcanic rock of the Windermere Tectonic Assemblage the Mount Harper volcanic complex is similar in overall continental affinities, but is more evolved. The Mount Harper Group resembles other basal Windermere rocks in evidence of extension faulting related to basin formation and sedimentation. A major difference is the lack of evidence for glacial sedimentation, a distinctive feature of some basal Windermere successions elsewhere in the Cordillera.*

## *Résumé*

*Le Groupe de Mount Harper datant de 750 Ma environ contient des roches volcaniques et clastiques grossières correspondant à la base de l'Assemblage tectonique de Windermere dans la Cordillère canadienne. La partie inférieure du Groupe de Mount Harper est un biseau de conglomérat et de grès de cône alluvial issus du compartiment soulevé sud d'une faille normale protérozoïque (faille de Harper) et conservés dans un demi-graben à direction ouest formé durant la distension initiale. Le complexe volcanique de Mount Harper forme un dépôt transgressif sur la faille de Harper et constitue un écran basaltique subaquatique à émergent coiffé de coulées de plateau rhyodacitiques et andésitiques. La partie supérieure du Groupe de Mount Harper est caractérisée par des cycles à granoclassement inverse de mudstone et de grès interstratifiés avec des conglomérats volcaniques d'origine locale, déposés dans des complexes sous-marins de débris formant des plaines et des cônes. La partie supérieure du Groupe de Mount Harper s'est formée dans un demi-graben de géométrie opposée et décalé par rapport au demi-graben de la partie inférieure du Groupe de Mount Harper. Cette géométrie est semblable à celle du rift continental de certains systèmes modernes. Le volcanisme a surtout touché la zone d'ajustement entre les deux sous-bassins, reflétant probablement une concentration de failles dans un réseau de failles de transfert au cours du rifting de propagation. Comparativement aux autres roches volcaniques de l'Assemblage tectonique de Windermere, le complexe volcanique de Mount Harper est semblable en ce qui concerne l'ensemble des affinités continentales, mais son évolution est plus avancée. Le Groupe de Mount Harper s'apparente aux autres roches de la base de l'Assemblage de Windermere si l'on se base sur les failles d'extension liées à la formation du bassin et à la sédimentation. La différence principale est l'absence d'indices de sédimentation glaciaire qui caractérisent certaines successions de la base de l'Assemblage de Windermere ailleurs dans la Cordillère.*

## SUMMARY

The circa 750 Ma Mount Harper Group, here formally defined at its type locality in west central Yukon Territory, is a three-part succession of volcanic and coarse clastic rocks which corresponds to the basal part of the Windermere Tectonic Assemblage in the Canadian Cordillera. The Mount Harper Group provides a uniquely complete and age-constrained record of initial Windermere Assemblage extension-related sedimentation and volcanism. This major extension event culminated in rifting of the late Precambrian margin of North America and formation of a major proto-Pacific oceanic basin.

The lower Mount Harper Group was locally derived from the uplifted south side of a preserved normal fault system (Harper Fault) and is preserved in a west-trending half graben basin which formed during initial extension. The lower Mount Harper Group is up to 1100 m thick and overlies Proterozoic platform dolostone at a paleokarst unconformity surface. The main lithofacies of the lower Mount Harper Group are coarse dolostone clast conglomerate combined with paleotalus and olistoliths, and interbedded mudstone and pebbly sandstone. Deposition occurred in subaerial alluvial fan complexes and associated braided stream environments with minor subaqueous (probably lacustrine) deposits.

The Mount Harper volcanic complex oversteps the Harper Fault and contains inferred vent areas aligned with this deep-seated break. The remnants of a 1200 m thick subaqueous-to-emergent basaltic shield (lower suite) is capped by small rhyodacitic and andesitic flood flows (upper suite). All volcanic products are tholeiitic. The Mount Harper volcanic complex is unlike all other igneous occurrences reported within the Windermere Supergroup in its compositional variety, perhaps as a result of protracted and voluminous volcanism. Although the lower basaltic suite is relatively primitive, with low  $\text{TiO}_2$  (less than 1.0%) and high  $\text{Mg}/\text{Mg}+\text{Fe}$  ratio, the upper bimodal suite has high  $\text{TiO}_2$  (1.5-3.0%) and a low  $\text{Mg}/\text{Mg}+\text{Fe}$  ratio (0.2). Only the uppermost andesitic flows compositionally resemble other igneous occurrences in the Windermere Supergroup (e.g. Little Dal, Irene/Huckleberry formations).

The upper Mount Harper Group disconformably overlies middle to upper Proterozoic platform dolostone in the north and intertongues with the volcanic complex in the south, and in turn is disconformably overlain by early Cambrian clastics and dolostone. The upper Mount Harper Group comprises coarsening-upward cycles of interbedded mudstone and sandstone with locally derived volcanic conglomerate, all totalling 400 m in maximum thickness. Debris was shed from the south during early stages of sedimentation with normal faults in the volcanic complex providing uplifted source areas, and from the north from

## SOMMAIRE

Le Groupe de Mount Harper d'environ 750 Ma, défini formellement à sa localité type dans le centre ouest du Yukon, est une succession en trois parties de roches volcaniques et clastiques grossières qui correspond à la partie basale de l'Assemblage tectonique de Windermere dans la Cordillère canadienne. Le Groupe de Mount Harper contient des indices exceptionnels par leur globalité et leur délimitation temporelle de la sédimentation et du volcanisme initiaux associés à la distension de l'Assemblage de Windermere. Cet important épisode de distension a culminé par le rifting de la marge du Précambrien tardif de l'Amérique du Nord et la formation d'un vaste bassin océanique proto-pacifique.

La partie inférieure du Groupe de Mount Harper a été localement formée à partir de sédiments provenant de la zone sud soulevée d'un réseau de failles normales conservées (faille de Harper) et elle est présente dans un bassin de demi-graben à direction ouest qui s'est formé durant la distension initiale. La partie inférieure du Groupe de Mount Harper mesure jusqu'à 1100 m d'épaisseur et repose sur une dolomie de plate-forme protérozoïque sur une surface de discordance paléokarstique. Les lithofaciès principaux de la partie inférieure du Groupe de Mount Harper sont des conglomérats de clastes dolomitiques grossiers combinés à des blocailles et des olistolithes et à des interstratifications de mudstone et de grès caillouteux. Les matériaux se sont déposés dans des complexes de cônes alluviaux subaériens et des milieux associés de cours d'eau anastomosés caractérisés par des sédiments subaquatiques (probablement lacustres) en faible quantité.

Le complexe volcanique de Mount Harper forme un dépôt transgressif sur la faille de Harper et contient des zones d'évent inférées, alignées avec cette rupture profonde. Les résidus d'un écran basaltique (suite inférieure) subaquatique à émergent de 1200 m d'épaisseur sont coiffés de petits amas de coulée de plateau rhyodacitiques et andésitiques (suite supérieure). Tous les produits volcaniques sont tholéiitiques. Le complexe volcanique de Mount Harper diffère de toutes les autres roches ignées décelées dans le Supergroupe de Windermere par la variété de sa composition, peut-être attribuable à un volcanisme long et volumineux. Même si la suite basaltique inférieure est relativement primitive, caractérisée par une faible concentration en  $\text{TiO}_2$  (moins de 1,0 %) et des rapports  $\text{Mg}/\text{Mg}+\text{Fe}$  élevés, la suite bimodale supérieure contient des concentrations élevées en  $\text{TiO}_2$  (1,5-3,0 %) et un faible rapport  $\text{Mg}/\text{Mg}+\text{Fe}$  (0,2). Seuls les coulées andésitiques sommitales s'apparentent par la composition aux autres occurrences ignées du Supergroupe de Windermere (p. ex. formations de Little Dal et d'Irene/Huckleberry).

La partie supérieure du Groupe de Mount Harper repose en discordance sur la dolomie de plate-forme du Protérozoïque moyen à supérieur dans le nord et s'interdigite au complexe volcanique dans le sud; elle est à son tour recouverte en discordance par des clastites et une dolomie du Cambrien précoce. La partie supérieure du Groupe de Mount Harper est caractérisée par des cycles à granoclassement inverse de mudstone et de grès interstratifiés avec des conglomérats volcaniques d'origine locale, totalisant 400 m d'épaisseur maximale. Les débris ont été évacués à partir du sud durant les premières étapes de la sédimentation, les failles normales du complexe volcanique

uplifted areas controlled by inferred normal faults in the underlying Fifteenmile group dolostones. Sedimentation occurred in submarine debris apron and fan complexes with debris flows and turbidity flows as the dominant processes.

The upper Mount Harper Group formed in a separate half-graben, slightly younger and offset with respect to the lower Mount Harper Group half-graben. This pattern, with opposed listric normal faults, is similar to the continental rift geometry of some modern rift systems. Volcanism occurred mainly in the accommodation zone between the two subbasins, probably reflecting a concentration of faults in a transfer fault system as part of the propagating rifting event.

In contrast to most examples of basal Windermere Supergroup and correlatives, the Mount Harper Group clearly reveals the sequence of faulting, sedimentation, and volcanism that occurred during an initial extension event. The main differences from other basal Windermere successions are: 1) extensive fan conglomerate sequences can be shown to be directly derived from synsedimentary extensional faults, with no evidence of a glacial component; and 2) volcanism is demonstrably synsedimentary, permitting the igneous age (750 Ma) to be applied to the enclosing sedimentary succession and thus provide a date of initial extension.

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## INTRODUCTION

Evidence for Late Proterozoic extension and rifting along the western margin of North America is preserved within the upper Proterozoic Windermere Tectonic Assemblage (Wheeler and McFeely, 1991) and U.S.A. correlatives (Fig. 1). The Windermere rift succession preserved in the Ogilvie Mountains of west-central Yukon Territory comprises a circa 750 Ma mixed volcanic and sedimentary sequence herein defined as the Mount Harper Group (new name). This bulletin documents the sedimentology, volcanology, and tectonic setting of the Mount Harper Group, which forms one of the best exposed and most complete successions related to initial Windermere rifting that is found in the Cordillera.

### *Location and physiography*

The Mount Harper Group is located in the remote southern Ogilvie Mountains, about 80 km northwest of Dawson, Yukon Territory (Fig. 2). The region is dominated by a rugged central area (80 by 35 km) of treeless ridges underlain mostly by Proterozoic carbonate rock. To the north and south this is flanked by more subdued, vegetated ranges generally composed of fine grained Proterozoic and Paleozoic clastic rocks. Mount Harper (64°49'N, 135°35'W; 1865 m elevation), near the southwest boundary of the carbonate-dominated central area, forms one of the higher peaks in that part of the Ogilvie

constituant des sources soulevées, ainsi qu'à partir de zones soulevées au nord, contrôlées par des failles inférées normales dans les dolomies du groupe de Fifteenmile sous-jacent. La sédimentation s'est produite dans des complexes sous-marins de débris formant des plaines et des cônes où les processus dominants ont été des coulées de débris et des coulées de turbidité.

La partie supérieure du Groupe de Mount Harper s'est formée dans un demi-graben distinct, légèrement plus récent et décalé par rapport au demi-graben de la partie inférieure du Groupe de Mount Harper. Cette configuration à failles normales listriques opposées est semblable à la géométrie de rift continental de certains systèmes de distension modernes. Le volcanisme a surtout touché la zone d'ajustement entre les deux sous-bassins, probablement reflétant une concentration de failles dans un réseau de failles de transfert au cours d'un épisode de rifting de propagation.

Contrairement à la plupart des exemples de la base du Supergroupe de Windermere et des corrélatifs, le Groupe de Mount Harper montre nettement la séquence de formation de failles, de sédimentation et de volcanisme qui s'est produite durant un épisode de distension initiale. Les principales différences par rapport aux autres successions basales de Windermere sont les suivantes : 1) il est possible de montrer que les vastes séquences de fanglomérat sont directement le résultat de failles de distension synsédimentaires sans trace de glaciation; 2) le volcanisme est de façon évidente synsédimentaire, permettant d'appliquer l'âge des roches ignées (750 Ma) à la succession sédimentaire enveloppante et de dater la distension initiale.

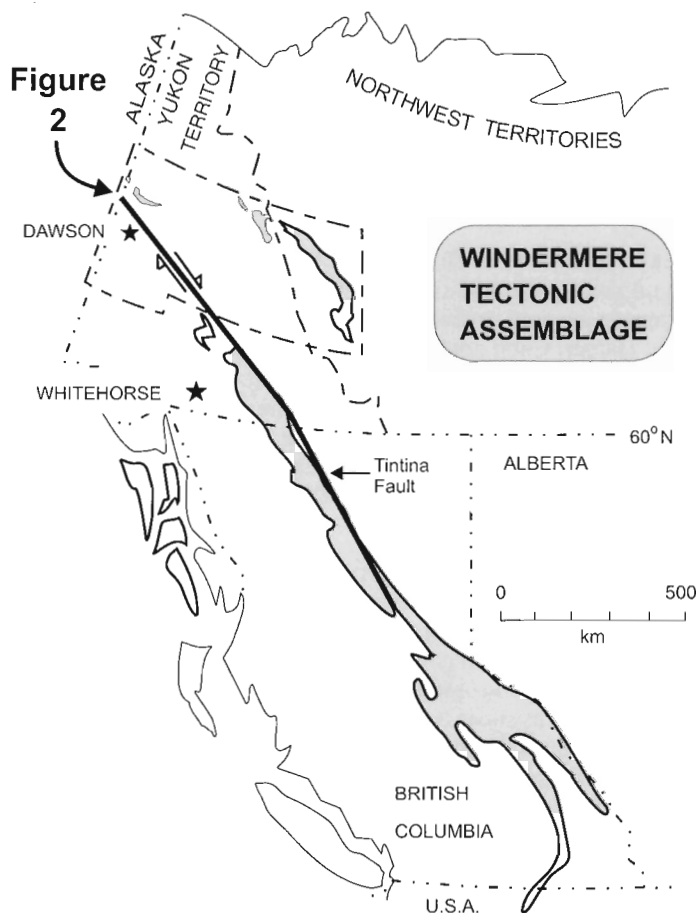
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Mountains. It is one of two peaks similarly named (the other is in adjacent Charley River quadrangle, Alaska) after Arthur Harper, a pioneer miner and outfitter in central Yukon Territory during the 1880s (Ogilvie, 1913).

Parts of western Yukon Territory and Alaska were not covered by Pleistocene ice sheets (the Beringia refugium of Hopkins et al., 1982), although some major valleys contained alpine glaciers. Coal Creek, the main drainage from Mount Harper, occupies one of the rare glacier-carved, flat-bottomed valleys, but most of its tributaries are narrow nonglaciated gorges.

### *Previous investigations*

The earliest research expedition which included the Ogilvie Mountains was undertaken in 1887 to determine the Alaska-Yukon Territory boundary (Ogilvie, 1913). A later transect along this boundary established the initial geological framework (Cairnes, 1914). Systematic (1:250 000 scale) mapping of the Ogilvie and Wernecke mountains began in 1959, and regional reports (Green and Roddick, 1962; Green, 1972) have been augmented by mapping and stratigraphic studies farther to the north (Bamber et al., 1963; Norris and Yorath, 1981). Studies of the southern Ogilvie Mountains include that of Paleozoic and younger units near Tombstone Mountain (Tempelman-Kluit, 1970) and Cretaceous syenite stocks (Anderson, 1987). Recent mapping has clarified Proterozoic



**Figure 1.** Distribution of Windermere Tectonic Assemblage in the northern Cordillera of North America (after Wheeler and McFeeley, 1991). The heavy line trending northwest across Yukon Territory is the Tintina Fault, with 450 km of post-Cretaceous dextral offset (Roddick, 1967).

and Paleozoic stratigraphy and structural relationships (Thompson and Roots, 1982; Thompson et al., 1987; Roots and Thompson, 1992). Related detailed studies include: central region stratigraphy (Blaise and Mercier, 1984; Mercier, 1985, 1989); setting of the volcanic rocks (Roots, 1982, 1983, 1987; Roots and Moore, 1983); Mount Harper Group sedimentology (Mustard et al., 1988; Mustard, 1990; Mustard and Donaldson, 1990; Mustard, 1991); Mount Harper volcanic complex paleomagnetism (Brunet, 1986); and genesis of middle Proterozoic intrusive breccia (Lane, 1990; Lane and Godwin, 1992).

Exploration for base and precious metals has been sporadic in the Ogilvie Mountains. No mines are currently operating, although Tertiary lignite was extracted along the Tintina Trench near Coal Creek at the turn of the century. The principal mineral prospects in the southern Ogilvie Mountains are zinc-lead-silver in Proterozoic carbonate rocks, uranium in Cretaceous granitic intrusions (Olade and Goodfellow, 1978) and adjacent copper skarns; and Proterozoic breccia pipes with uranium, gold, and rare-metals potential (Tempelman-Kluit, 1981; Yukon MINFILE, Department of Northern Affairs, Whitehorse, Yukon).

### Present work

This study results from the Ogilvie Mountains Project of the Geological Survey of Canada which involved investigation and 1:50 000 scale mapping of Dawson map area (NTS map areas 116B, 116C/E½) (Thompson and Roots, 1982; Thompson et al., 1987; Roots and Thompson, 1992). The volcanic rocks near Mount Harper were mapped and sampled, and stratigraphic sections measured (Roots, 1987). Fieldwork by R.I. Thompson and co-workers in adjacent regions led to recognition of rock successions representing intermittent extensional tectonics (Thompson et al., 1987; Roots and Thompson, 1992). Detailed field study of the Mount Harper Group sedimentary rocks was conducted during 1986 and 1987 (Mustard, 1990). The basis of this report is a map (1:25 000 scale) showing the distribution of sedimentary and volcanic rocks (Fig. 3, in pocket); detailed vertical profiles of representative stratigraphy of the Mount Harper Group (Appendix 1); petrography of rock samples using megascopic and microscopic methods (290 thin sections); whole-rock analyses of 106 representative volcanic and related intrusive rocks (Appendix 2); and more than 1500 paleocurrent indicator measurements from the sedimentary rocks (Appendix 3).

### Acknowledgments

Fieldwork was supported by the Geological Survey of Canada, Cordilleran Division as part of the Ogilvie Mountains regional mapping project. Dr. R.I. Thompson was the co-ordinator and principal investigator and also provided substantial support, advice, expertise, and encouragement, both during fieldwork and writing. Additional funding came from National Science and Engineering Council grant A5536 to J.A. Donaldson, as well as Carleton University and Northern Scientific Training Program grants to the first author. The advice and encouragement of J.A. Donaldson and J.M. Moore of Carleton University contributed to completion of this study. Superb field support included geological assistance by Jack Dennett, Hans Smit, David Handel, Randy Magillivary, Tiro Clarke, Kevin May, and Winiske Oltman-Widmeyer; expediting by Terri McKay and Ursula Oltman-Widmeyer; and helicopter transport by Adam Morrison, Trans-North Helicopters, Ltd. Thorough reviews by H. Gabrielse, R.I. Thompson, and S.P. Gordey greatly enhanced the manuscript.

### REGIONAL GEOLOGY

The Mackenzie, Wernecke, and Ogilvie mountains are part of the Foreland Belt of the Canadian Cordillera. They expose laterally shortened strata that formed the western margin of North America during the Paleozoic and the middle and upper Proterozoic.

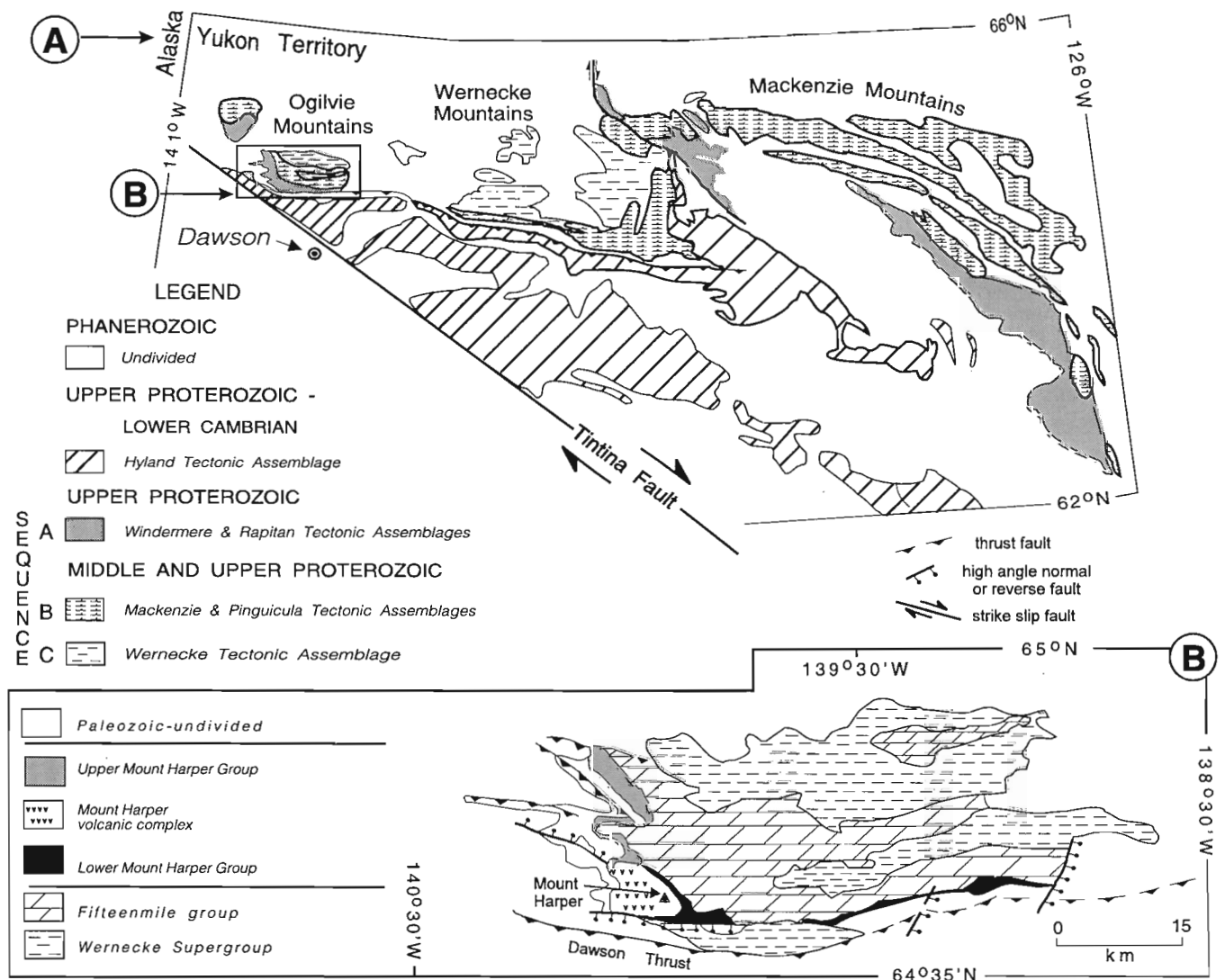
The Ogilvie Mountains include two Paleozoic tectonic elements known as the Mackenzie Platform and Selwyn Basin (Fig. 4 inset). South of Mount Harper they are separated by a steeply dipping thrust fault (Dawson Fault) which roughly coincides with the Paleozoic carbonate-to-shale facies transition.

The Selwyn Basin consists principally of Ordovician to Devonian black shale (Road River and Earn groups). South of Mount Harper a Late Proterozoic to Cambrian age grit unit is extensively exposed and correlated with the Hyland Group as defined in the Logan Mountains by Gordey and Anderson (1993). The Hyland Group forms part of the Hyland Tectonic Assemblage, a term used to refer to predominantly clastic successions that underlie the lowest Paleozoic carbonate and quartzite (Wheeler and McFeeley, 1991).

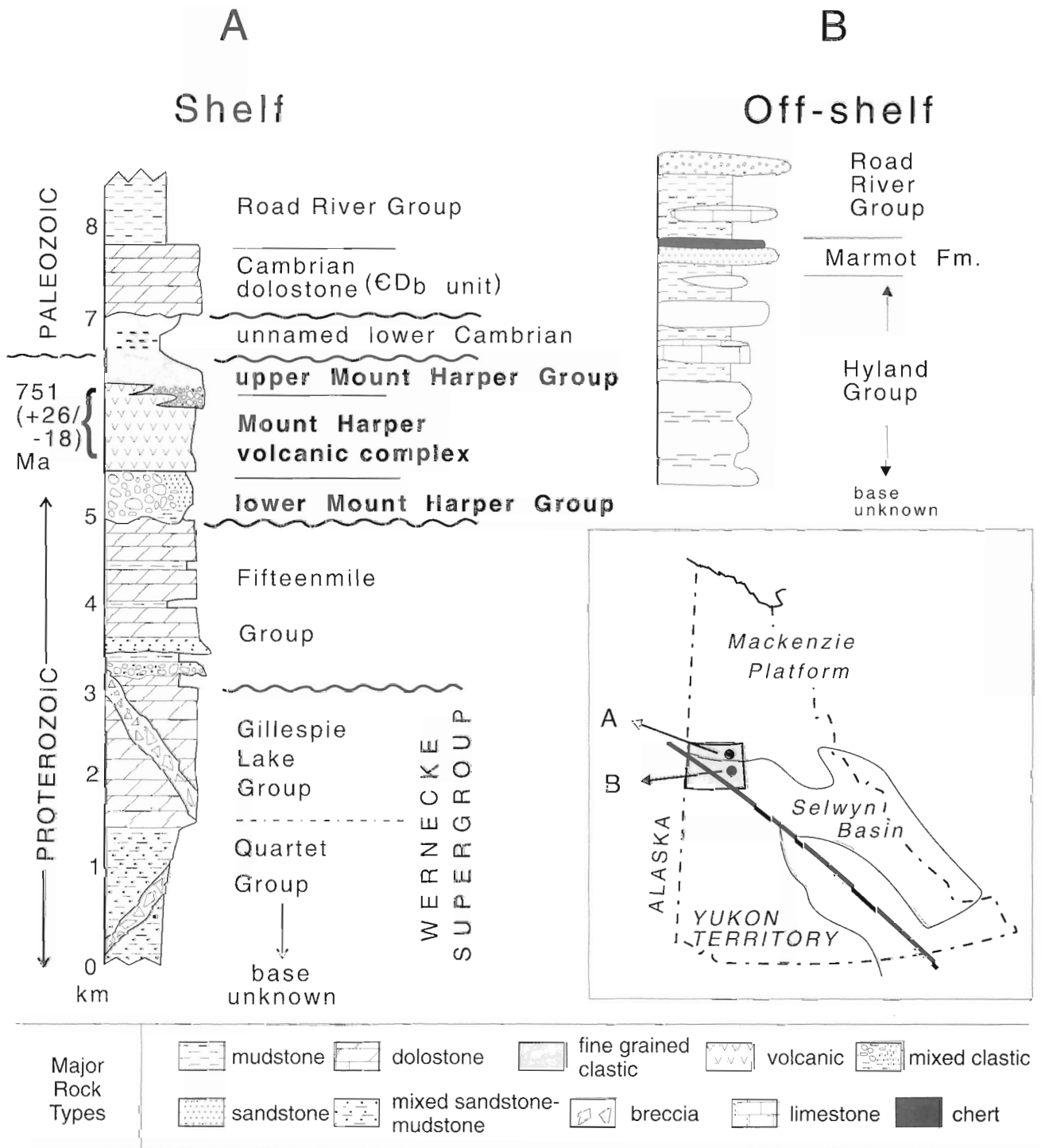
The Mackenzie Platform in the southern Ogilvie Mountains consists of thickly bedded Paleozoic dolostone (CD<sub>b</sub> formation, Fig. 4). A tripartite succession of middle and late Proterozoic strata is well exposed in an erosional inlier (the Coal Creek Dome of Green, 1972, termed the Coal Creek

Inlier in this publication). The Mount Harper Group is the uppermost unit of this Proterozoic package, which also contains the Fifteenmile group (informal name) and Wernecke Supergroup (Fig. 3B, 4), and all three are at different places unconformably overlain by the CD<sub>b</sub> dolostone unit.

The Wernecke Supergroup, the Fifteenmile group (informal name) and the Mount Harper Group are correlated with the sequence A, B, and C stratigraphic subdivisions commonly used for the sedimentary rocks which formed the western margin of North America at the end of the Precambrian (e.g. Young et al., 1979; Ross et al., 1989; Aitken and McMechan, 1992). The oldest (Sequence A in most reviews) includes the middle Proterozoic Belt-Purcell Supergroup of southeast British Columbia and Montana and the



**Figure 2.** A) Distribution of middle and upper Proterozoic to lower Cambrian strata in the Ogilvie, Wernecke, and Mackenzie mountains (after Wheeler and McFeeley, 1991). B) General geology of the Coal Creek Inlier, Ogilvie Mountains (after Thompson et al., 1987; Roots and Thompson, 1992).



**Figure 4.** Generalized stratigraphy in the Coal Creek Inlier. Most units show significant lateral gradations in thickness and facies. Shelf and off-shelf stratigraphy corresponds to Mackenzie Platform-Selwyn Basin divisions used in several regional studies (e.g. Gordey and Anderson, 1993) as shown in the inset map. In the Ogilvie Mountains the shelf and off-shelf assemblages are separated by the Dawson Fault, a zone of extension reactivated in Mesozoic time (Thompson et al., 1987).

Wernecke Supergroup of Yukon Territory. In the northern Cordillera the Wernecke Supergroup is unconformably overlain by a several kilometre thick sequence of platformal carbonate and siliciclastic units (Sequence B). This sequence, poorly age-constrained between about 1200 and 800 Ma, has been documented in most detail in the Mackenzie Mountains of eastern Yukon Territory and western Northwest Territories (the Mackenzie Mountain Supergroup, e.g. Aitken and McMechan, 1992). Possible equivalent units are the Pinguicula Group in the Wernecke Mountains (Eisbacher, 1981) and the Fifteenmile group in the Ogilvie Mountains. This sequence is not present in the southern Cordillera, where it was likely eroded before deposition of Sequence C.

Sequence C is termed the Windermere Tectonic Assemblage (Wheeler and McFeely, 1991) and consists of the Windermere Supergroup and correlatives, including the Mount Harper Group. The Windermere Tectonic Assemblage is a several kilometre thick succession composed of clastic rocks with minor volcanic and carbonate rocks that occur in linear belts from eastern Alaska to northern Idaho-Montana (Gabrielse and Campbell, 1992; Ross, 1991). This sequence contains evidence of a continental-scale rifting event at about 720-780 Ma, at least one period of global glaciation, and trace fossils of the earliest complex lifeforms (Hofmann et al., 1983; Young, 1984, 1988; Jefferson and Parrish, 1989).

### *Stratigraphy of the Coal Creek Inlier*

The oldest exposed rocks in the Coal Creek Inlier are correlated with the Quartet Group of the Wernecke Supergroup as described by Delaney (1981). In the centre and along the northern margin of the inlier the Quartet Group is mostly metasediment, but southeast and east of Mount Harper, micaceous, thinly bedded siltstone and chloritic phyllite predominate. These rocks are unconformably overlain by a laminated to thin-bedded, orange- and white-weathering stromatolitic dolostone correlated with the Gillespie Lake Group of the Wernecke Supergroup (cf. Delaney, 1981).

Intrusive breccia bodies are present in two irregular belts up to 1 km wide that trend northwesterly across the Ogilvie Mountains (Lane, 1990; R.I. Thompson, unpub. data 1987). They are similar to breccia bodies in the Wernecke Mountains described by Archer and Schmidt (1978), and Bell and Delaney (1977). The breccias intrude both the Wernecke Supergroup and the lowest part of the overlying Fifteenmile group, indicating emplacement occurred after deposition of the Wernecke Supergroup.

The Fifteenmile group is a laterally variable carbonate and shale succession up to 4 km thick. It unconformably overlies the Wernecke Supergroup and its lower part comprises fine- and medium-grained siliciclastic sediments with isolated carbonate blocks and breccia. North of Mount Harper the basal unit consists of about 350 m of red mudstone with metre-thick beds of jasper pebble conglomerate, overlain by thinly bedded, locally stromatolitic carbonate rocks. Above this siliciclastic-dominated unit, most of the Fifteenmile group

consists of dolostone punctuated by less common black shale intervals 1-10 m thick. The carbonate rock succession is about 2500 m thick north of Mount Harper. Its most prominent member totals more than 500 m of resistant, cliff-forming, craggy-weathering, medium grey dolostone with abundant chert as breccia and discontinuous layers. The Fifteenmile group is capped by distinctive light grey-weathering, resistant dolostone greater than 100 m thick, with abundant domal and less common columnar stromatolites.

The Mount Harper Group unconformably overlies the Fifteenmile group and comprises lower and upper clastic sedimentary successions, separated by intermediate to mafic lavas and breccias of the Mount Harper volcanic complex.

The Mount Harper Group is overlain by thickly bedded, medium crystalline, light grey dolostone, known as the Jones Ridge Formation in Alaska, and "Unit 8" of Green (1972) and here referred to as the 'CD<sub>b</sub>' formation (an informal name first used by Norris (1976) for correlative carbonate north of Dawson map area). It is at least 250 m thick where it unconformably overlies the volcanic complex and upper clastics of the Mount Harper Group. Archaeocyathid fragments found in the lower part of the CD<sub>b</sub> formation about 25 km west of Mount Harper are probably of Early Cambrian age.

### *Structure of the Coal Creek Inlier*

The Ogilvie Mountains are the northern continuation of the Jura-Cretaceous Cordilleran Foreland, or Rocky Mountain Fold and Thrust Belt (Monger, 1989). Regional contraction began in the Late Jurassic, because Early Jurassic shales are deformed, and was completed before intrusion of Late Cretaceous syenite in the Tombstone Mountain area, 70 km southeast of Mount Harper.

Several major thrust faults traverse the southern Ogilvie Mountains. In the southern part of the Dawson map area, south of a major thrust fault termed the Dawson Thrust, a generally fine grained succession has been severely shortened in recumbent folds and along imbricate thrust faults. Multiple thrust faults separate at least five panels, each containing a distinct lithological succession (commonly upper Hyland Group and Cambrian-Ordovician volcanic rocks). Because large areas of deformed strata expose only a limited stratigraphic thickness, this deformation is considered thin-skinned (Thompson and Eisbacher, 1984). Structures of this thrusting event are cut by undeformed Late Cretaceous syenite plutons.

In contrast, the carbonate-dominated shelf succession north of the Dawson Thrust (including the Coal Creek Inlier) has been uniformly tilted southward. Stratigraphic packages several kilometres thick are cut by high-angle reverse faults with minor displacement and only a few thrust faults. The continuity of the regional stratigraphy and the lack of exposed crystalline basement imply that the faults flatten to a sole detachment, at least beneath the southern part of the Coal Creek Inlier.

## MOUNT HARPER GROUP (new formal stratigraphic name)

The Mount Harper Group<sup>1</sup> consists of three units. The oldest is a conglomerate-rich succession a maximum of 1100 m thick, termed the lower Mount Harper Group. This unit is conformably overlain by the Mount Harper volcanic complex, a bimodal suite of predominantly extrusive rocks with a maximum preserved thickness of about 1200 m. The upper Mount Harper Group gradationally overlies and interfingers with the volcanics and comprises carbonate-clast and volcani-clastic conglomerate, sandstone, and mudstone of about 400 m maximum preserved thickness.

Total lateral extent of the Mount Harper Group spans about 75 km east-west. Regional correlations of the Mount Harper Group strata with Windermere Supergroup strata in other areas are discussed under "Tectonic implications", below.

### *Type area and reference sections*

The Mount Harper Group is defined on the basis of the stratigraphy exposed at and near Mount Harper (64°40.5'N, 139°52'W), the type area for the group. The complex lateral variations in stratigraphy preclude definition of a type section. Instead, several reference sections are used to illustrate stratigraphic components of the group (Appendix 1). The three main stratigraphic divisions are further subdivided into informal facies, members, or map units. These divisions and the reference sections for them are shown in Tables 1 and 2.

### *Age constraints*

Zircons from a rhyolite flow in the upper part of the Mount Harper volcanic complex indicate a U/Pb age of 751 ±26/-18 Ma (Roots and Parrish, 1988). There is no evidence for major time gaps within the volcanic complex, suggesting this U/Pb age can be applied to the complex in general.

**Table 1.** Table of formations; reference sections are shown in Appendix 1 except for Mount Harper volcanic complex members C through F for which no exposure contains the entire unit.

Formal units	Informal units	Lithology	Maximum thickness (metres)	Appendix 1 reference
Upper Mount Harper Group	PH <sub>2</sub>	very fine- to very coarse-grained dolarenite, graded; dolostone-clast conglomerate, graded-stratified to massive; silty dololite, graded	400	Section 9
	PH <sub>1</sub>	volcanic and dolostone clast conglomerate, poorly sorted, massive to poorly stratified; volcanic lithic wacke; silty nondolomitic mudstone	1300	Section 8
Mount Harper volcanic complex	Member F	andesitic flows; massive and pillowed; tuffs and minor breccia	>250	---
	Member E	andesitic flows; massive, rare pillowed; tuffs and andesite breccia	<100	---
	Member D	rhyolitic flows, columnar, flow banded or massive; minor felsic tuffs; minor ignimbrite intrusions	200	---
	Member C	basaltic breccia: pyroclastic and epiclastic lapilli tuff and tuff-breccia	170	---
	Member B	basaltic flows and volcanic breccia; massive to pillowed, chloritic to hematitic; pyroclastic tuff and lapilli-tuff breccia	500	Section 7
	Member A	basaltic flows, pillowed, rarely massive; basaltic breccia, massive, pillow breccia to cobble volcanic breccia	400	Section 7 Section 6
Lower Mount Harper Group	C-S facies	pebble-cobble conglomerate; moderate sorting, poor to well-stratified; coarse grained to pebbly dolarenite, moderate to well stratified	220	Section 5 Section 4
	S-M facies	fine- to very coarse-grained dolarenite; graded to massive, poor to well-stratified to cross-stratified; laminated to massive red dololite	360	Section 5 Section 4
	CC facies	boulder to pebble conglomerate (dolorudite), poorly sorted, nonstratified to graded-stratified; matrix- to clast-supported	1100	Section 3 Section 2
	B facies	breccia: unsorted rubble packbreccia of Fifteenmile group clasts; paleoregolith; rare silcrete and calcrete layers at unconformity	280	Section 4 Section 1

<sup>1</sup>The group is named after Mount Harper, the highest and only formally named peak in the study area.

**Table 2.** Reference sections for the Mount Harper Group. There are no reference sections for members C to F of the Mount Harper volcanic complex.

Formal units	Informal units	Appendix 1 reference	Location of base of reference section	Section thickness
Upper Mount Harper Group	PH <sub>2</sub>	Section 9	64° 50' 20"N, 140° 04' 40"W	296 m
	PH <sub>1</sub>	Section 8	64° 45' 16"N, 140° 09' 26"W	140 m
Mount Harper volcanic complex	Member F	none	---	---
	Member E	none	---	---
	Member D	none	---	---
	Member C	none	---	---
	Member B	Section 7 Section 6	64° 40' 00"N, 139° 57' 50"W 64° 40' 30"N, 139° 53' 00"W	290 m
				306 m
Member A	Section 7 Section 6	64° 40' 00"N, 139° 57' 50"W 64° 40' 30"N, 139° 53' 00"W	390 m	
			290 m	
Lower Mount Harper Group	S-M facies	Section 5 Section 4	64° 41' 08"N, 139° 07' 30"W	
			64° 40' 57"N, 139° 51' 35"W	
	C-S facies	Section 5 Section 4	64° 41' 08"N, 139° 07' 30"W	
			64° 40' 57"N, 139° 51' 35"W	
CC facies	Section 3 Section 2	64° 39' 37"N, 139° 44' 30"W		
		64° 39' 21"N, 139° 46' 16"W		
B facies	Section 4 Section 1	64° 40' 57"N, 139° 51' 35"W		
		64° 38' 55"N, 139° 45' 00"W		

There is also evidence that the time of sedimentation of both the lower and upper Mount Harper Group at least partly overlapped with the volcanic event. In western exposures, the upper conglomerate and sandstone of the lower Mount Harper Group are sharply overlain by the Mount Harper volcanic complex. The volcanic flows immediately overlying lower Mount Harper Group sandstone and mudstone have loaded the underlying sediments and contain angular sedimentary fragments obviously eroded from underlying beds. The fragments have convoluted internal stratification, a feature not seen in the lower Mount Harper Group below the volcanics. This feature, and the loaded contact, suggest that the lower Mount Harper Group was not completely lithified during the deposition of the initial volcanic flows, and that the time between initial volcanism and lower Mount Harper Group sedimentation was not significant. In addition, sandstone preserved a few metres below the volcanics contains up to 10% volcanic grains, a clast type absent from the rest of the lower Mount Harper Group. The only local source for these grains is the volcanic complex, presumably initial flows developed to the south of the site of sand deposition. This evidence for essentially contemporaneous sedimentation and volcanism permits the 751 ±26/-18 Ma age of volcanism to be roughly applied to the timing of lower Mount Harper Group sedimentation.

There is direct evidence that the timing of upper Mount Harper Group sedimentation overlapped with late stages of volcanism. The basal map unit of the upper Mount Harper Group (PH<sub>1</sub>, Fig. 3) is gradational from volcanic flows,

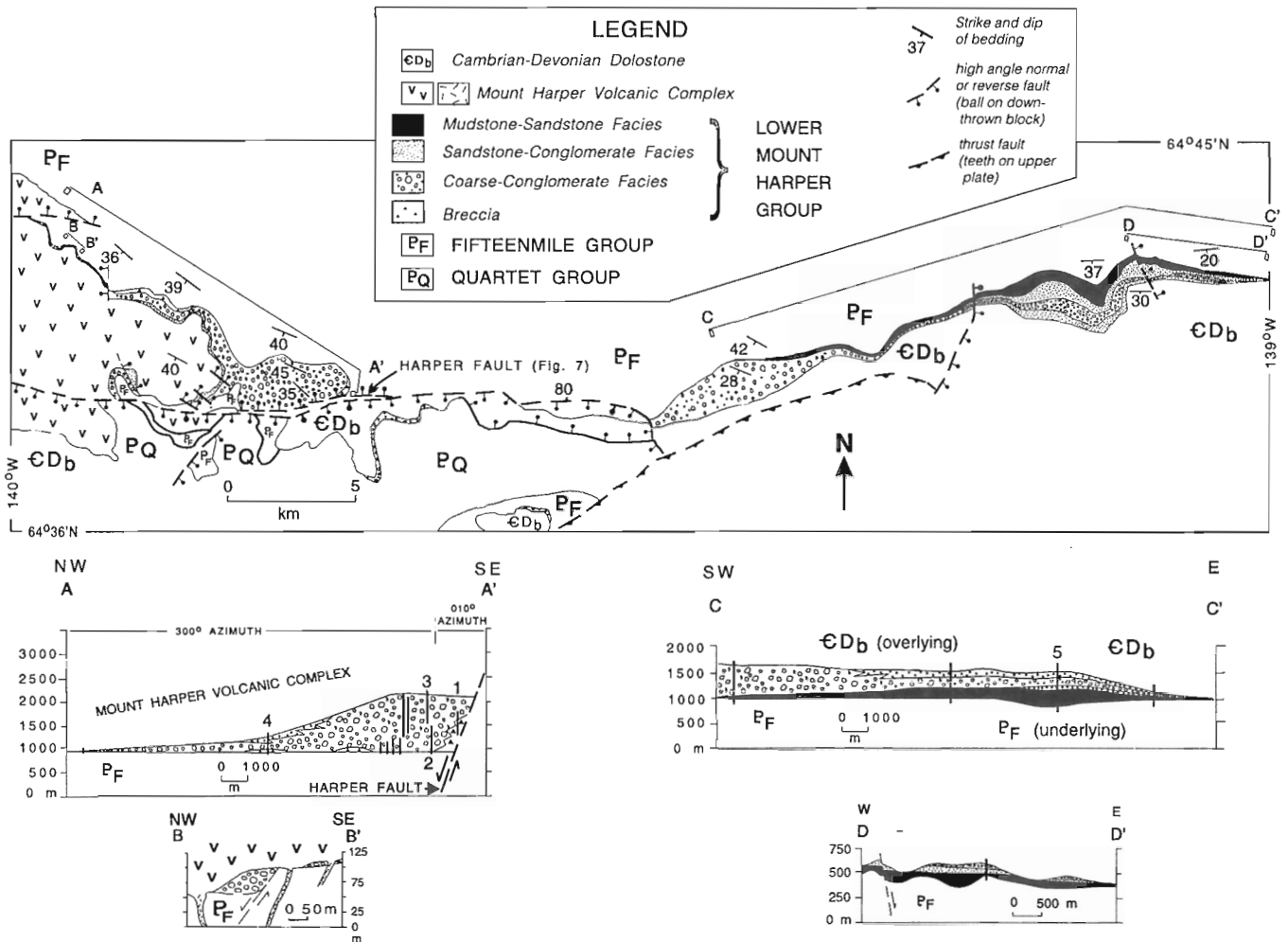
volcanic conglomerates, and tuffs of the Mount Harper volcanic complex. Rare volcanic rocks in this transitional interval include thin tuffs (some probably reworked) and possible flows, generally less than 20 cm thick and highly altered with abundant dolomite, but with a recognizable original composition of microlaths of feldspar within a dark, glassy chloritized groundmass. This map unit thins and intertongues northward with the other upper Mount Harper Group map unit (PH<sub>2</sub>) and in most places is gradationally overlain by unit PH<sub>2</sub>.

The upper age constraint on deposition is not well defined. Five mappable sedimentary units occur between the Mount Harper volcanic complex and the early to middle Cambrian CD<sub>b</sub> dolostone. The lower two map units (PH<sub>1</sub> and PH<sub>2</sub>) intertongue with each other and the upper Mount Harper volcanic complex, demonstrating an overlap of late volcanism and sedimentation. The upper three map units (PC<sub>3</sub>, PC<sub>4</sub>, and PC<sub>5</sub>) are structurally concordant with the lower two and were originally believed part of a continuous stratigraphic succession informally termed the upper Mount Harper Group (Mustard et al., 1988). Early Cambrian trace fossils were discovered in the top unit in 1986 (PC<sub>5</sub>, Mustard et al., 1988) and subsequently a subtle and discontinuous silicified and brecciated layer was documented at the contact between units PH<sub>2</sub> and PC<sub>3</sub> (Mustard, 1990). Units PC<sub>3</sub> to PC<sub>5</sub> have gradational contacts, suggesting a common early Cambrian age. This in turn suggests the contact between units PH<sub>2</sub> and PC<sub>3</sub> is a disconformity, and represents a major time gap, perhaps 150-200 Ma. For these reasons the upper Mount Harper Group

as defined here excludes the early Cambrian map units. The thin (less than 300 m) and coarse conglomeratic nature of the upper Mount Harper Group are compatible with a relatively short period of deposition (beginning at about 751 Ma). However there is no direct evidence to constrain the upper age of the upper Mount Harper Group more precisely than between 751 Ma and early Cambrian time.

## LOWER MOUNT HARPER GROUP

A detailed study of the setting and depositional history of the lower Mount Harper Group is presented in Mustard (1990, 1991) and Mustard and Donaldson (1990). The following descriptions and interpretations are summarized from these publications. Figure 5 is a simplified geological map of the



**Figure 5.** Distribution of the lower Mount Harper Group. Longitudinal stratigraphic profiles are based upon vertical measured sections of Mustard (1990) projected on to the section as black vertical bars (the numbered sections correspond to reference sections in Appendix 1). **Inset A-A'** depicts the wedge-shaped geometry of lower Mount Harper Group. The disconformity surface with underlying Fifteenmile group (top of unit PF) is drawn as the horizontal datum because mapping showed only minor paleorelief (<50 m) along this line of section. **Inset B-B'** depicts a small normal fault near the northwest depositional pinchout of the lower Mount Harper Group. This normal fault does not cut the overlying volcanics but is probably the source of boulder-rich conglomerates immediately north of the fault. Subvertical mafic dykes (cross-hatched) are interpreted as feeder dykes for the Mount Harper volcanics. **Inset C-C'**: the disconformity with the underlying Fifteenmile group was used as a horizontal datum to be consistent with inset A, except for section 5, which mapping indicates is about 125 m lower than the bases of sections to the east and west (i.e., within a paleotopographic low which slopes upward gently east and west). **Inset D-D'**: sketch from photos of north-facing ridge on which 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.

lower Mount Harper Group, with cross-sections which illustrate map unit geometries, lateral relationships of facies, and relationships along the basal unconformity. The detailed geology of the main area of lower Mount Harper Group outcrop is presented on a separate 1:25 000 scale map (Fig. 3, in pocket)

### ***Bounding contacts***

The basal contact is a disconformity with underlying dolostone of the Fifteenmile group. The disconformity surface is irregular and displays several tens of metres of paleorelief (Fig. 5, cross-section D-D' and Fig. 6A). Although typically a sharp, clean contact, lenses of breccia are preserved in some places on the unconformity surface, passing gradationally upward to lower Mount Harper Group conglomerates.

A high-angle north-side-down fault system (Harper Fault of Thompson et al., 1987) forms the southern limit of the main lower Mount Harper Group exposure (Fig. 7, Fig. 5 map and cross-section A-A'). The fault system is preserved over a lateral distance of several kilometres. The fault trace is stepped on its north side with several minor normal faults preserved, but in general strikes east-west and dips 50-60° northward (Fig. 7A, B). The southern fault is traceable to the west where it is overstepped by all but the lowest strata of the volcanic complex, suggesting fault movement ceased after initial volcanism. The minor normal faults north of the main fault do not cut overlying lower Mount Harper Group beds, demonstrating that faulting occurred as a series of synsedimentary growth faults that formed the original southern boundary of the lower Mount Harper Group basin.

The minimum vertical offset of the Harper Fault is about 1100 m (the measured thickness of the lower Mount Harper Group directly north of the fault). The footwall of the Harper Fault consists of dark grey metasedimentary rocks of the Quartet Group, the middle unit of the Wernecke Supergroup. In the hanging wall, the Quartet Group occurs about 3 to 4 km stratigraphically below the Mount Harper Group. Assuming that the sub-Mount Harper Group stratigraphy in the hanging wall is of similar thickness to that which must have been eroded from the footwall of the fault, the estimated total vertical offset of pre-Mount Harper Group strata across the Harper Fault is thus about 3 to 4 km.

In western exposures, conglomerate and sandstone of the lower Mount Harper Group are sharply but conformably overlain by volcanics of the Mount Harper volcanic complex.

Eastern exposures of the lower Mount Harper Group are disconformably overlain by light grey dolostone of early to middle Cambrian age (unit CD<sub>b</sub>). Reconstruction of the volcanic edifice suggests that the Mount Harper volcanic complex must have originally covered much, if not all, of the lower Mount Harper Group (Roots, 1987). Any previously existing volcanic rocks must have been eroded prior to Cambrian deposition in the eastern part of the study area. The sub-Cambrian disconformity is not exposed, although it can be delimited within a few tens of metres in several places.

To the northwest, the lower Mount Harper Group thins to less than 5 m of interbedded sandstone and pebble conglomerate about 15 km northwest of the Harper Fault (Fig. 5, cross-sections A-A', B-B'). The lower Mount Harper Group also thins significantly in eastern exposures to less than 20 m thick at the eastern limit of outcrop (Fig. 5, cross-section C-C'). Detailed mapping shows that thinning of the units reflects original depositional pinchouts.

### ***Facies of the lower Mount Harper Group***

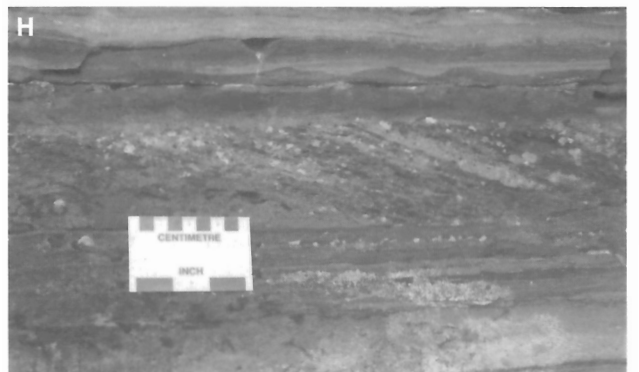
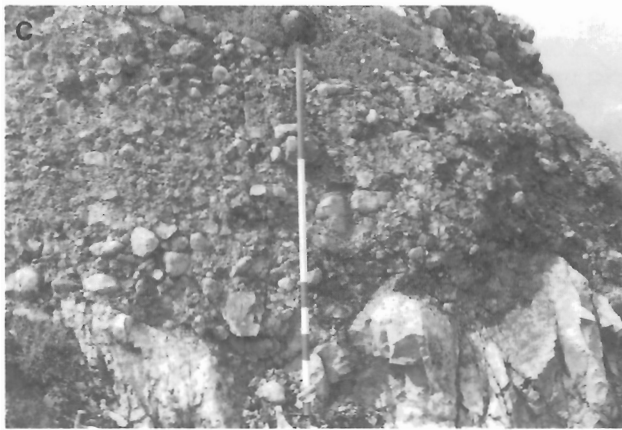
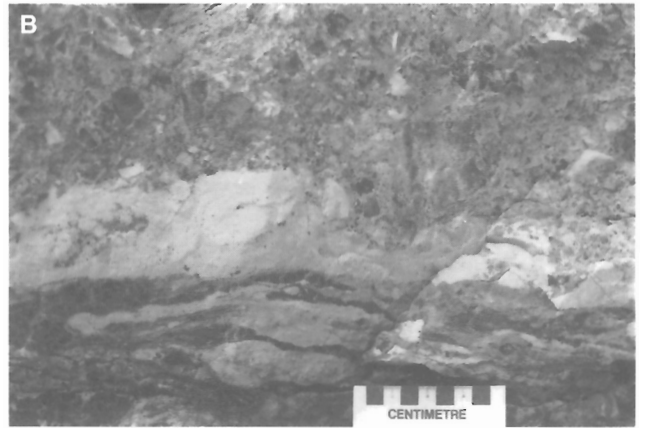
The four major map units shown on Figure 3 roughly correspond to the major facies associations of the lower Mount Harper Group. The essential features of these facies associations are summarized in Table 3. Reference stratigraphic sections are presented in Appendix 1.

A breccia facies (B) abuts the Harper Fault and occurs as discontinuous lenses on the basal unconformity surface. The breccia adjacent to the Harper Fault is a monomictic rubble of Fifteenmile group blocks up to 100 m in length which thins northward away from the fault. North of Mount Harper, a layer of highly altered (silicic and carbonate alteration) breccia several tens of metres thick is traceable for about 3 km laterally (Fig. 6B; Fig. 5: map and cross-section A-A'; Appendix 1: measured sections 1 and 4).

The bulk of the lower Mount Harper Group consists of a coarse conglomerate facies (C-C facies, Fig. 6C-E). It comprises poorly sorted, boulder- and cobble-rich, clast-supported conglomerate plus rare matrix-supported conglomerate and sandstone (dolowacke). A subtle organization into coarsening-upward sequences up to 150 m thick is apparent. Paleocurrents indicate a radial northerly pattern (Fig. 8). Clasts are mostly locally derived dolostone and less common chert, and indicate progressive exposure of older source rocks with time, with only Fifteenmile group rock types in the lower conglomerates and Wernecke Supergroup rock types (Gillespie Lake Group and rare possible Quartet Group clast types) also present in upper conglomerates.

The coarse conglomerate facies grades laterally northward into a facies of interbedded conglomerate and sandstone (C-S facies, Fig. 6F). This comprises cobble- and pebble-bearing clast-supported conglomerate, interbedded with massive or crossbedded, medium- to coarse-grained dolowacke. Paleocurrent trends are the same as for the coarse conglomerate facies, generally northward but displaying a radial pattern.

Interbedded sandstone and mudstone (S-M facies, Fig. 6G, H) occur as the basal lower Mount Harper Group in the eastern part of the map area. Distinctive maroon mudstone (dololutite) forms the lower part of a coarsening upward succession greater than 300 m thick in some areas. Fine- to medium-grained dolowacke beds are increasingly common upward in the package. Desiccation cracks, ripples, and cross-bedding are common features of this facies.



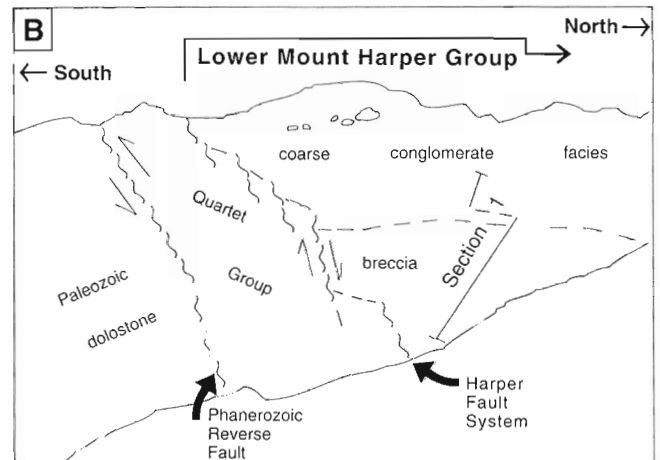
## Summary of lower Mount Harper Group tectonic setting and deposition

The lower Mount Harper Group was deposited in an asymmetric, east-trending half-graben basin bounded on the south by the synsedimentary Harper Fault. The half-graben basin was formed, and sedimentation controlled, by the southern margin faulting. Synsedimentary 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. Schematic interpretations of the inferred depositional environment of the lower Mount Harper Group are shown in Figures 9 and 10.

The original size of the lower Mount Harper Group half graben can be estimated from the preserved extent of lower Mount Harper Group strata. An eastern pinchout occurs about 40 to 50 km east of the thickest conglomerates which are preserved north of the Harper Fault. The western limit of the lower Mount Harper Group is obscured by overlying rocks of the volcanic complex and the upper Mount Harper Group, but

**Figure 6. A)** Basal disconformity of the lower Mount Harper Group showing irregular disconformity (arrowed) between Fifteemile group dolostones (well-bedded, medium grey) and overlying lower Mount Harper Group proximal conglomerates (vaguely bedded, dark grey). About 100 m of lower Mount Harper Group strata is shown in the photograph. GSC 1995-093A **B)** Weathering alteration products at the basal unconformity of the lower Mount Harper Group. Massive calcrete forms the continuous layers in this outcrop, partially replaced by dark lenses of silcrete. The overlying breccia contains clasts of the calcrete but is also slightly silicified. GSC 1995-093B **C)** Typical disconformity surface where weathering alteration products are not preserved. Unaltered dolostone of Fifteemile group is sharply overlain at a slightly irregular contact by coarse conglomerates (facies C-C) of the overlying lower Mount Harper Group. Jacob's staff is 1.5 m long. GSC 1995-093C **D)** Coarse conglomerate (facies C-C) well exposed in a cliff face about 500 m north of the Harper Fault. These proximal conglomerates show poor sorting and vague bedding typical of this facies. Largest boulder is 1.5 m in diameter. GSC 1995-093D **E)** Overlapping curved lenses in the coarse conglomerate lithofacies (foreshortened by telephoto lens). The main ridge face is oriented northwest and in the photo contains about 300 m (vertical thickness) of strata. GSC 1995-093E **F)** Overlapping sheeted pebble-cobble conglomerate and minor coarse-grained sandstone of the C-S facies. Jacob's staff (lower left corner) is 1.5 m long. GSC 1995-093F **G)** Laminated to massive maroon mudstone (dark grey in photo) and thin-bedded buff to pinkish sandstone (light grey in photo) of facies M-S. GSC 1995-093G **H)** Facies S-M displaying a planar crossbedded sandstone with abundant ripups of red mudstone interbedded with mudstone containing abundant desiccation cracks and rippled, thin sandstone beds. GSC 1995-093H

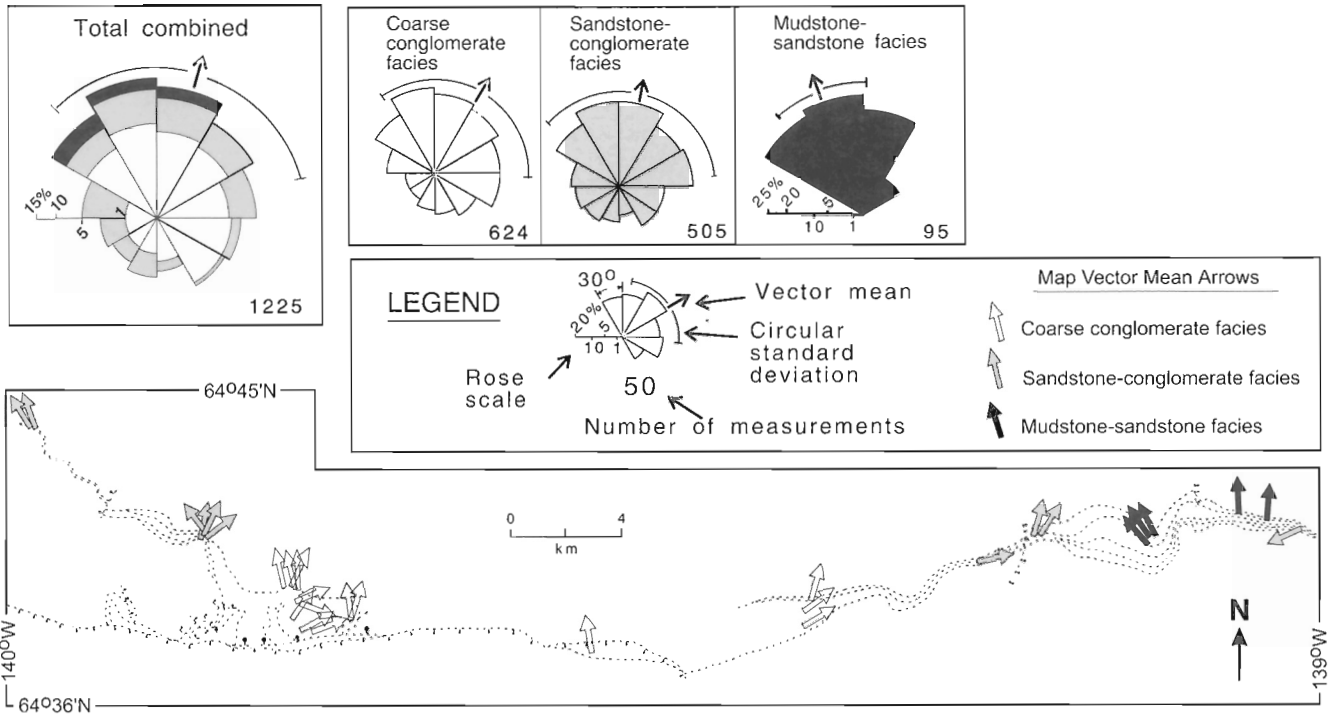
is inferred on the basis of mappable westerly thinning from 1100 m at the Harper Fault area to less than 100 m at the most westerly exposure. The distance between the preserved eastern pinchout and assumed western pinchout suggests the original east-west extent of the half graben was about 80 to 100 km. Depositional thinning of lower Mount Harper Group facies to the north of Harper fault suggests an original north-south extent of graben fill of about 15 km. The conformable contact with overlying volcanic rocks of the Mount Harper volcanic complex allows an estimate of the maximum post-compaction sediment fill of the half graben to be about 1100 m.



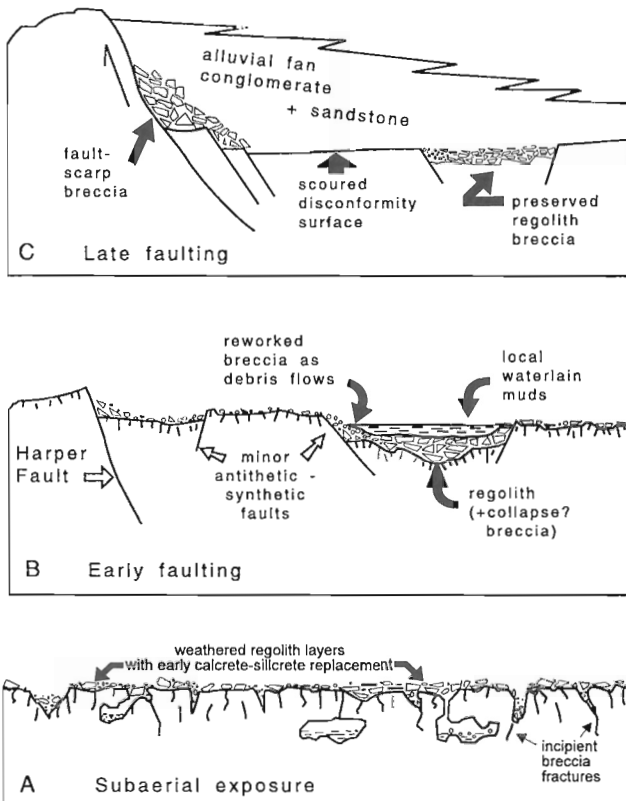
**Figure 7. A)** Looking west at exposure of the Harper Fault (located on Fig. 5). GSC 1995-0931 **B)** Sketch of photo in 7A. The stepped normal fault at center (Harper Fault) forms the southern boundary of the lower Mount Harper Group, here comprising a breccia and coarse conglomerate facies. The stepped faults north of the main fault are overlapped by overlying conglomerate beds, attesting to the coeval relationship between faulting and deposition of the lower Mount Harper Group. The reverse fault near the left edge of photo truncates Paleozoic dolostone and is therefore a younger (probably late Mesozoic-Tertiary) contraction fault. The Mount Harper volcanic complex, beyond this ridge about 5 km farther west, straddles the Harper Fault. Section 1 is shown in Figure A1-2.

**Table 3. Summary of the features of the major facies of the lower Mount Harper Group.**

Facies association	Contact relationships	Major lithofacies	Lithofacies description	Sedimentary structures	Paleo-flow	Interpretation	Further reference
<b>Breccia (B)</b> (map unit Ph <sub>a</sub> in Fig. 3) fault breccia = 280 m maximum unconformity breccia = 125 m maximum	Gradational to north to CC facies; base not exposed	Rubble packbreccia: (Harper Fault breccia)	>95% cm to >100 m diameter fragments in fine- to coarse-grained dolowacke matrix; vague layers 2-70 m thick; all fragments are upper Fifteenmile group composition	massive; random clast orientation	none	fault-scarp talus	Appendix 1, section 1; Mustard and Donaldson, 1990
	Gradational from Fifteenmile group and up to C-S facies	Rubble floatbreccia (Unconformity breccia)	abundant siltcrete and calcrete layers; multiple brecciation events; all clasts subjacent Fifteenmile group or earlier siltcrete/calcrete compositions	massive; random clast orientation	none	paleokarst regolith	Appendix 1, section 4; Mustard and Donaldson, 1990
<b>Coarse conglomerate (CC)</b> (map unit Ph <sub>b</sub> in Fig. 3)	Gradational and intertonguing laterally to C-S Sharp up to MHVC	Clast-supported conglomerate	80-90% pebble to boulder clasts in a coarse grained dolarenite matrix; poor sorting; clasts subangular to subrounded, subspherical to spherical; clasts all Fifteenmile group compositions and reworked where jasper and dolostone clasts of the upper Wernecke Supergroup occur; beds generally sheet-like, laterally continuous, 50 cm to 1.5 m thick	massive; >50% nongraded; common reverse-graded base and normal graded top -less common only reverse-graded base or normal-graded top; random clast orientation or poor imbrication at base; common projecting clasts; rare open-framework fabric; coarsening- and thickening-upward megasequences 80-150 m thick	radial to north (Fig. 8)	upper to middle sections of coalescing alluvial fans mostly cohesive high-density debris flows; rare sieve, landslide, sheetflood deposits	Appendix 1, sections 2, 3; Mustard, 1991
	Sharp at base to Fifteenmile group if no breccia	Matrix-supported conglomerate	30-70% pebbles to boulders in coarse grained dolowacke matrix; very poor sorting; clast textures and types as above; beds to 2.5 m thick	massive, no grading, random clast orientation; common projecting clasts	none	cohesive debris flows on upper alluvial fan	upper alluvial fan
<b>Conglomerate-sandstone (C-S)</b> (map unit Ph <sub>d</sub> in Fig. 3)	Gradational and intertonguing vertically and laterally to C-C facies (proximal) and to S-M facies (distal)	Clast-supported conglomerate	80-90% pebbles-cobbles and rare boulders in medium- to coarse-grained dolarenite matrix; textures and clast compositions as for C-C facies but beds generally thinner (<1 m) and sorting moderate	common normal graded or reverse-to normal graded; loaded bases into sandstone, rare erosive/channelized bases; imbrication common; rare planar crossbeds overall coarsening upward sequence but includes lining upward trends a few metres thick	radial to north; rare E or W at margin of main S-M facies	middle to lower sections of coalescing alluvial fans; density-modified debris flows; sheetfloods; proximal braided fluvial deposits	Appendix 1, sections 4, 5; Mustard, 1991
	Sharp up to MHVC or CDb	Sandstone	fine- to coarse-grained dolarenite; rare pebble bases; clasts all dolostone or chert, Wernecke Supergroup jasper clasts common in some beds	rare planar cross-strata; rare cross-laminated asymmetric ripples; very rare trough crossbeds	(Fig. 8)	braided stream flows; transition to fan deltas in east exposures	Appendix 1, sections 4, 5; Mustard, 1991
<b>Sandstone-mudstone (S-M)</b> (map unit Ph <sub>c</sub> in Fig. 3)	Gradational and intertonguing laterally and vertically to C-S facies	Sandstone	very fine- to coarse-grained dolarenite and dolowacke; coarse laminae to thin beds; rare thick beds up to 10 cm; beds commonly laterally continuous; rare lens up to 50 m laterally, sand clasts all dolostone or chert (jasper common), subangular to subround, moderate to high sphericity	common normal grading to silt or mud top; ripples and rare climbing ripples; rare symmetrical wave ripples; ripples of mudstone common in thick beds defining internal planar crossbeds; common desiccation cracks in muds	strong north trend with slight radial pattern (Fig. 8)	fan-deltas deposits at C-S transition and low density turbidites from fan delta slumps into low-energy water body (lacustrine?);	Appendix 1, sections 4, 5; Mustard, 1991
	Sharp over Fifteenmile group	Mudstone	silty clay to coarse silt dololite or dolostone; commonly hematitic and oxidized giving red colour; rare reduced grey-green spots or discontinuous layers; silt clasts all dolostone or chert	typically continuous, parallel to slightly wavy laminae, interbedded with graded sandstone laminae or thin beds; desiccation cracks common; overall coarsening- and thickening-upward sequence to C-S facies	density under-flows of sand or mud into low-energy basin; mud lamina deposited by suspension-settling	density under-flows of sand or mud into low-energy basin; mud lamina deposited by suspension-settling	Appendix 1, sections 4, 5; Mustard, 1991

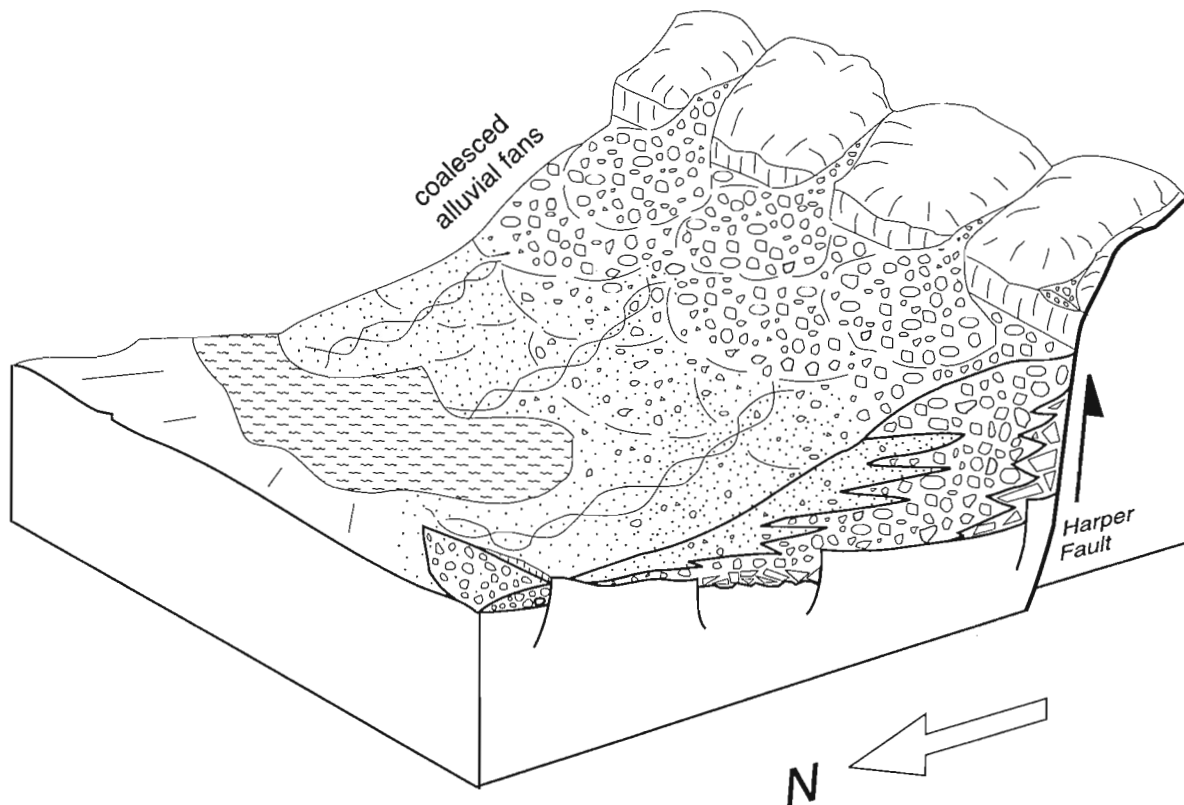


**Figure 8.** Summary diagram of lower Mount Harper Group paleocurrents. Contacts of the lower Mount Harper Group map units are outlined (see Fig. 5). Paleocurrent measurement sites are at the initiation point of the arrow. The direction indicated is the vector mean for that site. Current roses showing the paleocurrents combined for each facies and the entire lower Mount Harper Group are presented at top. Paleocurrent indicators consist primarily of conglomerate clast imbrication for both the proximal and intermediate facies, and planar cross-stratification for the distal facies. Circular standard deviation was calculated using the method of Krause and Geijer (1987). All measurements have been corrected for bed tilt.



**Figure 9.**

Schematic diagram showing inferred stages in the development of the lower Mount Harper Group (not to scale; modified from Mustard and Donaldson, 1990). **A)** 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. **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 conglomerate which filled the half graben, and covering the locally preserved disconformity surface breccia.



**Figure 10.** Schematic representation of the lower Mount Harper Group depositional environment. The major east-west oriented fault scarp (Harper Fault) controlled half-graben formation and the main pulses of sedimentation. Scarp talus breccia occurs adjacent to the fault. Alluvial debris shed northward from the fault scarp formed overlapping debris-flow dominated fan complexes which changed northward into lower fan braided stream facies. A lacustrine basin on the eastern part of the preserved outcrop area (wavy pattern) resulted in mudstone siltstone facies which coarsened upward as lower fan facies prograded into the water body.

The breccia layer preserved on a disconformity surface contains silcrete and calcrete that provide evidence of several episodes of subaerial exposure. The presence and types of silcrete and calcrete suggest that the climate at the onset of deposition in this area was temperate to equatorial, and probably semi-arid to arid. Figure 9 summarizes the initial basin evolution and breccia formation.

Coarse clastic debris shed from rising fault scarps formed a talus breccia adjacent to the fault and a series of overlapping alluvial fans 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 subaqueous (lacustrine?) setting which appears to have been localized by paleolows on the disconformity surface. Deposition in the water body was by gravity flows and suspension settling of mud, silt, and sand, all derived from the south as the alluvial fan complex prograded into the water body.

The thick conglomerate fill and repeated upward-coarsening megasequences required some mechanism to sustain high relief in the source area. Repeated fault reactivation seems the most likely control. 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. The lower Mount Harper Group shows some characteristics markedly different from those of pull apart basins; strike-slip movement on the main faults is not thought to have been significant.

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. Clastic deposition appears to have ended soon after volcanism was initiated, resulting in the overlying Mount Harper volcanic complex (ca. 750 Ma).

# MOUNT HARPER VOLCANIC COMPLEX

## Introduction

The Mount Harper volcanic complex consists of extrusive and related intrusive rocks that formed several large, super-imposed volcanic edifices. Remnants of these structures are visible in the steep valley walls. Only the central part of the original volcanic centre is available for study: the north and east extent has been eroded and it dips beneath Paleozoic strata to the west and south. The main area (105 km<sup>2</sup>) includes vents, indicated by a dyke plexus, proximal facies of some breccia units, outward paleoslopes, and flow directions. Dykes are rare outside the volcanic complex.

Regional strain appears to have been accommodated along brittle faults because most volcanic rocks are not stretched or flattened. The rocks are flat to moderately dipping and the spatial distribution of volcanic units appears consistent with their depositional relationships. Breccia fragments and original flow morphology are well preserved.

The Mount Harper complex is divided into six informal volcanic members that are defined by chemical composition and field relationships (Table 1). Basalt flows and breccias constitute the basal member A and overlapping member B. Member C comprises breccias of mixed pyroclastic and epiclastic origin. Members D and E are coeval rhyolite and andesite respectively. Member F, at the top, consists of quartz diabasic shallow intrusions and flows that are intercalated with upper Mount Harper Group sediments.

All the volcanic rocks are hydrated and contain low grade metamorphic mineral assemblages as a result of burial and fluid alteration. Subisotropic sideromelane has replaced glass in the relatively fresh flows and some breccia fragments, and most mafic rocks contain abundant albite and chlorite. Formerly glassy silicic rocks have been altered to quartz-feldspar-sericite intergrowths. Many have undergone Na<sub>2</sub>O-K<sub>2</sub>O and CaO-Na<sub>2</sub>O exchange, but contents of normally

**Table 4.** Terminology and interpretation of volcanic deposits, Mount Harper volcanic complex.

Lithology	Diagnostic features	Interpretation
Pillow flows	tubes with chill margins and concentric bands of vesicles, associated with hyaloclastite	subaqueous, relative water depth indicated by vesicle abundance
Massive flows	tabular or tapered; distinguished from sills by contacts, breccia margins	sheet flows (Ballard et al., 1979); blocky and aa types indicate subaerial
Intrusion breccia	internally crosscutting contacts	possible vent areas
Isolated pillow breccia	amoeboid, lenticular sacs, commonly prograding (Carlisle, 1963)	steep slope or breaks, insufficient lava supply at front
Broken pillow breccia	pillow fragments with concentric vesicle bands (Carlisle, 1963)	steep slope or breaks, thermal shock with water
Cobble breccia	equant fragments of pillows, flows	as for broken pillow breccia
Flow-top breccia	vesicular fragments; grades downward into massive flow	viscous flow
Hyaloclastite	angular shards between and surmounting pillows	subaqueous, as for pillows
Aquagene tuff	lenticular beds of globules and shards (Carlisle, 1963)	subaqueous effusions
Hydroclastic breccia	chloritic shards and flow fragments; layered and cross-stratified	thermal shock of flows in the littoral zone
Cinder	mafic, scoriaceous lumps	subaerial, Strombolian eruptions
Spatter	agglutinated, vesicular clasts	subaerial, near vent
Tuff	lithified fine to coarse ash	if thinly laminated, probably subaqueous
Lapilli-tuff	clasts 2-64 mm in tuff matrix	subaerial
Tuff breccia, block and ash breccia	some clasts >64 mm in tuff matrix	typically subaerial, from collapsed flows and domes
Pyroclastic breccia	monolithologic, dominantly blocks and bombs (>64 mm)	typically subaerial
Igimbrite	felsic, with fiamme, broken crystals	explosive, subaerial, emplaced hot
Volcanic epiclastic	weathered volcanic clasts and sedimentary fragments	subaqueous

immobile refractory elements, such as Ti, Zr, Nb, as well as most siderophile elements, do not appear to have changed with alteration.

During fieldwork volcanic flows were described as basaltic or silicic because most are fine grained, aphyric, and contain few visible indicators of composition. Chemical analysis and microphenocryst identification confirmed that identification of volcanic members from hand sample study and stratigraphic position have a primary compositional basis (see Fig. 22 and Appendix 2). Despite chemical alteration, original rock types can be deduced from morphology and textures, justifying the use of nonmetamorphic rock names (basalt, for example, rather than metabasalt or greenstone).

Open spaces, such as vesicles and spiracles are typically filled with calcite; textures of the original deposits are strikingly preserved on weathered surfaces where calcite has been dissolved. Local alteration minerals include hematite, blue chlorite, and agate. Veins of quartz and calcite are rare within the complex.

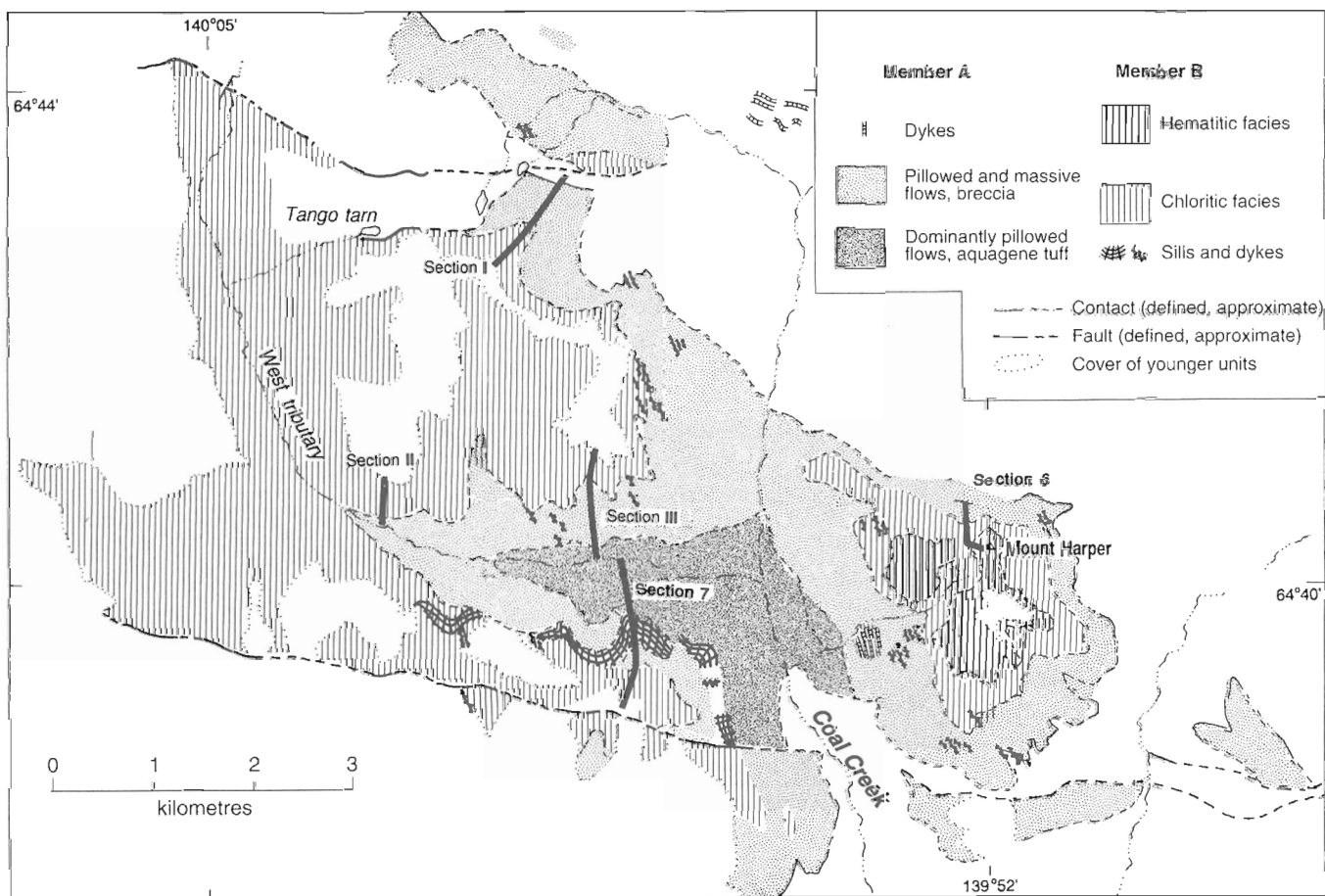
Table 4 lists some descriptive terms for volcanic rock types, their diagnostic characteristics, and implications for composition and depositional environment. The distribution

of individual volcanic members is shown on Figures 1 (all members), 11 (for members A and B), 16 (for member C), 19 (for member D), and 20 (for members E and F). Sample numbers in parentheses refer to chemical analyses in Appendix 2. To aid location, two informal geographic names are introduced: "West tributary" which flows into Coal Creek 3.2 km southwest of Mount Harper, and "Tango tarn", a small lake located 9 km northwest of Mount Harper.

## Member A

### Definition and distribution

Member A consists of basaltic flows and breccias. It is the basal unit of the Mount Harper complex, constitutes about a third of the exposed rock (Fig. 11) and extends an unknown distance west beneath younger volcanic members. The best exposures of member A are the lowest cliffbands on both sides of Coal Creek north of the confluence of West tributary. Flow units in member A generally consist of pillows tightly packed together and intercalated with monolithological chloritized breccia and massive flows. In contrast to younger,



**Figure 11.** Distribution of volcanic members A and B in the Mount Harper volcanic complex. The sections are shown in Figure 12. Blank areas outside the complex are underlain by older, nonvolcanic rocks, and blank areas within the complex are covered by younger units (see Fig. 16, 19, 21 and 25; or Fig. 3 for comparison).

more vesicular rocks in the complex, flows of member A are internally structureless or contain sparsely distributed spherical vesicles less than 1 mm in diameter.

### Contacts

Massive flows and breccias of member A paraconformably overlie the lower Mount Harper Group along the northern and eastern edges of the complex. The contact is everywhere sharp, but undulates over contorted sandstone and conglomerate beds. At the southernmost exposure of member A, 3 km south of Mount Harper, thick pillow flow units unconformably overlie bedded limestone, and discontinuous volcanic sandstone (reworked tuff?) occurs at the contact. The volcanoclastic beds indicate earlier volcanism and erosion before the area was inundated by younger lava flows.

The upper contact of member A is indistinct. Member B, distinguished by lower zirconium content than member A, includes moderately to highly vesicular hematized flows, as well as pyroclastic and explosively derived breccias not present in member A. The contact is gradational in breccia sections.

### Stratigraphy and thickness

Distinctive successions of flows and breccias are recognized but few flow units extend laterally more than several hundred metres. Abrupt lateral changes in rock type, unconformities, and undulating paleosurfaces are common in the stratigraphy. Member A varies between 200 and 400 m thick (Fig. 12). South of the West tributary, member A is 450 m thick, but contains numerous sills. Further south, across the Harper Fault, it is less than 100 m thick.

### Lithology

Member A contains pillowed and minor massive flow units 30 to 70 m thick, as well as subaqueous breccias and tuff deposits. Pillowed flows in member A comprise networks of twisted, bifurcating and overlapping tubes, some at least 15 m long (Fig. 13A), with smooth exteriors and simple cross-sectional shapes 30 to 70 cm in diameter (Fig. 13B, E). Internally, pillows have thin (<1 cm thick) darkened rims, shallow expansion cracks, evenly distributed microvesicles, and rare cavities.

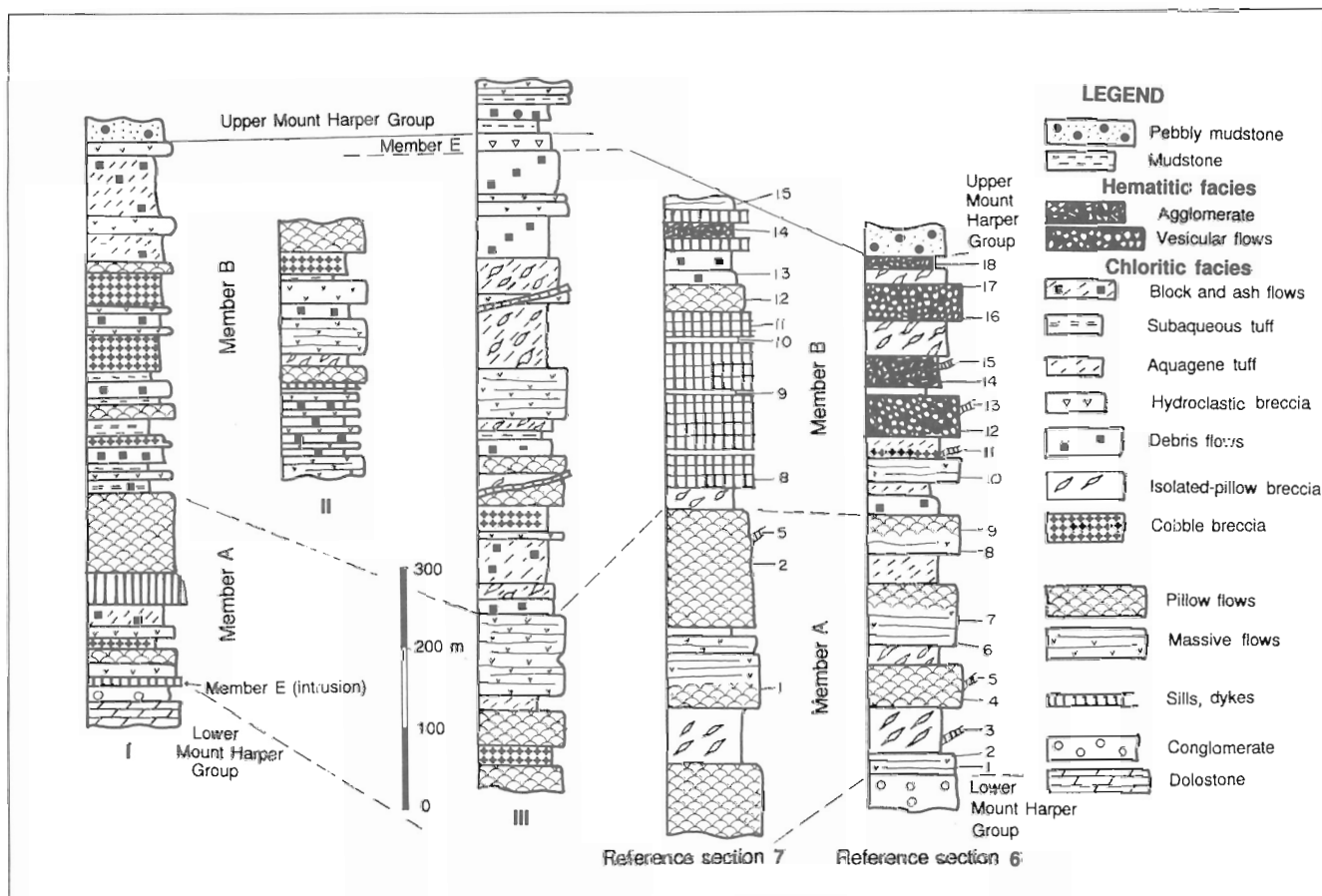
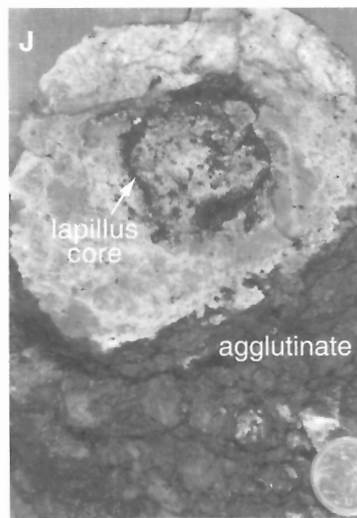
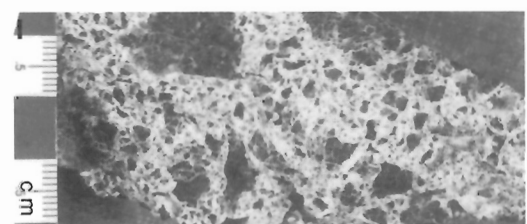
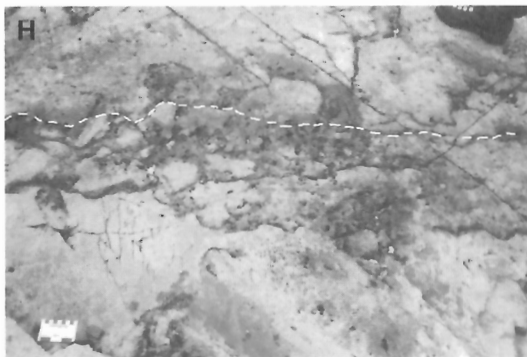
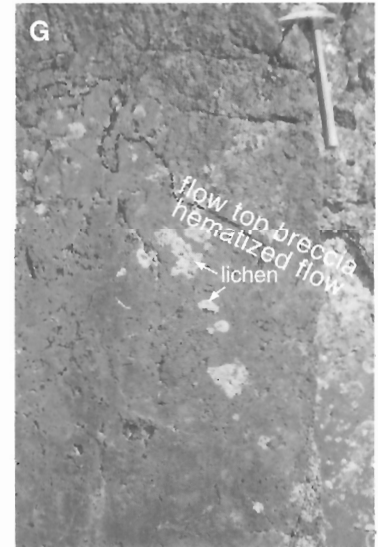
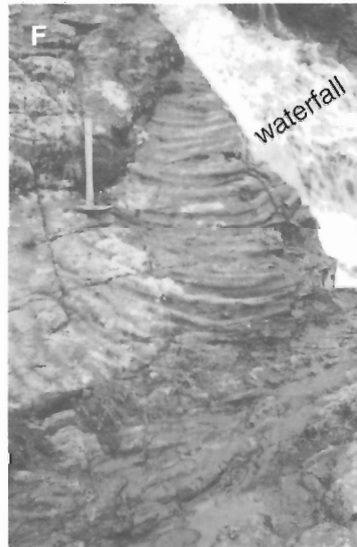
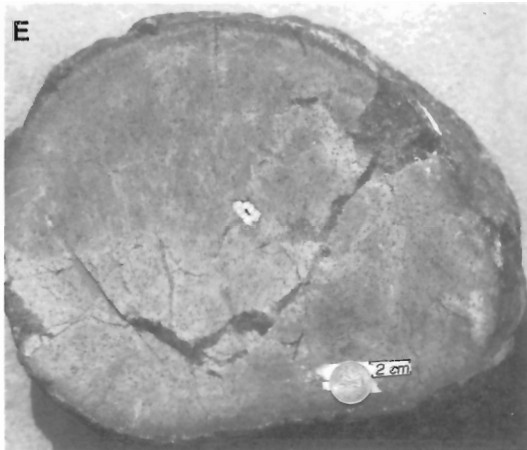
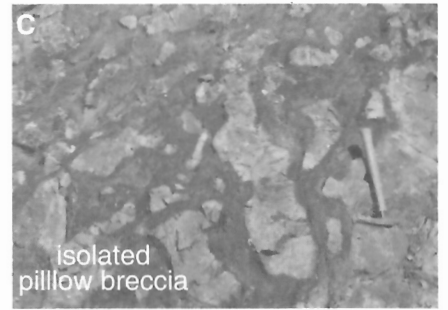
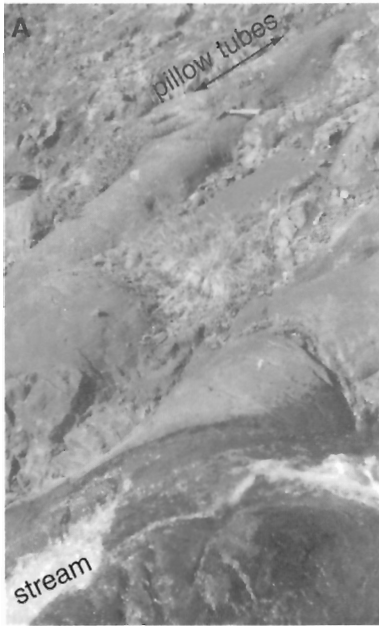


Figure 12. Representative sections for the Mount Harper volcanic complex. The locations are shown in Figure 11, and reference sections described in Appendix 2. Sections I, II, and III represent the volcanic stratigraphy north of the West tributary. Numbers on the right side of sections are sample numbers which correspond with whole rock analyses in Appendix 3. All sections were measured with a Jacob's staff.



←

**Figure 13.** Members A and B, Mount Harper volcanic complex. **A)** Overlapping tubular basalt pillows (member A), exposed in longitudinal section. Note bifurcation of tubes near hammer. From 1.9 km south of Mount Harper. GSC 1995-094A **B)** Closely packed pillows of Member A, exposed in cross-section. Dark selvage between pillows is chloritized aquagene tuff. Square encloses packsack, about 50 cm tall. From 500 m north of the summit of Mount Harper. GSC 1995-094B **C)** Isolated pillow breccia (member A) contains lenticular to amoeboid lava (light-coloured) suspended in aquagene tuff. It was formed by cascading of lava dribblets on the prograding apron of a major flow. From 2 m above base of volcanic complex, 2 km south-southeast of Mount Harper. GSC 1995-094C **D)** Cobble breccia (member A) consists of fragments from cooled and fractured flows (fragment at top centre may be from radially jointed pillow). Clasts with bleached rinds and incipient fractures probably reacted with matrix fluids after emplacement. From 1.3 km northeast of the summit of Mount Harper. GSC 1995-094D **E)** Joint surface provides cross-section of a pillow tube, 30 cm in diameter (member A). The thick darkened rim is mostly chlorite, replacing the original glassy rind. Evenly distributed microvesicles are filled with secondary celadonite. Calcite vug near centre may result from shrinkage during cooling. From 500 m northeast of Mount Harper. **F)** Rippled top surface of massive basalt flow (member B). From 6 km west-northwest of Mount Harper. GSC 1995-094E **G)** Indistinct top (dashed line) of subaerial flow (member B). Strongly hematized basalt (lower half of photo) increases in vesicularity upward, grading into monomictic flow breccia, formed by break-up of the cooled flow top. White spots are lichen. From 1.2 km southeast of Mount Harper. GSC 1995-094F **H)** Contact (dashed line) between massive, amygdaloidal basalt flows (member B). Flow-top breccia beneath contact contains elongate protrusions and comminuted lava in a chloritized matrix. From 6.6 km west-northwest of Mount Harper. GSC 1995-094G **I)** Hyaloclastic breccia from between pillows (member B). Matrix is replaced by epidote (naturally bleached in this sample) which highlights glass shards now replaced by chlorite. This breccia formed by shattering and spalling of quenched lava. From float 7 km west-northwest of Mount Harper. GSC 1995-094H **J)** Pyroclastic bomb consisting of hematized basaltic jacket (natural joint surface illuminated) around a scoriaceous core. Dark agglutinate contains vesicular basaltic lapilli indurated by heat and burial. Coin is 1 cm in diameter. From 500 m south of the summit of Mount Harper. GSC 1995-094I **K)** Cored bomb in reverse-graded, moderately indurated lapillistone that suggests reverse size grading. This massive, 7 m thick bed was probably deposited subaerially. From 500 m south of the summit of Mount Harper. GSC 1995-094J

Hyaloclastite (glassy shards spalled from quenched lava surfaces; Fisher and Schminke, 1984) is rare in member A: instead the matrix of pillow breccias consists of a fine grained chloritized breccia. It contains compacted globules and rounded 1 to 3 mm granules with shiny black, subvitreous surfaces. In texture and depositional setting, this breccia matches aquagene tuff (Carlisle, 1963) that was produced by disaggregation of fluid lava by turbulent water.

Two types of pillow breccia are well exposed in member A. Isolated pillow breccia (Carlisle, 1963; also called 'flow-foot breccia' by Furnes and Sturt, 1976) consists of elongate, amoeboid pillow shapes enclosed in aquagene tuff (Fig. 13C). The sacs roughly overlap downward in the direction of flow and form a 1 to 5 m thick base to pillowed flows. Such breccias form in the oceanic environment at the leading edge of large flows as a result of pillow lobes that detach and tumble down the prograding apron (Jones and Nelson, 1970; Lonsdale and Batiza, 1980). Later the breccia was over-run by the massive flow.

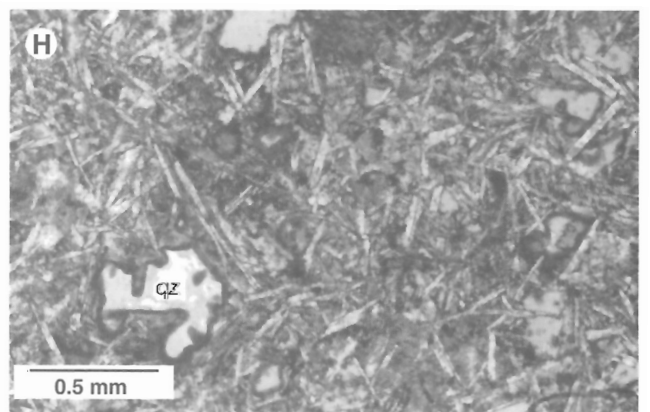
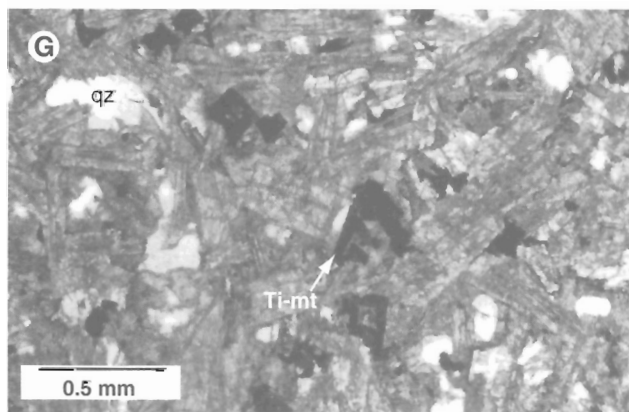
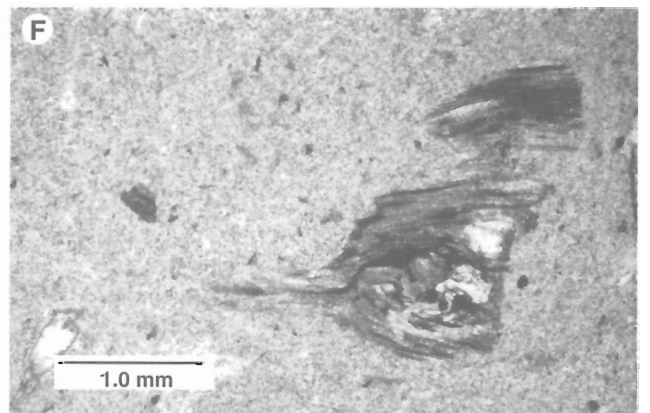
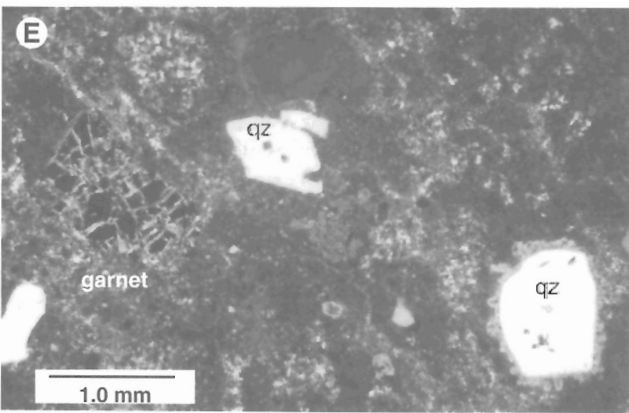
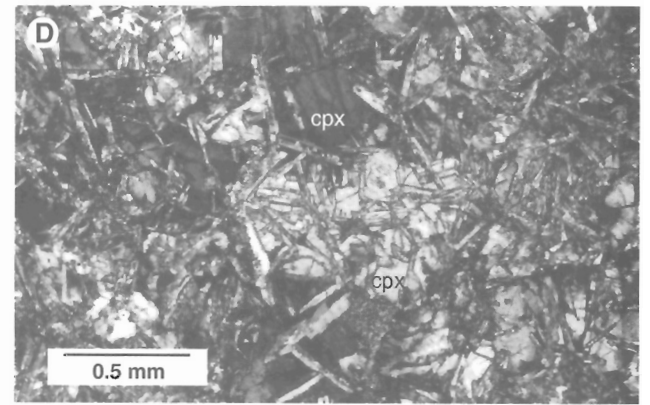
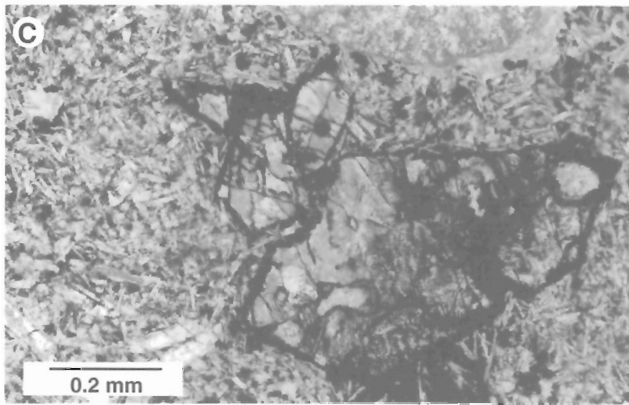
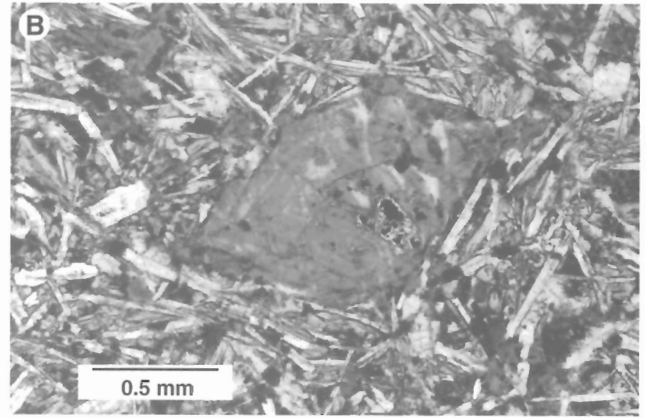
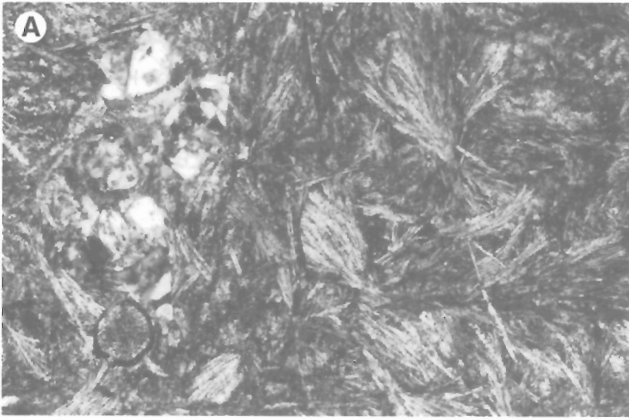
The second type, called broken-pillow breccia (Carlisle, 1963) contains fragments of former pillows (identified by portions of the original convex rind and vesicle bands) chaotically mixed with aquagene tuff. This breccia forms in the same way as a more common fragmental rock type here called cobble breccia, that consists of angular, mostly polyhedral blocks (Fig. 13D). Clean outcrops reveal that cobble breccia occurs as a continuous gradation from incipient fractured lava toward progressively smaller clasts away from the intact flow. It is not clear whether changes in slope or cooling of the lava produced brecciation. A minimum clast size (5 to 8 cm) below which no clast contains incipient fractures suggests that internal stresses (probably thermal shock or shrinkage during cooling) cause the flow to disintegrate.

Massive flows are 3 to 10 m thick, with unbrecciated tops and bases. Some are columnar jointed and others are massive with internal convoluted flow banding indicated by modal variations of plagioclase crystals within largely glassy zones. Typically they contain microvesicles (<1 mm in diameter) sparsely distributed throughout the flow. Most were probably sheet flows, indicated by their smooth, rippled tops. Sheet flows on the Recent seafloor appear to result from higher flow rates and lower magma viscosity than pillow-producing lava (Ballard et al., 1979).

Dykes and sills are fine- to medium-grained chloritic diabase, whose genetic relationship to member A is based upon field relationships and chemical analysis. The dykes are concentrated in a subcircular area 1 km southwest of Mount Harper (described below) and sills are common near the base of the complex, but are difficult to distinguish from massive flows unless both upper and lower contacts are clearly exposed.

### Petrography

Lower flows of member A are poorly crystallized. Thin sections from the interiors of pillows contain abundant fibrous mats of chlorite with albite and quartz which replace formerly glassy groundmass. Variolitic aggregates in many flows consist of fibrous feldspar and small opaque grains (Fig. 14A).



Better crystallized massive flows have pilotaxitic and intersertal texture. Prismatic plagioclase microlites, many with 'bow-tie' and 'belt-buckle' sections, form a loose mesh. Clinopyroxene (augite, estimated by extinction angle), apatite(?), and anhedral opaque grains (magnetite or pyrite; Brunet, 1986) fill interstices in the plagioclase network.

Microphenocrysts are widely distributed in flows of member A. Those that may have been olivine, on the basis of hexagonal outline (001 sections), irregular fractures, and lack of cleavage, are replaced by chlorite, sericite, and in some

cases silica (Fig. 14B). Some are skeletal or hopper pseudomorphs up to 1 mm long. The lowest flow on the north side of Mount Harper also contains 1 mm glomerophytic feldspars now completely pseudomorphed by subopaque clay minerals. The euhedral shape of these phenocrysts, in contrast to the poorly crystallized groundmass, implies that they were formed before extrusion of the lava flow.

### Primary structures and possible vent areas

On the east side of Coal Creek the sharply defined, straight upper surface of a thick accumulation of pillows imply that member A formed as broad submarine shield volcanoes. The predominance of tubular pillow lavas over sheet flows, by comparison with Neogene seafloor structures, indicates that the paleotopography was marked by fault scarps and walls, rather than broad axial valleys (Ballard and van Andel, 1977). In Coal Creek valley most pillow orientations indicate westward flow, implying that the source vent lies beneath Mount Harper or farther east.

Earliest eruptions probably issued from vents that were covered by later volcanic deposits, but several intrusions are exposed. A subcircular zone 150 m across exposed 1 km southwest of Mount Harper consists of mutually interpenetrating gabbroic intrusions that range from 10 cm to 7 m in width. It is interpreted to be the deeply eroded feeder pipe of upper flows because both aphanitic margins (sample A131-1<sup>2</sup>) and medium grained cores of dykes (sample A131-2) have compositional characteristics of member A.

The multiple injection of sills of member B south of West tributary appears to have increased the thickness of member A by about 150 m, raising the top of member A in the southern half of the complex. Inflation of seamounts by injection of dykes and sills has been deduced from cross-sectional exposures of extinct subaqueous seamounts (e.g. Staudigel and Schminke, 1984).

### Depositional environment and eruptive style

The predominance of aquagene tuff and pillows indicate that member A was extruded underwater. The absence of explosively-derived breccias in member A (and their abundance, by contrast, in member B) may reflect decreased hydrostatic pressure upon the later extrusions, although increased magma viscosity or volatile content could have produced a similar change.

The volcanic rocks at the base of the complex rest disconformably upon layers of conglomerate with some quartzite clasts incorporated in the lava flow. Where the flows overlie fine grained sediments, beds are crumpled, suggesting they were not consolidated. Also, along the base of one 5 m thick columnar jointed flow are epidote-lined cavities caused by trapped steam interpreted as spiracles (Macdonald, 1972, p. 89). The absence of interdigitated

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**Figure 14.** Petrography of members A, B, D, E and F (numbers correspond to samples; most with corresponding analyses in Appendix 2). **A)** Pillow core of member A basalt has variolitic texture, shown by radiating feldspar (white) in a dark, chloritic matrix. Crystalline mass at left is a microphenocryst, possibly olivine, replaced by quartz, calcite (white), and chlorite. Dark circle is a bubble in thin section. Cross-polarized light, A128-4. GSC 1995-095I **B)** Concentrically zoned microphenocryst probably originally olivine (distinctive 001 shape), with spinel(?) inclusion, replaced by serpentine and chlorite. Fine grained intersertal groundmass consists of prismatic plagioclase with interstitial clinopyroxene (grey) and magnetite. From basalt dyke feeding lowest flows of member A. Cross-polarized light, A128-3. GSC 1995-095J **C)** Aggregate of former olivine microphenocrysts, rimmed and replaced by hematite (black) and chlorite, in a maroon-weathering basaltic flow of member B. Groundmass contains white sodic plagioclase (An<sub>25</sub>) with interstices overgrown by hematite. Fibrous grey amygdale at the top consists of iron-rich chlorite and minor prehnite, with irregular calcite along rim. Plane-polarized light, B135-1. GSC 1995-095K **D)** Subophitic, medium grained basalt dyke is the freshest rock in the Mount Harper volcanic complex. Augite (cpx) crystals form interlocked clusters from which plagioclase (An<sub>60</sub>) prisms project. Interstices contain clinopyroxene and magnetite. Cross-polarized light, B158-1. GSC 1995-095L **E)** Felsic flow (member D) consists of phenocrysts of quartz (qz) and garnet (labelled) in recrystallized, sericitic matrix. Secondary quartz has nucleated on some quartz phenocrysts (lower right); detached slivers and concave edges on other phenocrysts indicate fracturing during cooling. Cross-polarized light, D138-1. GSC 1995-095M **F)** Ash-flow of member D contains dark chloritic fiamme (formerly pumice) and lithic fragments in a vitric ash matrix replaced by sericite. Plane-polarized light, D103. GSC 1995-095N **G)** Member E andesite intrusion contains tabular sericitized plagioclase (grey), skeletal and hopper magnetite crystals (Ti-mt), and interstitial quartz (qz). Plane-polarized light, E73. GSC 1995-095O **H)** Member F basalt flow has intergranular, diktytaxitic texture of sharp-tipped skeletal plagioclase with clinopyroxene (grey) and chlorite (dark). Amygdules of quartz (qz) rimmed with siderite are characteristic of this member. Cross-polarized light, F79. GSC 1995-095P

<sup>2</sup>Specific samples cited in text (prefix letter corresponds to volcanic member) have analysis and location in Appendix 2

conglomerate and volcanics near the base of member A implies that the conglomerate (interpreted as subaerial; Mustard, 1991) was rapidly submerged and subsequently overlain by pillow lavas and subaqueously deposited breccias.

Member A is insufficiently exposed to determine directly the shape and size of the seamount represented by member A. The initial volcanic deposits may have filled a hole resulting from continued extension along the Harper Fault. The superposition of subaqueous flows atop subaerially deposited conglomerate strongly implies synvolcanic subsidence. Typical modern seamounts are elongated above crustal fractures and have faulted margins (Basalt Volcanism Study Project, 1981, p. 733). Possibly the Mount Harper edifice resembled a seamount similar to those constructed near oceanic spreading ridges. For example, Ballard and Van Andel (1977) described a Holocene seamount with 2000 m relief in which fluid basalt flows were succeeded by more viscous and less extensive lavas that developed a shingle-like overlap.

## **Member B**

### **Definition**

Basaltic flows and breccias forming member B everywhere overlie member A and were mostly fed by southeast-trending dyke swarms that have similar primary composition. Member B is characterized by very large pillows, hematitic flows, and pipe vesicles filled with translucent pink, orange, and white agate. The subaqueous flow rocks and intrusions mostly weather dull orange-brown. Hematized rocks have maroon weathered and fresh surfaces.

### **Contacts and dimensions**

The base of member B is difficult to recognize because the compositional differences which distinguish it from member A are not reflected by an abrupt or obvious lithological change. The boundary was defined in reference sections from chemical analyses (see Fig. 23).

Member B is disconformably overlain variously by: member C (which contains mixed fragments of members A and B); hydroclastic tuff of member E; and the upper Mount Harper Group (in sedimentary outliers). Thickness varies to at least 500 m in western exposures. In places the volcanic edifice was deeply eroded before deposition of member C, and member B is absent. Subhorizontally layered hematitic flows comprise a 350 m thick section 2 km south of Mount Harper.

### **Lithology**

Two facies of member B are recognized. The boundary between the chloritic facies and the hematitic facies is transitional, but rocks of the hematitic facies always overlie the chloritic facies.

The chloritic facies includes massive and pillowed flows, as well as breccias formed by these flows and pyroclastic rocks. Massive flows of member B are fine grained, grey

basalt with delicate diabasic textures visible on etched weathered surfaces. Most flows are tabular, extend hundreds of metres laterally and are 3 m or more thick. Locally they pooled in paleodepressions to thicknesses of at least 30 m. Some flows have brecciated tops consisting of subangular flow fragments in a compositionally similar matrix, but others are smooth, locally exhibiting rippled or lobate surfaces (Fig. 13F). Vesicles are commonly concentrated in bands, and some are stretched, suggesting that they formed before or during emplacement of the flow. Pipe vesicles that occur above the basal chilled margin of some flows and locally in pillows, are several millimetres in diameter and up to 10 cm long.

Pillowed flows typically form discrete mounds or layers less than 10 m thick. Some layers grade upward into massive flows, and outward into broken pillow breccia. Hyaloclastite jackets surround most pillows and typically separate layers of pillows.

Two varieties of pillow shape occur. Common in the lower half of member B are elongate sacs with ellipsoidal cross-sections (50-150 cm), thick rims (2-4 cm), and contain concentric bands of spherical vesicles and short pipes. The pillows drape over one another and are commonly overlain by thin sheet lava flows with rill-like corrugations. Stratigraphically higher in member B are larger (70-200 cm across), bulbous and ovate pillows with large gaps between them filled with hyaloclastite, calcite, and aquagene tuff.

The breccias related to subaqueous extrusion of member B comprise several distinct types that vary in texture and dimensions. Hyaloclastite, present throughout the chloritic facies, is best revealed where resistant epidote has replaced the matrix and chloritic shards are in bold relief (Fig. 13I).

Spatially and genetically associated with elongate pillows are deposits that contain features of both isolated pillow breccia and broken pillow breccia types (previously described for member A). In the hyaloclastite matrix which constitutes most of the rocks, are individual pillows; pillow fragments, thin dribble flows, and feeder tubes (1 m diameter). Generally the deposits are part of a succession 30 to 50 m thick, grading from isolated pillow breccia upward to very large pillows and massive flows.

Subaqueous tuff is irregularly distributed in lenses 5 m thick and more than 20 m long beneath the hematitic facies south of Mount Harper. Cobble-sized, elongate clasts are embedded in a scaly chloritic matrix. Clasts with dark, spalling rinds and hematitic, flow-banded cores were probably pyroclastic bombs and armoured lapilli, similar to those illustrated by Fisher and Schminke (1984, p. 94).

The hematitic facies consists of purple, red, and brown highly vesicular flows and breccias principally exposed on Mount Harper and adjacent ridges. Hematitic lava flows are 1 to 5 m thick, with obscure interflow contacts (Fig. 13G). Vesicles increase in size and abundance upward within flows; 'dog-bone' and other angular shapes imply deformation by viscous flow, a characteristic of modern aa flows (Macdonald, 1972, p. 70, 88).

Pyroclastic breccia contains poorly stratified tuff and lapilli-bomb tuff which is scoriaceous basaltic lumps loosely distributed among hematitic granules. Cored bombs (Fig. 13J, K) are present 1 km south of Mount Harper and some deposits with annealed clasts are agglutinate or spatter close to subaerial vents.

Subvolcanic intrusions are distinguished from flows by regular jointing perpendicular to contacts and less alteration than flows. Some twenty subhorizontal sills, 2 to 7 m thick, are exposed on the mountain faces south and west of the confluence of the West tributary. The sills are indicated by 1 to 2 cm chill zones along contacts and appear to crosscut each other, enclosing slivers of pillowed flows up to 3 m thick and tens of metres long. Those near the middle of the section have medium grained, subophitic diabase interiors petrographically similar to dykes in the feeder pipe 1.5 km to the north-east. On weathered surfaces the outlines of former pyroxene crystals are discernible.

### **Petrography**

Member B flows are better crystallized than those of member A. They have intersertal textures characterized by a dense mesh of plagioclase enclosing 1 mm augite grains. Some contain 1-2% microphenocrysts which may have been olivine, now pseudomorphed by yellow-green chlorite and quartz with hematite at the edges (Fig. 14C). The groundmass contains 2-3% titanomagnetite and abundant secondary sphene.

Dykes of member B are the freshest mafic rocks in the volcanic complex. They consist of a mesh of well-formed, twinned plagioclase laths ( $An_{52-65}$ ) with embedded subophitic, strongly coloured pyroxene. The coarse grained centres of sills consist of 3 mm augite grains in mutual contact and partly enclosing small plagioclase prisms (Fig. 14D). Unlike flows, where mafic minerals are preferentially altered, in dykes the pyroxene is fresher than the plagioclase which is albitized or replaced by clays and sausserite.

### **Primary structures**

The disconformable upper contact of member B provides clues to the former shape of the volcanic edifice. A topographic bench beneath the sedimentary outlier 6 km west of Mount Harper (Fig. 15A) is probably an exhumed erosion surface of the original volcano. Lavas of higher viscosity in member B than member A are suggested by the steep paleoslopes and greater proportion of breccia in member B.

### **Depositional environment and eruptive style**

In the chloritic facies, scoriaceous bombs, amoeboid pillow shapes, and ribbon lava fragments indicate derivation from a shallow water vent. The thin flows and pillow breccia layers in the western part of the complex could have been deposited as an apron extending from a volcanic centre.

In the hematized facies, well-preserved aa flows, cinder-like breccias, and agglutinate containing cored bombs indicate subaerial eruptions. All known occurrences of these deposits contain hematite, but no pillows or other subaqueously erupted rocks were found; it is thought that the maroon rocks oxidized subaerially.

These two facies which overlie deeper water, volcanic deposits represent a shallowing subaqueous environment that probably resulted in an emergent volcanic landform. The deposits of member B may have formed part of a subaerial to shallow water cinder cone, similar to the modern volcano of Surtsey near Iceland (cf. K. Okalaar and Durant, 1983).

## **Member C**

### **Definition, distribution, and contacts**

Volcanic breccia of inferred pyroclastic and epiclastic origin generally occupy a stratigraphic interval above members A and B. The breccias contain no clasts that were clearly derived from members D, E, and F and are therefore grouped as member C. Breccias included in member C constitute a spectrum from wholly primary (pyroclastic) to completely reworked (epiclastic) breccias, although most outcrops range towards the latter. Clasts are basaltic and andesitic. No intact flows that could be shown to have been erupted during deposition of member C were found, so the composition of this stage of volcanism remains undetermined.

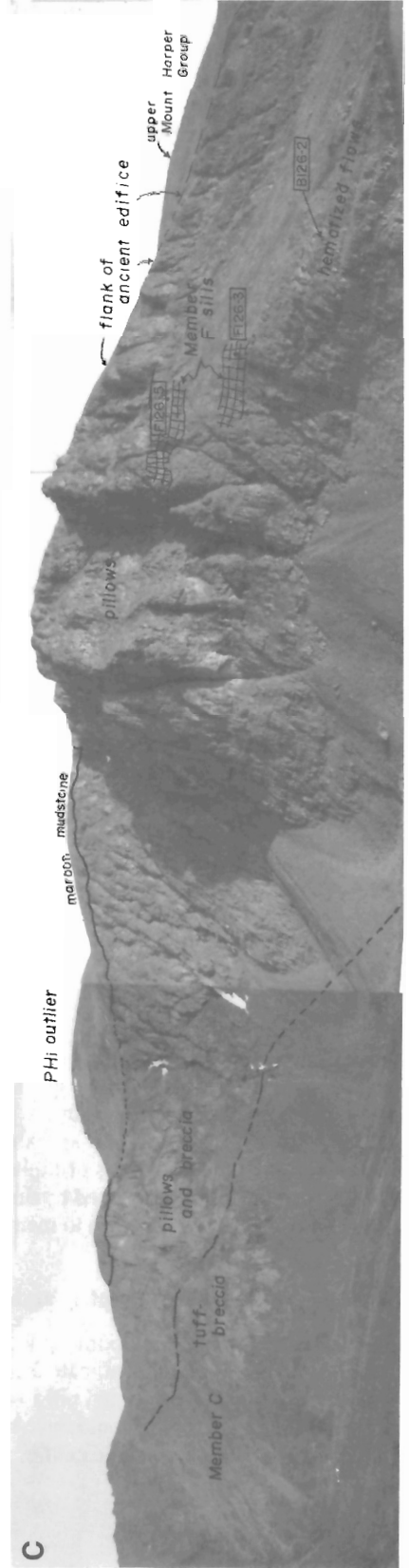
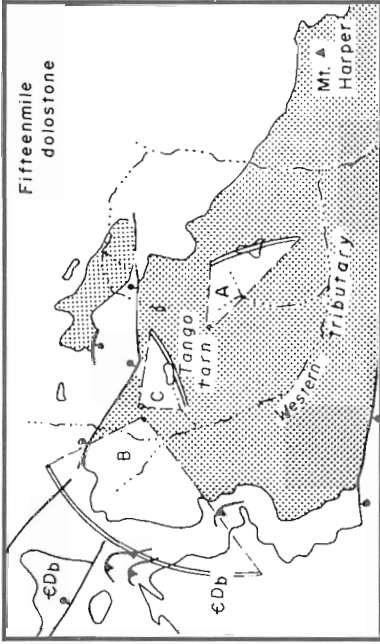
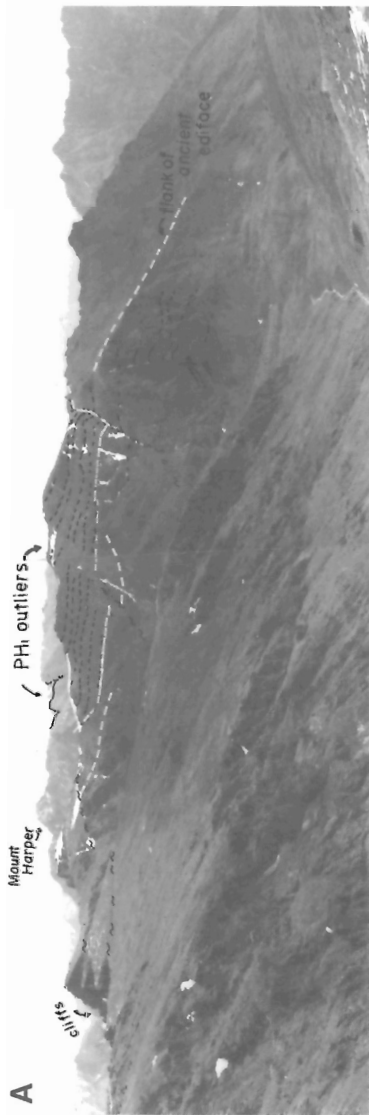
The distribution of volcanic breccias included in member C is shown on Figure 16. In the south block-and-ash breccias unconformably overlie rocks of members A and B that have been locally tilted. Topographic benches in the western part of the complex represent an exhumed erosion surface of members A and B upon which a veneer of member C breccias are locally preserved.

Basal contacts of member C are rarely exposed. Heterolithic conglomerate appears to drape over lenticular hyaloclastite and pillows of member B (Fig. 17A). In the northwestern part of the complex, member B pillows are succeeded by block and ash breccias, which have infilled cavities and contain broken pillow fragments.

Member C is overlain in the western part of the complex by conglomerate of the upper Mount Harper Group. The nature of the upper contact varies, but north of Tango tarn is a lithological transition within a 5 m thick bed (Fig. 17B) to debris flows derived from sedimentary rocks. It may be a reworked crystal tuff. South of West tributary the breccias are conformably overlain by hydroclastic tuff (member E). A green, laminated sandstone up to 30 cm thick which contains detrital feldspar is discontinuously present below the contact with felsic flows (member D).

### **Lithology**

Tuff-breccia consists of subangular basaltic fragments, loosely or densely packed in dark coloured tuff. Outcrops are distinctive because the crumbly chloritic matrix scales away, exposing fresh, dark undercut cliffs in which each bed is



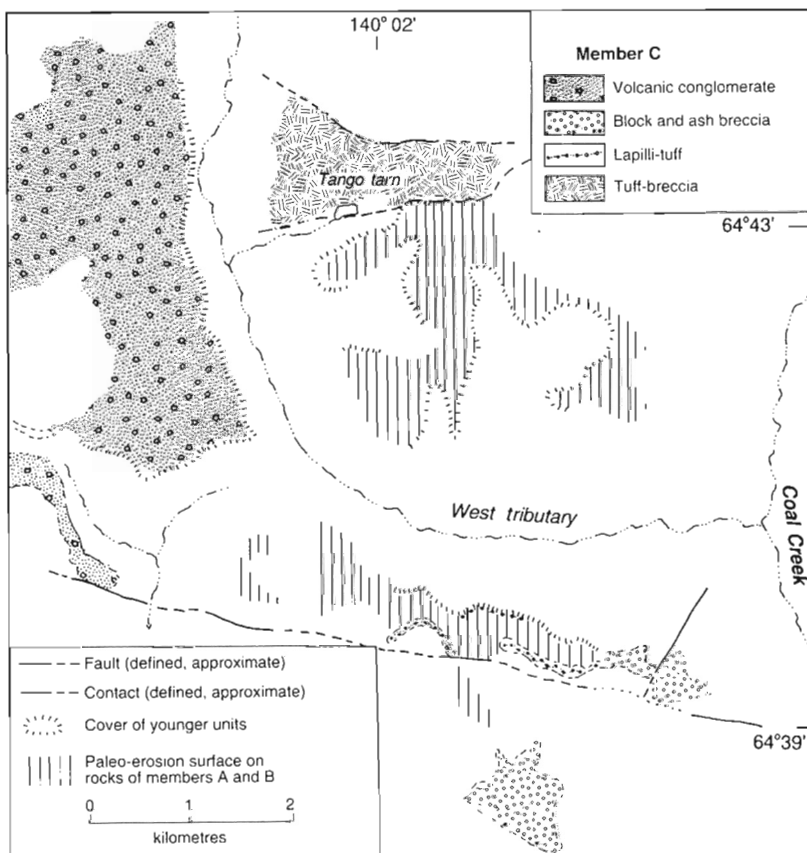
outlined by contacts more resistant to weathering. North of Tango tarn the tuff-breccia is homogeneous, more than 200 m thick, and consists of uneven, laterally persistent 2 to 6 m beds that are internally stratified by clast trains. The matrix is weakly foliated oblique to bedding contacts, resulting from

deformation of the poorly lithified, relatively incompetent deposits. Clasts are monomictic basaltic composition, 10 to 50 cm in diameter, vesicular with darkened rims (possible chill zones) within shells of scaly matrix, and resemble bombs (Fig. 17C).

Lapilli-tuff exposed 6.5 km southwest of Mount Harper consists of 70 cm to 2.5 m thick beds with normally and reversely graded, poorly consolidated vesicular and dense mafic lapilli (Fig. 17E). Bedding contacts are sharp and undulating, and basaltic fragments up to 10 cm long are concentrated near the top (Fig. 17G). Fine laminae that suggest quiet subaqueous conditions were not observed. Reworked lapillistone beds and pillow lavas indicate shallow water deposition.

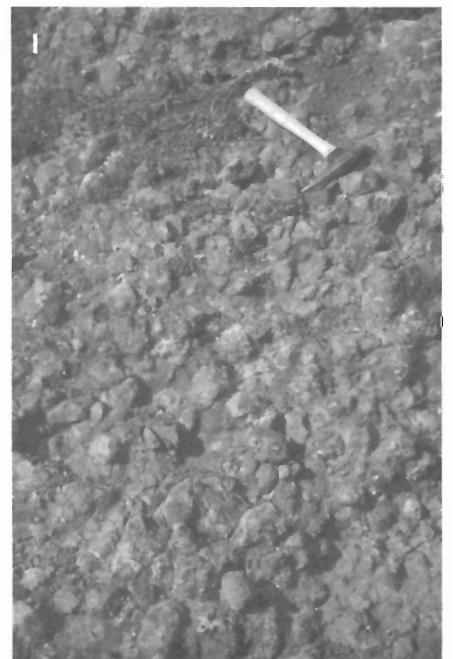
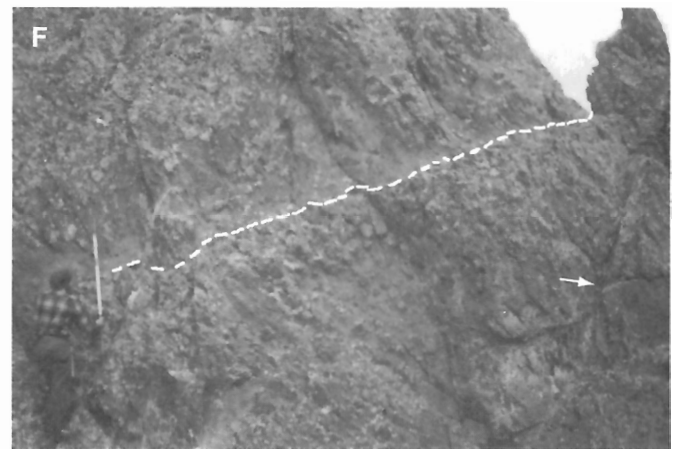
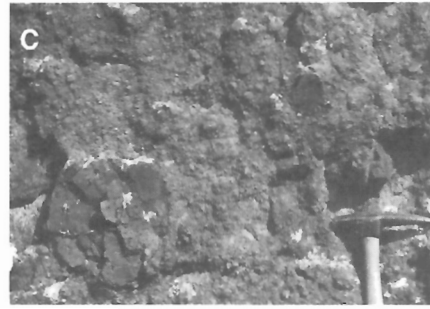
Block-and-ash breccia differs from tuff-breccia in containing a mixture of rock types as clasts. Bedding is uneven and deposits are locally tens of metres thick. Beds are poorly sorted and commonly reverse-graded at the top (Fig. 17F). Subangular clasts range from a centimetre to a metre across. Most clasts have fractured edges, indicating derivation from pre-existing rocks including hematitic and chloritic flows and pillow breccias and uncommon dolostone. The matrix is lighter coloured, and contains more dolomitic mud and less chloritic ash than tuff-breccias. Basal contacts are obscure for deposits that overlie lava flows and breccias, but for those that rest on fine grained beds contacts are sharp with no indication of basal scour (Fig. 17H). Block-and-ash breccias probably originated as debris flows derived from predominantly volcanic, and minor sedimentary source areas.

**Figure 15.** (Volcanic structures) **A**) View eastward of the central part of the Mount Harper volcanic complex. Planar slopes (on left) are a paleoerosion surface beneath a lava flow of member F; cliffs below expose member B pillows and breccias. Dark face of mountain in centre reveals a cross-section of the ancient member B edifice which was partly eroded before deposition of the upper Mount Harper Group, preserved in outliers of unit PH<sub>1</sub>. GSC 1995-095A; GSC 1995-095B **B**) View westward across the head of drainage into West tributary shows southward-dipping stratigraphy of CD<sub>b</sub> dolostone and underlying Cambrian shales. A thicker section of upper Mount Harper Group and member C is preserved on the down-faulted north side than on the south side. Map units as on Figure 1. Width of view: 8 km. GSC 1995-095C; GSC 1995-095D; GSC 1995-095E **C**) View across Tango tarn (bottom right corner) to a cross-section of the member B edifice. Maroon mudstone of unit PH<sub>1</sub> (upper Mount Harper Group) disconformably overlies member B. The tuff-breccia (member C) abuts member B along the synvolcanic Tango tarn fault scarp. GSC 1995-095F; GSC 1995-095G; GSC 1995-095H



**Figure 16.**


*Distribution of the major breccia deposits in member C, and area of eroded edifice of members A and B from which they were probably derived (vertical line pattern). Surrounding blank areas are underlain by units older than member C.*



Volcanic conglomerate contains a variety of clast types, including vesicular, hematitic to massive, or chloritic basalt that are densely packed in a sand-sized volcanic matrix (Fig. 17I). The pebble- to cobble-sized, subrounded clasts form poorly sorted tabular beds 1 to 2 m thick. In some beds crude stratification is defined by lensoid domains of larger clasts or sandy matrix.

### Primary structures

The distribution and lithological variations in member C yield clues to the paleotopography of the volcanic edifice. A syn-depositional, steep, north-side-down fault is inferred to lie in



**Figure 17.** Member C. **A)** Gradational contact (dashed line) between member C tuff-breccia (below dashed line) and overlying paraconglomerate of the upper Mount Harper Group. The transition from tuffaceous basaltic matrix with subrounded mafic cobbles, to dolomitic mudstone matrix containing both volcanic (dark) and carbonate (light) clasts is interpreted to be the result of continuous debris flow sedimentation from nearby volcanic and regional carbonate units. From 1 km north of Tango tarn. GSC 1995-095Q **B)** Abrupt contact (dashed line) of volcanic conglomerate with mudstone matrix above a basaltic flow with steep joints. Subangular cobbles are same rock type as underlying flow. From 8.5 km west-southwest of Mount Harper. GSC 1995-095R **C)** Reworked volcanic ash with probable breadcrust bomb (lower left) indicated by concentric vesicular bands and radial joints. This 3 m thick deposit is interpreted as a debris flow. From 1 km east-southeast of Tango tarn. GSC 1995-095S **D)** Block and ash breccia, from a 3 m thick, poorly sorted bed. White lichen grows preferentially on clasts of vesicular lava, such as the cluster below hammer head. Poorly consolidated matrix consists of chlorite (altered tuff) and comminuted lava. From 7 km west-southwest of Mount Harper. GSC 1995-095T **E)** Poorly indurated mafic tuff underlying hydroclastic tuff. Undercut cliffs represent fine grained, reworked tops of layers. Boxed area, 3 m high, is shown in (G). From 6.5 km southwest of Mount Harper. GSC 1995-095U **F)** Block and ash breccia showing reverse size grading toward planar top (dashed line), which indicates a nonerosive base of the subsequent flow. Note lava block greater than 1 m (arrow). From 5 km southwest of Mount Harper. GSC 1995-095V **G)** Detail of pyroclastic layers in (E) shows mafic tuff with reverse size grading upward. Subangular lava clasts near top of bed (arrows) are overlain by reworked ash (white, with lichen spots). The deposit is interpreted to have resulted from a Plinian eruption. Location as in (E) above. GSC 1995-095W **H)** Indurated, well bedded volcanic wacke, overlain (dashed line) by massive volcanic block and ash breccia. Bed in lower half is better sorted toward its reworked top. From 8 km west-southwest of Mount Harper. GSC 1995-095X **I)** Volcanic cobble conglomerate containing rounded basaltic clasts, framework supported in dark mudstone. From 8.5 km west-southwest of Mount Harper. GSC 1995-095Y

the valley of Tango tarn. Upper Mount Harper Group conglomerate overlies member C tuff-breccia on the north, but south of the fault the same conglomerate directly onlaps an erosion surface on member B (Fig. 18). Although lateral facies variations could not be determined, the breccia thickness diminishes northward. Possibly the breccia was deposited below a scarp created by vertical movement of the Tango tarn fault and was subsequently overlapped by the upper Mount Harper Group sediments.

### Depositional mechanisms and environment

Member C breccias record both explosive activity and simultaneous destruction of the volcanic pile composed of members A and B.

The tuff-breccia probably represents pyroclastic flows. Its matrix of intact shards and the high content of bomb-like clasts imply direct ejection from a vent, or slumps of previously-erupted unconsolidated debris. The large size and massive internal texture of the clasts is consistent with ejection during Plinian eruptions (L.D. Ayers, pers. comm., 1984).

The lapilli-tuff, which contains angular, internally fractured fragments and abundant ash-sized particles, is also typical of Plinian fallout (Fisher and Schminke, 1984, p. 117). The ash-filled debris flows probably plucked rock fragments from member B and carried them in a thick slurry.

Heterolithic block-and-ash breccias were probably volcanic debris flows (lahars). They may have begun as hot pyroclastic flows which incorporated broken rock and water, or could simply represent deposits formed as a result of slope failure on the flanks of the volcano. Typical laharc deposits are thin on steep slopes and much thicker on gentle slopes and form broad aprons around volcanoes (Cas and Wright, 1987). Lahars do not disturb underlying beds, retain clasts up to 1 m in size within the flow, and are commonly reverse-graded near the top (Fisher and Schminke, 1984, p. 307).

The heterolithic conglomerates were probably eroded from volcanic cliffs and reworked in shallow water. Subaerial erosion is implied by rounded clasts and layers of cobbles and pebbles.

The general distribution of breccias in member C, from pyroclastic flows in the north and east, to laharc and conglomeratic beds in the southwest, may broadly reflect southwesterly progression of mixing, reworking, and distance from the eruptive source. The deposits appear to have formed an apron sloping westward from a large volcanic edifice.

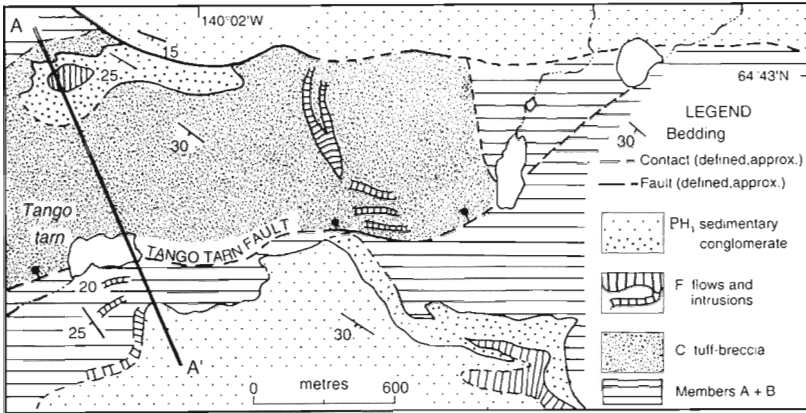
### Member D

#### Definition, distribution, and dimensions

Member D consists of massive silicic flows, tuffs, and intrusions. Flows are light pinkish grey or uniformly green and are easily distinguished from mafic rocks. Most rocks are columnar jointed and deeply fractured, so that few outcrops protrude from the rubble- and vegetation-covered slopes.

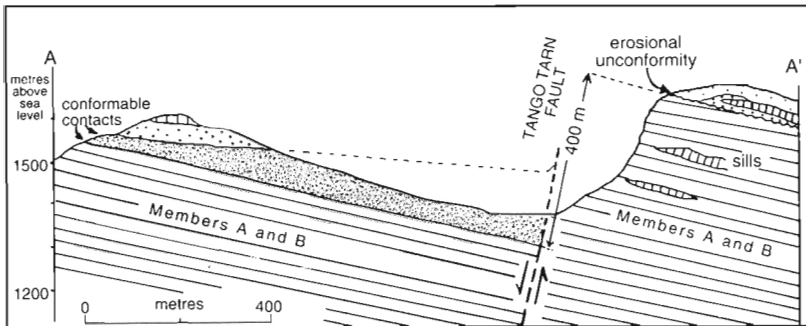
Member D is restricted to the southern half of the Mount Harper complex (Fig. 19) on both sides of Coal Creek. Several quartz-phyric flows constitute a 170 m thick section about 4 km south of Mount Harper. Plagioclase-phyric rocks west of Coal Creek are believed part of the same succession, which is estimated to be 150 m thick in a south-facing slope between members B and E. Plagioclase-phyric rocks that may be part of these flows are also present immediately north of the Harper Fault.

Three mounds of silicic rubble, thought to be centred on feeder dykes, lie on the high ridge south of West tributary. The mounds overlie hydroclastic breccia of member E and although at a higher stratigraphic level, are included in member D because of their silicic composition. Two quartz-porphry dykes and three silicic breccia occurrences that are probably intrusions are also included in member D.



**Figure 18.**

Stratigraphic relations of the 'Tango tarn' fault, near the west edge of the Mount Harper volcanic complex. Map (top) shows the distribution of member C tuff breccia on the north side of the fault. This unit is absent at a disconformity on the south side. The cross-section (bottom) shows true-scale topography and the possible shape of the tuff-breccia deposit if it was derived from the south, across the 'Tango tarn' fault.



**Figure 19.**

Distribution of felsic member D in the Mount Harper volcanic complex. Blank space surrounding the patterned area is exposure of older rocks (dashed contacts) or is covered by younger units (dotted contacts).

## Contacts

The basal contact of member D is not exposed, but there is clear angular unconformity between tilted amygdaloidal flows of members A and B and overlying rhyolite extrusions.

Member D is compositionally distinct from overlying member E, but the contact was not observed in continuous exposure. In two places a tuff layer less than 1 m thick is the highest preserved felsic rock, but generally the contact appears to be a disconformity beneath hydroclastic breccia and flows of member E. The upper contact of member D is locally marked by another thin crystal tuff horizon and is generally disconformable beneath hydroclastic breccia and flows of member E. The three mounds of silicic rubble that overlie the hydroclastic breccia do not have a preserved upper contact.

## Lithology

Massive rhyolite, which dominates member D, comprises thick lava flows, intrusions, or ash flows, but features that would unequivocally distinguish these rock types are absent. Locally member D contains flow bands (Fig. 20B) and sparse but uniform phenocryst distribution. Most outcrops consist of jointed columns (15-25 cm sides) forming upright palisades or fans, and the fluted paleotops of these flows are covered by lithified breccias composed of jointed lava fragments. Variations in proportions of quartz to feldspar phenocrysts in the outcrops south of Mount Harper suggest separate flows, each of which is tens of metres thick.

In comparatively fresh flows, phenocrysts less than 2 mm in length include: potassic feldspar (1-3%<sup>3</sup>), plagioclase (1-2%), and quartz (<2%). Rare garnet phenocrysts (or xenocrysts) were observed south of Mount Harper (sample 138-1; Fig. 14E). Inconsistent with an ash flow origin are the paucity of phenocrysts and absence of broken crystals, whereas the presence of several conformable breccia horizons (Fig. 20A) supports a flow origin. Strongly altered flows consist of crumbling limonitic clay, which locally reveal clusters of 0.5 mm spheres that may have been spherulites, thus implying that at least some flows were glassy.

Ignimbrite occurs at the base of the westernmost rubble mound (sample D-103). The rock is greenish, streaked with flattened fragments of devitrified pumice (5%), and speckled with broken feldspar and quartz phenocrysts (less than 1 mm long; 2%; Fig. 14F). This 4 m thick deposit is mostly overlain by rubble, but extends at least 40 m laterally.

The felsic tuff and arkose occur at or near the top of member D but it is not clear whether they are a single horizon. The layer is 1.0 to 1.5 m thick and consists of laminated green mudstone interpreted as waterlain, formerly vitric and now recrystallized tuff. South of the Harper Fault a crystal-lithic tuff varies laterally westward to medium grained arkose. Both the tuff and arkose are composed of broken feldspar crystals

(40%), dark angular rock fragments (25%), and quartz grains up to 1 mm long (10%), all set in a fine grained red and green matrix.

Felsic dykes and subvolcanic intrusions comprise two types. At least eight subparallel, north-trending dykes occur 5 km southwest of Mount Harper (sample D48-1) and are compositionally similar to the massive flows. They are single or multiple intrusions 3 to 5 m thick, characterized by broad columns lying perpendicular to planar, vertical margins. Most consist of flow-banded quartz-phyric rhyolite that locally contains hematite, with vesicular zones filled with clay minerals (celadonite).

A second type of felsic intrusion occurs 1.5 km northeast of Tango tarn. The dykes are up to 3 m wide, and consist of densely packed phenocrysts of plagioclase, potassium feldspar, and lesser quartz in a sparse chloritic matrix. Grain size decreases toward the margins of these dykes, where ragged patches of dark chlorite that may have been pumice fragments and angular andesitic rock chips 5 to 10 mm long dominate. The dykes intrude the hydroclastic tuff (member E) and therefore represent the last stage of silicic activity in the complex.

## Petrography

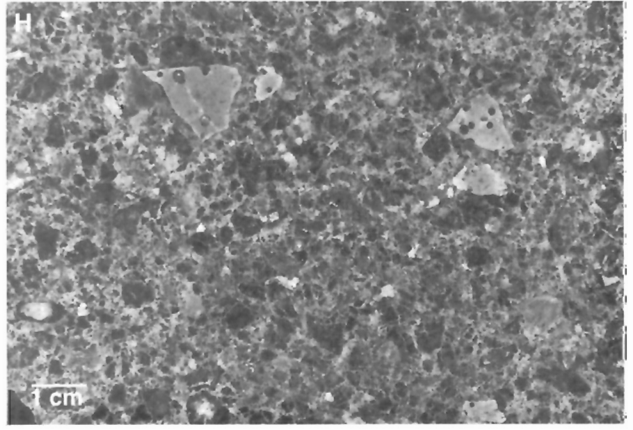
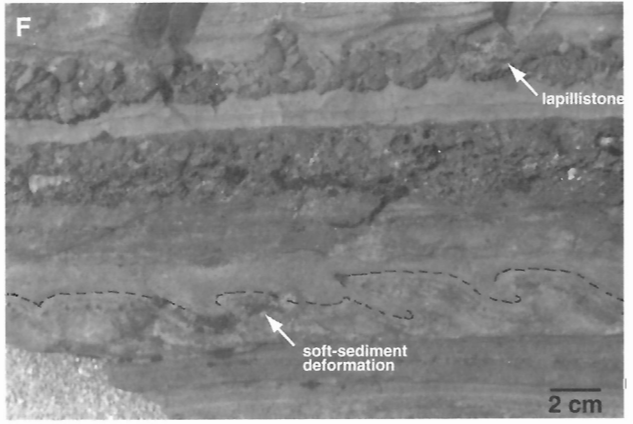
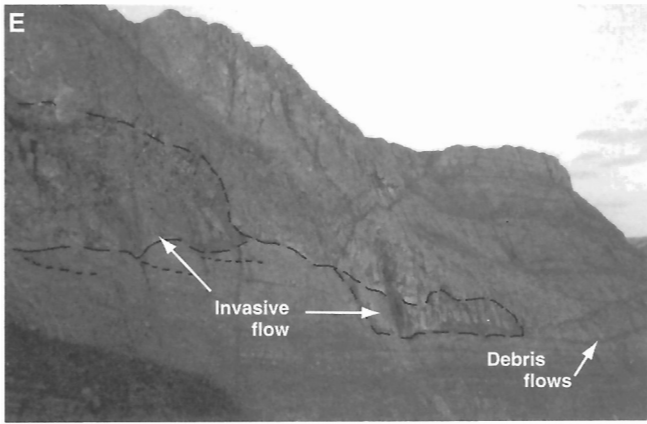
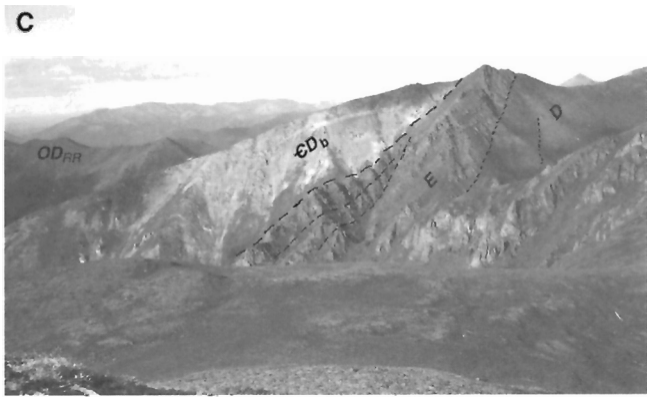
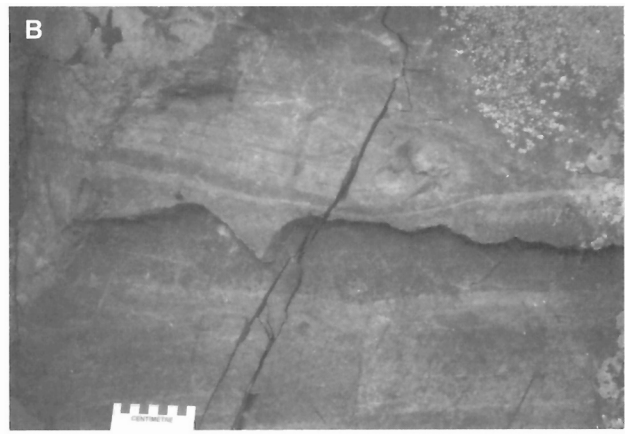
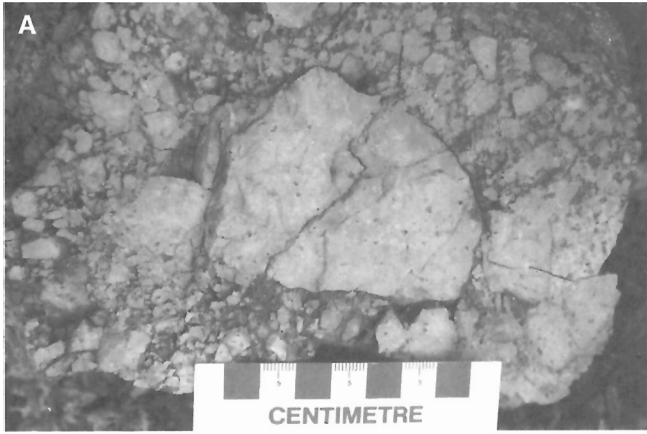
Thin sections of least altered massive rhyolitic rocks reveal arcuate streaks that resemble devitrified, perlitic fractures. These imply that the sericitized groundmass was probably originally glassy. The groundmass contains phenocrysts of potassium feldspar, plagioclase, and quartz. Plagioclase phenocrysts have tabular, euhedral outlines, but have been replaced by sericite, leaving cloudy or opaque cores. Phenocrysts of potassium feldspar show Carlsbad twinning in the replacement mineral (adularia?) and are filled with minute inclusions. Subhedral quartz phenocrysts, 0.2 to 0.4 mm in diameter, only occur in flows south of Mount Harper and in the rubble mounds on the ridge south of West tributary. Some quartz is fringed by hematite dust. Xenocrysts of iron-rich garnet (probably andradite) up to 1 mm across occur in one flow (Fig. 14E). Sphene, ilmenite, and zircon, all up to 0.5 mm long, are common in all flows.

## Eruptive style and depositional environment

Silicic volcanism at Mount Harper began explosively (ignimbrite) followed by extrusion of glassy flows. Only a single ignimbrite and rare pumiceous clasts were discovered. Mostly nonexplosive extrusion is indicated by thick glassy flows. Such flows are characterized by low water contents and are typically extruded from narrow fissures (Eichelberger et al., 1986).

Deposits of member D contain few clues to the environment of deposition. The thin arkosic beds were probably deposited in shallow water. The absence of fine-laminated beds and chill margins on flows suggest that member D was deposited subaerially.

<sup>3</sup> All mineral percentages visually estimated by area of thin section



## Member E

### Definition and distribution

Member E consists mostly of massive flows, tuffs, and breccia texturally similar to rock types in members A and B but easily distinguished from the lower units by petrography and chemical composition. These dark aphanitic rocks are named from their chemical composition: member E flows

**Figure 20.** A) Flow breccia (member D) containing comminuted rhyodacite lava. Dark specks are limonite replacing weathered ferromagnesian minerals. This deposit occurs on the margin of a rhyolite extrusion (exogeneous dome?) where it formed by comminution of viscous lava. From 7.5 km west-southwest of Mount Harper. GSC 1995-095Z B) Refolded flow banding in rhyolite lava (member D). White streaks are coalesced spherulites, indicating the previously glassy texture of this rock. From 6.5 km west-southwest of Mount Harper. GSC 1995-095AA C) View westward of the stratigraphically highest volcanic rocks, 9 km southwest of Mount Harper. Note that layered lava flows of member E are truncated (dashed line) by a gently dipping  $\text{CD}_b$  dolostone unit. This contact is interpreted as an erosional disconformity, modified by later faulting. GSC 1995-095BB D) Aerial view southward from 7 km southeast of Mount Harper shows plateau formed by a resistant, member E flow. Vegetated slopes beneath cliffs are hydroclastic breccia and member D rhyolite, but their upper contact is irregular. The planar surface of the member E flow suggest that lava floods spilled southward from the volcanic complex over a gently dipping, relatively flat surface. GSC 1995-095CC E) Westward view of the sedimentary outlier 7 km northwest of Mount Harper, showing an invasive flow (Wright et al., 1973) within interdigitated paraconglomerate layers that are interpreted as lobate debris flows. GSC 1995-095DD F) Laminated epiclastic siltstone, with basalt lapillistone and reworked tuff of unit  $\text{PH}_1$  of the upper Mount Harper Group, 1 km south-southeast of Mount Harper. Convolutions in dolomitic mudstone layer suggest slumping and the delicate stacking of lapillistone indicates low energy deposition. G) Coarse hydroclastic breccia consisting of angular and subequant glass fragments of andesitic flows (member E). Note the two clast types distinguished by their different reactions to quenching and alteration. Formerly glassy rock shows concentric 'liesegang banding' (oxidation/reduction fronts) and spherulite growth (white spots). Fragments that appear to have been more crystallized (e.g. in left centre) are uniformly chloritized and crumble, without forming splinters. This breccia is typical of glassy flows that have shattered upon contact with water. From 6.5 km southwest of Mount Harper. GSC 1995-095EE H) Fine grained hydroclastic breccia contains well-sorted fragments of formerly glassy andesite, now whitened by spherulitic alteration formed by shattering of quenched member E flows. These breccias are up to 60 m thick north of the West tributary. From south side of sedimentary outlier 5 km west of Mount Harper. GSC 1995-095FF

are andesites by silica content and icelandites in terms of iron enrichment. The flows are not visibly weathered. Distinctive dark blue chlorite alteration permeates brecciated rock, filling vugs and fractures. Hydroclastic breccia consisting of small, shard-like fragments underlie member E flows, and is also present up to 4 km north of the preserved extent of these flows.

Remnants of member E flows are exposed in the southwestern part of the Mount Harper complex (Fig. 21) as towers on ridge crests and broad plateaus (Fig. 20D). The hydroclastic breccia occurs in a layer of varying thickness near the tops of ridges on both south and north sides of West tributary.

### Contacts and dimensions

Member E overlies felsic flows and crystal tuff of member D. The hydroclastic breccia disconformably overlies members B, C, and D. Along the southwest margin of the complex, member E flows dip southwest and are covered by more gently dipping  $\text{CD}_b$  dolostone (Fig. 20C).

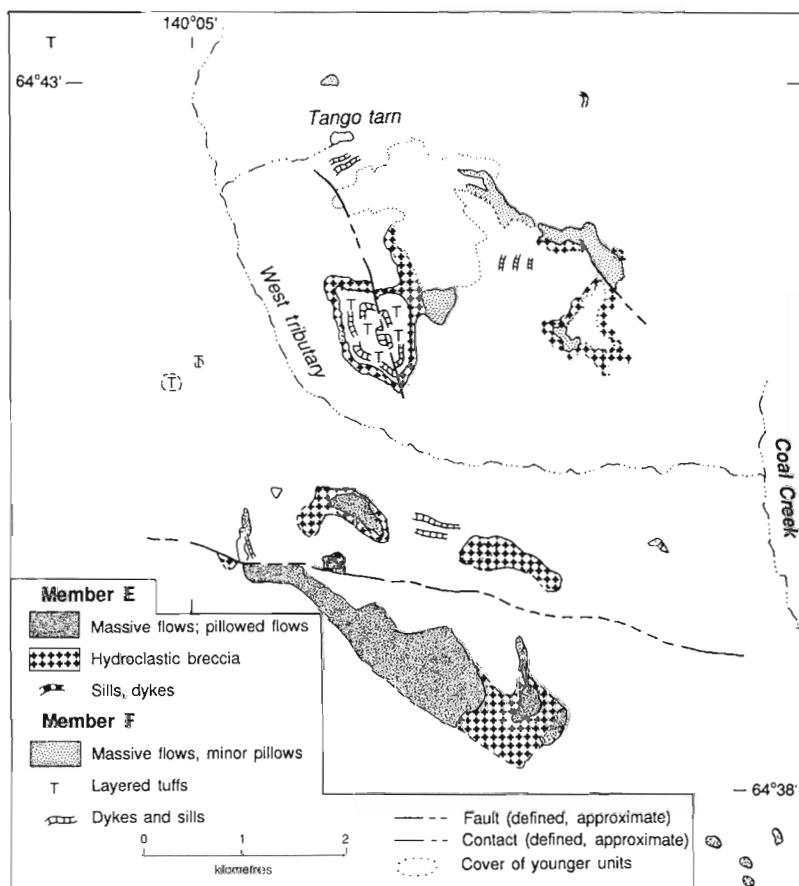
The thickest exposed succession of member E occurs at the south edge of the volcanic complex where remnants reach a thickness of about 200 m. The distribution of these remnants suggests that the flows once covered at least 12 km<sup>2</sup>. The hydroclastic breccia is up to 60 m thick beneath a sedimentary outlier and probably extended over an area of 15 km<sup>2</sup> in the northern part of the complex.

### Lithology

Massive flows are smooth-topped and 10 to 20 m thick, separated by thin or discontinuous layers of recessively weathering flow breccia. In one place the base of a flow reveals fragments of compositionally similar lava, and flow tops are wrinkled and ropy-textured like pahoehoe lava. Vesicles are sparse, except in the upper few metres of some flows, which contain abundant stretched bubbles. Epidote alteration and calcite precipitate are typically concentrated along flow contacts.

Less extensive pillowed flows are up to 20 m thick and associated with hyaloclastite and isolated pillow breccias. The juxtaposition of pillowed and massive flows suggest that pillows formed local accumulations where flows encountered small water bodies. Bulbous and mattress pillows are typically 1 m in diameter, have buds on top surfaces and are not tightly fitted together. Beneath the thin pillow rims are vugs and densely packed vesicles surrounded by bright blue chlorite. Some vugs are filled with celadonite and coloured agate. Breccias containing broken pillow fragments locally drape pillows. Volcanic conglomerate consists of monolithic sub-rounded cobbles.

Hydroclastic breccia (Fisher and Schminke, 1984, Chapter 12) is easily distinguished by delicately shaped black clasts that are prominently displayed in a matrix of blue chalcedony or yellow-green epidote. Clasts are sharply angular and internally fractured. Continuous cliff exposure along ridge spurs reveal how this breccia was formed by progressive disintegration of massive flows. Although a continuous gradation exists, breccia textures are described as 'coarse' and



**Figure 21.**

*Distribution of members E and F in the Mount Harper volcanic complex. Blank space surrounding the patterned areas is exposure of older rocks, except along the southwest margin. See Figure 3 for distribution of all units.*

'fine' end-members. The breccia extends away from and beneath flows, and these end-member types are, in general, proximal and distal facies respectively.

'Coarse' hydroclastic breccia consists of large blocks that are chaotically jumbled together within a matrix of comminuted fragments and former glass shards. Grading laterally over several metres from an intact flow, the breccia fragments themselves are partly disaggregated, and contain incipient fractures (Fig. 20G). Rough layering is revealed by size gradations, typically arranged like foreset bedding, with sloping trains of cobble-sized clasts.

'Fine' hydroclastic breccia consists of angular, 0.5 to 5 cm clasts of aphanitic vesicular and formerly glassy basalt, but includes rare, quartz-phyric, flow-banded siliceous fragments (Fig. 20H). Clasts are poorly sorted but planar cross-stratification and grading to smaller clasts occurs near the top of some of the 0.5 to 2.0 m thick beds.

Subvolcanic intrusions are compositionally correlated with member E. Two outcrops in valley bottoms consist of black, aphanitic rock compositionally similar to member E flows. Although at least 330 m below the lowest gently dipping silicic flows, these resistant exposures contrast with surrounding chloritized flows and breccias of member B. The lack of vesicles and surface flow features, as well as the apparent subcircular extent (contacts are recessive fracture zones) support an intrusive origin. They are considered deeply eroded feeders for overlying member E flows.

Sills that are compositionally related to member E are 5 m thick, massive, orange-weathering, and columnar jointed. They are present within the thick succession of member B flows and breccias north of Tango tarn and southwest of the confluence of the West tributary. Although not recognized as intrusions of member E in the field, they are clearly distinguished from member B rocks by thin section examination.

### **Petrography**

In contrast to basaltic members A and B, flows of member E andesite are extensively crystallized. These flows also lack olivine microphenocrysts and abundant mafic silicate minerals. The flows were generally vesicular, and the cavities are now filled by quartz and secondary clay minerals. In thin section a densely crystalline texture is visible, suggesting advanced cooling and solidification of the flow. This texture is typical of continental flood basalt (e.g. Schminke, 1967).

Intrusive rocks have intersertal texture, consisting mostly of subhedral, tabular, 0.5 to 1 mm long plagioclase (An<sub>40-45</sub>), some amphibole crystals and interstitial devitrified glass (Fig. 14G). Quartz blebs (<1 mm) between plagioclase crystals are probably micro-amygdules. Idiomorphic and skeletal magnetite grains up to 0.3 mm (5%) and minor ilmenite are primary accessory minerals, with minor secondary pyrite.

Pillowed flows have a hyalopilitic groundmass with skeletal, albitized plagioclase (An<sub>10</sub>) that typically forms 1 mm radial clusters. Quartz blebs are arranged in axiolytic nodes suggestive of late stage crystallization as described by Lambert (1974). Iron oxide and dark chlorite obscure most primary textures in the groundmass.

In the sills, stubby plagioclase (An<sub>40</sub> in eight determinations) forms an intergranular matrix, with irregularly shaped grains of yellow-green pleochroic amphibole. Granophyric intergrowth is visible at the edges of some plagioclase, and anhedral quartz occupies interstices.

X-ray diffraction analyses of the dark blue alteration of glassy portions of flows and of shards in hyaloclastite breccia indicate that it is iron-rich chlorite. X-ray diffraction also revealed white fibrous albite and prehnite in vugs within flows of member E.

### **Depositional environment and eruptive style**

The large area covered by the intact flow surface suggests that much of the southern part of the volcanic complex was over-run by lava floods. The fluid lavas spread southward, but north of West tributary the flow tops are not planar. Moreover the thermal quenching that resulted in a hydroclastic breccia apron implies a partly aqueous depositional environment. Thus the north area may have been under water but the lack of diagnostic subaqueous features in the south suggests that the flood-flows could have been subaerial.

### **Member F**

#### **Definition, distribution, contacts, and structure**

The youngest volcanic rocks in the Mount Harper complex include mafic to intermediate massive and pillowed flows, breccias, and tuffs, as well as compositionally similar dykes and sills. They weather orange to brown and have a diabasic texture. The intergrowths of feldspar crystals are best revealed by weathered, etched surfaces. Intrusions of member F physically resemble those of member B (except that they contain minute quartz amygdules), but chemically are closely related to member E. Although many outcrops in the complex can be mapped by their appearance from a distance, chemical analysis is required to identify rocks of member F.

The distribution of the known member F is shown in Figure 21. Member F flows form a resistant ridge-capping layer at least 200 m thick on the north side of West tributary where it overlies member B flows and hydroclastic breccia of member E. Columnar-jointed diorite sills 2 to 10 m thick south of the Tango tarn (sample F126-3, 5) intrude a succession of member B flows. A pillowed flow of member F (sample F121-10) lies within sediments of the upper Mount Harper Group. Farther east, the same flow overlaps an older surface of chloritized pillows of member B. Clearly the flow was extruded during deposition of the upper Mount Harper Group, and can be interpreted as an invasive flow (Wright et al., 1973) that intruded unconsolidated sediment.

### **Lithology and petrography**

Flows are planar, locally columnar jointed, 2 to 7 m thick and locally contain ellipsoidal vesicles concentrated near the top. Some flows are pillowed, consisting of short, thick tubes (60-80 cm diameter) that locally contain drainback cavities and shelves.

The rock is fine- to medium-grained, locally seriate and plagioclase-phyric (1-2%), with visible augite. Most flows contain vugs filled with quartz or celadonite amidst projecting plagioclase laths (Fig. 14H; called diktytaxitic texture (Williams et al., 1955) and suggest of high volatile content in the lava at the time of extrusion). One flow (sample F121-10) contains tabular plagioclase partly altered to clay, with uraltized subophitic pyroxene and 5 to 15% interstitial quartz in thin section. Some feldspars have albite twins (An<sub>10</sub>). Moderately pleochroic, ragged-edged crystals with parallel extinction are probably biotite.

Tuffs are recrystallized, partly silicified and rendered bluish by chlorite alteration. They are distinguished from granular flows by broken crystals of feldspar (10%) and quartz (1%). Most also contain fragments of broken lava and altered glass shards. Subtle layers 30 to 120 cm thick are distinguished by grain size variations (ash- to medium lapilli-size) and the relative proportion of chlorite to sericite in the matrix.

Dykes (typically 5-7 m wide) and sills (up to 10 m thick) have grey-green fresh surfaces and are mostly fine grained. Some medium grained cores display 1 mm spots that are probably altered pyroxene. Thin sections show equant plagioclase in subophitic clusters around birefringent pyroxene with interstitial opaques (probably titanomagnetite). The largely indistinguishable matrix contains areas of patchy sericite and micro-amygdules of quartz.

### **Depositional environment**

Member F flows intrude sediments of the upper Mount Harper Group and overlap the eroded member B edifice. This phase of volcanic activity therefore occurred after sedimentary deposition resumed atop of the volcano, perhaps resulting from continued subsidence of the graben feature.

Flows were probably erupted into shallow water or air because abundant ash was also produced. The lateral continuity of the underlying hydroclastic tuff and tabular nature of the flows suggest gently sloping terrain and shallow depressions. The lack of clasts larger than pebble size in beds stratigraphically above member F imply regional low relief. The wide distribution of north-trending dykes implies concomitant east-west extension.

### **Geochemistry of the volcanic rocks**

Whole rock analyses of 106 rock samples were used to determine the original nature of the volcanic rocks and to characterize the composition of the volcanic complex. The results support field evidence for two magmatic suites: members A and B whose composition is fairly uniform, and members D and E which, despite their andesite-rhyolite

dichotomy, are similarly enriched in large-ion lithophile (or incompatible) elements. Although all samples are altered it is clear that physical differences that allowed members to be distinguished in the field extend to their chemistry. These distinctions provide clues to the magmatic evolution and tectonic setting of the Mount Harper volcanic complex.

## Sampling and results

Representative stratigraphic and spatial coverage of the Mount Harper volcanic complex was gained through selected 2 to 4 kg samples of massive flows and intrusions. Members A, B, D, and E were recognized in the field and samples taken from the least fractured and altered outcrops. Member C, which consists mostly of breccias, was not sampled. Member F has a distinct chemical signature in addition to a characteristic petrographic texture, but was less adequately sampled than other members. The possibility of creating a bimodal compositional suite through sampling bias was reduced by selection of rocks that appeared andesitic. Variation with stratigraphic height was investigated by systematically sampling three sections.

The composition of representative samples from members A, B, D, E, and F are shown in Figures 22-24 with complete analyses in Appendix 2. Notwithstanding alkali metasomatism, no samples from the Mount Harper volcanic complex are peralkaline (all contain molar  $\text{Al}_2\text{O}_3 > [\text{K}_2\text{O} + \text{Na}_2\text{O}]$ ); all are hypersthene-normative and most contain normative quartz (normative mineralogy is in Appendix 2). Four samples (two basaltic dykes and two flows) from member B contain normative olivine, but none contain normative nepheline.

Histograms for all samples (Fig. 22) show that the volcanic members have distinct chemical signatures. Members D and E have lower MgO and  $\text{Cr}_2\text{O}_3$ , as well as higher  $\text{SiO}_2$ ,  $\text{K}_2\text{O}$ , Nb, Y, and Zr than the lower members. Members D and E are hereafter called the Upper suite, while members A and B comprise the Lower suite. Member F, which intrudes unit PH<sub>1</sub> (upper Mount Harper Group) and postdates member E, comprises flows which resemble those of member B, but has Mg, Zr, and other incompatible element contents that are intermediate between the Upper and Lower suites.

Compositional variation with stratigraphic height occurs in the Lower suite beneath Mount Harper (section 6, Appendix 1, Fig. A1-8). The most significant trend in member A is that (Mg number =  $\text{MgO}/(\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3)$ ) decreases (from 54 to 38, in nine flows over 370 m stratigraphically) with height in this section (Fig. 23A). The depletion suggests olivine crystallization depleted magnesium from later lavas. Figure 23A also shows decreasing magnesium-to-iron ratios and  $\text{Cr}_2\text{O}_3$  upward in member A. The MnO and CaO values decrease sympathetically in successively erupted flows of member B. In this section (and other sections through the volcanics that were sampled for compositional variation; Roots, 1987), Nb and Y remain fairly constant throughout the stratigraphy. Other variation in element oxides probably resulted from dilution by secondary minerals, addition or depletion by alteration fluids, inhomogeneous concentrations of phenocrysts, or a combination of these.

The early flows of member A are chemically distinct. The lowest sample (A128-1) has the highest  $\text{TiO}_2$ ,  $\text{P}_2\text{O}_5$ , Nb, Rb, Sr, Y, and Zr contents in the Lower suite. The second flow above the base of the complex (sample A128-2) has the highest magnesium-to-iron ratio and  $\text{Cr}_2\text{O}_3$  content.

The boundary between members A and B in the sampled sections corresponds to a gradual rather than sharp change in composition. In general, flows of member B above the contact are lower in  $\text{TiO}_2$ , MnO,  $\text{P}_2\text{O}_5$ , and Zr than those of member A beneath it. Oxidized flows are enriched in  $\text{Na}_2\text{O}$  and  $\text{Fe}_2\text{O}_3$ , and correspondingly depleted in CaO and MnO.

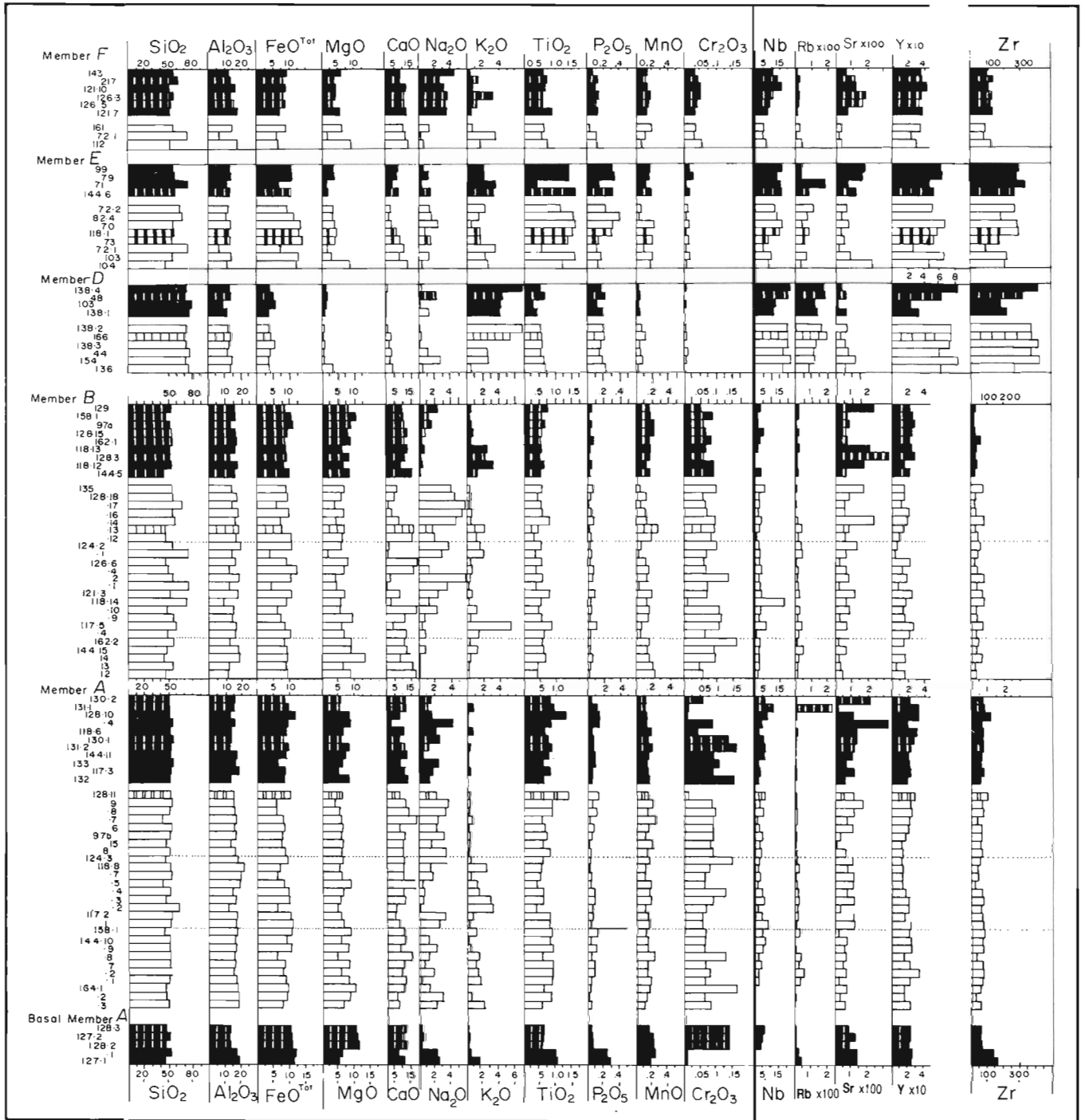
In order to investigate differences between volcanic members, samples were classified according to their chemistry. The least altered flows were initially used to define the chemical character of each member, principally by their characteristic Zr and  $\text{TiO}_2$  contents. The Upper suite is enriched two to three times over the Lower suite and on a Zr: $\text{TiO}_2$  diagram (Fig. 23B) samples of member A form a line of positive slope, and most of those in member B have a Zr content lower than 50 ppm.

Among the major elements, the distinction between the Upper and Lower suites is best shown by the alumina content and the magnesium-to-iron ratio (Fig. 23C). The Mg# provides a relative estimate of the extent to which a basaltic magma has evolved (e.g. Cox et al., 1979); primary magma derived from the lower crust or mantle is estimated to have Mg# = 65 (Basaltic Volcanism Study Project, 1981, p. 418). The lowest flows of member A are Mg# = 54, which is a relatively primitive value. Members A and B occupy a diffuse field with Mg# = 35-55 and 14-18%  $\text{Al}_2\text{O}_3$ , which are typical values for oceanic basalt such as MORB (mid-ocean ridge basalt; 15.4%  $\text{Al}_2\text{O}_3$ ; Bryan and Moore, 1977) and OIT (ocean island tholeiite; 14%  $\text{Al}_2\text{O}_3$ ; Macdonald and Katsura, 1964). In contrast, samples from members D and E, with Mg# = 18-32, have 10-13%  $\text{Al}_2\text{O}_3$ , in the range of CFB (continental flood basalt; 13.4%  $\text{Al}_2\text{O}_3$ ; Goldich et al., 1967) and continental rhyolite. Thus the compositional range of the volcanic complex encompasses a range of rock types and does not fit neatly into a single volcanic setting.

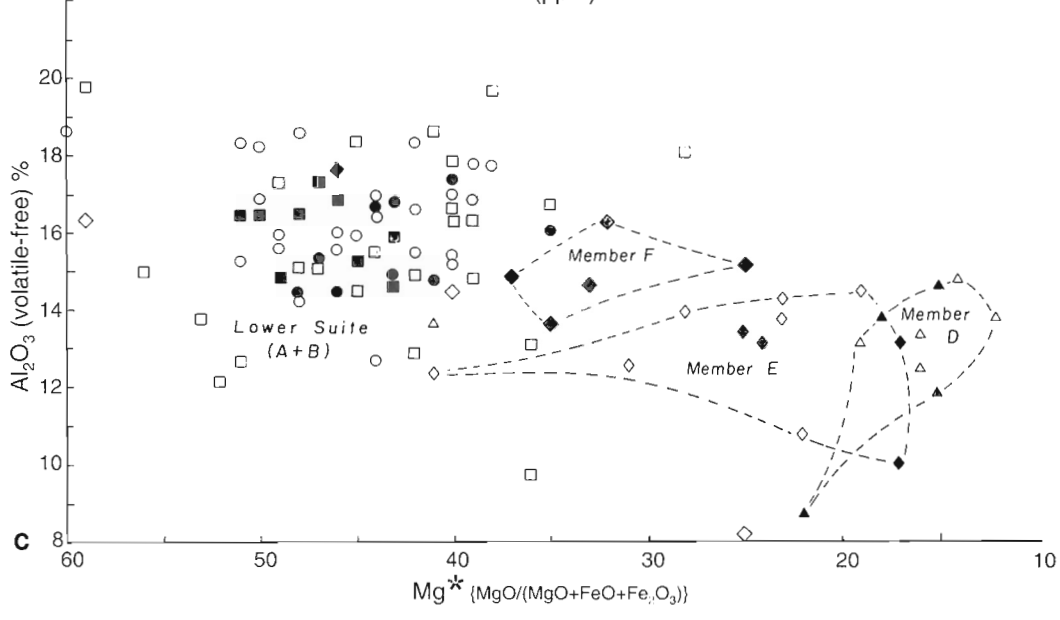
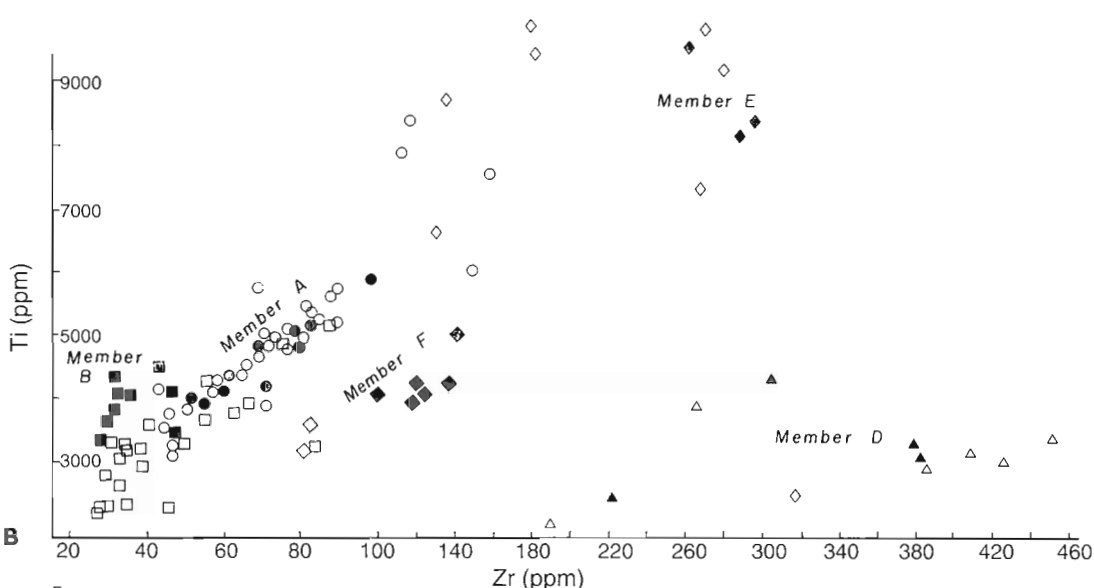
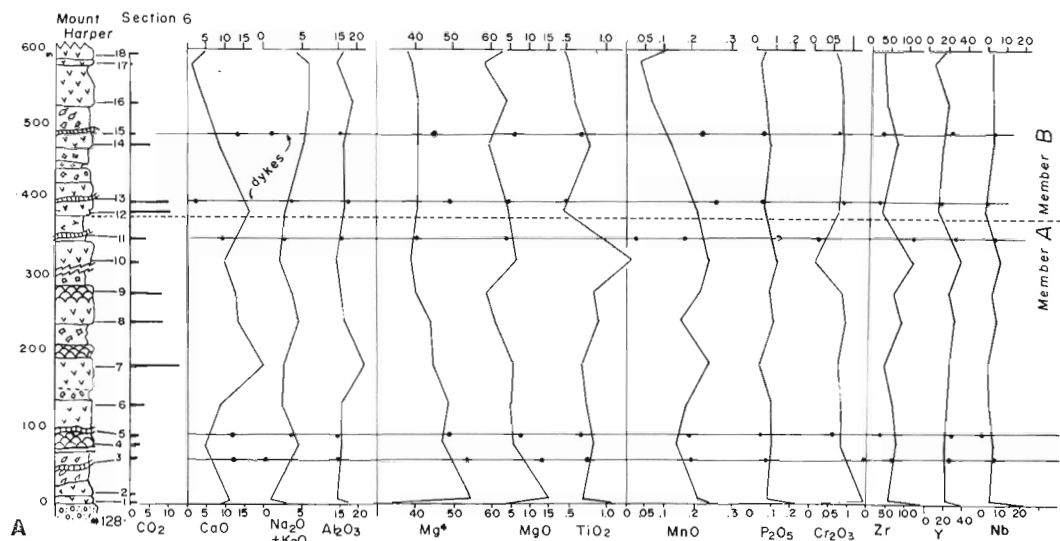
## Alteration

In any study of ancient volcanic rocks, chemical variations resulting from alteration during and after emplacement must be estimated before primary compositional variations, whether in comparison with other volcanic suites or within the complex, can be determined. Igneous rock in contact with water and hydrothermal fluids has little chance of retaining its primary composition, and these changes are likely to be nonuniform throughout a particular rock unit. Strongly altered rocks, which typically crumbled in the field, were not analyzed.

All volcanic rocks of the Mount Harper complex are altered and contain varying amounts of low grade metamorphic minerals. Glassy portions of mafic and felsic rocks have crystallized to fine grained quartz and feldspar. Phenocrysts in basaltic rocks are pseudomorphed by various minerals.



**Figure 22.** Histogram of the whole-rock composition of all samples from the Mount Harper volcanic complex. The solid bars represent samples selected for the least altered set (against which analyses from other igneous centres are compared); striped bars indicate dykes and sills (assigned to members on the basis of Ti:Zr contents; Fig. 23B). Sample numbers are in left hand column, and analyses of members A and B (prefixed 118-, 128-, and 144-) are arranged in stratigraphic order and dotted horizontal lines indicate the top of the unit in each section. Oxides SiO<sub>2</sub> through Cr<sub>2</sub>O<sub>3</sub> are in normalized weight per cent; other elements in parts per million.



In mafic rocks, olivine has been completely replaced by quartz and hematite (Fig. 14C, D), and plagioclase microphenocrysts are replaced by clay minerals. Prismatic crystals in the groundmass are albitized and filled with hematite specks. The matrix of maroon flows is obscured by hematite, and some vesicles, unavoidably included in analyzed samples, contain chlorite and prehnite. Andesitic flows of member E consist of sericitized plagioclase, and interstices between crystals are filled with quartz.

The freshest felsic rocks are cherty, and thin sections reveal the formerly glassy groundmass consists of cryptocrystalline silica and sericite. Feldspar phenocrysts are cloudy, obscuring primary characteristics such as twinning. Some quartz phenocrysts are partly resorbed, but fringes of secondary quartz (Fig. 14E) and spherulites suggest silicification.

Although the type of alteration depends upon the original composition of the rocks and that of the permeating fluids during burial and metamorphism, its intensity appears to reflect primary porosity. Thin, vesicular flows and fractured interflow zones are visibly more altered than cores of thicker flows, sills, and dykes. Quartz veins are rare and no defined alteration zone or hydrothermally altered rock was encountered to indicate an underlying intrusion. Alteration around dykes and sills is confined to sheared contacts. Principal alteration effects suggested by petrography and chemistry are hydration, carbonatization, iron oxidation, and sodium-potassium metasomatism.

Hydration products in the mafic rocks are mostly chlorite (13 wt.% H<sub>2</sub>O) and sericite (about 9 wt.% H<sub>2</sub>O; Deer et al., 1966) that constitute from 5% in some diabase dykes of member B to 35% (volume visually estimated in thin sections) of poorly crystallized, formerly glassy and devitrified pillows at the base of member A. In contrast, felsic flows of the complex contain only slightly more water than is normally present in fresh rhyolite.

Many mafic lavas in modern rift zones are water-rich (up to 3.5%; Bailey, 1974). The saturation or migration of water trapped within the volcanic pile may have resulted in pervasive internal alteration during cooling, rather than reflecting a regional metamorphic event. Lithic clasts in conglomeratic sandstone of the overlying upper Mount

Harper Group contain subisotropic basaltic glass and fresh plagioclase microlites, implying that alteration was more pronounced within the complex than in the surrounding region.

Carbonatization is indicated by calcite replacement of mafic minerals and patches of matrix in many altered samples. Although medium grained diorite has both high CaO and high MgO, indicating abundant augite, other samples show a positive correlation between CaO and CO<sub>2</sub> that suggest microscopic calcite is present.

Normally stable elements such as Ti, P, Zr, Y, and Nb are variably depleted from some hydrated basalt. Murphy and Hynes (1986) suggested that these elements were mobile under low CO<sub>2</sub> partial pressures during regional metamorphism. Their mobility would be indicated by formation of metasomatic minerals such as titanite, which release CO<sub>2</sub> (Mason, 1980). Mobility in the Mount Harper volcanic rocks is unlikely because titanite is lacking and the concentration of most incompatible elements is uniform despite the degree of apparent alteration in samples from the same member.

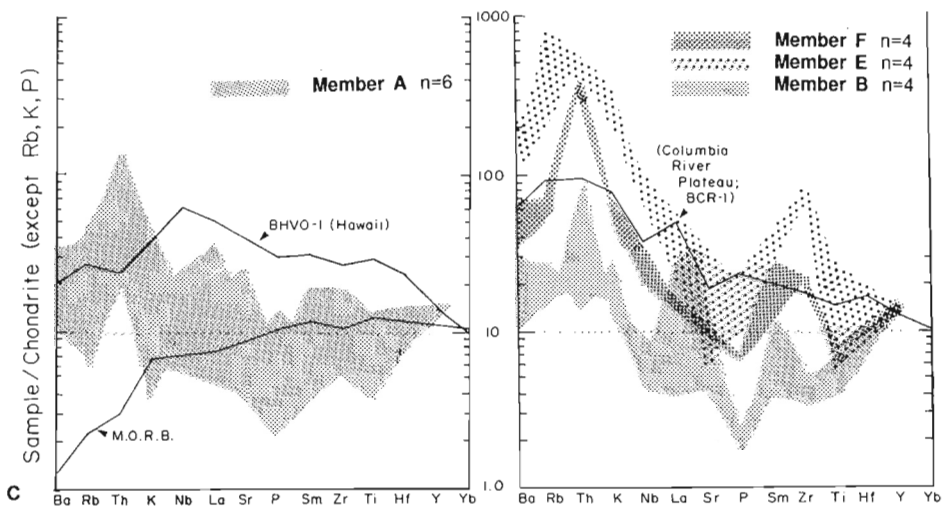
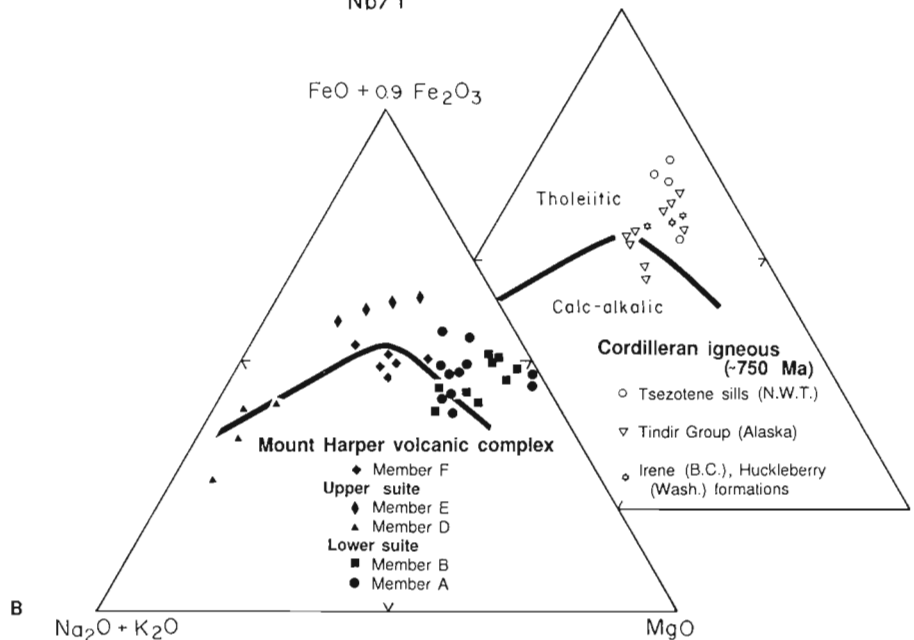
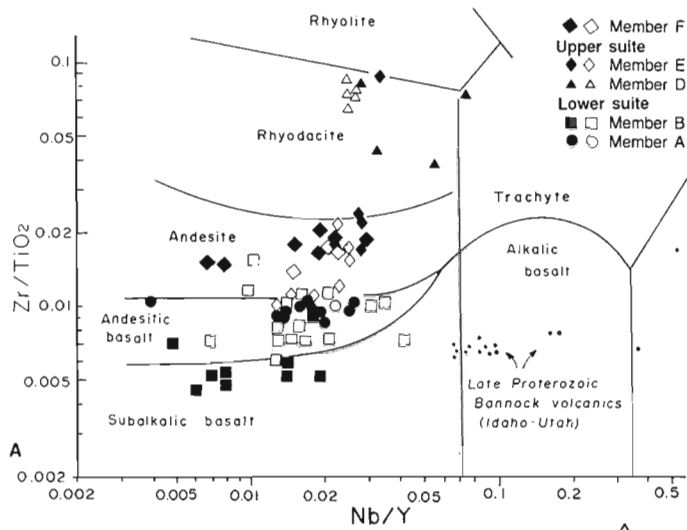
Iron oxidation of Lower suite rocks occurred during emplacement and weathering of some lavas (hematized facies) and also during secondary mobilization. Interstitial hematite is present in massive flows associated with highly vesicular breccias and lapillstone that were probably subaerially erupted. Both synvolcanic hematite formation and secondary coatings on minor pyrite and in amygdules were described by Brunet (1986).

Lower suite samples containing chlorite exhibit normal proportions of ferrous and ferric iron [ $\text{FeO}/(\text{FeO}+\text{Fe}_2\text{O}_3) = 0.7-0.8$ ], in comparison with ocean and continental basalt. Hematized rocks contain up to five times more Fe<sub>2</sub>O<sub>3</sub> than FeO, but indicate no marked increase in total iron content. However, iron oxidation is a visible indication of element mobility, because flows rich in hematite have higher Na<sub>2</sub>O as well as lower K<sub>2</sub>O, CaO, Sr, and Rb contents than chloritized basalt of the same member.

Sodic and potassic metasomatism is the major process which affected these volcanic rocks. It has different effects in mafic and felsic samples. Although some hematized basalt samples are sodic (up to 5.8% Na<sub>2</sub>O), most are below the average Na<sub>2</sub>O content for unaltered basalt. Several hematized basalt samples are below the detection limits in both Na<sub>2</sub>O and K<sub>2</sub>O (0.5% and 0.05% respectively).

Felsic rocks are also depleted in Na<sub>2</sub>O but are enriched in K<sub>2</sub>O (up to 7%) relative to fresh rhyolite from the Mount Harper volcanic complex. Potassic alteration is commonly noted in ancient felsic rocks (e.g. Annells, 1974; Reichenbach, 1986). Secondary potassium enrichment of seafloor rhyolite leads to K-feldspar+hematite+quartz+illite-montmorillonite assemblages (Munha et al., 1980). Sheppard and Gude (1968) described rhyolite tuff converted to K-feldspar by diagenesis in saline lake beds and cited experimental work that also suggests that under saline conditions silicic rocks devitrify to zeolites and K-feldspar rather than clay minerals. Possibly the felsic rocks at Mount Harper were altered in similar fashion during diagenesis by infiltration of

**Figure 23.** A) Compositional variation with stratigraphic height for volcanic members A and B along reference section 6, near Mount Harper (described and illustrated in Appendix 1, with analyses in Appendix 2, prefix 128-). The upward lines connect data points for sampled flows; oxide concentrations in intrusions are indicated by dots connected by horizontal lines. B) Titanium:zirconium diagram showing all sampled volcanic rocks; solid symbols indicate analyses selected for the less altered set. See Figure 24A for symbols legend. C) An Al<sub>2</sub>O<sub>3</sub>:Mg\* diagram for all sampled volcanic rocks; solid symbols indicate less altered set. Note that the field for member F lies between those of the Upper suite (members D and E) and the Lower suite.



waters from the overlying marine basin of the upper Mount Harper Group. Andesitic flows have also lost  $\text{Na}_2\text{O}$  and may contain secondary  $\text{K}_2\text{O}$  formed under similar conditions.

Silicification has not noticeably affected the Mount Harper volcanic complex. Several samples of member E, however, have a low  $\text{Al}_2\text{O}_3:\text{SiO}_2$  ratio relative to normal rock types. Chloritized basalt, and samples containing interstitial quartz blebs, are not significantly different in  $\text{SiO}_2$ , which suggests that the visible quartz formed from breakdown of within-rock constituents. Replacement of delicate primary minerals by secondary minerals indicates that little volume increase occurred during alteration.

Rift-related volcanic rocks are notoriously difficult to classify because of the variety of secondary alteration effects that may be superimposed on a wide compositional range of primary magmas. For comparison with other extension-related igneous suites, and to make relative estimates of the type and degree of alteration, a subset of the Mount Harper analyses was selected. Hereafter known as the less altered set, these samples were selected on the basis of low volatile contents. Samples with low ferrous iron [ $\text{FeO}/(\text{FeO}+\text{Fe}_2\text{O}_3) < 0.6$ ] or abnormal  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  are excluded. Strict limits on maximum volatile content could not be applied without excluding all samples from some members because all mafic rocks have been hydrated at least a small amount. The samples selected for the less altered set are indicated in Appendix 2.

Figures 22, 23B, 23C, and 24A show that the less altered set provides both a more homogeneous group within each member, and more clearly distinguishes differences between members. Although all samples are altered, some primary

mineralogical and chemical features have not been obliterated, and study of the less altered set is useful to assess magmatic trends within the volcanic complex.

### Deductions of primary composition

The  $\text{Zr}/\text{TiO}_2 : \text{Nb}/\text{Y}$  diagram (Fig. 24A) illustrates that members A and B are subalkaline basalt to andesitic basalt, member D is rhyodacite, and members E and F are andesites. An alkalic chemical suite is not indicated, in contrast to volcanic rocks related to the Windermere Supergroup in Utah and Idaho (Harper and Link, 1986).

On the AFM diagram (Fig. 24B), the less altered samples of the Lower suite fall in both the calc-alkalic and tholeiitic fields, but both the andesite and rhyolite samples of the Upper suite are clearly tholeiitic. The apparent iron enrichment of member E actually represents magnesium depletion because these later flows contain few mafic minerals. Member E is compositionally most similar to other Late Proterozoic, Windermere-related igneous rocks (Fig. 24B).

Despite their different rock types and major element contents, members D and E are similarly enriched in large-ion lithophile elements (Ba, Rb, Th, etc.; see Fig. 22). The high Zr and  $\text{K}_2\text{O}$ , as well as similar Nb and Y contents imply a genetic relationship between the two members. Temperature or mineral density gradients could have resulted in felsic extrusions from the upper part and andesite flows from deeper levels of a differentiated magma chamber.

Chondrite-normalized, incompatible element abundance diagrams (spidergrams) are used to gain insight into the original or parental composition of mafic rocks, because these elements tend to remain in the magma while early-crystallizing mineral phases settle out (Thompson et al., 1983). Figure 24C shows patterns for the mafic and intermediate members of the Mount Harper volcanic complex, based upon samples representative of the least altered composition. Members A and B have similar patterns that approximate those of typical ocean island volcanic suites, such as Hawaii. In contrast, member E (and a similar pattern for member D; not depicted) is enriched in the large-ion incompatible elements, and produce a spidergram pattern similar to continental volcanic suites, such as the Columbia River basalt.

Although rocks of member F physically resemble those of member B, they are separated from the Lower suite by the time span of member E volcanism. Furthermore, member F samples are more evolved ( $\text{Mg}\# = 25$ ) than the Lower suite; they contain a low proportion of mafic minerals and have enriched contents of Rb, Th, K, Na, Sm, and Zr, similar to member E. The concentration of large-ion lithophile elements in samples of member F is midway between the higher concentrations in Upper suite samples and the lower concentrations present in the Lower suite. Member F may have resulted from mixing between a relatively primitive magma (similar to that which fed the Lower suite) with an evolved magma (such as that which produced member E). Repeated extensional faulting and an additional magma pulse could have promoted eruption of member F.

**Figure 24.** Comparison of the composition of the Mount Harper volcanic complex with selected igneous suites from other areas: **A)**  $\text{Zr}/\text{TiO}_2:\text{Nb}/\text{Y}$  diagram (Winchester and Floyd, 1977) for all sampled rocks from the Mount Harper volcanic complex; solid symbols represent the least altered set. Dots in the alkali basalt field represent Late Proterozoic volcanic rocks sampled in Idaho and Utah (Harper and Link, 1986). **B)** Alkalis:iron:magnesium (AFM) diagram with line separating calc-alkalic from tholeiitic fields from Irvine and Baragar (1971), showing the least altered set from the Mount Harper volcanic complex and contemporaneous Cordilleran igneous rocks, from Armstrong et al. (1982; Tsezotene), Young (1982; Tindir), and Devlin et al. (1985; Irene/Huckleberry). **C)** Chondrite-normalized ( $Y_n=15$ ) incompatible element abundance diagrams (spidergrams: Thompson et al., 1983) showing fields that enclose samples selected from each mafic member of the Mount Harper volcanic complex. For comparison are spidergrams for standards from N-type mid-ocean ridge basalt and oceanic island basalt (BHVO-1; Hawaii, from Sun and McDonough, 1989) as well as continental flood basalt (Columbia River Plateau, BCR-1, Abbey, 1983). Note also that member F lies midway between the fields of members B and E.

In summary, at Mount Harper the following changes in magma types are inferred from the succession of Lower suite lavas, followed by Upper suite and Member F extrusions:

1. comparatively primitive (high Mg#) to evolved (low Mg#) magmas;
2. overall increase in silica-saturation (olivine basalt to andesite); and
3. increase in elements such as Zr, Y, Nb, Rb, and P<sub>2</sub>O<sub>5</sub>.

Initial extrusions (member A), high in Al<sub>2</sub>O<sub>3</sub>, constructed a thick pillowed section, suggestive of oceanic character, whereas final flows of member E which are low Al<sub>2</sub>O<sub>3</sub> but contain higher TiO<sub>2</sub>, resemble continental floods.

### Probability of crustal contamination

Lower suite flows at Mount Harper resemble most volcanics erupted in a continental rift setting. These flows are relatively primitive in terms of magnesium:iron ratio and contain low concentrations of elements typically abundant in Earth's crust. They are therefore considered to have been derived from a deep, possibly upper mantle source. It is difficult to assess the possibility that the magma assimilated crustal rocks, because the nature of crystalline basement beneath the Ogilvie Mountains remains unknown.

Two indications that the composition of Upper suite flows has been influenced by the crust are: 1) the presence of garnet in one rhyolite flow, and 2) probable inherited zircon. The garnet xenocrysts may have been carried from middle or lower crustal depth, as suggested by Pallister (1987) for a Miocene complex with similar chemistry and tectonic setting. Partial melting of garnet-bearing rocks could have supplied the Upper suite magma with incompatible element concentrations similar to typical crust. Secondly, one of the zircon crystal fractions selected for isotopic dating (analysis 86-3; see Roots and Parrish, 1988) is thought to contain older zircon (relict grains derived from older crust) which resulted in an older age than that of the Mount Harper complex. Although crustal influence cannot be proven, these indications show clearly that compositional variation in the Mount Harper volcanic complex resulted from many processes, and is masked by low-grade metamorphism and alteration.

### Conclusions

The Mount Harper volcanic complex includes six members. The oldest three are basaltic and record the growth of a subaqueous to subaerial volcano. These were succeeded by rhyolite domes, andesitic lavas, and diabasic intrusions. The Mount Harper Group accumulated in a broadening rift basin that may have been earlier than, or coeval with, continental separation that eventually formed the divergent western margin of cratonic North America. At this site extension did not continue and no oceanic crust was produced.

The evolution of the Mount Harper volcanic complex is deduced from the sequence and composition of the volcanic rocks that also allows inferences to be made about underlying structural and magmatic processes. Interpretation of the

geological record, however, must be tempered according to the type and quality of deposits that are preserved. Although a continuously subsiding rift environment affords excellent preservation potential, subaqueous deposits are more likely to be preserved than are unconsolidated, subaerially erupted rocks such as pyroclastic ejecta. Furthermore, inferences about types of volcanic activity are dependant on deposits that vary in volume and likelihood of preservation. Phreatomagmatic eruptions, for example, produce huge volumes of subaqueous breccia from relatively small vents; the physical abundance of these deposits belie the brief activity that caused them when compared to the life of the volcano (see Ayers, 1982). Similarly, the products of a brief catastrophic eruption could have been greater in volume, or wholly destroy the thinner accumulation of a longer and more significant time period.

The Harper Fault could have triggered volcanism by penetrating to great depth. The causal relationship between faulting and volcanism is suggested by their coeval activity and the location of the volcanic complex at the west end of the Harper Fault. The initial basaltic composition of the magma implies its mantle derivation although the first extrusions had a higher lithophile element content than later flows, perhaps as a result of contamination during ascent or a lesser degree of partial melting at its source.

The interpretations below summarize the stratigraphy, structure, and chemistry of the Mount Harper volcanic complex. The geological evolution of the volcanic centre has two stages, which begin after faulting and deposition of the lower Mount Harper Group sediments. These are: 1) seamount and island basalt volcanism (Lower suite); followed by 2) felsic and andesitic subaerial volcanism (Upper suite). These stages are summarized according to a) depositional record; b) structural regime; and c) magmatic evolution.

### Stage 1: seamount and island volcanism (Lower suite)

#### *Depositional history*

Basaltic volcanism constitutes four phases at different vents in the area which varied in duration and were not synchronous. The earliest highly fluid flows overlapped submerged clastic fans and formed subaqueous shields of tubular pillows, breccia, and aquagene tuff (member A). Pillowed units 200 m thick that comprise the base of the western part of the complex were erupted later than those in the east.

The second eruptive phase consisted of shallow water effusions that produced flows and cobble breccias resulting from their disintegration (chloritic facies of member B). These eruptions were probably from broad vent areas (indicated by concentrations of dykes) and large blocks in nearby breccia that suggest the vents were periodically choked by lava rubble.

In the third phase, Surtseyan eruptions are implied by the presence of lapillistone, vesicular pillows, and breccia (member B). Explosive activity in shallow water, and rapid erosion of emergent deposits resulted in broad subaqueous platforms around vents.

The fourth phase of activity produced aa flows, agglomerate, and cinder-like lapilli (hematitic facies of member B). Vulcanian and Strombolian eruptions inferred from these deposits produced short-lived volcanic islands from subaerial vents. Lavas that flowed into water were transformed into large pillows, hyaloclastite, and breccia containing hematized clasts.

The maximum height and shape of the volcanic edifice is unknown because it underwent erosion concurrent with volcanism. Volcanic conglomerate and breccias (member C) represent mass wasting and explosive eruptions.

### *Structural regime*

The earliest known flows are located several kilometres north of Harper Fault, suggesting extrusion began on the floor of the half-graben. The subaerially deposited conglomerate is overlain by thick pillows lava successions, indicating subsidence during volcanism. Islands were formed when volcanic accumulation outstripped the rate of subsidence, but preservation of lithified cinder attests to rapid subsidence and burial of the extrusive rocks. Toward the end of Lower suite volcanism, two contrasting depositional regimes began. The area south of West tributary was uplifted, possibly as a result of inflation of the volcanic structure by sills, whereas the northern part subsided, forming the initial basin of upper Mount Harper Group deposition.

### *Magmatic evolution*

The Lower suite lavas were derived from a primitive basaltic parent magma which evolved by fractionation of olivine. Early flows were glassy; later flows contain plagioclase, pyroxene, and magnetite. The higher proportion of breccias and greater thickness of later flows could have resulted from the increasingly crystallized magma, with higher viscosity and reduced supply rates. Explosive eruptions occurred in shallow water from exsolving gases or mixing with steam, and subaerially erupted flows and breccias became oxidized.

## **Stage 2: bimodal volcanism (Upper suite)**

### *Depositional record*

Thick rhyolite flows (member D) were extruded unconformably over basalt in the southern part of the complex. Arkosic sediments, crystal tuff, and a single ash flow occurrence at the contact indicate initially explosive eruptions. Thick flows and possible domes appear to have been subaerial. They were covered by andesitic flood lavas (member E) that flowed east and southeast. Large vesicular pillows suggest the presence of shallow pools, but flows also disintegrated in larger water bodies, forming a hydroclastic breccia apron. The water body into which the upper Mount Harper Group was deposited covered the northern part of the volcanic complex and contained debris flows derived from both volcanic and uplifted carbonate sources. The upper Mount Harper Group succession represents increasing depth and low energy conditions.

### *Structural regime*

The contrast in depositional record between the north and south parts of the complex could have resulted from topographic relief. The high-standing southern area may have been inflated by sills, the rise of Upper suite magmas, reactivation of Harper Fault, or a combination of these. Along the projected trace of Harper Fault are silicic dykes and inferred vents for member E, suggesting that the fault may have continued to focus rising magma. The northern area was at that time below water level. The distribution of hydroclastic breccia north of the member E flows from which they were probably derived, indicates a topographically high-standing area near Harper Fault.

### *Magmatic regime*

A dormant period following Lower suite volcanism is indicated by unconformities and intercalated sedimentary intervals. Initial explosive eruptions of the Upper suite consisted of volatile-rich rhyolite probably derived from the upper part of a shallow differentiated magma chamber. Fissure-erupted felsic flows (member D) and andesitic floods (member E) have similar incompatible element abundances and may have differentiated from the same magma. The final pulse (member F) produced pyroclastic eruptions and emplaced sills. Its composition implies that a new batch of relatively primitive magma might have mixed with Upper suite magma.

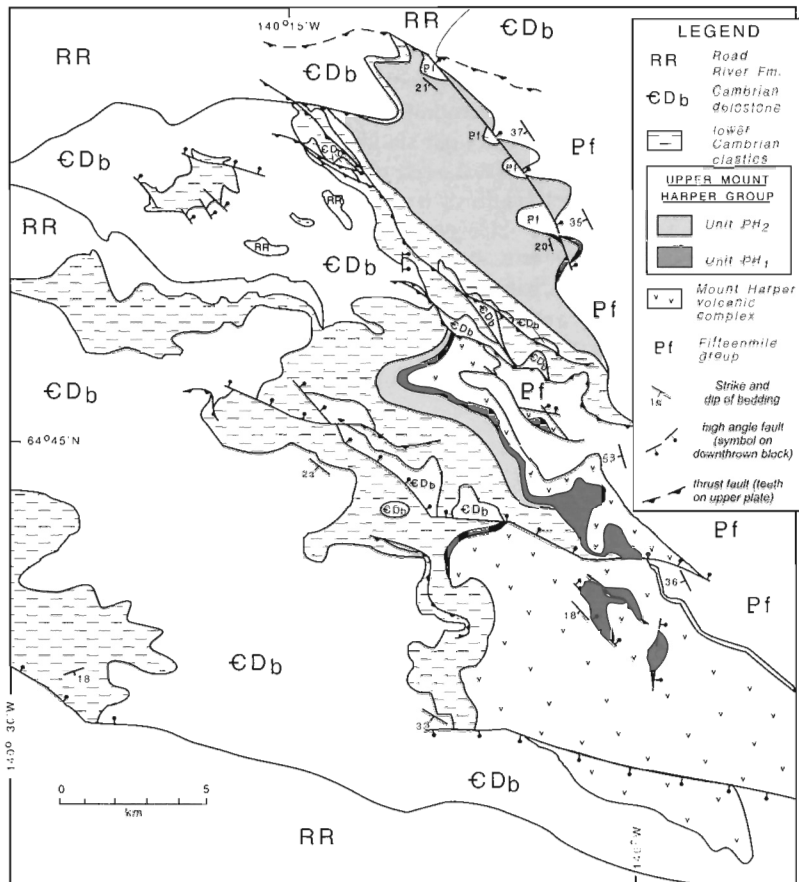
Most of the Mount Harper volcanic complex is considered the product of a single igneous pulse (member F could have been a late minor resurgent phase). Relatively primitive early flows ascended directly, while later magmas, less extensive than those of the Lower suite, crystallized and ascended more slowly. Upper suite magma may have originated in the middle or lower crust, or assimilated crustal rocks.

## **UPPER MOUNT HARPER GROUP**

The upper Mount Harper Group is a conglomerate-dominated sedimentary succession with a maximum preserved thickness of about 400 m. Two mappable units are recognized (PH<sub>1</sub> and PH<sub>2</sub>, Fig. 25, simplified from Fig. 3). Descriptions of these units have not been published previously, hence more detail is presented here than for the lower Mount Harper Group.

### *Bounding contacts*

The upper Mount Harper Group generally dips 20-30° southwest, and overlies more steeply dipping 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 paleorelief. No breccia is preserved on the unconformity surface, but the upper few metres of the underlying dolostone commonly is heavily fractured, with some vertical and horizontal fractures lined or



**Figure 25.**

*Simplified geology of the upper Mount Harper Group (modified from Mustard, 1990). See Figure 3 for detailed geology of the outcrop areas north and west of the Mount Harper volcanic complex.*

filled by both chert and dolomite, inferred to reflect subaerial exposure and erosion of the Fifteenmile group dolostone prior to upper Mount Harper Group deposition.

Constraints on the original depositional extent of the upper Mount Harper Group are limited. The most northerly exposures have been thrust northeast during Mesozoic compression over Cambrian to Devonian strata, so that the original northern limit of the basin (if preserved) is not exposed. The PH<sub>2</sub> conglomerate thins markedly from northeast to southwest. In addition, except in the area immediately east of Mount Harper, the lower Mount Harper Group is disconformably overlain by unit €Db. The eastward-thinning of units, lack of lower Mount Harper Group clasts in conglomerate of the upper Mount Harper Group, and lack of upper Mount Harper Group strata above the lower Mount Harper Group, together suggest that the upper Mount Harper Group basin did not continue far to the east of present exposures. High-angle faults (probably Mesozoic) define the southern limit of exposure of the upper Mount Harper Group. Rocks immediately south of the faults are €Db dolostone or clastics of the Ordovician to Devonian Road River Formation. The upper Mount Harper Group is absent adjacent to the southern faults, where map unit PC<sub>3</sub> (probably early Cambrian age) disconformably overlies poorly exposed and partly dolomitized MHVC volcanic conglomerate and breccia. This probably reflects a major period of erosion before PC<sub>3</sub> deposition. To the west, the topography is subdued and exposure is poor.

However, discontinuous exposures of the map units which directly overlie the upper Mount Harper Group (PC<sub>3</sub>-PC<sub>5</sub>) persist almost to the Alaska border.

### ***Facies of the upper Mount Harper Group***

#### **Map unit PH<sub>1</sub>**

Unit PH<sub>1</sub> is thickest immediately north of the main ridges of the preserved part of the Mount Harper volcanic complex, thins and intertongues northward with unit PH<sub>2</sub> and in most places is gradationally overlain by PH<sub>2</sub>. Fault-bounded inliers of PH<sub>1</sub> also are present at the top of the Mount Harper volcanic complex. A stratigraphic section measured through this unit is shown in Appendix 1 (section 8, Fig. A1-10). The base is gradational from volcanic flows, volcanic conglomerate, and tuff of Mount Harper volcanic complex Member C.

Unit PH<sub>1</sub> comprises coarse, crudely bedded conglomerate with less common intercalated sandstone and mudstone (Table 5, Fig. 26A, B, C). Most rocks weather either pale orange-grey or green-grey, with medium grey fresh surfaces. Volcanic clasts make up 90% of the conglomerate clast types in some beds close to the base of the map unit, but more typically constitute a maximum of 10% of the clasts. They are spotted to vesicular mafic to intermediate volcanic composition. The nonvolcanic clasts are greater than 95% dolostone,

most commonly medium to light grey laminated dolostone, including cryptalgal laminates, stromatolites, and oolites/oncolites (Fig. 26D, E, F).

Interbedded mudstone and sandstone in the inliers tend to be dark green-grey, with a high component of volcanoclastic detritus and rare interbeds of volcanic tuffs, flows, and sills. This is also typical of the mudstone and sandstone in areas where a thick gradational contact from the underlying volcanics is present. Most mudstone in these strata are nondolomitic.

Rare lonestones are present in the mudstone-sandstone layers (Fig. 26G, H). Most do not show evidence of being dropped into the surrounding sediments (i.e. noncompactional deformation of surrounding strata). The few exceptions occur in the interval transitional from underlying Mount Harper volcanic complex volcanics, where a few pebble to small boulder-sized lonestones of vesicular volcanic rocks have disrupted and deformed the enclosing strata, suggesting impact deposition. Their composition and restriction to volcanoclastics with intercalated tuffs and flows strongly supports an origin as volcanic bombs during pyroclastic volcanic events during late stages of Mount Harper volcanic complex deposition. The pyroclastic origin of these lonestones is significant in that they could be mistaken as glacial dropstones and used as evidence to link the upper Mount Harper Group to basal Windermere strata elsewhere in the Cordillera which have been interpreted to be of glacial origin.

### Map unit PH<sub>1</sub> – interpretation

The conglomerate-sandstone-mudstone sequence of unit PH<sub>1</sub> 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 are laterally extensive and in some places several metres thick, but 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 subaqueous. However, the abundance of cobbles and boulders in the conglomerates, their very poor sorting and the restriction of conglomerate clast compositions to Mount Harper volcanic complex and upper Fifteenmile group types, suggest local sources for the detritus.

Map unit PH<sub>1</sub> 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 Nemeč and Steel (1984) for sediment gravity flows that show evidence of plastic behaviour. Most conglomerates contain a significant (>3%) proportion of mud-sized material, a source of high matrix strength (Rodine and Johnson, 1976; Hampton, 1979).

Clast types in the conglomerates suggest local derivation. The volcanic clasts were almost certainly derived entirely from the Mount Harper volcanic complex. Extensive volcanic

conglomerates interbedded with flows, tuffs, and rare sills and dykes occur in member C of the Mount Harper volcanic complex. This member gradationally underlies unit PH<sub>1</sub>, and volcanic flows of this member intertongue with the southern part of unit PH<sub>1</sub>. Significantly, member C volcanoclastics thicken north of an east-trending linear break a few kilometres south of the main PH<sub>1</sub> outcrops. This covered break contains a synvolcanic fault (labelled “Tango tarn” fault in Fig. 18), and detritus of the member C conglomerates could have been shed from the fault scarp. The gradational basal contact and intertonguing of volcanics with map unit PH<sub>1</sub> demonstrates that deposition of unit PH<sub>1</sub> was initially coincident with this stage of Mount Harper volcanism. Thus the inferred fault scarp (probably one of several) supplied clasts for member C and the volcanic conglomerates of unit PH<sub>1</sub>. Dolostone clasts in the conglomerates are identical to the rock and stromatolite types which make up 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 lower Mount Harper Group at the top of the Fifteenmile group (Mustard and Donaldson, 1990). These clasts probably reflect erosion of a similar regolith from the original sub-Harper group unconformity surface during initial upper Mount Harper Group deposition. This interpretation is supported by the more common presence of such clasts in the lowermost conglomerate beds.

The graded sandstones and mudstone, which are intercalated with the conglomerates, are also interpreted as sediment gravity flows. They probably reflect deposition from grain flow and turbidity currents, initiated by a combination of seasonal sedimentation events, backstreaming turbulence at the head of the moving debris flows as mentioned above, separate turbiditic flows initiated on proximal subaqueous slopes, and minor slumps at the irregular and unstable head of the stationary debris-flow lobes (cf. Postma, 1984). Rare crosslaminated ripples in these beds indicate a northerly source for much of this nonconglomeratic material. This is interpreted to reflect a balance between two major depositional processes (see Fig. 30, top): 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 PH<sub>2</sub>, discussed below). This interpretation is supported by the lack of volcanoclastic detritus in the sandstone. All appear to have been derived from the erosion of Fifteenmile group dolostone. Exceptions are greenish-grey sandstone and mudstone in the transitional interval from Mount Harper volcanic complex volcanic to unit PH<sub>1</sub>. These volcanoclastics are interpreted as sediment gravity flows related to the local debris flow processes described above and as deposits from suspension settling of mud between flow events.

### Map unit PH<sub>2</sub>

Map unit PH<sub>2</sub> is restricted to the northeastern third of the map area. The unit has a preserved maximum thickness of about 400 m at the northern extent of exposure, thinning southward

Table 5. Summary of major facies and features of the upper Mount Harper Group map units.

Facies association	Contact relationships	Major lithofacies	Lithofacies description	Sedimentary Structures	Paleoflow	Interpretation	Further Reference
<p><b>Map unit PH<sub>1</sub></b> maximum measured thickness = 175 m</p>	<p>gradationally overlies MHVC in all places inter tongues with MHVC at south contact disconformably overlain by map unit PC<sub>3</sub> in south areas inter tongues with, and overlain by, map unit PH<sub>2</sub> in north areas</p>	<p>Conglomerate interbedded with sandstone and mudstone described below</p>	<p>20-70% pebble-boulder clasts, generally matrix-supported in a poorly sorted dolowacke matrix (rarely a lithic wacke matrix rich in volcanic fragments); crudely bedded 1 to &gt;2 m thick but common amalgamation and subtle welded contacts give common appearance of beds up to 10 m thick; beds sheetlike but thicken/and thin laterally, loaded bases but nonerosive; clasts subround to subangular, high sphericity; clast types 10-90% volcanic, 10-90% dolostone (laminated, cryptalgal, stromatolitic, oolitic types common), rare chert/chalcedony replaced dolostone; volcanoclastic detritus most abundant in lower and south parts of unit</p>	<p>massive, generally nongraded; random clast orientation; common projecting clasts; rarely vaguely to well-stratified internally with normal graded top to sandstone; rare poor reverse-graded base and cobble-boulder-rich central layers; no obvious major vertical trends in clast size or bed thickness, but definite thinning and fining of unit from south to north; rare, &lt;5 m thick lining-upward trends from dolorudite to bedded dolarenites-wackes</p>	<p>none</p>	<p>subaqueous cohesive debris flows grain flows, turbidites in debris aprons adjacent to paleoscarps of MHVC; dolostone-rich strata derived from north source of paleoscarps in Fifteemile group; all clasts local MHVC or upper Fifteemile group;</p>	<p>Appendix 1, section 8 Mustard, 1990</p>
		<p>Sandstone</p>	<p>lithic wacke in inliers, lower and south parts of unit; dolowacke in upper and north parts; lithic wacke is fine- to coarse-grained with mixed volcanic and dolostone sand clasts; poor to moderately sorted; thick laminae to thin beds; dolowacke is fine- to coarse-grained, moderately sorted, thin bedded, continuous, often gradationally overlying dolorudites</p>	<p>lithic wackes generally massive, nongraded or poor normal graded to mudstone; no ripples or crosslaminae; dolowacke generally massive, normal-graded or nongraded, rare parting lamination, asymmetric ripples, ripple crosslaminae; rare limestones; generally volcanic pebble-cobbles associated with pyroclastic beds in transition from MHVC</p>	<p>N-S parting lineations; crosslamina show paleoflow of dolowackes toward south</p>	<p>limestones mostly derived as pyroclastic bombs, rarely from gravity sliding; sandstones and mudstones deposited as grain flows, turbidites, and through suspension settling</p>	
		<p>Mudstone</p>	<p>nondolomitic silty claystone in inliers and lower parts of units; dololite and dolosiltite in upper and north parts of unit</p>	<p>laminated; rarely massive and nonlaminated; laminae continuous, parallel, slightly wavy; rare limestones</p>	<p>none</p>		
<p><b>Map unit PH<sub>2</sub></b></p>	<p>base with Fifteemile group sharp, irregular, angular unconformity laterally to south complexly grades and inter tongues with upper part of unit PH<sub>1</sub>, and gradationally overlies PH<sub>1</sub></p>	<p>Conglomerate top of coarsening and thickening up mega-sequences up to 150 m thick from sandstone-conglomerate facies and sandstone-mudstone facies</p>	<p>alternating matrix- and clast-supported beds; matrix-supported conglomerate as in facies below; apparent beds up to 18 m thick probably several amalgamated beds in overlapping lenses 100s m wide, clast-supported conglomerate 80-90% pebble-boulder clasts in fine- to coarse-grained dolarenite-wacke matrix; moderate to poor sorting; overlapping broad, shallow lens 10s to 100s cm thick and 10s to 100s m wide, coalesce into apparently continuous layers 10s m thick; bases lead to slightly erode into beds below; clasts commonly equant, subround, clast types &gt;90% dolostone (many stromatolitic, cryptalgal)</p>	<p>massive; nongraded or poor to fair normal grading (only in clast-supported cgls); projecting clasts common; loaded bases common to rare interbedded sandstones; clasts random oriented or fair to poor imbrication of tabular clasts near base of beds</p>	<p>clast imbrication and ripple crosslamina show overall south but radial paleoflow</p>	<p>prograding submarine debris aprons and submarine fans; deposition by sediment gravity flow; matrix-supported conglomerate by cohesive debris flow; clast-supported conglomerate by debris flow, density-modified gravel-rich grain flow and turbiditic flow;</p>	<p>Appendix 1, section 9 Mustard, 1990</p>

Facies association	Contact relationships	Major lithofacies	Lithofacies description	Sedimentary Structures	Paleoflow	Interpretation	Further Reference
maximum measured thickness = 400 m	top contact with PC <sub>3</sub> generally covered; in places displays abundant brecciation, silica and dolomite alteration of PH <sub>2</sub>	Sandstone-conglomerate	fine- to very coarse-grained dolarenites, thin-thick beds (most 5 to 20 cm; some 20 to 50 cm); thickest with pebbly bases; Bouma turbidite types A, AB, ABC; interbedded with thin bedded dolarenite as described below; conglomerates randomly interbedded with sandstone, most matrix-supported; 40-70% pebble-boulder clasts in poorly sorted mud-granule dolowacke matrix; beds 10s cm to 10s m thick (probably amalgamated multiple beds); beds continuous laterally but thicken/thin; nonerosive, loaded bases; clast-supported conglomerate as above but thinner and better sorted, some as discont broadly channelized lens 10s to 100s m width	sandstones massive to planar laminated, rare rippled tops; common normal graded; loaded bases; matrix-supported conglomerates massive, nongraded, loaded bases; clast-supported conglomerate poor to good normal graded; rare reverse graded base; rare pebble-cobble limestones in sandstone beds	clast imbrication, ripple crosslamina indicate overall south, but radial paleo-flow	sandstone/mudstone deposited as classic turbidites; convolute bedding formed by soft sedimentary deformation; limestones all deposited by gravity sliding and gravity winnowing deposition	
		Sandstone-mudstone	very fine- to fine-grained dolarenites interbedded or grading to silty dololutes; Bouma AE +BE turbidite types most common, less common ABCE, BCE, BCDE, and ACE types; rare pebble-based ABE beds up to 10 cm thick	continuous, parallel to slightly wavy lamina or thin beds (rarely to 10 cm thick); rare convolutedly deformed layers; common normal graded sand to mud; crosslaminated ripples in upper sands;	overall south, but radial	mudstones deposited by suspension settling during waning turbidite flow	

to less than 50 m thick where it intertongues with and partly overlies map unit PH<sub>1</sub>. Thicknesses measured for this unit are minima, because the top contact is an unconformity with overlying unit PC<sub>3</sub>.

The basal contact with Fifteenmile group dolostone is a sharp, angular unconformity. Laterally to the south, PH<sub>2</sub> complexly grades and intertongues with the upper part of unit PH<sub>1</sub>, and gradationally overlies unit PH<sub>1</sub>. In these areas the lower contact of PH<sub>2</sub> was placed above the last observed presence of volcanic clasts in the conglomerates.

Most PH<sub>2</sub> rocks weather greyish-orange with a medium grey fresh surface. Distinctive coarsening and thickening-upward sequences about 75 to 150 m thick are well developed in the lower part of the unit, and display a gradational upward change from dololite to dolarenite (or dolowacke) to dolorenite; thinner (2 to 25 m) and more subtle coarsening- and fining-upward sequences can be discerned within the major sequences (Fig. 27, Table 5). Conglomerates form the upper 10 to 80 m 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.

Paleocurrent indicators include fair to poor imbrication of tabular clasts at the base of some conglomerate beds, ripple crosslaminae in the dolarenite, and rare parting lineation on the top surface of fine grained dolarenite. All indicate southerly paleoflow, although a slightly radial pattern is suggested (Fig. 28).

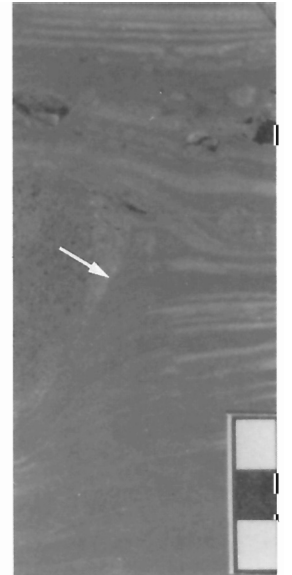
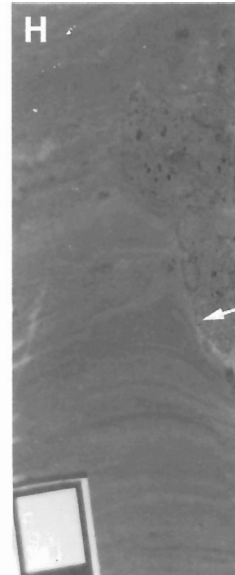
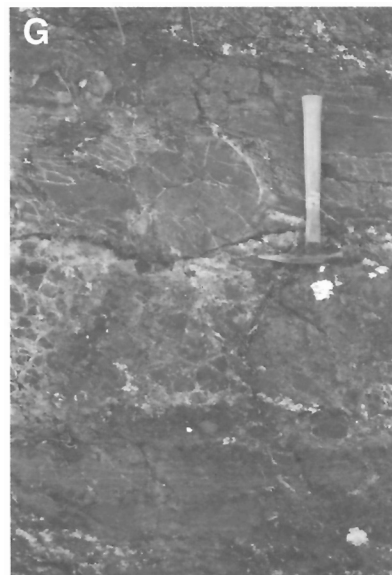
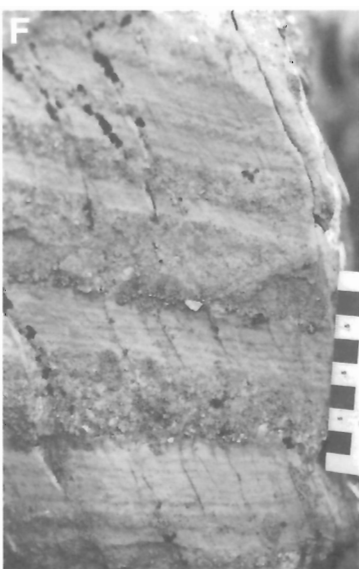
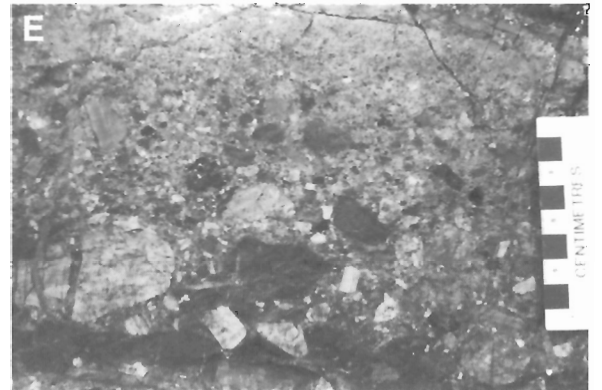
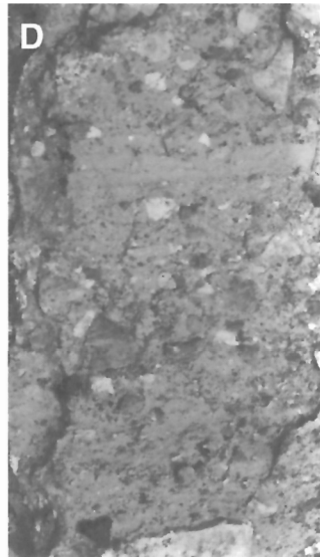
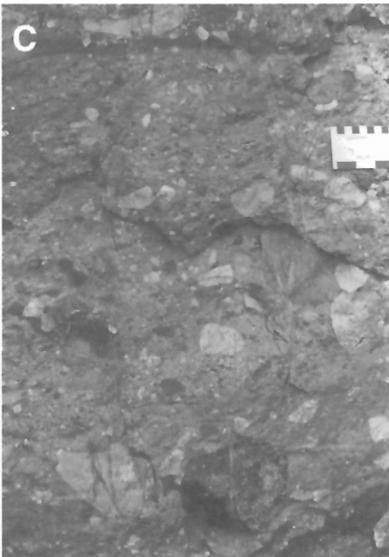
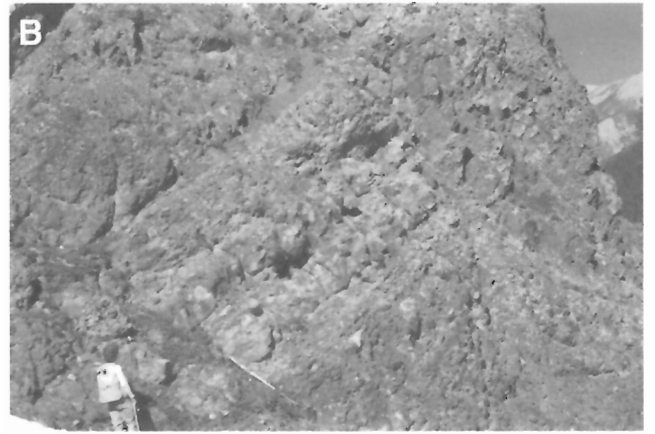
The best-developed major sequences are subdivided into three major facies: sandstone-mudstone, sandstone-conglomerate, and conglomerate.

#### *Sandstone-mudstone facies*

Dolarenite and dololite occur in continuous and parallel to slightly wavy laminae or thin beds (rarely up to 10 cm thick) in the lower part of the major sequences, and less commonly in the upper part of small fining-upward sequences. A few layers display convolute deformation. The most common rock types are fine- to very fine-grained dolarenite which show normal grading in which the abundance of brown dolomicrite matrix increases upward, grading upward to dolowacke and uppermost layers of silt-rich dololite.

#### *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. 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. The thickest beds include granule- or small pebble-rich bases. Most dolarenite display normal grading with either massive, planar laminated, and rarely rippled tops (Bouma sequence A, AB, ABC types). Thin beds of the types listed in the previous facies are also present.



←

**Figure 26.** Features of map unit PH<sub>1</sub>. Stratigraphic top is towards the top in all photos. **A)** Conglomerate-rich outcrop of unit PH<sub>1</sub> (about 100 m vertical extent). Beds thicken and thin considerably, and some can be seen to pinch out, but most beds extend laterally for hundreds of metres. GSC 1995-092H **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 nonconglomeratic interbeds, but the precise location of bed contacts in many places is not obvious. GSC 1995-092I **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. GSC 1995-092J **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. GSC 1995-092K **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). Scale in centimetres. GSC 1995-092L **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 crosslaminated ripples at the top of these beds indicate southerly paleoflow. Scale in centimetres. GSC 1995-092M **G)** Bedded volcanoclastic conglomerates from lower part of a PH<sub>1</sub> unit. Conglomerates contain >90% volcanic clasts and are intercalated with dark green-grey, noncalcareous mudstones and sparse volcanic flows and tuffs. Rare lonestones, such as the large cobble to the left of the 35 cm long hammer, are all vesicular volcanic rocks, most of which have pierced and deformed the surrounding strata (probably reflecting pyroclastic deposition). GSC 1995-092N **H)** Vesicular, chlorite-spotted, volcanic pebble lonestone (pyroclastic bomb) in green-grey noncalcareous mudstones, from the gradational succession between the Mount Harper volcanic complex and the overlying map unit PH<sub>1</sub>. 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 (e.g. 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 syndimentary 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. GSC 1995-092O

The conglomerates are interbedded randomly with the sandstone (Fig. 29A). 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. 29B). They are in beds ranging from a few tens of centimetres to tens of metres thick, but the latter probably 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 lenses hundreds of metres long. Most are nongraded, but some show poorly developed and laterally discontinuous reverse grading at the base and/or normal grading at the top.

The clast-supported conglomerates in general 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 reverse-graded base (Fig. 29C). The conglomerate with distinct normal grading generally grade upward to pebbly sandstone, some laminated or thin bedded. The latter conglomerates tend to have gently concave-upward basal contacts which appear to have been eroded into the underlying beds, and the conglomerates are laterally discontinuous over tens to hundreds of metres. Many of these conglomerates form the lower parts of fining-upward sequences, overlain by bedded sandstones and sandstone-mudstone sets as described above.

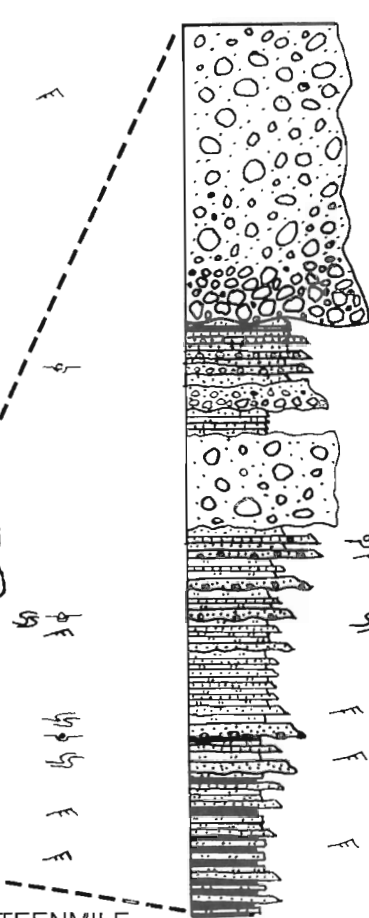
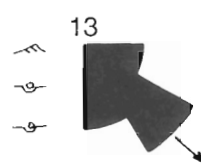
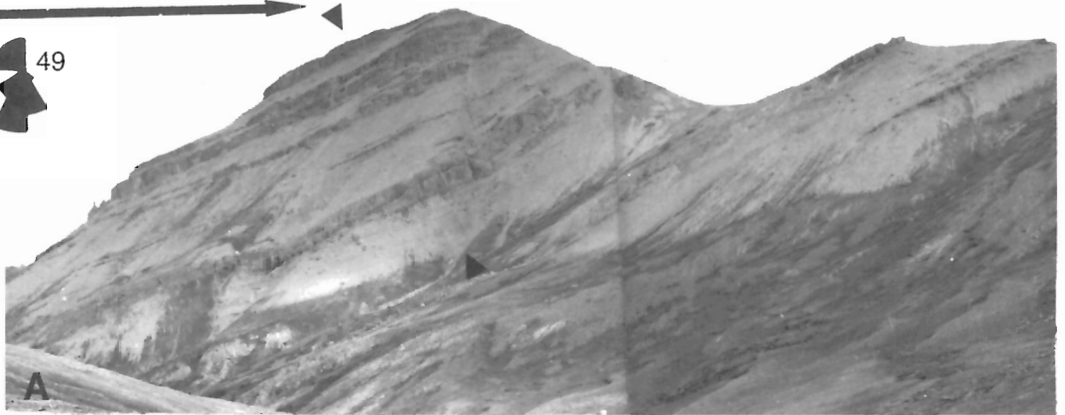
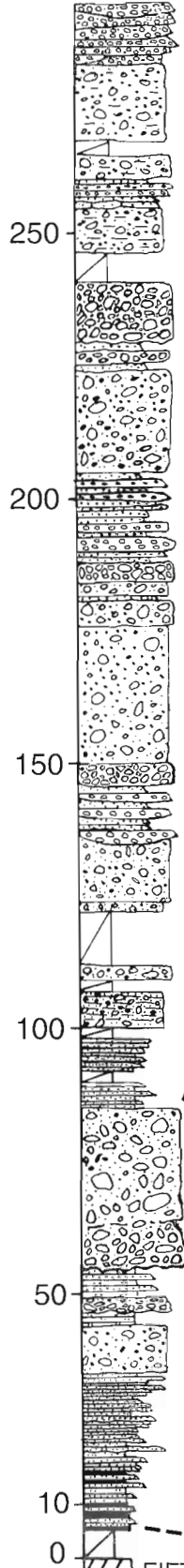
The upward gradation from interbedded conglomerate-sandstone facies to the main conglomerate facies is relatively uniform over a few metres to (rarely) tens of metres. Convolutely deformed layers and dewatering structures are most common in sandstone and mudstone interbedded with conglomerate in this interval, although such structures also are present in other facies (Fig. 29D). Pebble- to cobble-sized lonestones are also common in this transition (Fig. 29E-G). These clasts, markedly outsized in terms of the immediately surrounding strata, interrupt, but do not significantly deform the enclosing sandstone beds. Lonestones in some places can be demonstrated to occur at the same stratigraphic level, but in isolation from, discontinuous conglomerate beds containing 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 PH<sub>2</sub> 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.

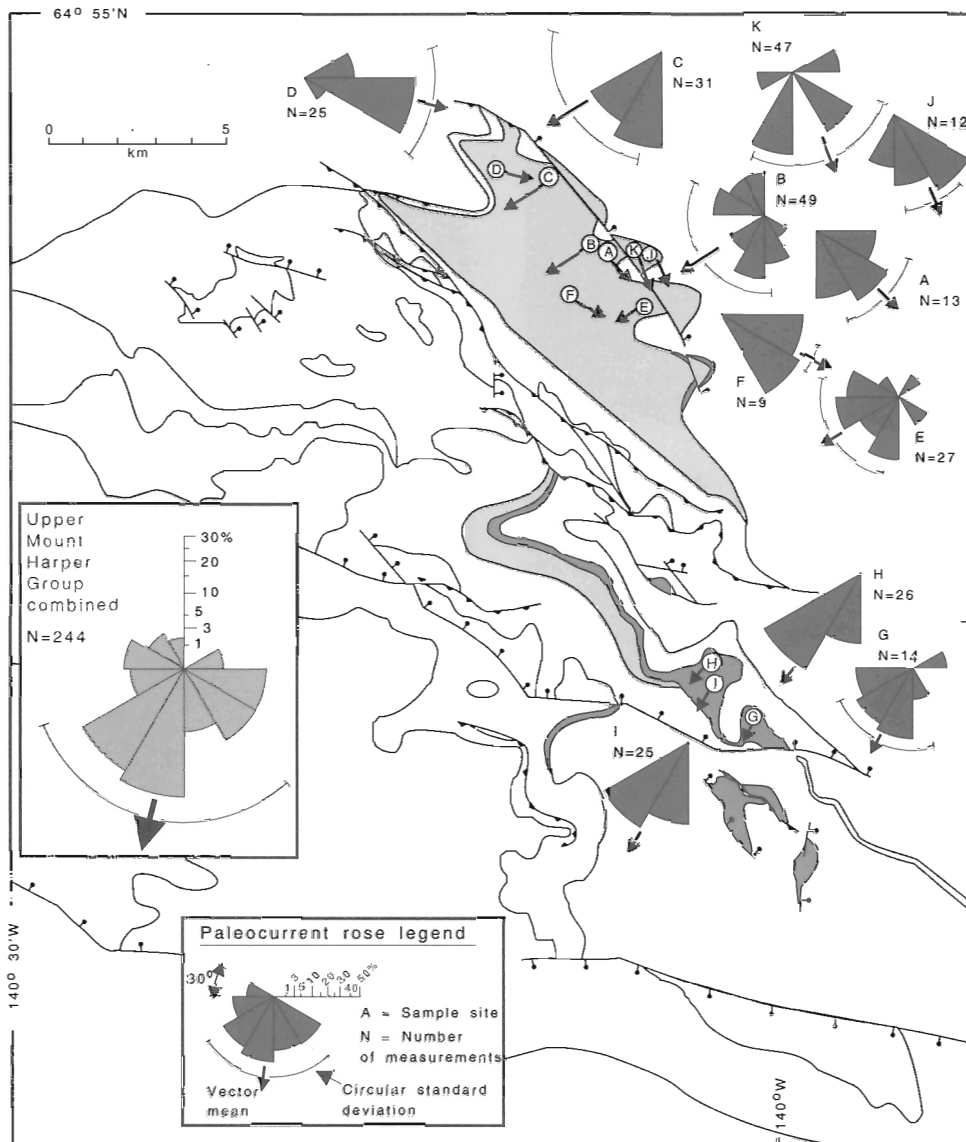
The matrix-supported conglomerates are similar to those of the sandstone-conglomerate facies, with apparent bedding up to 18 m thick. However many of the very thick beds show a crude internal stratification, suggesting that they are composites of several thinner beds, but others are massive, non-graded, and structureless. These conglomerates appear

300 metres



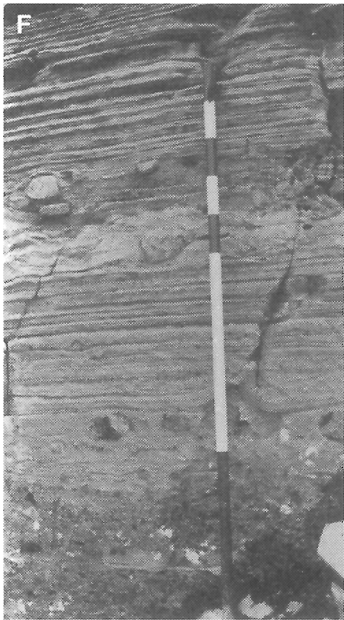
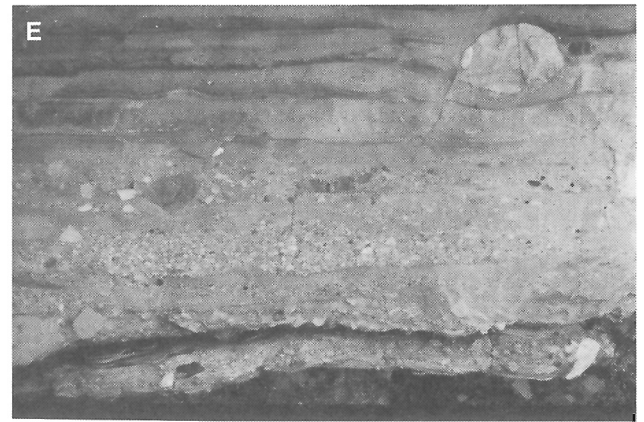
Vertical Trends	FACIES	INTERPRETATION	
	Conglomerate-Sandstone	Gravel-rich, high-conc. sediment gravity flows in overlapping sheets and broad channels	UPPER FAN
	Sandstone-Conglomerate	Mixed high and low concentration turbidity currents, rare debris flows, in sheets and migrating lobes and channels	MID-FAN
	Sandstone-Mudstone	Sand-mud turbidity currents, generally in sheets, but rare small channels	LOWER FAN

FIFTEENMILE GROUP



**Figure 28.** Upper Mount Harper Group paleocurrents, with summary rose diagrams for the map units at the lower left. Individual rose diagrams are patterned as for the summary roses. The geological contacts of the upper Mount Harper Group map units are outlined, but not patterned (see Fig. 3 and 25 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 letter that references a 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 nonlinear scale as suggested by Nemeč (1988). All measurements have been corrected for bed tilt.

**Figure 27.** Stratigraphic section through unit PH<sub>2</sub> megasequences measured on the exposure shown between triangles on A) (northeast to the right in photo). Also shown in Appendix 1, section 9. Lowermost coarsening-upward megasequence (85 m thick) is shown in greater detail, with facies divisions and interpretations (discussed in text). The outcrop of this megasequence is shown in B) (oriented with east to the left). Symbols as in Appendix 1. GSC 1995-092P, GSC 1995-092Q



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 lenses hundreds of metres wide (Fig. 27, photo A).

Clast-supported conglomerates are moderately to poorly sorted, with 80 to 90% pebble- to boulder-size clasts in a fine- to coarse-grained dolarenite or dolowacke matrix. Beds are up 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. 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. The bases of these conglomerate beds are slightly eroded into the underlying rocks. The clast-supported conglomerates are generally massive; many show poor normal grading, but nongraded beds are also common. 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. 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 25 cm thick) capping normally graded conglomerate.



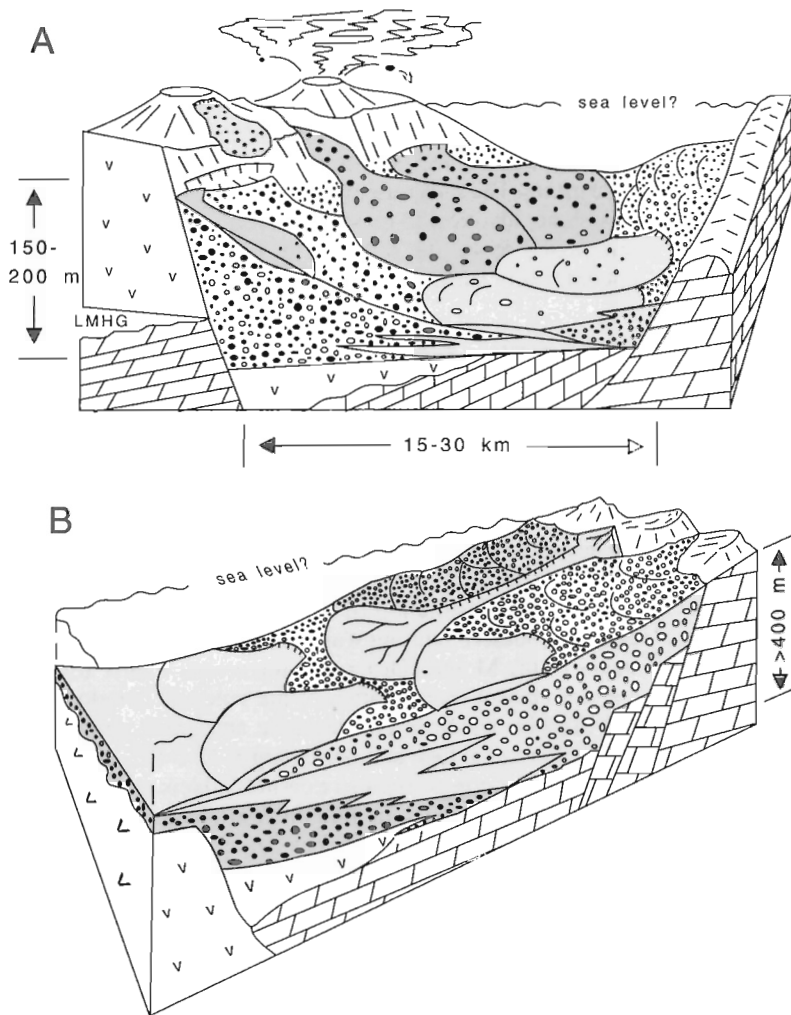
**Figure 29.** Sandstone-conglomerate facies of map unit PH<sub>2</sub>. Stratigraphic top towards top in all photos. **A)** Interbedded resistant conglomerates and recessive sandstones. Jacob's staff is 1.5 m long. GSC 1995-092A **B)** Clast-rich matrix-supported conglomerate. Staff is divided into 10 cm segments. GSC 1995-092B **C)** Normally graded, clast-supported conglomerate showing slight erosion of underlying dolarenite. Staff is divided into 10 cm segments. GSC 1995-092C **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. GSC 1995-092D **E)** Normally graded small pebble and granule conglomerates which grade to laminated dolarenites. A cobble lonestone is present at the top right of the photo. Scale (top right corner) is in centimetres. GSC 1995-092E **F)** Lonestones (here within unit PH<sub>2</sub>) commonly occur at about the same stratigraphic level as the conglomerates of the previous photo and in some places laterally can be traced into beds of matrix-supported conglomerate. GSC 1995-092F **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). GSC 1995-092G

Clast compositions are greater than 90% medium to light grey dolostone, many cryptalgal or stromatolitic. As for unit PH<sub>1</sub>, 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 PH<sub>1</sub>, and similarly interpreted to be the result of erosion of a regolith at an unconformity surface at the top of the Fifteenmile group.

### Map unit PH<sub>2</sub> – interpretation

Paleocurrents demonstrate that all PH<sub>2</sub> material was derived from the north, but the PH<sub>2</sub> clastics intertongue over a few tens of kilometres southward with poorly sorted PH<sub>1</sub> conglomerates, in part locally derived from the Mount Harper volcanic complex, probably mostly from the south. This suggests a restricted basin setting. The major control on basin formation is likely extensional faulting. Faulting directly controlled sedimentation of the lower Mount Harper Group and this southern faulting was active at least during the early stages of the Mount Harper volcanic event. Faults also were a major control on formation of the volcanic conglomerates and breccias which in part underlie and grade into the PH<sub>1</sub> conglomerates at their southern margin. Unit PH<sub>2</sub> contains an abundance of conglomerates rich in boulders and cobbles of composition identical to the Fifteenmile group preserved beneath the upper Mount Harper Group, as well as silicified Fifteenmile group regolith that is locally preserved on the unconformity surface below the lower Mount Harper Group. 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-upper Mount Harper Group 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 PH<sub>2</sub>. All of the above evidence suggests that fault-controlled uplift north of the present outcrop area was the primary control on PH<sub>2</sub> deposition.

Deposition is interpreted to have taken place predominantly in southward-prograding clastic fans (Fig. 30B). The PH<sub>2</sub> conglomerates only superficially resemble alluvial fan facies models (see review in Nilsen, 1982 and Rust and Koster, 1984). Direct indicators of subaerial exposure (e.g. 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). 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; Nemeč and Steel, 1984; Nemeč, 1988). However, in addition to the lack of subaerial indicators, unit PH<sub>2</sub> lacks features indicative of shoreline or littoral processes suggesting that deposition was at least at a subwavebase depth. Large-scale planar and trough cross-bedding are generally an abundant structure in fan delta sandstones and finer conglomerates as part of shoreline and



**Figure 30.**

Schematic diagrams illustrating depositional models for units PH<sub>1</sub> and PH<sub>2</sub>. A) Unit PH<sub>1</sub> deposition coincided with a late stage of Mount Harper volcanic complex volcanism. Syn-volcanic faults (only one shown for simplicity) formed fault scarps, initiating generally northward deposition in debris aprons (to right in diagram). Early stages of normal faulting north of the volcanic complex formed the northern margin of the upper Mount Harper Group half graben, and shed detritus derived from uplifted Fifteenmile group dolostones southward, intermixing with the volcanic detritus of the PH<sub>1</sub> debris aprons; LMHG = lower Mount Harper Group B) Most unit PH<sub>2</sub> deposition was postvolcanic and controlled by normal faulting at the north end of an east-trending half graben. Subaqueous debris aprons and radial fans prograded southward (to left in diagram), both intermixing and covering PH<sub>1</sub> detritus rich in volcanic clasts.

delta front sequences (Ethridge and Wescott, 1984; Kleispehn et al., 1984, Nemeic and Steel, 1984). These structures are absent in PH<sub>2</sub> strata.

The repeated, large-scale coarsening-upward sequences (termed megasequences below) fit well the general facies models proposed for submarine fans. Based on the size of the largest preserved sequences, lateral continuity of the nonconglomeratic sediments, and the limited three-dimensional exposure of the units, dimensions of the fans were probably small (less than 10 km 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 (Howell and Normark, 1982; Nelson and Nilsen, 1984; Walker, 1984; Stow et al., 1985). The sandstone and mudstone show no evidence of wave reworking or tidal

influence on deposition, suggesting subwavebase deposition, but no other features were observed which reliably demonstrate either water depth or salinity.

The features of the coarsening upward sequences shown in Figure 27 correspond well to the traditional submarine radial fan facies models. A submarine fan model for PH<sub>2</sub> deposition is presented in the rather simplified terms of lower, middle, and upper fan depositional processes as summarized by Walker (1984) and detailed in Nelson and Nilsen (1984).

Deposition was almost exclusively by sediment gravity flow processes. The basal dololomite and dolarenite-dolowacke 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 midfan 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- 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. Nonchannelized, 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 mudstone 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 (Postma, 1984, Postma et al., 1988) probably a common feature in this setting. However, 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 conglomerates which occur in the upper part of the megasequences were deposited in an upper fan environment where migrating channelized conglomerates were rapidly deposited in overlapping lenses. The conglomerates lack crossbedding 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, the less common channelized conglomerates which grade up to normally graded pebbly sandstones may reflect a more evolved channelized flow where turbulence was significant.

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). Rare clast-supported conglomerates in this facies are attributed to high-density, gravel-rich sediment gravity flows (cf. Lowe, 1976, 1982).

In summary, PH<sub>2</sub> deposition initially constructed well-developed coarsening-upward sequences which mimic established models of prograding sand- and gravel-rich submarine fans. The upper conglomerate-rich part 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 (review in Nelson and Nilsen, 1984 and Nelson, 1983).

### ***Upper Mount Harper Group tectonic setting and controls on deposition***

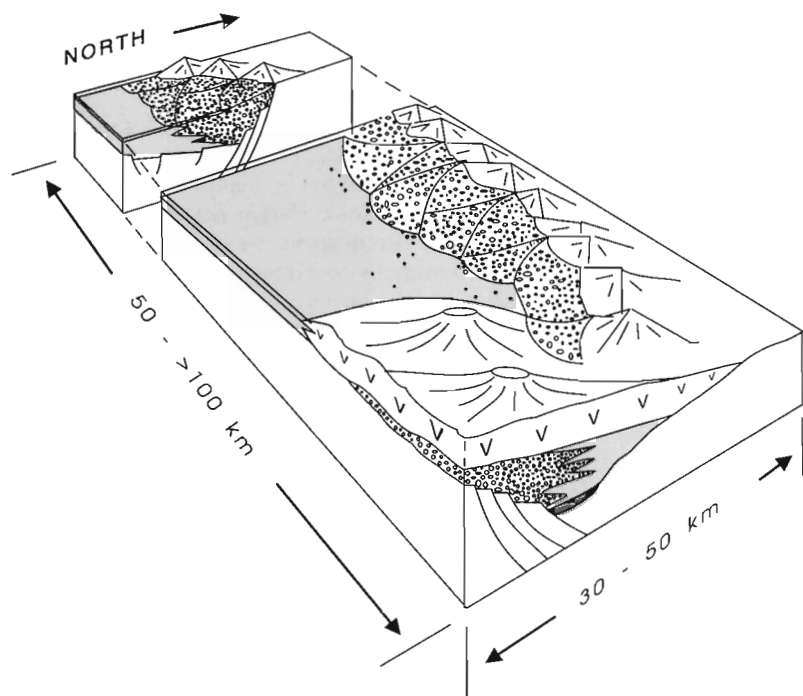
The lower Mount Harper Group was deposited in an east-trending, north-facing half-graben. A significant change is apparent in the slightly younger upper Mount Harper Group sedimentary succession. The lowest upper Mount Harper Group conglomerates contain volcanic clasts derived from lower units of the Mount Harper volcanic complex, and also interfinger with part of the volcanic complex. This demonstrates that initial upper Mount Harper Group deposition slightly postdates that of the lower Mount Harper Group strata. Upper Mount Harper Group deposits are preserved north and west of the lower Mount Harper Group strata. No lower Mount Harper Group rocks are preserved below the upper Mount Harper Group, and no clasts of lower Mount Harper Group composition were noted in the upper Mount

Harper Group conglomerates. Clearly the lower Mount Harper Group sediments did not extend into the area of proximal upper Mount Harper Group deposition.

Because the exposed part of unit PH<sub>2</sub> 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 Mount Harper volcanic complex and lower Mount Harper Group rocks are demonstrably related either directly or indirectly to extensional faulting and half-graben formation. A similar tectonic control is inferred for PH<sub>2</sub> 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 PH<sub>1</sub> sediments (Fig. 31).

Other possible first-order controls on sedimentation include changes in source rocks, climatic changes, and major sea-level fluctuations. Source rock changes can be discounted; all detritus was derived from the Fifteenmile group dolostone. 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 (Stow et al., 1985).

Glaciation could influence the depositional regime, even on an active margin, both by direct glacial transport and deposition and also by sea-level fluctuations as major ice sheets formed and melted. Lower Windermere Supergroup coarse clastics, possibly coeval to unit PH<sub>2</sub>, 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 (see Hambry and Harland, 1985). Of the many features commonly cited as evidence for direct or indirect glacial deposition (exotic clasts, faceted and multiply striated clasts, glacially modified substrates, glaciotectionic deformation etc.; see Boulton and Deynoux, 1981), only the presence of abundant poorly sorted, matrix-supported conglomerate (diamictite) and lonestones could be cited as possible evidence for glacial deposition of unit PH<sub>2</sub>. However, the diamictites contain only locally derived clasts and in the context of their facies association, they best fit an origin as nonglacial debris flows. The lonestones 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 (e.g. Thomas and Connell, 1985). Thus there is no compelling evidence for a direct glacial influence on PH<sub>2</sub> 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 PH<sub>2</sub>. However, as discussed previously, basin-margin faulting is the most likely primary control on sedimentation, and this control alone can account for the features of unit PH<sub>2</sub>.



**Figure 31.**

*Schematic diagram illustrating tectonic setting of the Mount Harper Group. The ca. 750 Ma Mount 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 (see Ebinger, 1989).*

Postdepositional uplift resulted in exposure, alteration, and the creation of a disconformity between PH<sub>2</sub> and coeval to younger sedimentary and volcanic rocks and the overlying map units. This uplift and the resultant disconformity may correspond to the break-up unconformity generally associated with the late stages of continental rifting (Bond and Kominz, 1988). However, the overlying map units PC<sub>3</sub> to PC<sub>5</sub> are clearly much younger than the underlying Mount Harper Group rocks; trace fossils in the top 50 m of unit PC<sub>5</sub> attest to an early Cambrian age (Mustard et al., 1988), and the contacts between the upper units are gradational except locally, suggesting that strata above the disconformity are approximately dated by these fossils. Thus a time gap of about 150 to 200 Ma appears to exist between the time of deposition of the upper three sedimentary units and the underlying rift-related rocks.

## TECTONIC IMPLICATIONS

### *Evolution of the Mount Harper Group and local tectonic setting*

Lower Mount Harper Group sedimentation was controlled by the synsedimentary Harper Fault, which formed the southern margin of an asymmetric, east-trending half-graben basin. Deposition was mainly subaerial, with coalescing alluvial fans and braided streams building northward into the half-graben basin. Conglomerate clast compositions reflect the progressive exposure of older source rocks south of the Harper Fault and the direct control of the synsedimentary extensional faulting to basin deposition.

Mount Harper complex volcanism began with fluid basaltic flows that overlapped the submerged clastic fans and formed shield volcanoes that overstepped the Harper Fault.

As the edifice entered shallow water, eruptions became more explosive and locally culminated in island eruptions that are recorded by hematitic breccias and flows. During a hiatus much of the edifice was eroded and the magma chamber evolved a bimodal composition. Thick rhyolite flows were then extruded in the southern part of the complex and later covered by andesitic floods that also spread an apron of hyaloclastite to the north. Volcanism ebbed as invasive flows spread within the accumulating epiclastic and volcanoclastic sediments.

The coarse clastic rocks of the upper Mount Harper Group were dominantly shed from the north. Most deposition was postvolcanic, controlled by inferred normal faulting at the north end of an east-trending south-facing half graben. Subaqueous debris aprons and radial fans prograded southward, both intermixing and covering volcanic-rich detritus.

The evidence for normal faulting, half-graben sedimentation, rift-related volcanism, and synvolcanic faulting supports the contention that upper Mount Harper Group deposition also occurred in a half-graben basin, but slightly younger than the lower Mount Harper Group half-graben. The upper Mount Harper Group half-graben had a footwall scarp opposed, but offset to the west, from footwall faults of the lower Mount Harper Group (Fig. 31). This setting, with two slightly diachronous subbasins fed by sediments shed from opposed, but offset footwall scarps generated by listric normal faults, resembles the continental rift geometry deduced from observations in the west arm of the East African rift system (Bosworth, 1985; Ebinger, 1989). Although the regional structural mechanics of these alternating basins is complex and debated (e.g. Wernicke, 1985; Mohr, 1987; Ebinger, 1989), volcanic centres are common at the overlap zone of the opposed basins. Volcanism at these sites may reflect an

underlying, deep-rooted transfer fault system or accommodation zone between the two subbasins, and the cluster of localized faults could have served as magma conduits (e.g. Ebinger, 1989).

The Harper Fault zone appears to have been fundamental to the development and preservation of the Mount Harper Group. Its initial movement resulted in deposition of the basal conglomerate wedge, provided a weak zone for magma ascent, and possibly hosted magma chambers that gave rise to the Upper suite of the Mount Harper volcanic complex. Little if any lateral extension is indicated, but it became the northern limit of a zone of extended or thinned crust, later overlain by the Selwyn Basin. During Mesozoic contraction much of the Harper Fault zone was reactivated, and its movement may have localized strain around the volcanic complex and the associated sedimentary succession, thus preserving primary features. The Harper Fault is therefore implicated in the creation of the rift, the volcanic and clastic succession within it, preservation of these rocks, and their uplift to present view.

### ***Regional significance of the Mount Harper Group***

The Mount Harper Group is one of the regional correlatives of the Windermere Supergroup (the Neoproterozoic, clastic successions in the Canadian Cordillera which together comprise the Windermere Tectonic Assemblage of Wheeler and McFeely, 1991). They are exposures of a discontinuous belt, now shortened by Mesozoic contraction and accretion along the active westward margin of North America, from the Sonoran Desert in Mexico to east-central Alaska (Fig. 32A). Stewart (1972) and Gabrielse (1972) were first to recognize these widely distributed groups as evidence of continental separation.

The Mount Harper Group resembles many successions found at the base of the Windermere Tectonic Assemblage (reviewed by Ross, 1991). It occurs in the same stratigraphic position between middle Proterozoic and early to middle Paleozoic platformal carbonates, has conglomeratic and mafic volcanic rocks at the base, and a thick silt, sand, and maroon shale package above (although the upper Mount Harper Group is more conglomeratic than most correlatives and there is a disconformity between this succession and the thick, fine grained clastic succession which resembles the upper part of Windermere Tectonic Assemblage elsewhere). In contrast to most examples of basal Windermere Tectonic Assemblage, the Mount Harper Group clearly reveals the sequence of faulting, sedimentation, and volcanism that occurred during an initial extension event. The main differences from other basal Windermere successions are: 1) extensive conglomerate sequences can be shown to be directly derived from synsedimentary extensional faults, with no evidence of a glacial component, and 2) volcanism is demonstrably synsedimentary, permitting the igneous age (ca. 750 Ma) to be applied to the enclosing sedimentary succession and provide a date of initial extension.

As Burke (1980) and others have noted, well preserved continental rifts are those that have failed to develop completely and were abandoned. In a well developed extension setting the early deposits will be buried beneath thick

sediments of the ensuing basin. Perhaps initial block faulting is preserved at the Mount Harper region because this area was on the continental side of the main rift, and escaped subsequent burial beneath the basinal facies during the subsidence phase of the rifting event. This later regional subsidence phase is not found in the Mount Harper area, although a regionally extensive, late Precambrian to early Cambrian age succession of basinal clastics (the Hyland Group), is widely distributed as close as 15 km south of Mount Harper.

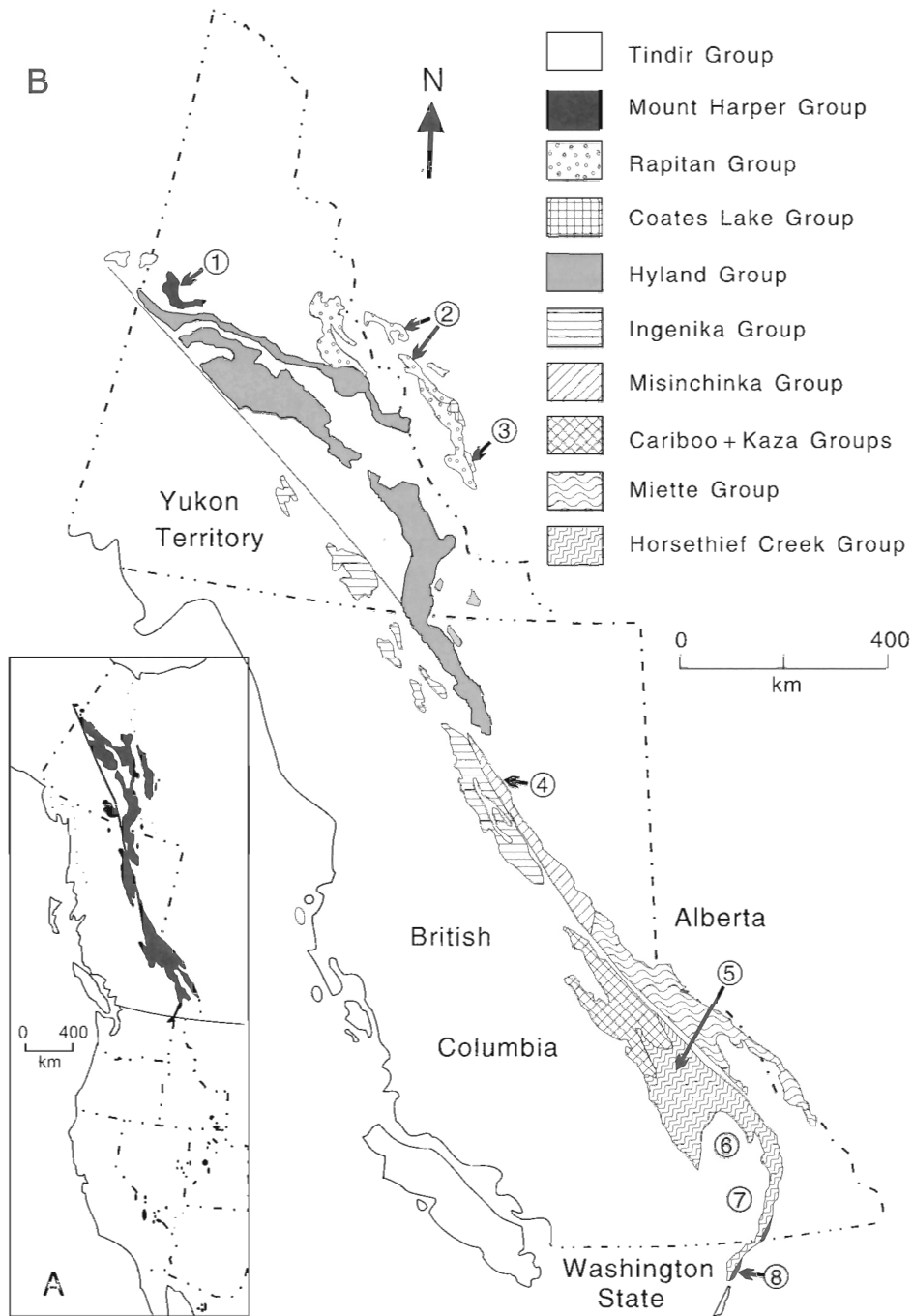
### ***Comparison of volcanic composition for Mount Harper volcanic complex and other Windermere volcanic rocks***

Geochemical discriminant diagrams, a commonly used method to determine tectonic provenance for volcanic rocks, produce conflicting and misleading results when applied to continental basalt and to volcanic rocks related to extension (Morrison, 1978; Holm, 1982; Arculus, 1987). The wide variations among magmatic suites in continental extensional settings could reflect inhomogeneous source rocks as well as differing depths of formation, fractionation paths, degrees of partial melting, and contamination (Mohr, 1987; Hildreth et al. 1985; Duncan, 1987) which probably obscure primary chemical characteristics of extensional magmas. Chemistry is therefore only one of many factors upon which the recognition or interpretation of ancient rift settings should be based (Sengor and Burke, 1978; Pearce, 1987).

Bivariant and triangular plots concisely display chemical variations among rocks which are geographically grouped or tectonically related. The Mount Harper volcanic complex is unlike all other igneous occurrences related to the Windermere Supergroup in its compositional variety, perhaps as a result of protracted and voluminous volcanism. The large number of analyzed samples, and selection of a less altered set with which to conduct comparisons, allow each of several members of the Mount Harper volcanic complex to be compared with the limited database of other igneous occurrences in the Windermere Supergroup.

The AFM diagram of Figure 24B shows that Mackenzie Mountain diabase, basalts from east central Alaska and those from southeastern British Columbia are all iron-rich tholeiites, most similar to member E of the Mount Harper complex. The entire Lower suite of the Mount Harper complex has lower Ti and Zr content (Fig. 23B), but higher Mg# (Fig. 23C) than all other igneous occurrences in the Windermere Supergroup; it appears to be a less evolved phase than the others. Furthermore, most occurrences, with the exception of the Mount Harper volcanic complex, have indications of alkalic affinity and represent strongly undersaturated magmatism. In contrast, Mount Harper volcanism began with a more primitive basaltic outpouring, followed by a bimodal suite of flows.

The continental affinity of Mount Harper and other Windermere-related igneous rocks is demonstrated by the limited rare-earth element (REE) data (Fig. 24C). The REE patterns for continental basalts are characterized by a negative slope and the influence of continental crust with magma is indicated by a negative Nb anomaly (Dupuy and Dostal, 1984).



**Figure 32.** A) Late Proterozoic succession of western North America part of, or correlative to, the Windermere Tectonic Assemblage (modified from Ross, 1991). B) Major late Proterozoic (to early Cambrian for Hyland Group) stratigraphic assemblages of the western Canadian Cordillera and adjacent Alaska and Washington State (modified from Ross, 1991). Circled numbers show localities of geochronological dates from igneous rocks either directly associated with Windermere sedimentation or interpreted to be part of the basal Windermere igneous event (see Table 6). Circled numbers six and seven are shown at the sample site localities.

Other Windermere-related igneous rocks are alkalic continental tholeiites (Devlin et al., 1985) but at Mount Harper there is no evidence of alkali enrichment (not indicated by the igneous mineralogy nor the Nb/Y ratio), nor a general increase in silica undersaturation characteristic of some continental rifts (e.g. East Africa: Bailey, 1974; Mohr, 1987). The lack of these characteristics supports interpretation of the Mount Harper area as an incipient continental rift.

### ***Comparison and significance of the Mount Harper Group to basal Windermere Tectonic Assemblage elsewhere in the Canadian Cordillera***

Synsedimentary tectonism during deposition of basal Windermere rocks has been well documented in the northern Canadian Cordillera (e.g. Eisbacher, 1981, 1985; Jefferson and Parrish, 1989), in British Columbia (Bennett, 1985; Root, 1987) and for possible United States Windermere equivalents (Miller, 1985). Jefferson and Parrish (1989) reviewed the evidence for rift-related faulting in the Canadian Cordillera during the late Proterozoic. They concluded that extensional faulting began before Windermere sedimentation, was most active during basal Windermere deposition, and intermittently continued during deposition of the rest of the Windermere Supergroup.

Volcanic rocks associated with the basal Windermere Tectonic Assemblage in the Cordillera are inferred to be coeval with dated intrusive rocks (dated examples are given in Table 6). This inference implies that Windermere deposition began during a 730-780 Ma igneous event, but this can only be directly demonstrated in the 751 Ma Mount Harper Group. Another date of  $762 \pm 44$  Ma obtained by Sm-Nd isotopic analysis of volcanic rocks from the Huckleberry Formation of northeastern Washington, which overlie conglomerate-rich basal Windermere rocks (Devlin et al., 1988) is preliminary because open-system behaviour with respect to the Sm-Nd system has likely taken place (Devlin et al., 1988; p. 1908).

Some of the conglomeratic successions of the basal Windermere Tectonic Assemblage in the Canadian Cordillera have been interpreted as glacial diamictites (Aalto, 1971; Eisbacher, 1981) indicating a major late Precambrian glacial event (Hambrey and Harland, 1985) coincident with rifting. Distinguishing glacially derived conglomerates from those directly related to tectonism, and assessing the relative importance of tectonism versus glaciation in forming those deposits has been problematical. The Toby Formation of southern British Columbia (and equivalent rocks in the northern United States) contains poorly sorted conglomerate and related clastics at the base of the Windermere Supergroup. In two areas, however, it contains abundant evidence (including synsedimentary normal faults)

**Table 6.** Summary of geochronological dates for igneous activity related or interpreted as associated with inception of Windermere Supergroup deposition. The diabase sills and quartz diorite in the Mackenzie Mountains (2, 3) intrude strata of the Mackenzie Mountain Supergroup, and are considered coeval with Little Dal Lavas at the base of the Coates Late Group or with Windermere volcanism. The Deserters Range granite (4) and Hugh Allen gneiss (5) are interpreted as basement to Windermere Supergroup strata, providing a maximum age for Windermere deposition in their respective areas. Late Proterozoic ages from Monashee Complex gneiss bodies (6, 7) are interpreted as ages of protolith volcanic or sedimentary successions correlated with the Windermere Supergroup (6) or as reset ages from regional igneous events (7). The Huckleberry volcanics are interbedded with basal Windermere sedimentary rocks, however the age cited is preliminary only, based on a two-point isochron (Devlin et al., 1988).

#	Rock unit	Age Ma	Method	Source
1	Mount Harper volcanic complex rhyolite	751 +26/-18	U-Pb zircon	Roots and Parrish, 1988
2	Diabase sills, Mackenzie Mountains	766 ± 24 769 ± 27	Rb-Sr whole rock	Armstrong et al., 1982
3	Quartz Diorite intrusion Coates Lake, Mackenzie Mountains	778 +3/-2	U-Pb zircon	Jefferson and Parrish, 1989
4	Deserters Range gneissic granite, northern B.C.	728 + 9/-7	U-Pb zircon	Evenchick et al., 1984
5	Hugh Allen gneiss, part of Malton Complex	736 +23/-17	U-Pb zircon	McDonough and Parrish, 1991
6	Mt. Copeland syenite gneiss, Monashee Complex	740 ± 36	U-Pb zircon	Parrish and Scammell, 1988
7	Layered paragneiss, Thor-Odin gneiss dome, Monashee Complex	744 ± 53	Rb-Sr slab isochron	Duncan, 1984
8	Huckleberry volcanics northeast Washington State	762 ± 44	Sm-Nd mineral separate isochron	Devlin et al., 1988

that indicate extension (Bennett, 1985; Root, 1987). However, indicators of glacial influence, including limestones, nonlocal clast types and striated clasts are present elsewhere (Root, 1987; Eisbacher, 1981).

Glaciogenic deposition of basal Windermere rocks in the northern Canadian Cordillera is documented by Eisbacher (1981, 1985) and Yeo (1981) in the Rapitan Group of the Mackenzie and Wernecke mountains of the western Northwest Territories and eastern Yukon Territory. The diamictite-rich Shezal Formation contains limestones of convincing dropstone origin, abundant striated and faceted clasts (some of nonlocal origin), and in one place overlies a striated pavement (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, limestones, 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.

Although a glacial influence on the Sayunei Formation depositional environment is not disputed here, deposition of some of the conglomerates and associated sedimentary rocks due to syndimentary faulting also seems likely. Eisbacher (1981) first documented syndimentary faulting related to Rapitan Group deposition. Yeo (1984, p. 37, 38, plates 1d-f) identified paleoscarps at the base of the Rapitan Group and at least one associated "talus breccia wedge" (Yeo, 1984; p. 37). Jefferson and Parrish (1989, Fig. 5 and p. 1786, 1798) also illustrated preserved syndimentary faults and adjacent "fanglomerates", up to 200 m thick and in gradational contact with overlying Sayunei Formation.

The presence of glacial deposits associated with extensional faulting in some areas, and the absence in others such as within the Mount Harper Group, could reflect diachronous rifting along the then western margin of North America. Another possibility is that glaciation did not effect all of the rifted western margin, conceivably a result of a mountainous coastline in which glaciers only locally advanced into the basins (first suggested by Yeo, 1984).

A succession of nonglacial carbonates, evaporites, redbeds, and minor conglomerates, the Coates Lake Group, occurs locally below the Rapitan Group in the Mackenzie Mountains. This succession has been included as part of the basal Windermere by some workers (Aitken, 1981; Morris and Aitken, 1982; J.D. Aitken pers. comm., 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; C.W. Jefferson pers. comm., 1990).

The redbeds and abundant evidence for a hot, arid climate during Coates Lake deposition are features permissive with correlation of this succession with at least the lower Mount Harper Group. However, although there is some evidence at the base of the lower Mount Harper Group for arid and

temperate paleoclimate (Mustard and Donaldson, 1990), the paleoclimatic evidence for most of the rift-related part of the Mount Harper Group is ambiguous.

Several features suggest the Mount Harper Group is not correlative with the Coates Lake Group. Conglomerates form only a minor part of the Coates Lake Group, exceeding 30 m in thickness in only one place, whereas evaporites are common in the Coates Lake Group, but absent in the Mount Harper Group. Although the Mount Harper Group is directly related to a major extensional event, Jefferson and Parrish (1989) argued that in the Mackenzie Mountains the main period of Late Proterozoic faulting occurred after Coates Lake Group deposition, either before or during the time of initial Rapitan Group deposition. Yeo (1984) interpreted the local abundance of volcanic clasts and the presence of rare tuffs in the Rapitan Group as evidence of a volcanic event associated with deposition of the Rapitan Group. This indirect evidence for volcanism, combined the evidence for major faulting and thick associated conglomerates given previously for basal Rapitan Group, more strongly support correlation of the the Mount Harper Group with the Rapitan Group than the Coates Lake Group.

### Conclusion

In a region characterized by minor compressive deformation and gently dipping thrust panels, the Mount Harper Group is the best known exposure of igneous extrusive activity and sedimentation associated with the initial Windermere rifting event. The extensive vertical exposure and great lateral continuity in the Mount Harper area allows an unusually detailed record of the sequence of faulting, sedimentation, and volcanism to be documented. The U-Pb zircon date from a volcanic flow at Mount Harper provides a precise chronological fix for volcanism directly associated with Windermere rifting, and in conjunction with the faulting history provides an unparalleled record of the initial tectonism and deposition of the Windermere Supergroup.

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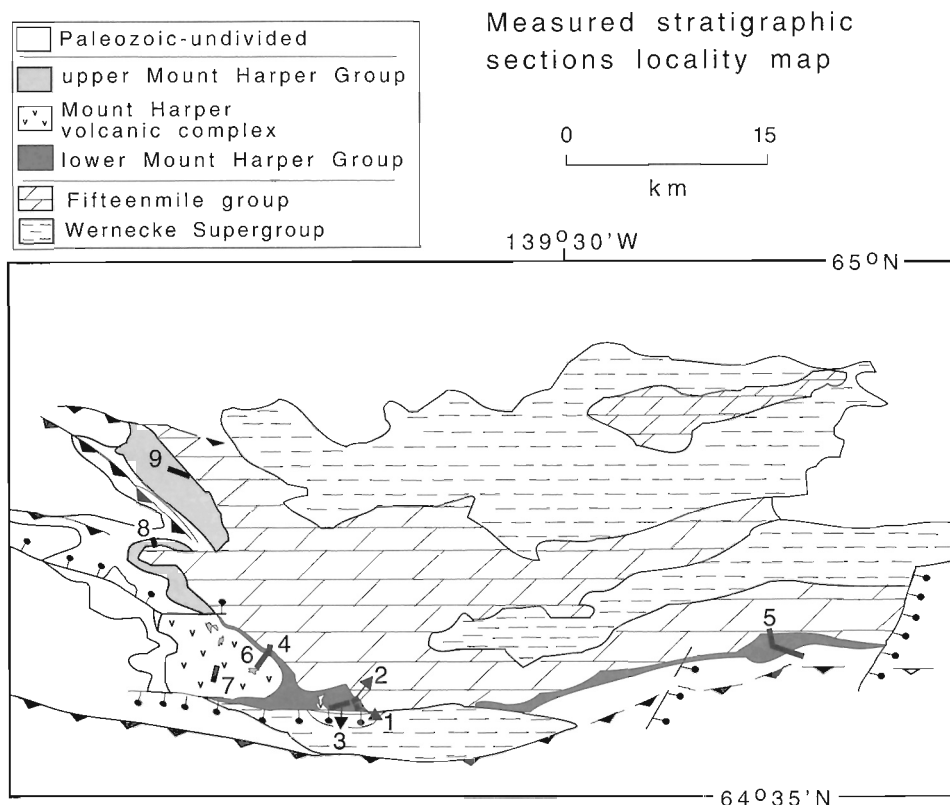
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# APPENDIX 1

## Measured sections

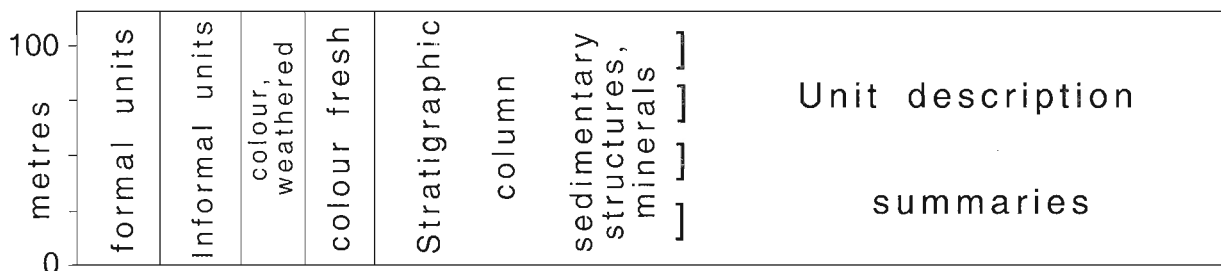
This appendix consists of 9 measured stratigraphic sections displayed in columnar form. Section locations are shown in Figure A1-1 with section bases detailed in Table 2. All symbols, patterns and abbreviations are explained in Figure A1-2.

All sections were measured at surface using a Jacob staff. Sections 1 to 5 were measured in June-August of 1986. Sections 6 and 7 were measured in June-July of 1982. Sections 8 and 9 were measured in June-July of 1987.



**Figure A1-1.** Coal Creek Inlier geology showing approximate locations of reference sections 1 to 9. Section locations are detailed in the heading of each reference section log.

## KEY TO COLUMNAR SECTIONS



### COLOUR SYMBOLS

	black
	dark grey
	medium grey
	light grey
m-b	medium brown
g-b	grey-brown
g-g	grey-green
g-o	grey-orange
brn	brown
grn	green
org	orange

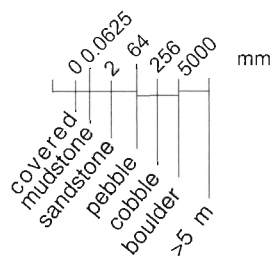
### ROCK TYPES

	massive flows		pillow flows
	mafic dykes, sills		pillow breccia, isolated
	clast-supported conglomerate		pillow breccia, broken
	matrix-supported conglomerate		breccia in hyaloclastite matrix
	sandstone		intrusion breccia
	siltstone		flow breccia
	breccia		pebbly mudstone
	mudstone		volcanic conglomerate
	dolostone		hyaloclastite
	limestone mudstone		
	covered		

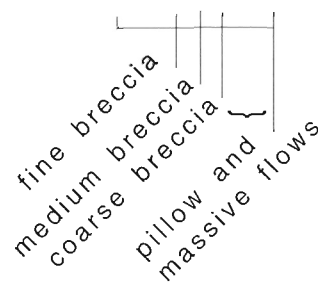
### SYMBOLS

	desiccation cracks
	clast imbrication
	asymmetric ripples
	planar crossbedding
	trough crossbedding
	flute casts
	stomatolites
	cherty or silicified
	carbonate concretions

### SEDIMENTARY ROCKS



### VOLCANIC AND VOLCANICLASTIC ROCKS



	syndimentary folding
	lonestone
	chemical sample

*Figure A1-2. Legend for reference sections.*

SECTION 1

Section located in south-facing bowl near trace of Harper Fault; UTM 7169688N, 559718E in NTS map area 116B-116C (E half) (Dawson, Yukon Territory; 1:50 000 scale map 116B/12 (Mount Harper). Best seen in RCAF airphoto A13135-146.

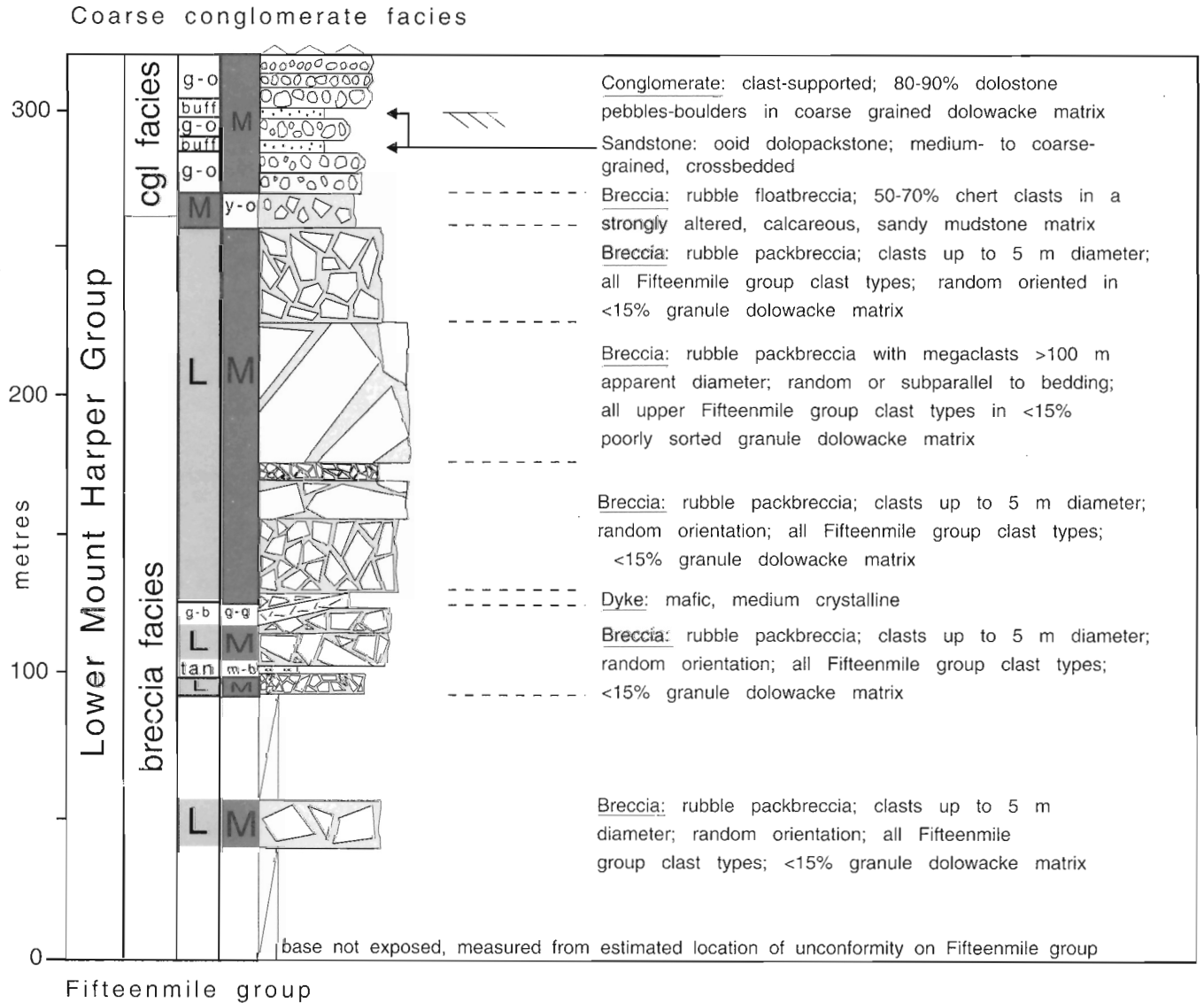


Figure A1-3. Lower Mount Harper Group: reference section 1.

SECTION 2

Section located on north face of peak (elev. 1770 m) at intersection of north-trending ridge of Fifteenmile group, low west-northwest-trending ridge of lower Mount Harper Group and southwest-trending ridge immediately north of Harper Fault. UTM 7170996N, 560091E in NTS map area 116B-116C(E half) (Dawson), Yukon Territory; 1:50 000 scale map area 116B/12 (Mount Harper). Best seen in RCAF airphoto A13135-146. Total thickness = 406 m.

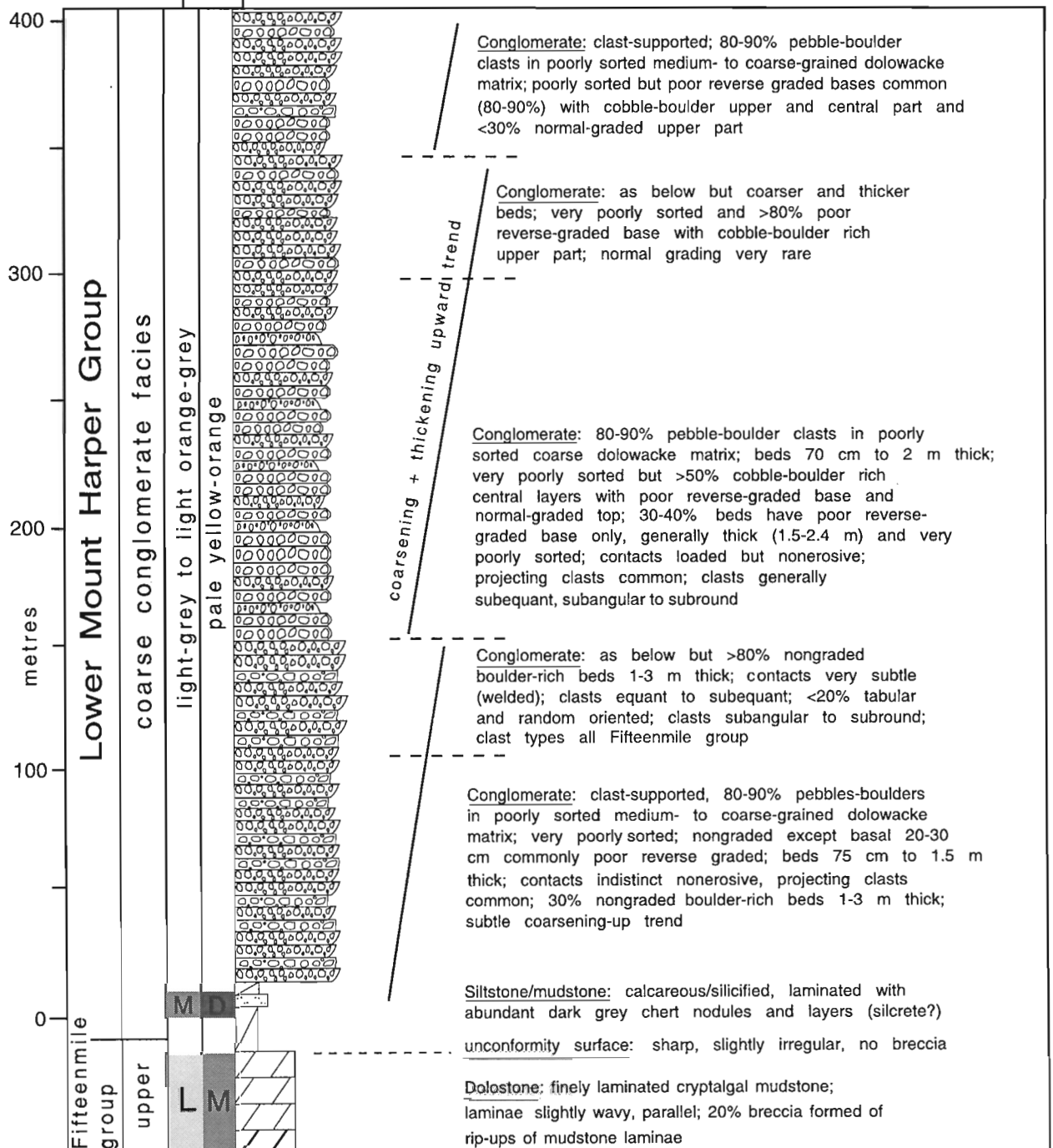


Figure A1-4. Lower Mount Harper Group: reference section 2.

### SECTION 3

Section base located in creek near the west end of west-southwest-trending main lower Mount Harper Group conglomerate ridge. UTM co-ordinates 7170473N, 558694E in NTS map area 116B-116C(E half) (Dawson), Yukon Territory; 1:50 000 scale map 116B/12 (Mount Harper). Best seen in RCAF airphoto A13135-146.

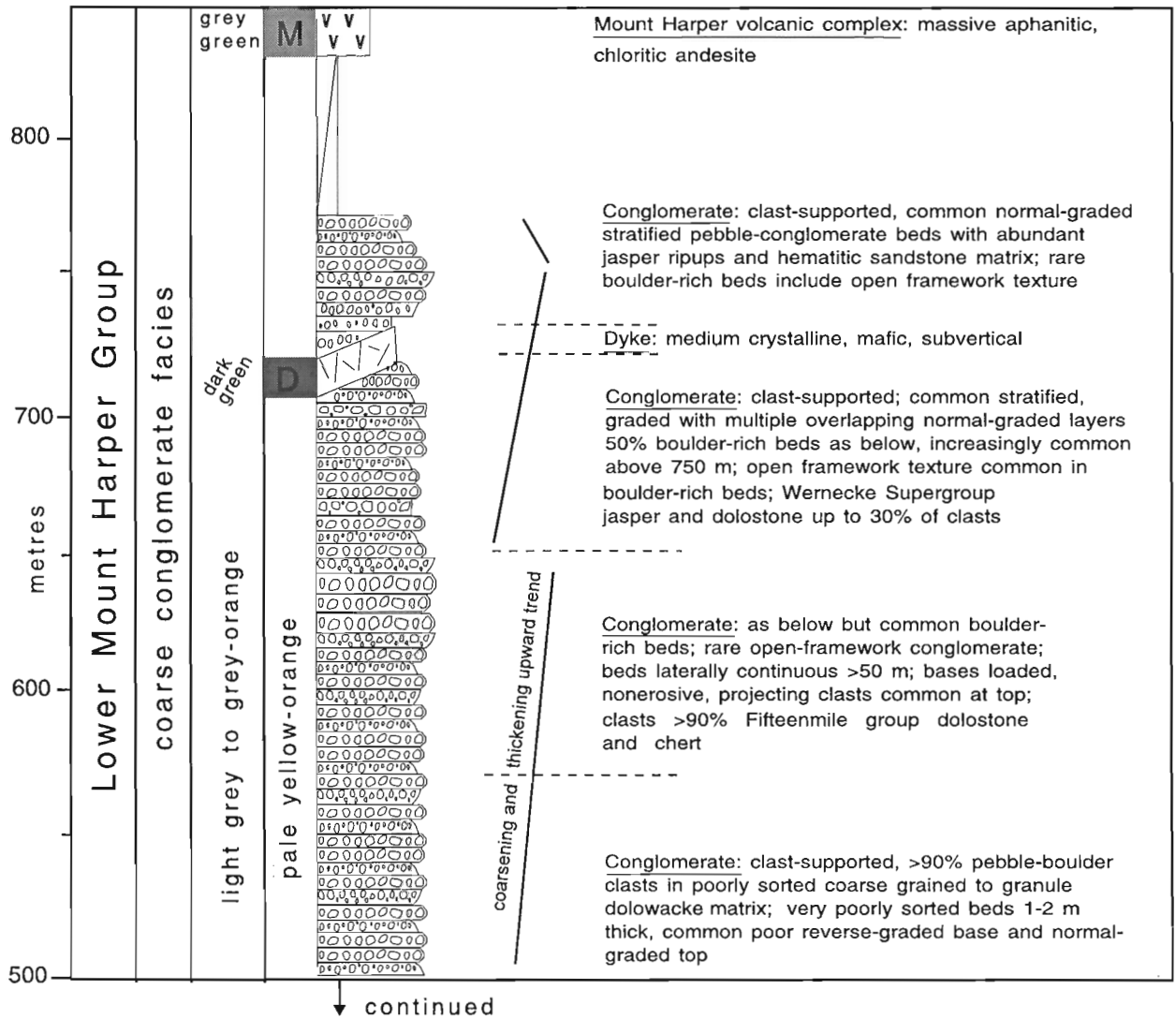


Figure AI-5. Lower Mount Harper Group: reference section 3.

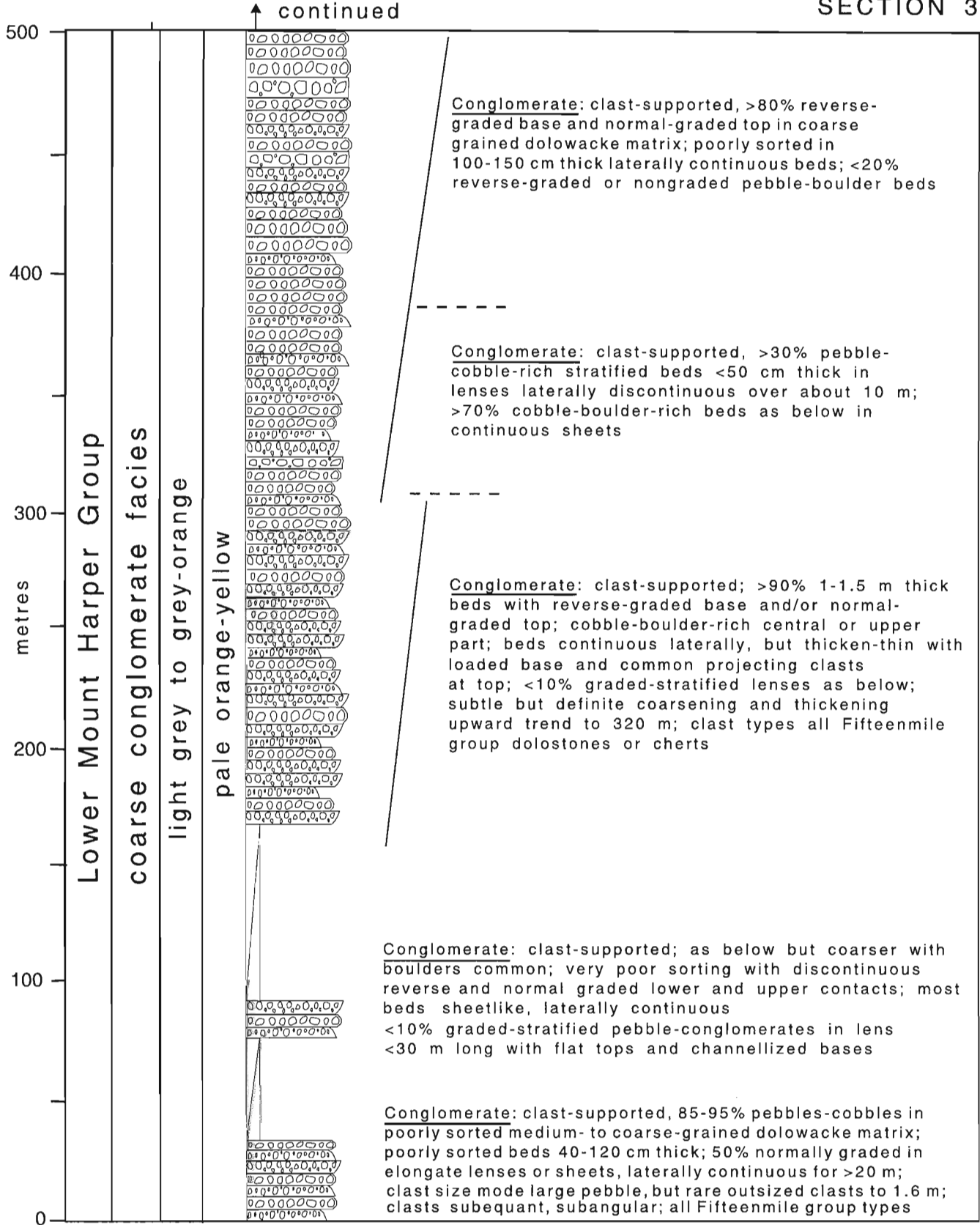


Figure A1-5. (cont.)

## SECTION 4

Section located on north-trending ridge north of Mount Harper peak. UTM coordinates 7173365N, 554409E in NTS map area 116B-116C(E half) (Dawson), Yukon Territory; 1:50 000 scale map 116B/12 (Mount Harper). Best seen in RCAF airphoto 13135-146. Total thickness = 251 m.

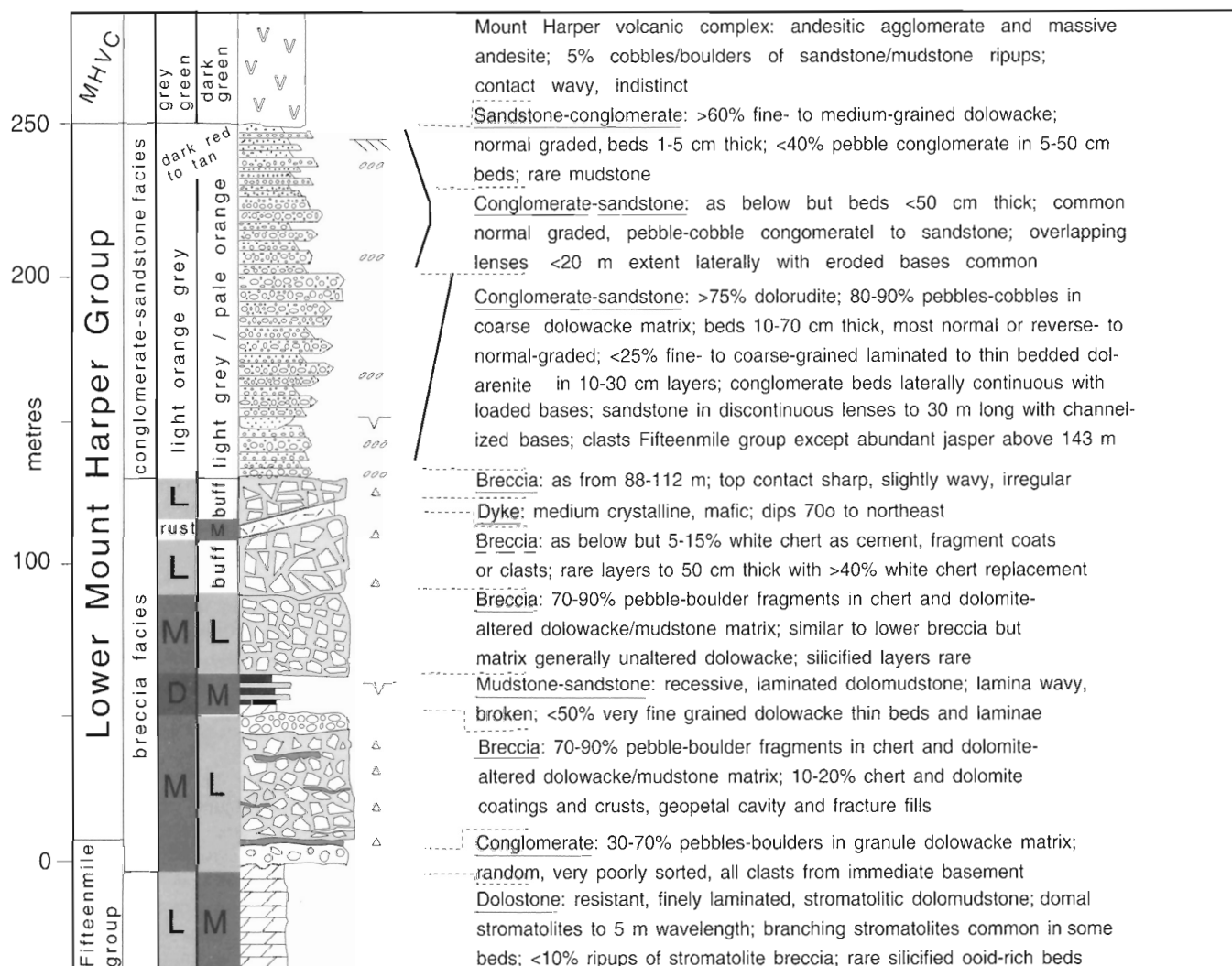


Figure A1-6. Lower Mount Harper Group: reference section 4.

## SECTION 5

Section located in south-flowing creek cutting east-trending ridge north of Seela Pass and on west-facing slope of ridge. UTM co-ordinates 7174540N, 589450E in NTS map area 116B-116C(E half) (Dawson), Yukon Territory; 1:50 000 scale map area 116B/11. Best seen in RCAF airphoto A13230-155. Total Thickness = 612 m

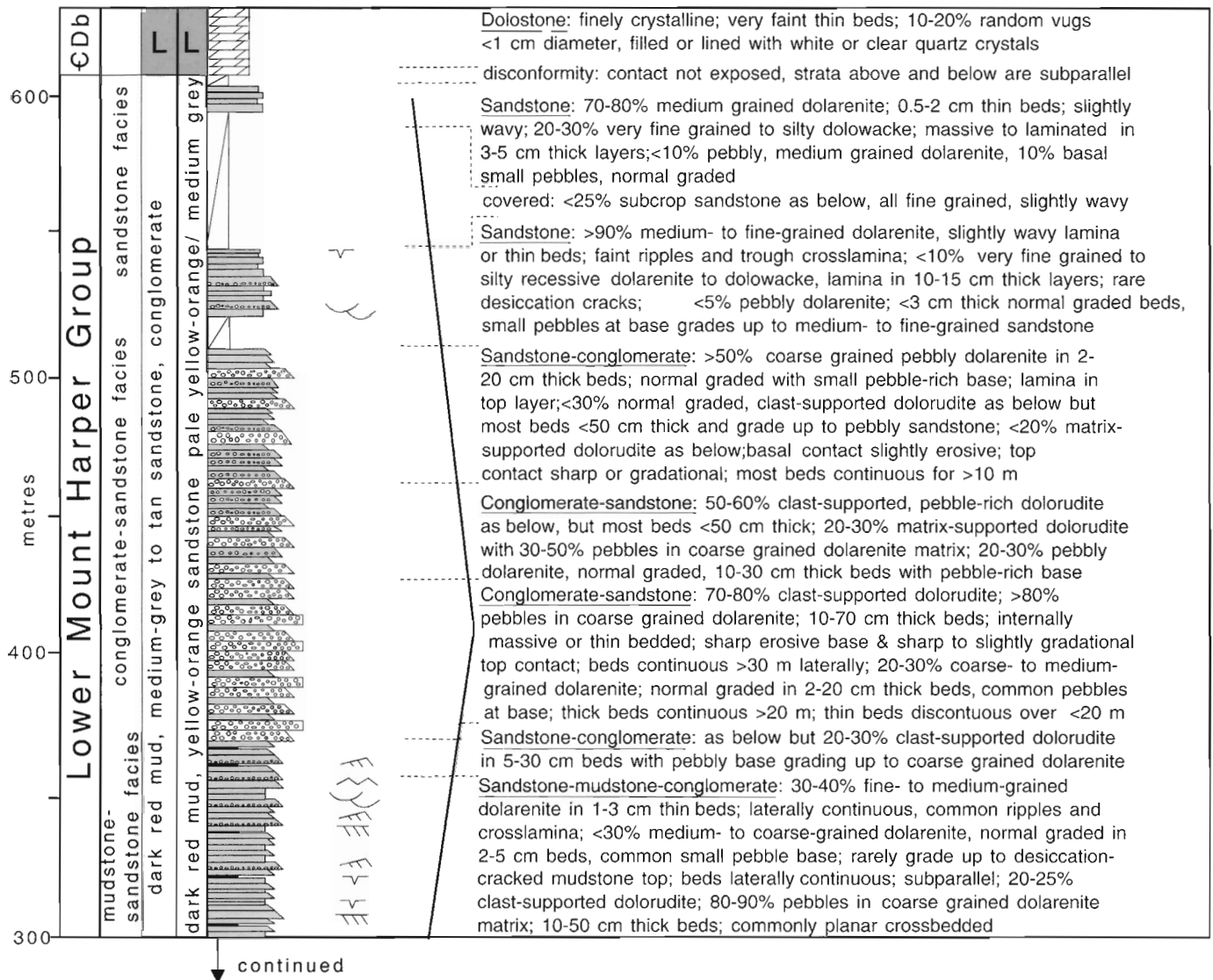


Figure A1-7. Lower Mount Harper Group: reference section 5.

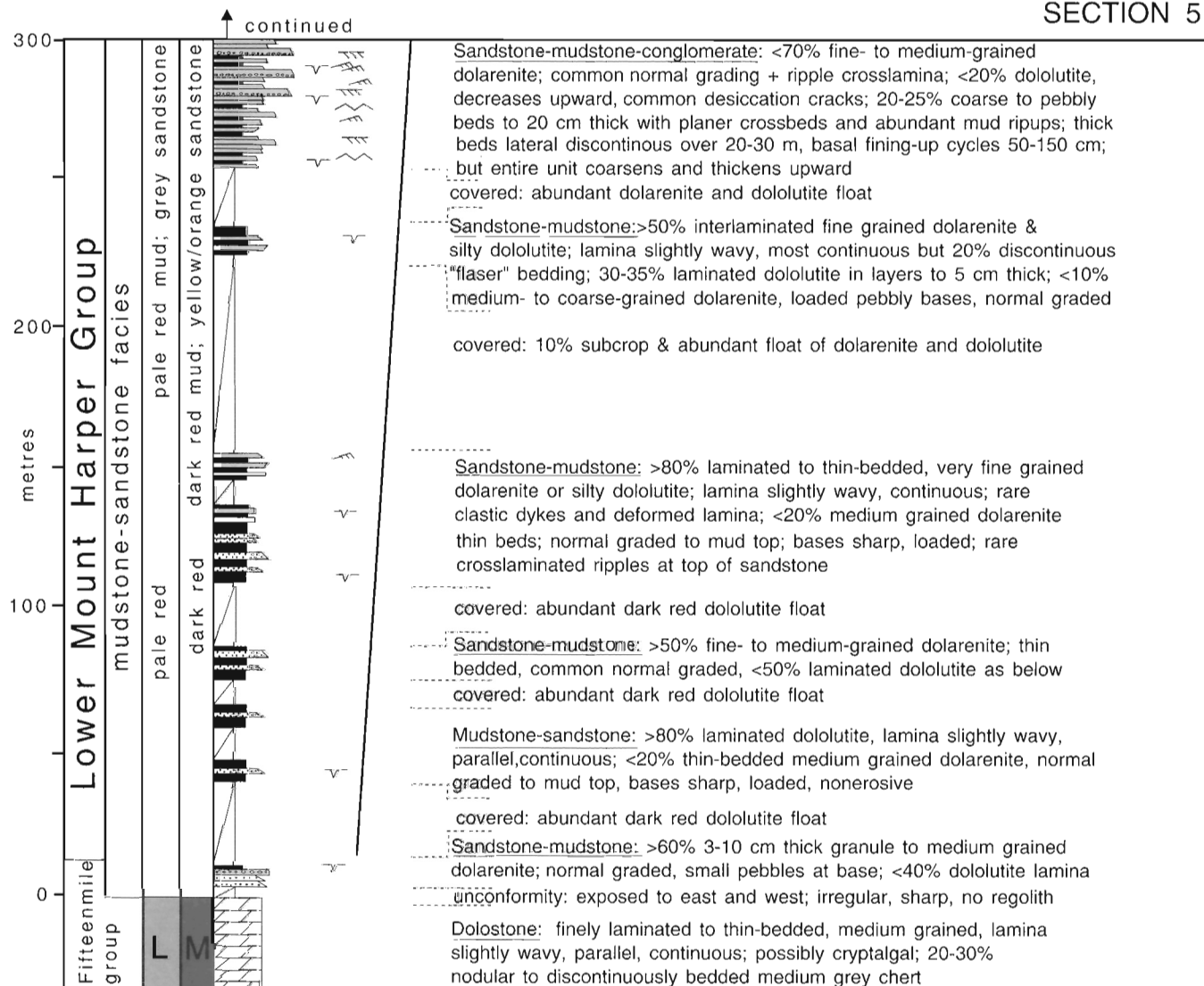


Figure A1-7. (cont.)

## SECTION 6

Section located on north-facing cliff immediately north of Mount Harper summit. UTM co-ordinates 7172510N, 553297E in NTS map area 116B - 116C (east half) (Dawson) Yukon Territory; 1:50 000 scale map area 116B/12. Total thickness 596 m

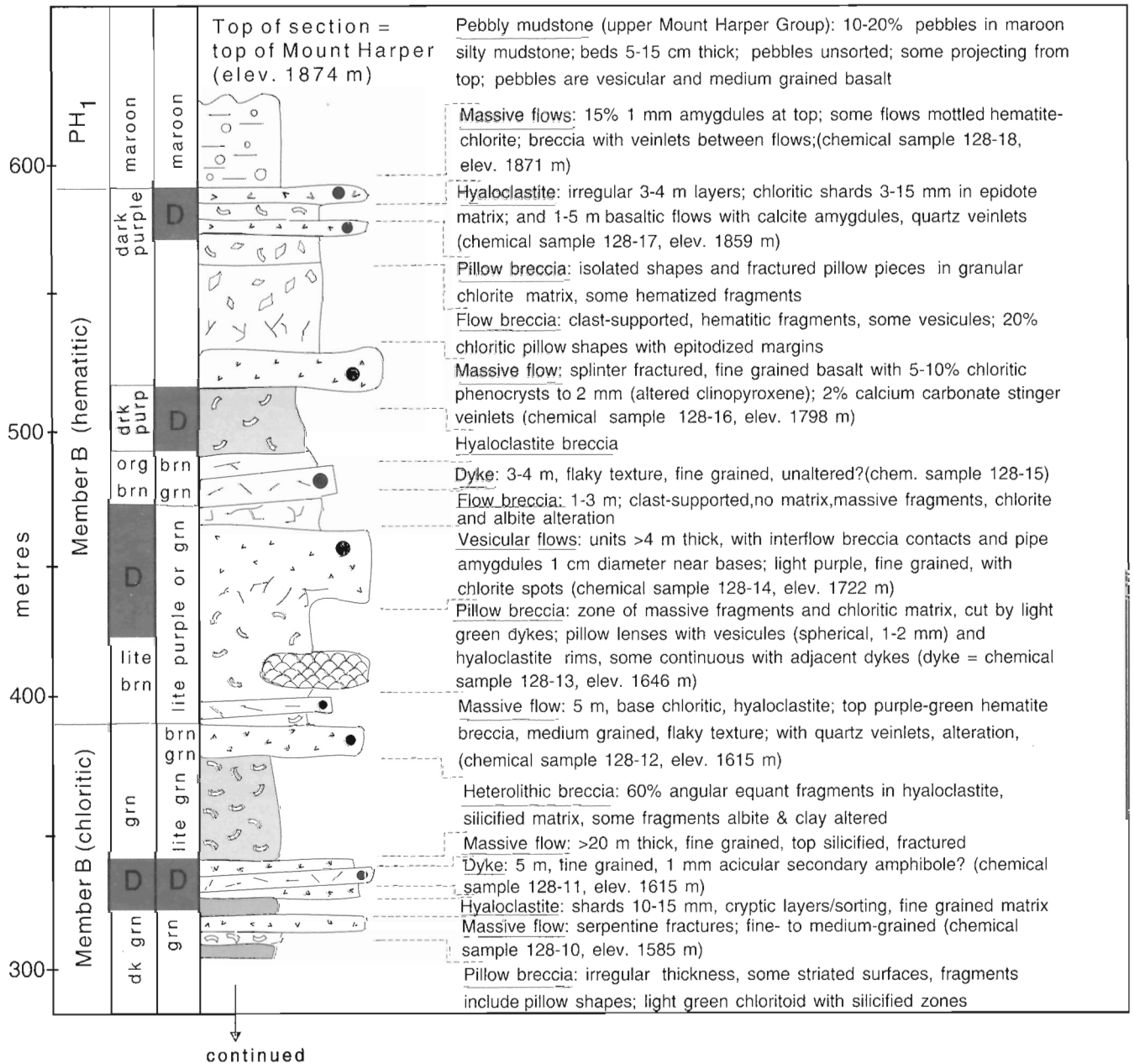


Figure A1-8. Mount Harper Volcanic Complex: reference section 6.

SECTION 6

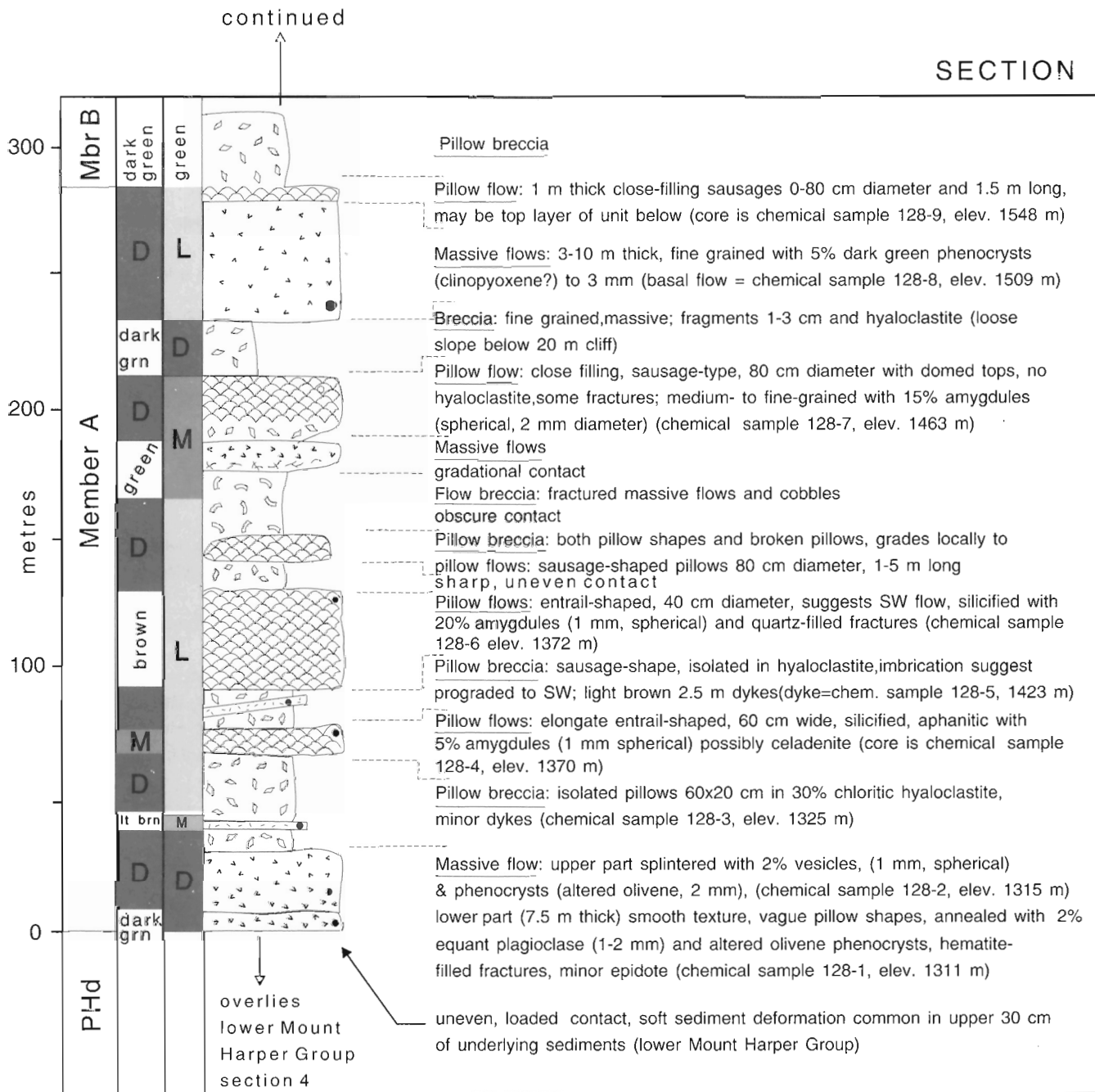


Figure A1-8. (cont.)

## SECTION 7

Section located on northeast spur of ridge 4.5 km southwest of Mount Harper. UTM co-ordinates 7171516N, 549468E in NTS map area 116B-116C (east half) (Dawson) Yukon Territory; 1:50 000 scale map area 116B/12  
 Total thickness 596 m.

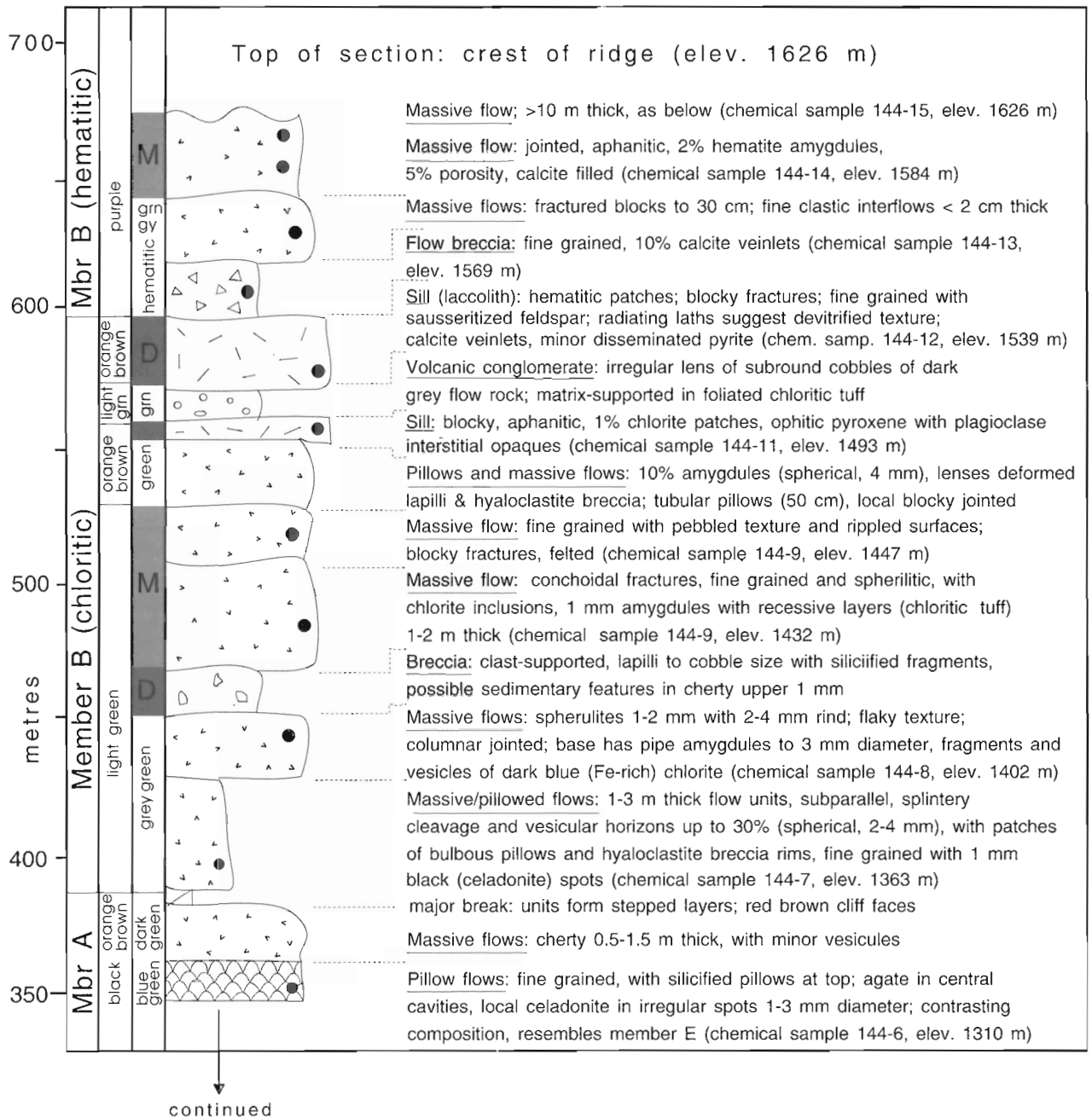


Figure A1-9. Mount Harper Volcanic Complex: reference section 7.



## SECTION 8

Section located on south-facing slope of east-trending ridge north of Eagle Creek headwaters. UTM co-ordinates 7184083N 54107E in NTS map area 116B-116C(E half) (Dawson), Yukon Territory; 1:50 000 scale map 116C/16. Best seen in RCAF airphoto A13231-167. Total thickness = 295 m.

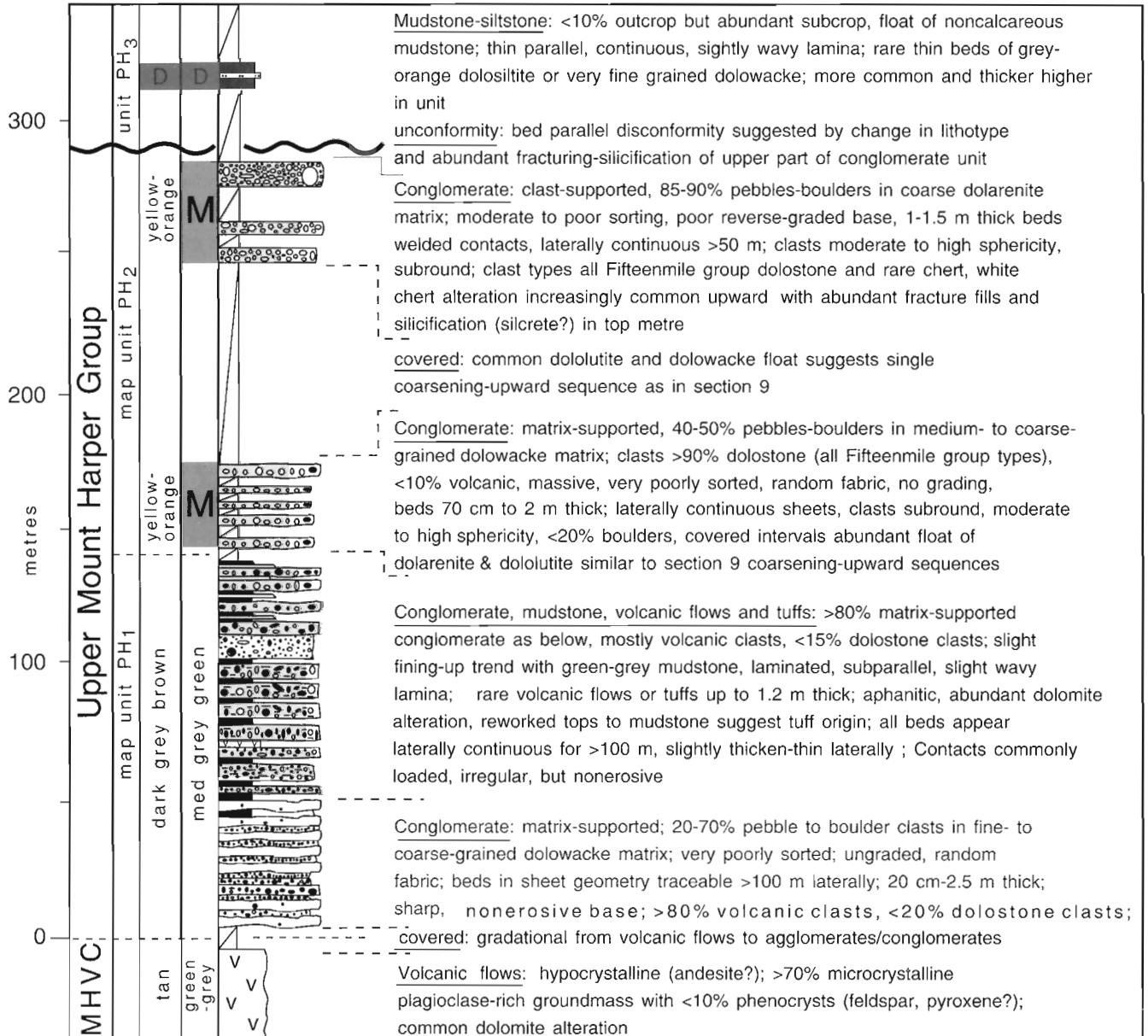


Figure A1-10. Upper Mount Harper Group: reference section 8.



## APPENDIX 2

### Mount Harper volcanic complex geochemistry

Whole rock analyses of 106 rock samples were used to determine the original nature of the volcanic rocks and to characterize the composition of the volcanic complex. The results support field evidence for two magmatic suites: members A and B whose composition is fairly uniform, and members D and E which, despite their andesite-rhyolite dichotomy, are similarly enriched in large-ion lithophile (or incompatible) elements. Although all samples are altered it is clear that physical differences that allowed members to be distinguished in the field extend to their chemistry. These distinctions provide clues to the magmatic evolution and tectonic setting of the Mount Harper volcanic complex.

#### *Sampling and results*

Representative stratigraphic and spatial coverage of the Mount Harper volcanic complex was gained through selected 2 to 4 kg samples of massive flows and intrusions. Members A, B, D, and E were recognized in the field and samples taken from the least fractured and altered outcrops. Member C, which consists mostly of breccias, was not sampled. Variation with stratigraphic height was investigated by systematically sampling three sections.

The samples were collected as follows: intact rocks weighing 2 to 4 kg (largest for medium grained rocks) were collected from freshest outcrops at preselected localities. They include cores of pillows, micro- and nonvesicular flows and central zones of dykes and sills. Weathered surfaces, discoloration along fractures, and secondary minerals in amygdules and veinlets were trimmed and removed in the field; visibly altered rocks were avoided. In thin sections of these samples secondary minerals were distinguished from primary minerals and samples found to be dominantly secondary calcite or quartz were not sent for chemical analysis.

Major oxide and trace element analyses were done in February 1984 at the Geological Survey of Canada, Ottawa, by X-ray fluorescence (XRF) spectroscopy following standard procedures of the Analytical Chemistry laboratory. One gram of sample (ground to -325 mesh) was mixed with 5.0 g of  $\text{LiB}_2\text{O}_7$  and 0.3 g LiF, and fused to a glass disc within a platinum holder. Major elements were measured on this disc using the wavelength dispersive method, with readings of 20 min/disc, starting with 100 seconds for K and Na and 100 seconds for background Na. Matrix effects resulting from adsorption and enhancement caused by excitation of other elements within the sample were corrected by alpha coefficients determined theoretically by D.M. Rousseau (pers. comm., 1987) of the Geochemistry laboratory. Minor elements were measured on the powdered sample in a mylar-floored holder using the energy dispersive method (G.R. Lachance, pers. comm., 1984).

Volatile fractions ( $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , and S) were determined by mixing the sample with oxides of vanadium and tungsten in nickel combustion boats, decomposing them at  $950^\circ\text{C}$  in a nitrogen atmosphere, and measuring evolved gases by nondispersive infrared absorptiometry (Bouvier and Abbey, 1980); FeO was determined by titration;  $\text{Fe}_2\text{O}_3$  was calculated from: (total Fe as  $\text{Fe}_2\text{O}_3$  by XRF) - 1.1134 FeO (volumetric). Accuracy of the analyses was determined by checks on five GSC samples run for internal verification, as well as three samples submitted blind for which analyses were available from other laboratories. Precision was estimated by analysis of four sets of duplicate samples. Tables of precision and accuracy are found in Roots (1987).

The CIPW normative calculations and numerous graphical presentations were performed by computer at the Geological Survey of Canada (IMALECA program). For these calculations  $\text{Fe}_2\text{O}_3$  in excess of ( $\text{TiO}_2 + 1.5$ ) was converted to ferrous iron (Irvine and Baragar, 1971). To minimize differences between samples that result from variations in water and carbon dioxide content analyses have been recalculated to 100% on a volatile-free basis.

The composition and CIPW norms of all samples from members A, B, D, E, and F are shown in the following table, subdivided by member.

Table A2-1. Whole rock analyses from member A (p. 1 of 3).

#	131-1*	118-6	144-11*	130-2*	132*	130-1*	131-2*	128-3*	133*	127-2	128-4 *
Lith.	mI5	mF	mF	mI3	pc	fl4	fl3	mF3	pc	mF	mF
Unit	A	A	A	A	A	A	A	A	A	A	A
East.	55231	54815	54946	55279	55205	55275	55215	55350	55298	55358	54954
North	717109	717670	717080	717121	717110	717115	727100	717290	717155	717295	717385
Elev.	3150'	5400'	4900'	4075'	2700'	4100'	3150'	4350'	3425'	4400'	4500'
SiO <sub>2</sub>	50.50	50.20	46.10	49.80	47.70	52.30	48.40	47.30	53.50	47.70	52.70
Al <sub>2</sub> O <sub>3</sub>	15.20	14.00	15.30	15.90	13.00	13.60	13.60	14.00	14.10	13.60	14.20
Fe <sub>2</sub> O <sub>3</sub>	2.10	2.10	1.50	1.60	1.50	1.40	2.00	1.90	1.60	2.00	1.20
FeO	7.20	7.20	7.40	6.60	6.00	5.60	7.40	7.70	4.50	7.60	7.00
MgO	5.08	7.04	6.79	6.35	6.94	6.51	8.17	10.80	6.39	11.30	7.17
CaO	11.20	10.40	12.00	11.20	11.50	8.53	11.30	11.40	8.08	11.10	4.36
Na <sub>2</sub> O	1.10	2.10	0.90	1.70	1.60	2.70	1.00	0.20	2.60	0.40	4.00
K <sub>2</sub> O	0.92	0.74	0.12	0.62	0.30	0.22	0.38	0.12	0.28	0.16	0.10
TiO <sub>2</sub>	0.93	0.67	0.69	0.83	0.61	0.76	0.79	0.69	0.61	0.66	0.75
P <sub>2</sub> O <sub>5</sub>	0.10	0.06	0.09	0.09	0.07	0.08	0.08	0.07	0.09	0.07	0.10
MnO	0.18	0.19	0.17	0.16	0.15	0.17	0.19	0.18	0.15	0.20	0.13
S	0.03	0.08	0.0	0.01	0.0	0.0	0.0	0.31	0.0	0.04	0.29
Ba	0.028	0.070	0.008	0.029	0.008	0.011	0.017	0.010	0.010	0.013	0.10
Cr <sub>2</sub> O <sub>3</sub>	0.02	0.04	0.08	0.06	0.14	0.13	0.16	0.13	0.10	0.13	0.08
CO <sub>2</sub>	2.10	2.40	3.90	2.00	5.40	2.50	2.80	0.20	4.30	0.30	2.10
H <sub>2</sub> O	<u>3.00</u>	<u>3.20</u>	<u>3.40</u>	<u>3.50</u>	<u>3.60</u>	<u>3.70</u>	<u>3.70</u>	<u>3.90</u>	<u>3.90</u>	<u>4.00</u>	<u>4.60</u>
Total	99.66	100.47	98.44	100.42	98.51	98.70	99.97	98.9	100.30	99.26	98.78
As	4	4	12	7	21	0	12	12	1	4	0
Br	3	4	1	1	4	5	0	4	1	1	3
Mo	2	0	1	2	3	0	0	7	0	4	2
Nb	6	2	6	6	4	5	6	6	3	5	5
Pb	12	9	10	6	14	13	13	11	11	11	10
Rb	26	12	4	15	12	6	9	2	8	3	0
Sr	268	142	102	218	66	144	121	91	72	125	364
Th	6	6	7	4	3	5	1	2	2	5	5
U	0	0	0	0	0	0	0	1	3	0	0
Y	34	32	23	23	20	29	24	25	21	22	20
Zr	98	71	70	83	52	79	77	61	55	59	73
Q	12.48	6.44	10.79	7.44	13.84	12.31	9.39	4.99	20.43	4.01	11.04
C	0.0	0.0	1.18	0.0	1.91	0.0	0.0	0.0	5.20	0.0	4.98
OR	5.63	4.50	0.75	3.78	1.87	1.37	2.33	0.75	1.72	0.99	0.63
AB	9.63	18.27	8.01	14.84	14.26	24.05	8.79	1.78	22.84	3.55	35.94
AN	34.99	27.34	36.08	35.00	23.66	25.62	32.72	38.90	12.79	36.57	8.18
DI	3.89	5.19	0.0	4.61	0.0	0.99	3.64	11.17	0.0	11.16	0.0
HE	2.74	2.70	0.0	2.45	0.0	0.41	1.69	3.99	0.0	3.94	0.0
EN	11.28	15.74	17.79	14.18	18.21	16.60	19.44	23.13	16.52	24.36	18.96
FS	9.10	9.39	12.05	8.65	9.41	7.85	10.36	9.47	6.36	9.86	10.83
FO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MT	3.15	3.13	2.29	2.39	2.29	2.90	3.01	2.90	2.40	3.04	1.85
IL	1.83	1.30	1.38	1.63	1.22	1.52	1.56	1.38	1.20	1.31	1.51
CR	0.03	0.06	0.12	0.09	0.22	0.20	0.24	0.20	0.15	0.20	0.12
AP	0.24	0.14	0.22	0.21	0.17	0.19	0.19	0.17	0.22	0.17	0.24
PY	0.06	0.17	0.0	0.21	0.0	0.0	0.0	0.67	0.0	0.08	0.63
CC	4.94	5.61	9.32	4.69	12.94	5.98	6.61	0.48	10.15	0.71	5.07

\* Less altered set; **Lithology**: F = flow, I = intrusion; prefix **medium** or **fine grain**; suffix is thickness in metres, where known; **pc** = pillow core. **Unit** designation from stratigraphy and chemical discriminants; **Easting** and **Northing** are UTM coordinates (prefixed 7WEB, on 116B/12 and 116C/9 maps), **Elevation** in feet. Major elements in wt.%; minor elements in ppm; normative calculations in wt.%

Table A2-1. Whole rock analyses from member A (p. 2 of 3).

#	128-11	128-9	128-8	128-7	128-6	97b	15	8	124-3	118-8	118-7
Lith.	I5	pc	mF	pc	pc	pc	pc	pc	pc	mF8	fF1
Unit	A	A	A	A	A	A	A	A	A	A	A
East.	55365	55360	55355	55350	55350	55390	55392	55410	54590	54790	54800
North	717260	717273	717278	717275	717280	717010	717035	716985	717732	717645	717660
Elev.	5300'	5080'	4950'	4800'	4670'	4800'	4900'	4600'	4700'	5400'	5475'
<hr/>											
SiO <sub>2</sub>	47.70	48.50	45.90	34.80	52.00	44.80	38.90	46.80	43.40	45.50	49.80
Al <sub>2</sub> O <sub>3</sub>	14.00	13.90	14.00	13.90	14.40	14.30	11.80	14.10	16.00	19.00	18.70
Fe <sub>2</sub> O <sub>3</sub>	2.30	0.80	1.00	0.60	1.50	1.30	1.20	1.30	2.00	1.30	1.40
FeO	7.90	4.90	4.80	5.80	5.70	5.40	4.90	6.40	6.90	5.30	5.00
MgO	6.25	3.84	4.57	5.10	6.86	5.93	5.68	5.55	5.69	5.24	5.62
CaO	8.64	11.40	12.00	17.60	8.09	10.80	17.50	9.15	9.30	9.28	9.50
Na <sub>2</sub> O	2.20	3.50	3.30	1.90	2.10	2.80	1.60	3.30	3.30	1.30	1.10
K <sub>2</sub> O	0.28	0.33	0.91	0.67	0.24	0.37	0.26	0.46	0.71	2.10	0.49
TiO <sub>2</sub>	1.30	0.74	0.79	0.45	0.68	0.65	0.59	0.72	0.57	0.49	0.51
P <sub>2</sub> O <sub>5</sub>	0.13	0.08	0.10	0.03	0.09	0.08	0.04	0.08	0.06	0.04	0.07
MnO	0.16	0.18	0.14	0.23	0.17	0.14	0.17	0.14	0.16	0.10	0.10
S	0.16	0.04	0.0	0.69	0.12	0.01	0.0	0.05	0.0	0.01	0.0
Ba	0.010	0.033	0.019	0.017	0.010	0.006	0.006	0.023	0.013	0.062	0.022
Cr <sub>2</sub> O <sub>3</sub>	0.02	0.08	0.09	0.07	0.08	0.08	0.07	0.08	0.13	0.07	0.06
CO <sub>2</sub>	4.20	8.80	9.00	13.00	3.90	8.40	12.70	6.50	7.10	5.40	2.90
H <sub>2</sub> O	<u>4.60</u>	<u>3.20</u>	<u>3.50</u>	<u>4.40</u>	<u>4.50</u>	<u>4.20</u>	<u>3.90</u>	<u>4.30</u>	<u>4.10</u>	<u>4.80</u>	<u>4.10</u>
Total	99.84	99.79	100.70	99.24	100.43	98.71	99.31	99.03	99.45	99.99	100.05
<hr/>											
As	0	9	0	4	4	0	0	0	4	2	0
Br	1	0	5	3	2	1	1	0	2	0	4
Mo	0	0	0	3	0	1	2	1	0	1	2
Nb	6	4	6	2	3	5	4	5	3	3	4
Pb	9	10	10	15	12	8	10	6	12	11	9
Rb	6	8	20	16	5	11	5	15	15	35	6
Sr	102	182	111	74	102	47	59	68	103	89	100
Th	2	4	4	1	5	0	0	1	0	0	1
U	2	2	1	2	0	0	3	0	0	0	0
Y	30	23	29	23	22	19	18	18	14	15	15
Zr	116	68	82	42	65	66	58	71	51	47	48
<hr/>											
Q	13.75	18.28	12.78	8.06	19.31	14.79	14.78	12.32	8.28	13.87	14.07
C	4.63	7.39	7.67	8.69	5.45	9.83	6.90	7.18	9.89	10.77	5.02
OR	1.74	2.02	5.54	4.18	1.48	2.31	1.61	2.87	4.40	13.42	3.02
AB	19.54	30.66	28.72	16.96	18.52	25.07	14.19	29.47	29.28	11.55	15.87
AN	16.24	0.42	2.04	5.21	15.52	0.0	6.57	3.99	1.06	12.23	29.53
DI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EN	16.34	9.9	11.71	13.39	17.81	15.74	14.82	14.59	14.86	13.70	14.58
FS	10.93	7.55	7.06	8.12	8.45	8.39	7.64	10.11	10.76	8.35	7.63
FO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MT	3.50	1.20	1.49	.92	2.26	1.99	1.82	1.99	3.04	1.98	2.11
IL	2.59	1.45	1.54	0.90	1.35	1.31	1.17	1.44	1.13	0.98	1.00
CR	0.03	0.12	0.14	0.11	0.12	0.12	0.11	0.12	0.20	0.11	0.09
AP	0.32	0.19	0.24	0.07	0.22	0.19	0.09	0.19	0.15	0.09	0.17
PY	0.35	0.85	0.0	1.49	0.26	0.02	0.0	0.11	0.0	0.02	0.0
CC	10.35	20.72	21.06	31.19	9.25	20.21	30.27	15.60	16.93	12.90	6.87

\* Less altered set; **Lithology**: F = flow, I = intrusion; prefix **medium** or **fine grain**; suffix is thickness in metres, where known; **pc** = pillow core. **Unit** designation from stratigraphy and chemical discriminants; **Easting** and **Northing** are UTM coordinates (prefixed 7WEB, on 116B/12 and 116C/9 maps), **Elevation** in feet. Major elements in wt.%; minor elements in ppm; normative calculations in wt.%

**Table A2-1.** Whole rock analyses from member A (p. 3 of 3).

#.	118-5	118-4	118-3	118-2	117-2	117-1	158-2	144-10	144-9	144-8	144-7	144-2
Lith.	mF	mF	fl	pc	pc	mF	mF	mF	fl5	fl3	mF	mF
Unit	A	A	A	A	A	A	A	A	A	A	A	A
East.	54811	54817	54821	54820	54870	54870	55042	55448	54946	54943	54940	54920
North	717661	717667	717670	717669	717750	717760	717069	717095	717100	717110	717120	717155
Elev.	5225'	5150'	5100'	5050'	3850'	3700'	3800'	4750'	4700'	4600'	4475'	4000'
SiO <sub>2</sub>	35.20	45.80	42.80	58.00	48.90	47.20	39.60	45.00	45.90	46.00	45.10	49.20
Al <sub>2</sub> O <sub>3</sub>	15.40	13.50	14.70	11.50	16.20	16.50	15.80	14.90	14.60	14.00	14.50	14.60
Fe <sub>2</sub> O <sub>3</sub>	0.90	1.30	1.20	0.50	1.20	2.40	1.10	1.70	1.40	0.90	1.20	1.00
FeO	6.40	7.50	7.60	5.20	7.90	8.00	7.60	6.60	7.70	4.80	6.40	5.90
MgO	7.56	6.28	5.63	4.55	5.83	6.48	7.97	5.62	6.70	4.33	7.23	5.83
CaO	15.50	9.59	10.40	6.02	5.86	8.14	10.80	11.20	8.18	13.90	10.00	9.65
Na <sub>2</sub> O	0.60	0.70	0.70	0.50	3.10	2.40	0.0	1.40	2.00	1.30	1.10	1.80
K <sub>2</sub> O	1.24	1.54	2.57	3.17	0.67	0.32	1.11	0.27	0.47	1.39	1.05	1.29
TiO <sub>2</sub>	0.41	0.71	0.72	0.59	0.77	0.79	0.81	0.76	0.83	0.55	0.77	0.79
P <sub>2</sub> O <sub>5</sub>	0.04	0.09	0.09	0.08	0.08	0.08	0.07	0.10	0.06	0.10	0.07	0.09
MnO	0.17	0.16	0.17	0.15	0.14	0.18	0.11	0.15	0.13	0.18	0.14	0.18
S	0.0	0.0	0.0	0.33	0.08	0.05	0.0	0.0	0.02	0.04	0.06	0.11
Ba	0.044	0.021	0.026	0.075	0.0	0.019	0.018	0.010	0.026	0.021	0.020	0.019
CR <sub>2</sub> O <sub>3</sub>	0.05	0.11	0.08	0.06	0.05	0.06	0.06	0.06	0.06	0.11	0.06	0.07
CO <sub>2</sub>	11.60	7.70	9.10	5.00	3.90	2.80	8.50	6.90	5.50	9.00	7.60	6.40
H <sub>2</sub> O	<u>5.10</u>	<u>4.90</u>	<u>4.90</u>	<u>3.80</u>	<u>4.60</u>	<u>5.40</u>	<u>6.80</u>	<u>4.00</u>	<u>5.10</u>	<u>3.30</u>	<u>4.60</u>	<u>4.30</u>
Total	100.17	99.88	100.66	99.45	99.28	100.79	100.36	98.62	98.69	99.47	99.64	100.61
As	0	6	1	6	1	6	0	0	0	4	0	0
Br	5	1	0	4	4	1	1	2	0	5	2	2
Mo	2	0	3	0	1	7	1	4	1	1	0	0
Nb	3	5	6	3	5	8	5	6	5	3	5	4
Pb	13	10	13	9	11	15	9	9	9	10	10	10
Rb	14	23	31	30	16	7	37	7	14	44	30	36
Sr	111	86	122	48	106	123	21	87	56	63	52	59
Th	4	1	2	3	5	5	3	3	2	0	0	2
U	0	0	0	0	1	1	0	0	0	0	0	2
Y	12	19	23	22	19	29	24	26	24	16	23	35
Zr	39	76	80	71	70	76	89	88	88	46	82	83
Q	9.92	22.61	17.14	34.64	13.03	7.72	19.49	19.07	15.92	19.39	20.02	18.86
C	12.47	11.24	11.23	7.57	9.45	4.26	15.60	8.53	9.52	6.35	11.75	7.41
OR	7.71	9.59	15.86	19.59	4.19	1.98	7.02	1.69	2.97	8.55	6.52	7.92
AB	5.34	6.23	6.18	4.42	27.70	21.29	0.0	12.52	18.08	11.43	9.77	15.81
AN	3.47	0.0	0.0	0.0	4.11	23.30	0.0	12.21	5.51	12.07	1.03	7.09
DI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EN	19.80	16.05	13.14	11.28	15.33	16.92	21.00	14.79	17.83	11.21	18.90	15.07
FS	11.15	12.04	11.27	7.67	12.99	12.43	12.55	10.24	12.59	6.85	10.18	9.09
FO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MT	1.37	1.98	1.81	0.76	1.84	3.48	1.70	2.60	2.17	1.36	1.83	1.56
IL	0.82	1.42	1.43	1.17	1.54	1.57	1.69	1.52	1.68	1.09	1.53	1.56
CR	0.08	0.17	0.12	0.09	0.08	0.09	0.09	0.09	0.09	0.17	0.09	0.10
AP	0.09	0.22	0.22	0.19	0.19	0.17	0.25	0.15	0.25	0.17	0.22	0.23
PY	0.0	0.0	0.0	0.71	0.17	0.11	0.0	0.0	0.04	0.09	0.0	0.23
CC	27.75	18.43	21.59	11.89	9.37	6.68	20.66	16.58	13.36	21.28	18.15	15.11

**Lithology:** F = flow, I = intrusion; prefix medium or fine grain; suffix is thickness in metres, where known; pc = pillow core. **Unit** designation from stratigraphy and chemical discriminants; **Easting** and **Northing** are UTM coordinates (prefixed 7WEB, on 116B/12 and 116C/9 maps).

**Elevation** in feet.

Major elements in wt.%, minor elements in ppm; normative calculations in wt.%.

Table A2-2. Whole rock analyses from member B (p. 1 of 3).

#	129*	158-2	128-15*	97a*	162-1*	118-13*	144-5*	118-12*	128-5*	128-17	158-1
Lith.	ml3	ml	fl4	fl3	ml5	mF	fl7	mF	fl2	mF	ml
Unit	B	B	B	B	B	B	B	B	B	B	B
East.	55390	55020	55391	55390	54920	54760	54920	54765	55355	55390	55037
North	717250	717050	717261	717010	717065	717635	717155	717632	717285	717250	717074
Elev.	5950'	4300'	5680'	4800'	4950'	5300'	3925'	5350'	4500'	5950'	3800'
SiO <sub>2</sub>	49.70	45.90	48.40	48.70	48.10	49.20	43.40	48.60	47.90	64.80	45.9
Al <sub>2</sub> O <sub>3</sub>	15.80	15.60	14.70	14.30	15.60	15.20	15.80	16.10	13.80	14.50	15.60
Fe <sub>2</sub> O <sub>3</sub>	4.10	1.80	1.90	3.10	1.70	1.80	2.00	1.70	1.50	4.10	1.80
FeO	4.00	8.00	7.60	7.70	7.20	6.60	7.70	5.70	7.00	2.10	8.00
MgO	7.62	10.30	7.80	8.87	8.91	6.58	8.28	6.69	8.08	4.03	10.30
CaO	10.80	10.90	13.30	11.20	11.00	12.10	14.20	8.99	11.00	1.59	10.90
Na <sub>2</sub> O	2.20	1.10	0.90	1.30	0.40	2.60	1.10	3.10	2.40	5.80	1.10
K <sub>2</sub> O	0.34	0.29	0.39	0.33	0.29	0.79	0.36	0.48	0.48	0.17	0.29
TiO <sub>2</sub>	0.72	0.54	0.65	0.71	0.59	0.63	0.58	0.64	0.62	0.52	0.54
P <sub>2</sub> O <sub>5</sub>	0.05	0.04	0.05	0.05	0.07	0.04	0.03	0.06	0.04	0.02	0.04
MnO	0.17	0.18	0.20	0.21	0.18	0.18	0.18	0.13	0.18	0.04	0.18
S	0.0	0.03	0.02	0.02	0.0	0.0	0.0	0.0	0.23	0.01	0.03
Ba	0.016	0.009	0.014	0.015	0.014	0.015	0.015	0.012	0.025	0.010	0.09
Cr <sub>2</sub> O <sub>3</sub>	0.05	0.09	0.07	0.06	0.08	0.07	0.08	0.08	0.06	0.09	0.50
CO <sub>2</sub>	0.10	0.50	1.30	0.80	1.70	1.80	3.10	2.80	2.20	0.50	0.10
H <sub>2</sub> O	3.60	3.60	1.70	2.70	3.00	3.00	3.10	3.40	3.50	3.60	3.60
Total	99.25	98.87	98.98	100.06	98.82	100.59	99.91	98.47	99.9	100.55	98.87
As	2	1	10	0	8	4	0	0	6	0	1
Br	3	0	0	2	4	2	0	1	3	4	0
Mo	3	7	6	5	1	2	4	0	2	0	7
Nb	3	2	5	2	4	2	3	0	0	3	2
Pb	9	7	10	11	12	13	11	7	10	6	7
Rb	11	7	11	8	8	19	8	7	9	1	7
Sr	236	63	55	87	88	208	56	87	36	73	63
Th	1	1	0	0	5	5	0	2	1	0	1
U	0	0	0	0	0	0	0	0	0	0	0
Y	22	24	26	29	22	24	21	15	28	7	24
Zr	43	28	34	32	55	31	30	46	32	38	28
Q	2.54	0.0	4.96	3.08	8.70	0.38	0.0	3.77	1.15	20.68	0
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.81	0.0	3.15	0
OR	2.10	1.80	2.37	2.00	1.79	4.79	2.20	2.99	2.97	1.02	1.8
AB	19.50	9.77	7.83	11.31	3.53	22.54	9.61	27.59	21.27	50.06	9.77
AN	33.77	38.59	35.89	33.12	41.66	28.15	38.33	27.88	26.67	4.69	38.59
DI	12.72	8.27	12.39	9.96	2.03	11.44	7.59	0.0	8.74	0.0	8.27
HE	9.48	3.51	6.44	5.06	0.89	6.01	3.78	0.0	3.94	0.0	3.51
EN	13.94	19.15	14.22	18.09	22.21	11.49	15.27	17.52	17.02	10.24	19.15
FS	5.65	9.33	8.48	10.54	11.12	6.92	8.73	8.60	8.79	4.81	9.33
FO	0.0	1.48	0.0	0.0	0.0	0.0	1.76	0.0	0.0	0.0	1.48
FA	0.0	0.0	0.0	0.0	0.0	0.0	1.10	0.0	0.0	0.0	0.0
MT	3.37	2.74	2.83	3.29	2.57	2.67	2.99	2.59	2.28	2.99	2.74
IL	1.43	1.08	1.27	1.38	1.17	1.23	1.14	1.28	1.23	1.01	1.08
CR	0.07	0.14	0.10	0.09	0.12	0.11	1.22	0.12	0.09	0.10	0.14
AP	0.12	0.09	0.12	0.12	0.17	0.09	0.07	0.15	0.09	0.05	0.09
PY	0.0	0.06	0.04	0.06	0.0	0.0	0.0	0.0	0.49	0.02	0.06
CC	0.30	1.94	3.04	1.87	4.03	4.19	7.28	6.69	5.24	1.16	1.94

\* Less altered set; **Lithology**: F = flow, I = intrusion; prefix **medium** or **fine grain**; suffix is thickness in metres, where known; **pc** = pillow core. **Unit** designation from stratigraphy and chemical discriminants; **Easting** and **Northing** are UTM coordinates (prefixed 7WEB, on 116B/12 and 116C/9 maps). **Elevation** in feet. Major elements in wt. %; minor elements in ppm; norm. calculations in wt.%.

Table A2-2. Whole rock analyses from member B (p. 2 of 3).

#	126-2	124-1	128-14	126-1	144-8	128-16	135	144-15	118-10	128-18	144-13	144-12
Lith.	mF4	fF2	fF	mF	fi3	mF	fF5	mF	mF	mF	F9	ml2
Unit	B	B	B	B	B	B	B	B	B	B	B	B
East.	54555	54575	55378	54550	54943	55392	55420	54948	54792	55395	54944	54945
North	717627	717610	717256	717110	717110	717260	717180	717055	717651	717256	717061	717072
Elev.	4500'	5150'	5650'	4460'	4600'	5900'	5200'	5336'	5350'	6140'	5150'	5050'
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SiO <sub>2</sub>	53.40	70.80	51.60	71.20	46.00	49.20	51.80	43.90	41.30	53.20	47.70	41.00
Al <sub>2</sub> O <sub>3</sub>	17.00	14.00	15.00	11.80	14.00	17.30	13.60	16.80	13.00	15.30	10.90	10.40
Fe <sub>2</sub> O <sub>3</sub>	7.40	0.50	3.80	0.80	0.90	6.00	6.50	4.90	0.60	6.30	6.00	0.80
FeO	3.00	2.30	3.00	3.50	4.40	3.60	2.20	4.40	4.40	3.40	1.40	6.90
MgO	4.12	2.30	4.40	4.59	4.33	6.54	6.77	7.27	4.23	6.16	4.75	8.10
CaO	2.77	1.16	8.10	0.59	13.90	4.25	5.91	11.40	16.40	4.64	13.30	14.00
Na <sub>2</sub> O	7.00	2.90	4.40	3.10	1.30	5.30	3.80	0.90	1.80	4.40	0.0	0.0
K <sub>2</sub> O	0.17	1.95	0.63	0.11	1.39	0.28	0.28	1.12	1.07	0.18	0.15	0.32
TiO <sub>2</sub>	0.60	0.38	0.72	0.38	0.55	0.56	0.61	0.50	0.44	0.46	0.32	0.32
P <sub>2</sub> O <sub>5</sub>	0.06	0.03	0.08	0.0	0.07	0.05	0.06	0.02	0.04	0.04	0.03	0.03
MnO	0.10	0.02	0.11	0.03	0.18	0.07	0.07	0.13	0.15	0.10	0.16	0.19
S	0.0	0.0	0.0	0.0	0.04	0.0	0.02	0.0	0.06	0.0	0.0	0.28
Ba	0.018	0.075	0.030	0.011	0.021	0.018	0.016	0.030	0.011	0.013	0.008	0.005
Cr <sub>2</sub> O <sub>3</sub>	0.12	0.07	0.08	0.07	0.11	0.08	0.09	0.07	0.09	0.06	0.04	0.05
CO <sub>2</sub>	1.90	0.90	5.50	0.50	9.0	2.10	3.90	4.40	11.40	2.10	10.40	11.40
H <sub>2</sub> O	<u>2.60</u>	<u>2.80</u>	<u>3.10</u>	<u>3.30</u>	<u>3.30</u>	<u>3.40</u>	<u>3.40</u>	<u>3.50</u>	<u>3.60</u>	<u>3.70</u>	<u>3.80</u>	<u>5.00</u>
Total	99.24	100.11	100.56	99.97	99.47	98.73	98.99	99.31	98.63	100.04	98.95	98.51
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As	3	1	18	7	4	5	11	12	0	3	10	0
Br	3	2	6	5	5	1	2	3	4	2	4	0
Mo	2	0	0	0	1	1	2	1	2	1	4	3
Nb	3	3	4	4	3	3	6	3	3	3	3	3
Pb	9	10	7	11	10	11	13	13	9	9	10	4
Rb	2	43	19	3	44	7	7	44	32	5	5	1
Sr	75	63	246	27	63	169	168	86	80	94	31	43
Th	4	0	1	1	0	2	2	4	4	0	4	0
U	3	0	1	0	0	0	0	3	0	0	2	1
Y	18	3	17	3	16	20	17	20	14	18	14	15
Zr	63	46	70	3	46	41	66	35	32	39	27	27
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Q	0.0	42.77	12.81	54.12	19.39	0.0	13.47	6.69	13.99	8.96	38.60	25.94
C	5.0	7.31	5.34	6.81	6.35	5.83	5.76	3.79	5.86	4.58	11.32	11.07
OR	1.05	11.85	3.83	0.67	8.55	1.74	1.74	6.94	6.66	1.11	0.94	0.25
AB	61.66	25.21	38.26	27.13	11.44	47.25	33.80	7.97	16.03	38.83	0.0	0.0
AN	1.39	0.0	5.28	0.0	12.07	7.88	4.49	29.96	9.50	9.84	0.04	0.0
DI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EN	8.43	5.85	4.24	11.76	11.21	16.10	17.73	18.96	11.21	16.03	12.49	20.80
FS	10.04	3.23	5.35	5.28	6.85	10.36	8.95	11.02	7.29	11.57	8.06	11.56
FO	1.22	0.0	0.0	0.0	0.0	0.75	0.0	0.0	0.0	0.0	0.0	0.0
FA	1.51	0.0	0.0	0.0	0.0	0.53	0.0	0.0	0.0	0.0	0.0	0.0
MT	3.17	0.74	3.31	1.20	1.36	3.15	3.22	3.04	0.91	2.96	2.78	1.24
IL	1.19	0.74	1.41	0.75	1.09	1.12	1.22	0.99	0.88	0.91	0.64	0.65
CR	0.18	0.10	0.12	0.11	0.17	0.12	0.14	0.11	0.14	0.09	0.06	0.08
AP	0.14	0.07	0.19	0.0	0.17	0.12	0.15	0.05	0.09	0.09	0.07	0.07
PY	0.0	0.0	0.0	0.0	0.17	0.0	0.0	0.0	0.13	0.0	0.0	0.61
CC	4.49	2.10	12.86	1.18	21.28	5.03	9.33	10.48	27.28	4.98	24.98	27.71
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Lithology: F = flow, I = intrusion; prefix medium or fine grain; suffix is thickness in metres, where known; pc = pillow core. Unit designation from stratigraphy and chemical discriminants; Easting and Northing are UTM coordinates (prefixed 7WEB, on 116B/12 and 116C/9 maps). Elevation in feet.												
Major elements in wt.%; minor elements in ppm; normative calculations in wt.%. <hr/>												

**Table A2-2.** Whole rock analyses from member B (p. 3 of 3).

#	128-13	128-12	124-2	126-6	126-4	121-3	118-14	118-9	117-5	117-4	162-2	144-14
Lith.	f12	mF	F2	F8	ff3	mF	mF	fF1	mF	mF	mF	mF
Unit	B	B	B	B	B	B	B	B	B	B	B	B
East.	55390	55378	54600	54565	54560	54750	54755	54800	54887	54885	54967	54945
North	717260	717250	717730	717611	717615	717610	717615	717658	717029	717730	717050	717065
Elev.	5400'	5350'	5100'	4900'	4700'	5400'	5375'	5395'	4350'	4300'	5050'	5200'
<b>SiO<sub>2</sub></b>	39.30	38.30	51.10	42.80	41.60	45.10	65.60	47.40	52.70	44.70	49.10	39.50
<b>Al<sub>2</sub>O<sub>3</sub></b>	14.90	14.10	18.30	14.00	11.10	16.00	9.00	12.90	15.20	13.60	12.10	17.00
<b>Fe<sub>2</sub>O<sub>3</sub></b>	1.20	4.20	5.40	2.90	6.30	1.50	1.70	1.00	1.40	0.0	1.00	1.10
<b>FeO</b>	5.20	4.90	4.90	4.70	4.60	8.40	6.80	5.40	6.40	9.10	6.10	6.90
<b>MgO</b>	6.21	6.11	6.16	7.03	6.20	6.67	4.82	8.02	4.84	6.56	8.10	11.70
<b>CaO</b>	15.20	14.50	1.41	20.20	13.20	8.79	3.49	9.59	4.28	12.40	9.05	8.53
<b>Na<sub>2</sub>O</b>	1.40	1.70	3.70	0.0	1.00	2.00	1.10	0.40	0.20	0.80	0.0	0.0
<b>K<sub>2</sub>O</b>	1.73	0.87	1.68	0.04	0.47	0.53	0.13	0.58	5.03	1.36	0.18	0.16
<b>TiO<sub>2</sub></b>	0.41	0.38	0.52	0.52	0.34	0.74	0.52	0.45	0.79	0.61	0.51	0.61
<b>P<sub>2</sub>O<sub>5</sub></b>	0.04	0.05	0.04	0.03	0.05	0.09	0.05	0.04	0.10	0.06	0.05	0.07
<b>MnO</b>	0.22	0.17	0.06	0.14	0.15	0.18	0.11	0.11	0.07	0.18	0.13	0.13
<b>S</b>	0.02	0.0	0.04	0.0	0.0	0.02	0.11	0.0	0.13	0.32	0.01	0.0
<b>Ba</b>	0.044	0.027	0.342	0.006	0.009	0.018	0.006	0.009	0.089	0.022	0.006	0.009
<b>Cr<sub>2</sub>O<sub>3</sub></b>	0.08	0.07	0.09	0.06	0.07	0.06	0.01	0.10	0.10	0.05	0.15	0.08
<b>CO<sub>2</sub></b>	10.20	10.60	1.00	2.80	10.20	3.70	1.60	7.30	3.40	6.80	7.10	6.90
<b>H<sub>2</sub>O</b>	<u>4.50</u>	<u>4.50</u>	<u>4.90</u>	<u>4.40</u>	<u>4.00</u>	<u>4.80</u>	<u>3.90</u>	<u>5.80</u>	<u>4.40</u>	<u>4.00</u>	<u>5.20</u>	<u>7.80</u>
<b>Total</b>	100.61	100.45	99.30	99.62	99.28	99.58	98.94	99.09	99.04	100.54	98.78	100.48
<b>As</b>	2	0	2	4	2	2	0	0	2	4	3	7
<b>Br</b>	0	1	1	0	1	2	1	4	0	0	1	2
<b>Mo</b>	3	1	1	4	6	3	0	4	1	1	0	2
<b>Nb</b>	1	0	3	3	4	4	19	2	6	0	3	3
<b>Pb</b>	7	9	10	11	5	10	9	8	8	13	7	7
<b>Rb</b>	49	26	38	0	15	11	0	11	41	17	4	4
<b>Sr</b>	73	51	138	18	63	111	53	39	62	95	18	20
<b>Th</b>	0	0	0	3	0	1	5	2	1	0	0	4
<b>U</b>	0	0	0	0	0	0	0	0	0	1	0	0
<b>Y</b>	14	10	7	22	13	25	18	15	28	24	14	13
<b>Zr</b>	29	33	50	31	35	74	82	33	88	36	47	56
<b>Q</b>	7.22	9.45	8.87	2.77	19.13	7.47	46.20	28.45	22.31	10.61	34.22	18.17
<b>C</b>	7.09	9.07	10.89	0.0	9.17	5.27	4.77	11.94	9.95	4.31	12.72	18.14
<b>OR</b>	10.65	5.38	10.57	0.25	2.93	3.34	0.81	3.68	31.41	8.33	1.14	1.02
<b>AB</b>	12.32	15.03	33.29	0.0	8.92	18.04	9.79	3.63	1.79	7.01	0.0	0.0
<b>AN</b>	11.09	4.80	0.44	40.03	0.71	20.93	7.23	1.25	0.0	18.79	0.0	0.0
<b>DI</b>	0.0	0.0	0.0	27.08	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>HE</b>	0.0	0.0	0.0	10.45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>EN</b>	16.09	15.90	16.31	5.85	16.29	17.71	12.63	21.41	12.51	16.92	21.46	30.89
<b>FS</b>	8.51	11.35	12.70	2.59	14.63	14.08	10.73	9.07	9.41	15.89	10.24	11.58
<b>FO</b>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>FA</b>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>MT</b>	1.81	2.85	3.11	3.08	2.81	2.32	2.59	1.55	2.14	0.0	1.55	1.72
<b>IL</b>	0.81	0.75	1.05	1.04	0.68	1.50	1.04	0.92	1.58	1.20	1.03	1.25
<b>CR</b>	0.12	0.11	0.14	0.09	0.11	0.09	0.15	0.16	0.15	0.07	0.24	0.13
<b>AP</b>	0.09	0.12	0.10	0.07	0.12	0.22	0.12	0.10	0.24	0.14	0.12	0.17
<b>PY</b>	0.04	0.0	0.04	0.0	0.0	0.04	0.24	0.0	0.28	0.68	0.02	0.02
<b>CC</b>	24.14	25.19	2.42	6.69	24.47	8.97	3.83	17.79	8.17	16.02	17.25	16.92

**Lithology:** F = flow, I = intrusion; prefix medium or fine grain; suffix is thickness in metres, where known; pc = pillow core. **Unit** designation from stratigraphy and chemical discriminants; **Easting** and **Northing** are UTM coordinates (prefixed 7WEB, on 116B/12 and 116C/9 maps). **Elevation** in feet.  
Major elements in wt.%; minor elements in ppm; normative calculations in wt.%.

**Table A2-3.** Whole rock analyses from member D.

#	138-1*	138-2	166	48-1*	103*	138-4*	138-3	154	44	136-1
Lith.	8q2f	2q9f	l6f	l5q3f	A5f	3q5f	5f	8f	8f	cx5q1f
Unit	D	D	D	D	D	D	D	D	D	D
East.	55405	55400	54750	55035	54655	56400	55465	54845	54795	55390
North	716883	716887	717110	716930	717143	716892	716891	716982	716992	717765
Elev.	3900'	3800'	5000'	3950'	4600'	4000'	4000'	4050'	4250'	5000'
<hr/>										
SiO <sub>2</sub>	75.40	70.10	66.60	68.60	76.70	69.10	68.50	67.50	70.50	67.10
Al <sub>2</sub> O <sub>3</sub>	11.60	12.70	13.10	14.30	8.40	13.50	12.90	14.10	11.80	12.90
Fe <sub>2</sub> O <sub>3</sub>	1.50	0.80	0.50	3.40	0.80	1.20	0.80	0.80	1.40	0.90
FeO	1.80	2.10	3.90	1.60	4.60	2.70	4.20	3.80	3.30	2.70
MgO	0.59	0.67	0.60	0.89	1.55	0.84	0.94	0.73	0.88	2.76
CaO	1.11	2.08	3.79	0.90	0.87	1.33	1.60	2.59	2.07	3.83
Na <sub>2</sub> O	1.20	0.00	0.30	2.00	0.00	0.0	0.00	2.70	1.20	0.40
K <sub>2</sub> O	4.05	7.17	5.59	4.61	4.32	7.40	7.03	2.33	2.59	2.81
TiO <sub>2</sub>	0.40	0.52	0.50	0.71	0.26	0.52	0.52	0.55	0.48	0.62
P <sub>2</sub> O <sub>5</sub>	0.20	0.19	0.19	0.23	0.11	0.17	0.17	0.19	0.17	0.22
MnO	0.04	0.08	0.11	0.05	0.03	0.03	0.03	0.09	0.06	0.02
S	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.0
Ba	0.101	0.204	0.065	0.081	0.030	0.225	0.205	0.075	0.120	0.16
Cr <sub>2</sub> O <sub>3</sub>	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.0
CO <sub>2</sub>	0.90	1.80	2.80	0.40	0.70	1.00	1.30	1.80	1.30	2.60
H <sub>2</sub> O	<u>1.80</u>	<u>1.70</u>	<u>1.90</u>	<u>2.10</u>	<u>2.10</u>	<u>2.10</u>	<u>2.10</u>	<u>2.10</u>	<u>2.60</u>	<u>3.30</u>
Total	100.59	99.92	99.89	99.79	100.47	99.9	100.09	99.29	98.36	100.16
<hr/>										
As	5	14	3	0	0	6	8	0	1	2
Br	0	8	2	6	0	0	3	0	0	3
Mo	0	0	0	0	2	0	0	0	0	0
Nb	12	20	20	20	13	22	20	22	17	17
Pb	9	26	23	16	9	12	15	12	23	18
Rb	140	179	199	166	111	161	138	119	120	9
Sr	79	86	23	52	9	48	57	121	83	62
Th	14	27	19	20	15	25	25	26	21	17
U	0	8	13	4	1	3	4	4	0	3
Y	31	77	77	61	21	83	75	88	60	63
Zr	222	379	384	305	194	421	411	453	386	266
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Q	41.70	52.30	40.60	37.80	55.75	39.10	38.40	40.28	52.17	49.49
C	5.02	5.30	6.64	6.00	3.78	5.60	5.39	7.25	6.97	9.07
OR	43.20	24.20	33.70	27.90	25.97	44.75	42.44	14.18	15.99	17.16
AB	0.0	10.20	2.58	17.30	0.0	0.0	0.0	23.50	10.60	3.49
AN	0.0	0.0	0.0	0.44	0.0	0.0	0.0	0.23	0.98	1.16
DI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EN	1.30	1.18	1.51	2.27	3.80	1.99	2.22	1.87	2.29	7.09
FS	1.93	1.18	6.19	2.02	7.25	3.01	5.93	5.72	4.40	3.33
FO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MT	1.81	2.20	0.74	3.28	1.18	1.78	1.18	1.19	2.12	1.34
IL	1.00	0.77	0.969	1.38	0.50	1.01	1.01	1.07	0.95	1.22
CR	0.01	0.0	0.15	0.0	0.01	0.01	0.0	0.01	0.01	0.0
AP	0.45	0.47	0.45	0.54	0.26	0.40	0.40	0.45	0.41	0.52
PY	0.0	0.0	0.0	0.0	0.42	0.0	0.0	0.0	0.0	0.0
CC	4.17	2.07	6.49	0.93	1.16	2.32	3.02	4.21	3.08	6.10
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<p>* Less altered set; Massive flows unless otherwise indicated; Intrusions, Ash flow; <b>cx</b> = clast in unit PH<sub>1</sub>;  Phenocrysts estimated in % <b>q</b> = quartz, <b>f</b> = feldspar. <b>Unit</b> designation from stratigraphy and chemical  discriminants; <b>East</b>ing and <b>North</b>ing are UTM coordinates (prefixed 7WEB, on 116B/12 and 116C/9 maps).  Elevation in feet.  Major elements in wt.%; minor elements in ppm; normative calculations in wt.%.</p>										

Table A2-4. Whole rock analyses from member E.

#	71*	99*	144-6*	79-1	82-4	102	104	72-2	73	118-1	79
Lith.	mF	mF	fl	fFbx	mF	fF	ml	mF6	ml9	fl5	Fbx
Unit	E	E	E	E	E	E	E	E	E	E	E
East.	54320	54695	54935	54645	54445	54699	54642	54521	54558	54835	54631
North	717135	717045	717135	717445	717082	717082	717130	717082	717090	717690	717450
Elev.	4850'	4250'	4300'	4800'	4600'	4700'	4600'	4350'	3750'	4675'	4800'
SiO <sub>2</sub>	69.00	55.70	54.60	56.10	64.90	48.10	38.90	60.70	48.80	53.00	56.10
Al <sub>2</sub> O <sub>3</sub>	9.60	12.90	12.20	12.80	10.30	12.90	10.40	12.10	12.40	12.80	12.80
Fe <sub>2</sub> O <sub>3</sub>	2.00	2.00	2.30	2.90	4.00	1.20	1.70	2.80	2.30	1.60	2.90
FeO	4.50	8.50	7.80	7.80	6.60	11.40	9.20	7.20	10.40	9.10	7.80
MgO	1.35	3.34	2.08	3.59	3.03	2.88	7.45	4.43	3.75	4.18	3.59
CaO	3.51	7.03	6.62	6.95	1.98	7.13	12.40	2.94	7.48	6.24	6.95
Na <sub>2</sub> O	0.50	0.90	1.50	1.10	1.50	1.10	0.30	1.50	1.50	0.50	1.10
K <sub>2</sub> O	3.74	1.93	3.02	1.93	1.26	2.01	2.25	2.10	1.24	1.81	1.93
TiO <sub>2</sub>	0.39	1.30	1.47	1.31	1.51	1.48	1.05	1.17	1.30	1.41	1.31
P <sub>2</sub> O <sub>5</sub>	0.13	0.28	0.29	0.29	0.38	0.15	0.11	0.22	0.13	0.28	0.29
MnO	0.10	0.18	0.18	0.18	0.07	0.20	0.18	0.08	0.19	0.15	0.18
S	0.03	0.02	0.0	0.05	0.04	0.17	0.08	0.17	0.09	0.03	0.05
Ba	0.089	0.197	0.094	0.191	0.014	0.028	0.045	0.046	0.018	0.025	0.00
Cr <sub>2</sub> O <sub>3</sub>	0.01	0.02	0.02	0.03	0.01	0.02	0.01	0.02	0.02	0.01	0.03
CO <sub>2</sub>	2.30	1.70	3.30	1.80	1.10	7.60	11.80	0.80	5.50	4.40	1.80
H <sub>2</sub> O	<u>2.60</u>	<u>2.90</u>	<u>2.90</u>	<u>3.20</u>	<u>3.30</u>	<u>3.80</u>	<u>4.10</u>	<u>4.20</u>	<u>4.20</u>	<u>4.40</u>	<u>3.20</u>
Total	99.76	98.20	98.28	100.03	99.98	100.14	99.93	100.43	99.30	99.91	100.03
As	1	1	9	4	0	4	7	10	2	3	4
Br	0	4	5	2	8	3	3	0	0	6	2
Mo	0	0	0	0	0	1	1	0	0	0	0
Nb	15	17	16	13	13	10	8	12	7	15	13
Pb	17	18	22	25	20	13	15	21	9	9	25
Rb	185	34	92	32	57	56	45	103	54	70	132
Sr	59	182	127	176	41	80	228	66	54	31	176
Th	16	12	14	11	12	13	6	8	3	15	11
V	0	0	7	5	5	2	1	0	0	2	5
Y	46	60	54	62	56	67	44	51	53	58	62
Zr	318	296	262	289	183	165	120	266	136	275	289
Q	47.33	24.09	23.22	23.92	44.17	25.69	14.65	30.87	23.31	31.74	23.92
C	4.10	0.69	2.90	1.17	6.35	9.27	7.78	4.58	8.46	9.98	1.17
OR	22.77	11.98	18.73	11.79	7.72	12.37	13.86	12.91	7.71	11.21	11.79
AB	4.35	7.99	13.31	9.61	13.14	9.68	2.64	13.19	13.34	4.43	9.61
AN	2.08	23.39	10.57	21.90	0.39	0.0	0.0	8.41	1.56	1.37	21.90
DI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EN	3.46	8.73	5.43	9.23	7.81	5.67	16.02	11.47	9.82	10.89	9.23
FS	6.54	12.68	10.81	0.0	9.11	13.83	12.01	9.44	15.98	13.89	11.00
FO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MT	2.81	3.04	3.49	4.21	4.52	1.81	2.57	4.02	3.51	2.43	4.21
iL	0.76	2.59	2.93	2.57	2.97	2.92	2.07	2.31	2.59	2.80	2.57
CR	0.01	0.03	0.03	0.01	0.01	0.01	0.01	0.03	0.03	0.01	0.04
AP	0.31	0.68	0.70	0.69	0.91	0.36	0.26	0.53	0.32	0.68	0.70
PY	0.06	0.04	0.0	0.10	0.08	0.36	0.17	0.36	0.19	0.06	0.11
CC	5.38	4.05	7.87	4.23	2.59	17.98	27.94	1.89	13.15	10.48	4.23

\* Less altered set; **Lithology**: F = flow, I = intrusion; prefix **medium** or **fine** grain; suffix is thickness in metres, where known; **Fbx** = flow breccia. **Unit** designation from stratigraphy and chemical discriminants; **Easting** and **Northing** are UTM coordinates (prefixed 7WEB, on 116B/12 and 116C/9 maps).  
**Elevation** in feet.  
Major elements in wt.%; minor elements in ppm; normative calculations in wt.%

**Table A2-5.** Whole rock analyses from members E & F.

#	143*	126-5*	121-7*	126-3*	121-10	21-7*	161	112-1	72-1	70
Lith.	pc	ml	ml3	ml3	mF	mF	mF	ml	mF	mF
Unit	F	F	F	F	F	F	F	F	E	E
East.	54879	54520	54825	54550	54732	54732	54810	54665	54482	54557
North	717060	717613	717500	717615	717615	717615	717080	717430	717085	717165
Elev.	5250'	4750'	5000'	4600'	5650'	5650'	5100'	5000'	4800'	5000'
<b>SiO<sub>2</sub></b>	54.90	50.20	57.10	50.60	49.10	46.50	52.50	42.60	64.30	53.70
<b>Al<sub>2</sub>O<sub>3</sub></b>	12.90	13.60	13.60	13.60	15.00	15.60	13.60	13.90	4.80	13.50
<b>Fe<sub>2</sub>O<sub>3</sub></b>	3.80	1.60	1.60	1.30	1.50	1.00	2.70	0.70	1.80	2.50
<b>FeO</b>	5.60	6.20	5.20	6.30	6.40	5.10	6.50	4.60	3.60	11.00
<b>MgO</b>	4.94	2.66	3.33	4.39	3.76	5.24	6.02	7.90	1.82	3.99
<b>CaO</b>	7.94	9.92	7.33	9.62	11.20	10.30	9.42	11.80	9.22	3.31
<b>Na<sub>2</sub>O</b>	4.40	3.10	2.60	3.30	2.80	3.20	1.00	0.80	0.00	2.40
<b>K<sub>2</sub>O</b>	0.05	1.23	1.14	1.08	0.89	0.87	0.88	1.56	3.29	0.89
<b>TiO<sub>2</sub></b>	0.65	0.61	0.60	0.62	0.65	0.75	0.59	0.63	0.48	1.54
<b>P<sub>2</sub>O<sub>5</sub></b>	0.07	0.10	0.11	0.12	0.10	0.11	0.04	0.09	0.11	0.30
<b>MnO</b>	0.14	0.15	0.13	0.17	0.15	0.13	0.19	0.07	0.09	0.20
<b>S</b>	0.0	0.04	0.02	0.03	0.01	0.0	0.02	0.03	0.05	0.16
<b>Ba</b>	0.008	0.068	0.073	0.066	0.052	0.027	0.022	0.012	0.007	0.029
<b>Cr<sub>2</sub>O<sub>3</sub></b>	0.02	0.04	0.04	0.05	0.05	0.03	0.03	0.05	0.01	0.02
<b>CO<sub>2</sub></b>	1.90	6.40	2.50	5.60	4.70	6.50	0.80	8.70	7.20	1.70
<b>H<sub>2</sub>O</b>	<u>2.50</u>	<u>3.10</u>	<u>3.20</u>	<u>3.20</u>	<u>3.70</u>	<u>2.80</u>	<u>4.60</u>	<u>6.00</u>	<u>2.20</u>	<u>4.50</u>
<b>Total</b>	95.66	98.95	98.96	99.99	100.01	99.13	98.89	99.43	98.97	99.71
<b>As</b>	0	3	1	3	7	0	4	0	5	15
<b>Br</b>	1	1	1	3	8	0	2	2	4	2
<b>Mo</b>	0	0	0	0	4	1	4	0	1	2
<b>Nb</b>	6	9	7	6	9	8	5	6	5	17
<b>Pb</b>	11	11	13	11	16	4	11	18	12	19
<b>Rb</b>	1	27	23	24	18	17	19	38	252	32
<b>Sr</b>	51	54	119	81	124	78	32	32	17	88
<b>Th</b>	4	5	11	9	15	3	4	4	1	16
<b>U</b>	0	2	0	6	7	0	2	5	0	3
<b>Y</b>	33	31	36	35	40	36	31	28	21	67
<b>Zr</b>	100	21	138	17	120	140	82	109	81	272
<b>Q</b>	8.32	16.98	20.77	11.71	8.85	9.76	14.98	16.91	48.66	22.76
<b>C</b>	0.0	4.38	0.09	2.87	0.20	6.28	0.0	10.50	1.27	7.59
<b>OR</b>	0.30	7.59	7.04	6.60	5.47	5.39	5.52	9.87	20.10	5.53
<b>AB</b>	38.38	27.36	21.97	28.85	24.59	28.40	8.98	7.24	0.0	21.33
<b>AN</b>	15.78	8.45	22.74	11.92	26.16	9.74	31.86	3.16	0.0	3.89
<b>DI</b>	5.31	0.0	0.0	0.0	0.0	0.0	6.14	0.0	0.0	0.0
<b>HE</b>	3.74	0.0	0.0	0.0	0.0	0.0	3.75	0.0	0.0	0.0
<b>EN</b>	10.22	6.91	8.66	11.29	9.72	13.69	13.07	21.05	4.57	10.44
<b>FS</b>	8.62	9.61	7.62	10.00	10.02	7.88	9.17	7.33	4.43	16.40
<b>FO</b>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>FA</b>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>MT</b>	3.21	2.47	2.42	1.95	2.26	1.52	3.21	1.09	2.69	3.81
<b>IL</b>	1.27	1.20	1.31	1.22	1.28	1.49	1.19	1.28	0.94	3.07
<b>CR</b>	0.03	0.06	0.06	0.07	0.07	0.05	0.05	0.08	0.01	0.03
<b>AP</b>	0.17	0.24	0.26	0.29	0.24	0.27	0.09	0.22	0.26	0.73
<b>PY</b>	4.43	0.08	0.04	0.06	0.02	0.0	0.04	0.07	0.10	0.35
<b>CC</b>	4.45	15.18	5.43	13.16	11.09	15.51	1.43	21.18	16.92	4.06

\* Less altered set; **Lithology:** F = flow, I = intrusion; prefix medium or fine grain; suffix is thickness in metres, where known; **pc** = pillow core. **Unit** determined from chemical discriminants; **Easting and Northing** are UTM coordinates (prefixed 7WEB, on 116B/12 and 116C/9 maps).

**Elevation** in feet.

Major elements in wt.%; minor elements in ppm; normative calculations in wt.%.

## APPENDIX 3

### Paleocurrent data, Mount Harper Group rocks

Summaries of paleocurrent data and trend statistics are given for the lower Mount Harper Group in Table A3-1 and for the upper Mount Harper Group in Table A3-2. This data forms the basis for the current roses shown in Figures 8 and 28. The current roses were plotted using a nonlinear frequency scale. 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 nonlinear scale provides a more accurate representation of the data.

#### *Collection methods*

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 to 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 subspherical) necessitated fewer 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.

Map unit PH<sub>2</sub> of the upper Mount Harper Group 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 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.

#### *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 (e.g. 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 nonrandom (i.e. a Rayleigh value of less than 0.05, the cut-off value recommended by Curray, 1956). 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).

Table A3-1a.

LOWER MOUNT HARPER GROUP

COARSE CONGLOMERATE FACIES

N = 624

STATION OR SECTION	LOCATION OR METRES	PALEO-CURRENT MAP UNIT TYPE	OBSERVATIONS PER 30 DEGREE INTERVAL													Number of Observations	Vector Mean	Vector Magnitude (%)	Rayleigh Significance	Circular Standard Deviation	Circular Variance
			0-30	31-60	61-90	91-120	121-150	151-180	181-210	211-240	241-270	271-300	301-330	331-360							
MS-7	39-40.3	PHb	imbrication	2	5	5	2	1	2	0	1	2	0	3	3	26	38	9	1.87E-02	63	3967
MS-7	133-133.4	PHb	imbrication	8	5	3	0	1	3	1	1	0	7	11	11	51	344	56	8.80E-08	53	2817
MS-8	80-80.5	PHb	imbrication	3	3	1	0	1	1	3	0	0	3	3	7	25	342	44	7.10E-03	60	3612
MS-8	169.5-171.5	PHb	imbrication	2	3	0	6	0	0	1	0	1	1	6	11	31	358	53	1.70E-04	55	3052
MS-10	18-21	PHb	imbrication	4	4	8	2	0	2	4	1	0	1	1	3	30	67	39	9.40E-03	63	3946
MS-11	39.5-40	PHb	imbrication	6	1	3	11	12	1	1	4	4	0	5	2	50	110	26	3.30E-02	70	4834
PM87	main outcrop	PHb	imbrication	7	0	1	0	0	0	0	1	0	1	2	8	20	351	82	1.70E-06	34	1148
MS-11	545-545.9	PHb	imbrication	9	7	5	6	3	3	3	0	0	5	4	6	51	34	37	9.40E-04	64	4110
MS-13	402.3-403.8	PHb	imbrication	9	8	6	6	7	5	1	0	1	1	4	2	50	69	46	2.80E-05	59	3524
MS-13	403.8-404.8	PHb	imbrication	5	7	11	11	3	1	1	0	1	1	3	6	50	59	55	2.60E-07	54	2908
MS-18	296.1-297.9	PHb	imbrication	10	4	2	1	0	2	1	1	0	2	6	21	50	353	71	1.10E-11	43	1846
MS-18	307.4-308.7	PHb	imbrication	12	15	1	2	1	1	2	1	0	0	4	11	50	17	65	7.40E-10	48	2259
MS-21	33.5-34	PHb	imbrication	3	9	6	4	4	0	1	0	0	5	10	8	50	16	46	2.20E-05	59	3491
MS-21	122-122.7	PHb	imbrication	7	11	6	7	3	0	0	0	0	0	0	6	40	54	73	7.00E-10	42	1744
MS-21	142-142.7	PHb	imbrication	6	4	9	9	8	0	0	0	1	1	5	7	50	59	51	2.10E-06	56	3166
<b>TOTAL</b>				<b>93</b>	<b>86</b>	<b>67</b>	<b>67</b>	<b>44</b>	<b>21</b>	<b>19</b>	<b>10</b>	<b>10</b>	<b>28</b>	<b>67</b>	<b>112</b>	<b>624</b>	<b>33</b>	<b>40</b>	<b>2.16E-36</b>	<b>62</b>	<b>3898</b>
<b>PER CENT</b>				<b>15</b>	<b>14</b>	<b>11</b>	<b>11</b>	<b>7</b>	<b>3</b>	<b>3</b>	<b>2</b>	<b>2</b>	<b>4</b>	<b>11</b>	<b>18</b>	<b>100</b>					

Explanation: Station or Section refers to original measured section (MS-??) or field station (PM??) of Mustard (1990). Location or Metres refers to distance above base of section or to position in reference to field station location. Paleocurrent Type abbreviations are: imbrication for conglomerate clast imbrication, crosslam for crosslamination and part lineation for parting lineation.

CONGLOMERATE-SANDSTONE FACIES

N = 505

Station or Section	Location or Metres	Map Unit	Paleo-current Type	OBSERVATIONS PER 30 DEGREE INTERVAL													Number of Observations	Vector Mean	Vector Magnitude (%)	Rayleigh Significance	Circular Standard Deviation	Circular Variance
				0-30	31-60	61-90	91-120	121-150	151-180	181-210	211-240	241-270	271-300	301-330	331-360							
MS-14	126-126.3	PHd	imbrication	10	15	19	1	2	0	0	0	0	0	0	3	50	53	85	1.70E-16	30	907	
MS-14	138-138.3	PHd	imbrication	20	12	4	0	3	0	1	0	0	1	3	6	50	25	76	2.90E-13	39	1521	
MS-14	154-154.5	PHd	imbrication	6	2	0	4	5	3	3	1	4	7	10	9	54	322	31	5.80E-03	67	4514	
MS-14	204-204.25	PHd	imbrication	10	7	7	1	2	1	0	0	1	2	9	10	50	12	62	4.40E-09	49	2445	
MS-27	260	PHb	imbrication	7	9	5	5	2	1	4	4	3	1	5	5	51	33	28	2.00E-02	69	4723	
MS-27	273	PHb	imbrication	13	5	7	2	2	1	1	0	0	1	6	12	50	15	62	4.60E-09	50	2451	
PM44	E edge map	PHd	imbrication	7	6	20	11	4	0	1	1	0	0	0	0	50	77	80	9.00E-15	35	1224	
PM81a	NW end LMHG	PHb	imbrication	2	2	1	0	0	0	0	0	1	5	23	16	50	327	88	1.60E-17	27	723	
PM81b	NW end LMHG	PHb	imbrication	15	1	0	0	0	0	0	0	1	0	7	27	51	349	92	1.20E-19	21	428	
PM42	E end map	PHd	imbrication	3	1	2	1	4	1	3	11	9	9	1	4	49	256	42	1.70E-04	61	3765	
<b>TOTAL</b>				<b>93</b>	<b>60</b>	<b>65</b>	<b>25</b>	<b>24</b>	<b>7</b>	<b>13</b>	<b>17</b>	<b>19</b>	<b>26</b>	<b>64</b>	<b>92</b>	<b>505</b>	<b>14</b>	<b>58</b>	<b>1.72E-56</b>	<b>52</b>	<b>2720</b>	
<b>PER CENT</b>				<b>18</b>	<b>12</b>	<b>13</b>	<b>5</b>	<b>5</b>	<b>1</b>	<b>3</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>13</b>	<b>18</b>	<b>100</b>						

SANDSTONE-MUDSTONE FACIES

N = 96

Station or Section	Location or Metres	Map Unit	Paleo-current Type	OBSERVATIONS PER 30 DEGREE INTERVAL													Number of Observations	Vector Mean	Vector Magnitude (%)	Rayleigh Significance	Circular Standard Deviation	Circular Variance
				0-30	31-60	61-90	91-120	121-150	151-180	181-210	211-240	241-270	271-300	301-330	331-360							
MS-20	271-271.1	PHc	crosslam	0	0	0	0	0	0	0	0	0	0	9	10	19	332	99	9.30E-09	4	17	
MS-20	272-272.5	PHc	crosslam	0	0	0	0	0	0	0	0	0	0	14	6	20	323	98	4.40E-09	7	52	
MS-20	275-303.25	PHc	crosslam	1	0	0	0	0	0	0	0	0	4	9	3	17	319	92	5.60E-07	21	456	
MS-28	0-20	PHc	crosslam	14	0	0	0	0	0	0	0	0	0	0	1	15	4	99	4.10E-07	2	4	
MS-28	20-30	PHc	crosslam	11	0	0	0	0	0	0	0	0	0	0	14	25	358	98	4.20E-11	9	73	
<b>TOTAL</b>				<b>26</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>4</b>	<b>32</b>	<b>34</b>	<b>96</b>	<b>340</b>	<b>93</b>	<b>2.09E-36</b>	<b>21</b>	<b>422</b>	
<b>PER CENT</b>				<b>27</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>4</b>	<b>33</b>	<b>35</b>	<b>100</b>						

Explanation: Station or Section refers to original measured section (MS-??) or field station (PM??) of Mustard (1990). Location or Metres refers to distance above base of section or to position in reference to field station location. Paleocurrent Type abbreviations are: imbrication for conglomerate clast imbrication, crosslam for crosslamination and part lineation for parting lineation.

Table A3-1b.

SUMMARY OF LOWER MOUNT HARPER GROUP PALEOCURRENTS N = 1225

Facies	OBSERVATIONS PER 30 DEGREE INTERVAL												Number of Observations	Vector Mean	Vector Magnitude (%)	Rayleigh Significance	Circular Standard Deviation	Circular Variance
	0-30	31-60	61-90	91-120	121-150	151-180	181-210	211-240	241-270	271-300	301-330	331-360						
Coarse conglomerate	93	86	67	67	44	21	19	10	10	28	67	112	624	30	42	2.2E-36	62	3898
Sandstone-conglomerate	93	60	65	25	24	7	13	17	19	26	64	92	505	12	47	1.7E-56	59	2720
Mudstone-sandstone	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
PER CENT	17.3	11.9	10.8	7.5	5.6	2.3	2.6	2.2	2.4	4.7	13.3	19.4						

Table A3-2.

UPPER MOUNT HARPER GROUP

MAP UNITS PH1 and PH2 N = 246

Station or Section	Location or Metres	Map Unit	Paleocurrent Type	OBSERVATIONS PER 30 DEGREE INTERVAL												Number of Observations	Vector Mean	Vector Magnitude (%)	Rayleigh Significance	Circular Standard Deviation	Circular Variance	
				0-30	31-60	61-90	91-120	121-150	151-180	181-210	211-240	241-270	271-300	301-330	331-360							
MS-19B	200-205	PH2	crosslam	0	0	0	3	6	4	0	0	0	0	0	0	13	135	88	4.3E-05	27	721	
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	
PM-52	S of MS22	PH2	part lineation	0	0	0	0	0	0	18	13	0	0	0	0	31	238	70	2.2E-07	44	1917	
PM-55	S of MS22	PH2	crosslam	0	0	4	20	1	0	0	0	0	0	0	0	25	102	98	3.1E-11	8	57	
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	
PM-62	S of MS19	PH2	crosslam	0	0	0	4	5	0	0	0	0	0	0	0	9	119	98	1.8E-04	8	57	
MS-29	42-43	PH1	crosslam	0	0	1	0	0	1	5	4	3	0	0	0	14	206	76	3.0E-04	39	1507	
MS-17	38.5	PH2	part lineation	0	0	0	0	0	0	8	18	0	0	0	0	26	216	99	9.6E-12	2	4	
MS-17	102	PH2	part lineation	0	0	0	0	0	0	11	14	0	0	0	0	25	209	99	2.0E-11	2	4	
MS-19A	148	PH2	crosslam	0	0	0	0	6	4	2	0	0	0	0	0	12	155	94	2.4E-05	18	323	
MS-19A	218-222	PH2	crosslam	0	0	2	0	4	0	6	0	1	0	0	0	13	157	65	4.1E-03	47	2249	
TOTAL				0	1	7	27	26	17	69	59	11	14	7	6	244	193	54	1.0E-31	55	2974	
PER CENT				0	0	3	11	11	7	28	24	5	6	3	2	100						

Explanation: Station or Section refers to original measured section (MS-??) or field station (PM??) of Mustard (1990). Location or Metres refers to distance above base of section or to position in reference to field station location. Paleocurrent Type abbreviations are: imbrication for conglomerate clast imbrication, crosslam for crosslamination and part lineation for parting lineation.

