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Discrimination of hot *versus* cold avalanche deposits: implications for hazards assessment at Mount Meager, British Columbia

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Abstract

Avalanche deposits within the Mount Meager volcanic complex are nearly monolithological and comprise mainly intermediate volcanic rock clasts up to 10.5 m, lack internal structure, and are very poorly sorted. Despite these physical similarities, the deposits originate from two distinct processes, cold rock-avalanche deposits from mass wasting and hot block-and-ash avalanche deposits derived from gravitational collapse of active lava domes and flows. Hot block-and-ash deposits are recognized by the presence of features indicative of high emplacement temperatures. Clasts within rock-avalanche deposits preserve predepositional weathering and jointing surfaces as well as fragmentation surfaces from transport. The ability to discriminate between hot and cold avalanche deposits and the recognition of multiple volcanic events are critical to hazard assessment in volcanic terranes. Misidentification can lead to underestimating the risk of one (i.e. volcanic) hazard whilst overestimating the other (i.e. mass wasting).

Résumé

Les dépôts d'avalanche dans le complexe volcanique de Mount Meager sont presque tous du même type lithologique et comprennent essentiellement des fragments de roches volcaniques de composition intermédiaire pouvant atteindre 10,5 m de diamètre; ils sont très mal triés et dépourvus de structure interne. Malgré ces similarités physiques, ces dépôts sont issus de deux processus distincts : dépôts d'avalanche de pierres froide provoquée par un mouvement de masse et dépôts d'avalanche de cendres et de blocs chaude provoquée par l'effondrement gravitaire de dômes et de coulées de lave active. Les dépôts de cendres et de blocs chauds se distinguent par des caractéristiques indicatrices de températures de mise en place élevées. Les fragments se trouvant dans les dépôts d'avalanche de pierres préservent les surfaces d'altération et de débit antérieures à leur accumulation ainsi que les surfaces de fragmentation issues du transport. Afin de pouvoir évaluer les risques dans les terranes volcaniques, il est essentiel de distinguer les dépôts d'avalanche chaude des dépôts d'avalanche froide et de reconnaître les événements volcaniques multiples. Si l'identification est inexacte, on risque de sous-estimer la probabilité d'un danger (p. ex. un aléa volcanique) tout en surestimant la venue d'un autre danger (p. ex. le mouvement de masse).

INTRODUCTION

Volcanic landscapes along convergent plate margins typically feature large volcanic structures situated in regions of extreme topographic relief. They represent one of the most hazardous natural environments on the planet. Volcanic eruptions represent an obvious set of hazards. Additionally, stratovolcanoes form relatively unstable structures and when situated in a high-relief landscape are optimal sources of rock avalanches. The steep slopes also have an impact on the nature of volcanic hazards associated with an eruption. Specifically, steep slopes are an efficient mechanism for changing the style of volcanism. For example, lava flows and domes that would, in other environments, represent lower risk events can be quickly transformed into explosive pyroclastic avalanches when reaching steep slopes. For these reasons, in the stratigraphic successions that underlie these landscapes, avalanche deposits derived from both volcanic and mass-wasting events are common.

The Mount Meager volcanic complex is a deeply eroded stratovolcano in the Coast Mountains that has produced numerous rock avalanches and, most recently, has erupted in 2360 BP. Our objectives in this paper are twofold. Firstly, we use our revised geological map to document the distribution and characteristics of two distinct types of avalanche deposits. These deposits are superficially similar in character, but derive from mass wasting ('cold' avalanches) and volcanic eruption ('hot' avalanches). Secondly, we discuss the implications of recognizing the origins and timings of these two types of avalanche deposits. The discrimination of these two different deposits is essential to identify natural hazards properly (e.g. Hickson, 1994). Furthermore, proper identification of these hazards is critical when it comes to quantitatively assessing the risk of specific hazards (Morgan and Henrion, 1990).

GEOLOGICAL SETTING

The Mount Meager volcanic complex is the most recently active volcano on the Canadian side of the Cascade magmatic arc within the Coast Mountains of southwestern British Columbia (Fig. 1). The Quaternary stratovolcanoes of southwestern British Columbia, including Mount Meager, Mount Cayley, and Mount Garibaldi, make up the Garibaldi volcanic belt (Mathews, 1958). Mount Meager comprises a number of volcanic centres that have been active during the past 2.2 Ma (Read, 1978). The volcanic deposits overlie basement rocks of the southern Coast Belt including greenschist- to amphibolite-facies supracrustal rocks of the Cadwallader Terrane, and Tertiary monzonite intrusions of the Coast plutonic suite (Read, 1978; Gabrielse et al., 1991). This region of the Coast Mountains has been characterized by rapid rates of uplift over the past 4 Ma (K.A. Farley, M.E. Rusmore, and

S.W. Bogue, pers. com., 2000), which has led to relatively high rates of erosion. Thus, the Mount Meager volcanic complex is highly dissected and is presently perched at 1100 to 1200 m elevation, well above the present day erosion surface marked by the Lillooet River (400–500 m elevation). The three most prominent peaks of the volcanic edifice, Meager, Capricorn and Plinth, rise to elevations of 2650 m, 2551 m, and 2677 m, respectively.

The geology of the Mount Meager volcanic complex has been well described by Anderson (1975), Read (1977, 1978, 1990), Stasiuk and Russell (1989, 1990), Stasiuk et al. (1996), and Hickson et al. (1999). For the purposes of this paper we review the general distribution and nature of two formations, namely the Plinth Formation and the Pebble Creek Formation. The Plinth Formation is 90 000 to 110 000 years old and comprises volcanic deposits and subvolcanic stocks and feeders (Read, 1978). The Pebble Creek Formation represents the youngest known volcanism at Mount Meager and has recently been redated at 2360 BP (Clague et al., 1995; Leonard, 1995). This formation includes Plinian- and Merapi-style deposits of intermediate volcanic rocks (Stasiuk and Russell, 1989; Stasiuk et al., 1996; Hickson et al., 1999). The latter Merapi-style avalanche or pyroclastic block-and-ash-flow style deposits are distributed as a broad, valley-filling apron extending downslope below an inferred vent crater seated on the northeastern flank of Plinth Peak. We describe and contrast avalanche deposits that derive from, or are part of, these two stratigraphic formations.

HOT *versus* COLD AVALANCHE DEPOSITS

Figure 2 is a revised geological map for the area of interest based on results of the 2000 field season (cf. Hickson et al., 1999). It shows the distribution of three distinct and mappable avalanche deposits. These avalanche deposits result from mass-wasting processes, as well as from the explosive collapse of lava flows or domes. Three detailed stratigraphic sections have been prepared for type localities where the avalanches are well exposed (**Fig. 3**); these sections schematically portray the thicknesses and stratigraphic relationships of the individual avalanche deposits.

All three deposits are very poorly sorted, clast-rich, but matrix supported, and feature a fine- to medium-grained sand-sized matrix. Internal structures are rare in these deposits though some reverse grading and concentrations of coarse blocks are visible in the upper layers. All the avalanche deposits discussed here are monolithological and comprise almost entirely fragments of intermediate volcanic rocks. In this regard, the rock avalanches superficially resemble primary block-and-ash pyroclastic flow deposits when in reality they are mechanically reworked materials from previous episodes of eruption. Below, we use our descriptions of the deposits at Mount Meager to develop a preliminary set of criteria (**Table 1**) for distinguishing between 'hot' and 'cold' avalanche deposits.

Section A: 'cold' avalanche from Plinth Peak

At Mount Meager, an upper rock-avalanche deposit (unit Av_{bx}) derived from Plinth Peak is exposed in roadcuts north of the Lillooet River opposite Plinth Peak. This deposit forms a large apron that mantles the southern slope of Mount Atheistan, north of Mount Meager, up to an elevation of 880 to 900 m. Roadcuts through this apron show it to have a lateral width of at least 3.4 km. It directly overlies thick pumice beds of the Pebble Creek Formation (unit PCf_{tf}) at location A (Fig. 3) and extends upslope and to the east from location A. At lower elevations in the Lillooet River valley (location B; **Fig. 3**), it lies on the irregular upper surfaces of the Pebble Creek Formation block-and-ash flows (unit PCf_{bx}). No paleosol is developed on this lower contact although it is unclear whether the contact is erosional or preserves the original upper surface of the underlying deposit. Incised creek valleys cut through the rock-avalanche deposit at numerous locations and are filled by younger debris flows. Reworked pumice-rich surface wash commonly overlies and obscures large sections of the deposit on shallow-dipping, higher slopes.

Unit Av_{bx} is typically poorly sorted, matrix supported, and contains clasts as large as 2.5 m in diameter (**Fig. 4a**). Clasts are primarily porphyritic Plinth Peak dacite lavas. This deposit contains angular blocky clasts characterized by oxidized flat-faced joints and parting surfaces and fresh angular faces (**Fig. 4b**). The oxidized surfaces are inferred to be columnar jointing from the original deposits whereas the freshly broken surfaces formed during the rock avalanche. Clasts range from a medium bluish-grey through very dark red and black. In rare instances, fine, well rounded lithic pebbles and cobbles of altered greenstone and metawacke are present. The matrix commonly varies from the same grey as the Plinth Peak fragments to an oxidized moderate yellowish brown. This unit is always unconsolidated.

Section B: 'hot' avalanche of the Pebble Creek Formation

Within the drainage system of the Lillooet River, the Pebble Creek Formation preserves a series of pyroclastic block-and-ash-flow deposits (PCf_{bx}) that were generated by the decrepitation of thick dacite lava flows or domes (**Fig. 2**) (Stasiuk et al., 1996). These deposits show facies variations from densely welded to poorly indurated or unconsolidated. The latter facies are important because they superficially resemble and share a close spatial relationship with unit Av_{bx} (Fig. 2). The unconsolidated Pebble Creek block-and-ash flow unconformably overlies densely welded pyroclastic block-and-ash flows of the early stages of the eruption (**Fig. 3**). Both unit Av_{bx} and a late rounded-pumice sheet wash can be seen onlapping onto unit PCf_{bx}.

Unit PCf_{bx} is unsorted, unstructured, matrix supported, and comprised almost exclusively of blocks of intermediate volcanic materials (**Fig. 5a**). Clasts range from grey through salmon pink to black and can be massive or pumiceous. Some clasts are subangular to subrounded, but the majority are distinctly angular. Although closely resembling the rock avalanche deposits derived from the Plinth Formation, they are distinguishable by several unique features that are indicative of hot emplacement temperatures. For example, delicate 'breadcrust' textures are commonly preserved on the surfaces of inflated blocks (**Fig. 5b**). This breadcrust texture consists of a multitude of irregular fractures up to 3 cm deep that are oriented normal to the clast surface.

Within the matrix of the block-and-ash flow are abundant fine black glassy fragments. The matrix ranges from a distinct red at the type section locality to grey in equivalent upstream sections. It is variably indurated and in places welded (**Fig. 5c**).

Section C: 'hot' avalanche of the Plinth Formation

The Plinth Formation pyroclastic block-and-ash flow (unit PLf_{bx}) is represented by a small exposure in the eastern half of the map area (**Fig. 2**). It is closely associated with the eastern limits of both units Av_{bx} and PCf_{bx}. Unit PLf_{bx} lies directly on Cadwallader metasedimentary bedrock. The upper 1 to 2 m of this deposit appears reworked and is overlain by an indurated lodgement till (Fig. 3).

The deposit contains numerous large blocks of Plinth Formation lava up to 10.5 m in diameter. The blocks are generally not vesicular except along planar flow-banding features, which are moderately vesicular (**Fig. 6a**). Clasts in this unit are not breadcrusted, but show smooth, subrounded surfaces. A significant proportion of intermediate- and large-sized blocks (>50%) contains radially oriented joint sets (**Fig. 6b**). Locally, small blocks have radially oriented joints although most have irregular joint patterns.

The joint sets are concentric regions where internal sets have relatively coarse and widely spaced joints, whereas outer sets are progressively finer and more closely spaced (Fig. 6b, **6c**). Locally, these fine joints are expressed on the surface of the blocks as fine crenulated fractures.

Clasts are mineralogically identical although they show variations in matrix colour similar to the blocks in unit Av_{bx}. A coarse- to fine-sand-sized matrix ranges from the same medium bluish grey to a moderate yellowish brown. The unit is poorly to moderately indurated.

Discrimination of 'hot' vs 'cold' avalanches

All the avalanche deposits discussed herein have formed from an initial brittle failure of oversteepened source material due to gravitational stresses induced by flow or tectonic uplift. After this initial loss of cohesion their respective kinetic paths diverge. In rock avalanches, such as the Plinth rock avalanche (unit Av_{bx}), potential energy is converted to kinetic energy, which imparts momentum to the deposit as well as energy to cause the mechanical breakdown of particles. In Merapi-style hot block-and-ash pyroclastic flows, such as the Plinth and Pebble Creek formation block-and-ash flows, gravitational potential supplies the same energy. Additional kinetic energy can be provided to the block-and-ash flow from explosive degassing of the still hot viscous material and thermal expansion of entrained cold gases (Bardintzeff, 1984; Ui et al., 1999). This added energy contributes to both the velocity and fragmentation of the material as it cascades down the mountain side. In both cases the resultant deposits are an unsorted mixture of the original source material.

Our work has shown that the hot pyroclastic deposits can be distinguished by features indicative of high emplacement temperatures. Our criteria include the presence of breadcrust textures on clast surfaces where degassing was allowed to continue after emplacement of the clast, or radially oriented cooling joints in blocks, or incipient welding of a glassy matrix. In younger rocks, incipient welding can be considered diagnostic if correctly identified. Induration can derive from numerous processes, including welding, groundwater interaction, and glacial loading. For example, the presence of a strongly indurated lodgement till and reworked Plinth Formation fragments overlying unit PLf_{bx} suggests that, in this case, the induration may not be a primary depositional feature, but, rather, derives from glacial interaction.

The presence of significant magmatic heat at the time of failure does not guarantee that any or all of the hot features described above are preserved in the resultant deposit. Thus, volcanic avalanche deposits may occur where the ‘hot’ character, or volcanic origin, cannot be recognized. Conversely, diagnostic evidence of cold deposition is elusive at best. The juxtaposition of weathered columnar joint faces on clasts with fresh fracture surfaces formed during transport indicates that the source of unit Av_{bx} was cold. This is consistent with the known stratigraphy and age relationships of the Plinth and Pebble Creek formations.

DISTINGUISHING SOURCES

In the above discussion, we have described three avalanche deposits that are produced from two rheologically distinct sources, mass-wasting of cold ‘bedrock’ and viscous lava flows or domes. The deposits are monolithological; the clasts are plagioclase-porphyritic, aphanitic (very fine-grained), intermediate volcanic rocks. In fact, it is difficult to distinguish between all three avalanche deposits on the basis of composition. In this specific situation, chemical analysis of the rock fragments from each of the three deposits cannot resolve the issue because volcanic rocks within the Plinth and Pebble Creek formations have overlapping compositions (Stasiuk and Russell, 1989; Stasiuk et al., 1996). However, the two formations can be distinguished in thin section on the basis of mineralogy and texture (Stasiuk et al., 1996; Hickson et al., 1999). These criteria can be used to determine the source of each of the avalanches.

Plinth Formation volcanic rocks are highly porphyritic and contain abundant phenocrysts. Plagioclase, quartz, biotite, and amphibole make up the major mineral assemblage. Plagioclase phenocrysts are distinctly zoned with some internal concentric resorption surfaces. Subrounded to rounded, resorbed, 1 to 3 mm quartz grains are abundant. The groundmass preserves abundant microphenocrysts suspended in a devitrified glassy matrix. Clasts collected from both avalanche deposits at locales A (Av_{bx}) and C (PLf_{bx}) are identical in mineralogy and texture with Plinth Formation rocks (**Fig. 7**).

Volcanic material from the Pebble Creek Formation contains phenocrysts of plagioclase, biotite, and amphibole (Fig. 7). Quartz is rare in rocks of the Pebble Creek Formations and is almost never visible in hand specimen. This contrasts Plinth Formation rocks, which feature ubiquitous, large (1–3 mm), rounded, visible quartz phenocrysts. The character of plagioclase phenocrysts provides additional, albeit more cryptic, textural differences with resorption textures. Most of the plagioclase found in Pebble Creek Formation volcanic products are strongly resorbed with sieve textures that penetrate entire phenocryst cores and locally preserve fine, normal-zoned plagioclase overgrowths.

Plinth Formation clasts are quite homogeneous throughout all Plinth-derived units, whereas Pebble Creek clasts show complex and varied mixing textures and phenocryst assemblages on all scales (submillimetre to metre). The matrix of Pebble Creek Formation rocks preserves vitric, massive glass and abundant vesicles whereas that of Plinth Formation rocks shows devitrification, few vesicles, and abundant microphenocrysts. In this case, petrography provides a reliable means by which to differentiate deposits deriving from Plinth sources and those deposited during the recent Pebble Creek eruption.

The Pebble Creek Formation has been dated at 2360 BP. The Plinth volcanic deposit described above is demonstrably preglacial. Although separated by at least 10 000 to 15 000 years (a relatively long time in comparison to rock-avalanche periodicity in the region), the recognition of multiple events associated with this complex has implications for hazard assessment. In addition to the Plinth and Pebble Creek formations, Read (1978) suggests that Capricorn, Meager and The Devastator peaks within the Mount Meager complex all represent the preserved conduits and feeder intrusions of individual volcanic events of varied ages.

NATURAL HAZARD ASSESSMENT

The rock avalanche deposits studied at Mount Meager result from two distinct processes, 1) mass wasting of the volcanic edifice through gravitational collapse, and 2) pyroclastic block-and-ash flows derived from the collapse of lava domes and/or flows. These two distinct processes create deposits that are similar on a mesoscopic scale, but dissimilar at a finer scale. The importance of discriminating between these two processes is related to their differing risk implications.

Long avalanche runout distances can derive from processes such as acoustic fluidization and may be assisted by pore pressures from trapped fluids or gases (Hungr, 1990). The maximum fall distance in the Mount Meager area is at least 1400 m, but the valley is very narrow and runs parallel to the probable failure surface. The Plinth rock avalanche, described in this study, is confined to the opposite valley wall and has a runup heights of at least 180 m. It has not travelled any distance downvalley, despite the possibility that it originated from high up on the slopes of Plinth Peak.

Pyroclastic block-and-ash avalanche deposits at Mount Meager share a similar distribution and runup height with the rock-avalanche deposits. The block-and-ash pyroclastic flows are characterized in part by the same mechanical and frictional controls that act on rock avalanches. Magmatic heat and degassing from the lava blocks that make up a pyroclastic avalanche can add additional buoyancy and the potential for development of explosive pyroclastic flows. Additionally, mobile and fast-moving clouds of elutriated ash and hot gases (nuées ardentes) can decouple from a flow and subsequently travel great distances, overcoming significant topographic boundaries (Fisher, 1995; Fujii and Nakada, 1999). High temperatures, coupled with high particle concentrations, make such flows extremely destructive. The deposits (ash-cloud facies deposits) are also thin, erodible, and difficult to find in the geological record, but represent a significantly greater hazard, especially to people, than that found in cold rock avalanches. At Mount Meager, the hot pyroclastic flow deposits are found 5.5 km downstream from the vent area. Their ash clouds likely extended over even greater distances.

Risk analysis of specific hazardous events involves an *assessment* of the hazard (nature and probability) and an *evaluation* of its impact (Massmann, 1990; Morgan and Henrion, 1990). The assessment part of risk analysis depends on scientific and technical input to provide an accurate accounting of the type, distribution, intensity, and frequency of individual hazards. It is implicit that the nature of the hazard be correctly identified. In contrast, the evaluation part of risk analysis addresses the societal impact; it is based on a valuation of the resources, infrastructure, human lives, and other societal issues that could be adversely affected by the hazard (Massmann, 1990; Morgan and Henrion, 1990).

Because the hazard characteristics of cold and hot rock avalanches differ, our field results have important consequences for natural hazard mapping and risk assessment in this part of the Lillooet River valley. Distinguishing between volcanic block-and-ash avalanches (with their attendant hot ash clouds) and mass-wasting events also extends the hazardous area higher up on the valley walls and farther downvalley than if all three deposits were cold rock avalanches. Furthermore, misidentifying the hazard (i.e. cold or hot avalanche) could lead to underestimating the consequences of one hazard (i.e. volcanic) and overestimating the consequences of the other (i.e. mass wasting).

Lastly, our work has shown that the block-and-ash flow deposits within this part of the Lillooet River valley derive from at least two separate volcanic events. The youngest deposit is a product of the 2360 BP eruption that produced the Pebble Creek Formation. The older block-and-ash deposit represents a preglacial eruption of the Plinth magmatic system. These results are critical to establishing the frequency of volcanic events and thereby provide the necessary data for more quantitative studies of risk.

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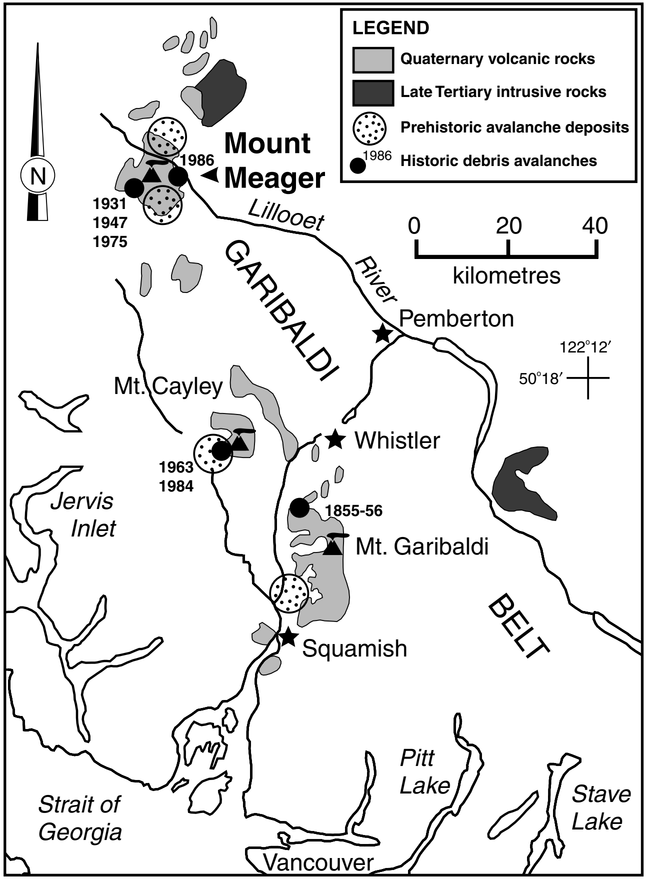

Figure 1. Location of the Mount Meager volcanic complex with respect to other Quaternary volcanic edifices in the Garibaldi Volcanic Belt of southwestern British Columbia (*after* Hickson, 1994). Also shown are the locations of large accumulations of prehistoric avalanche deposits and historical rock avalanches associated with the same volcanic terranes (*after* Evans, 1992).

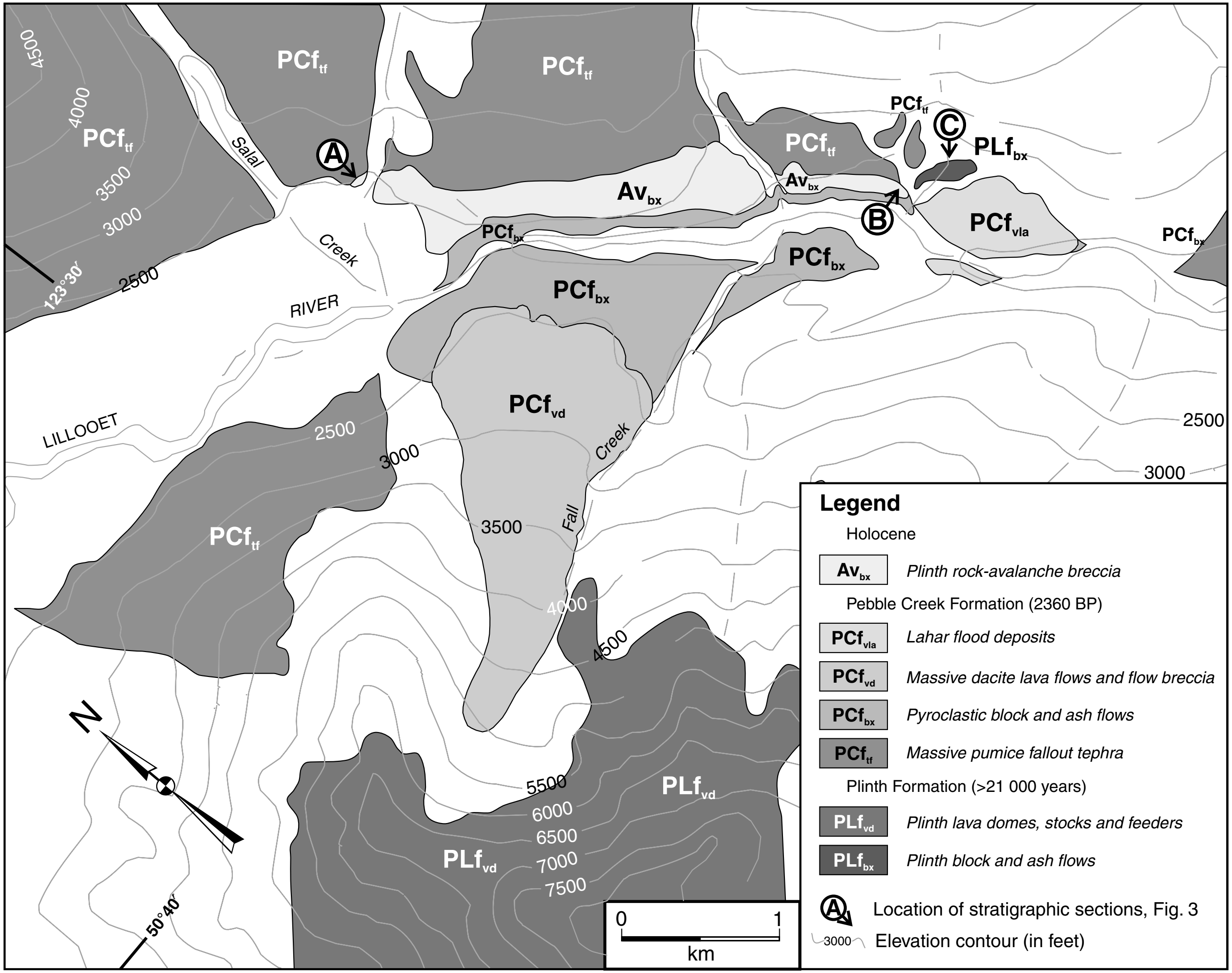

Figure 2. Geological map for the area situated immediately north of Mount Meager and along the Lillooet River. Stratigraphic units in the map legend include deposits of the Pebble Creek Formation defined by Hickson et al. (1999) and units identified or revised in this work. The locations of important stratigraphic sections discussed in the text are noted (*see* Fig. 3).

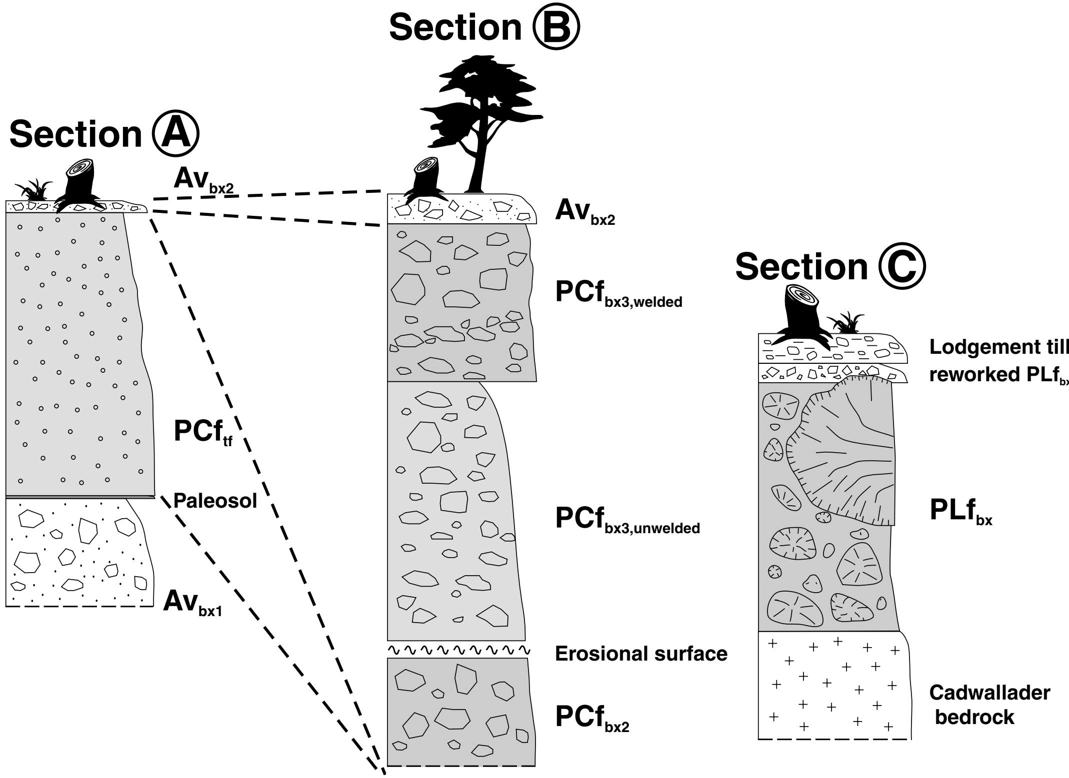

Figure 3. Schematic stratigraphic sections summarizing the distribution and stratigraphic relationships of major units of the Pebble Creek Formation. Locations are keyed to the geological map (Fig. 2) by letters: A) western limit of the Plinth avalanche overlying pyroclastic fall, B) eastern toe of the Plinth avalanche overlying late Pebble Creek block-and-ash flows, C) Plinth block-and-ash outlier sitting on bedrock upslope and east of B). Unit names and codes are the same as in Figure 2 (*see* text). Shaded units are volcanic in origin.

Figure 4. Field photographs showing the matrix-supported and very poorly sorted character of avalanche deposits east of section A (Fig. 2) derived from mass wasting of Plinth Peak. Specific details include **a**) the general character of an unconsolidated, cold rock-avalanche deposit comprising almost exclusively fragments of intermediate volcanic rocks, and **b**) detail of a block derived from Plinth Peak and showing preservation of original joint surfaces. Note the dollar coin for scale.

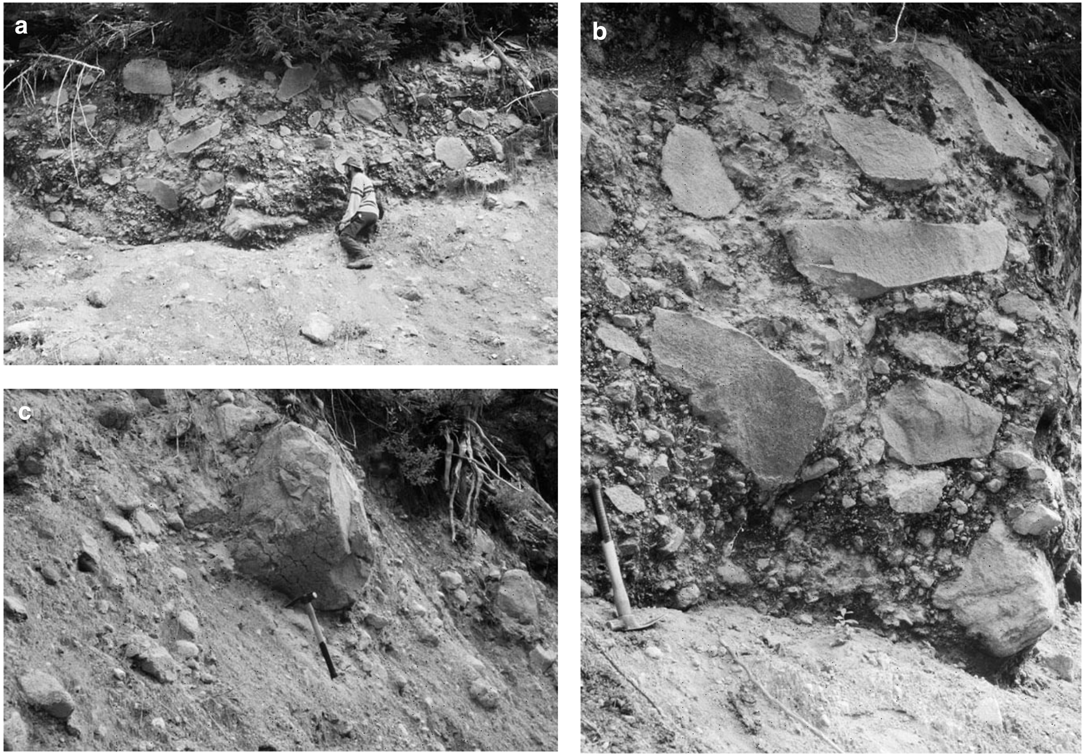

Figure 5. Field photographs of the block-and-ash avalanche deposit of the Pebble Creek Formation (Section B, Fig. 2) produced by the collapse of lava flows or domes. **a**) the deposit is variably welded and the photograph shows both an upper indurated facies and a lower unconsolidated facies. **b**) Close-up view of angular blocks within indurated facies of the Pebble Creek block-and-ash flow. There is little compaction of the blocks. **c**) An example of a delicate 'breadcrust'-textured block found within the poorly indurated facies of the Pebble Creek block-and-ash flow deposits. The hammer is 45 cm long.

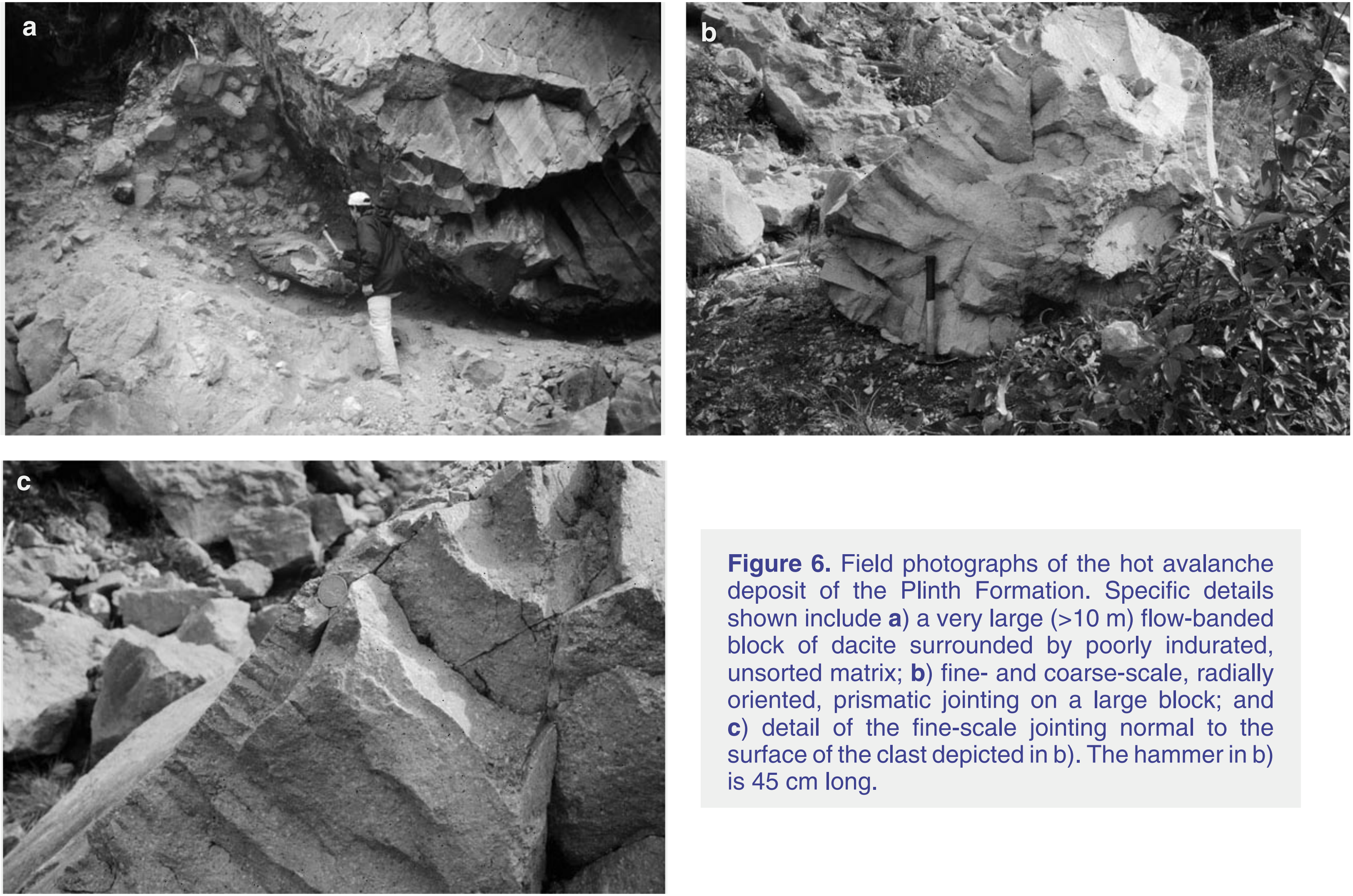

Figure 6. Field photographs of the hot avalanche deposit of the Plinth Formation. Specific details shown include **a**) a very large (>10 m) flow-banded block of dacite surrounded by poorly indurated, unsorted matrix; **b**) fine- and coarse-scale, radially oriented, prismatic jointing on a large block; and **c**) detail of the fine-scale jointing normal to the surface of the clast depicted in b). The hammer in b) is 45 cm long.

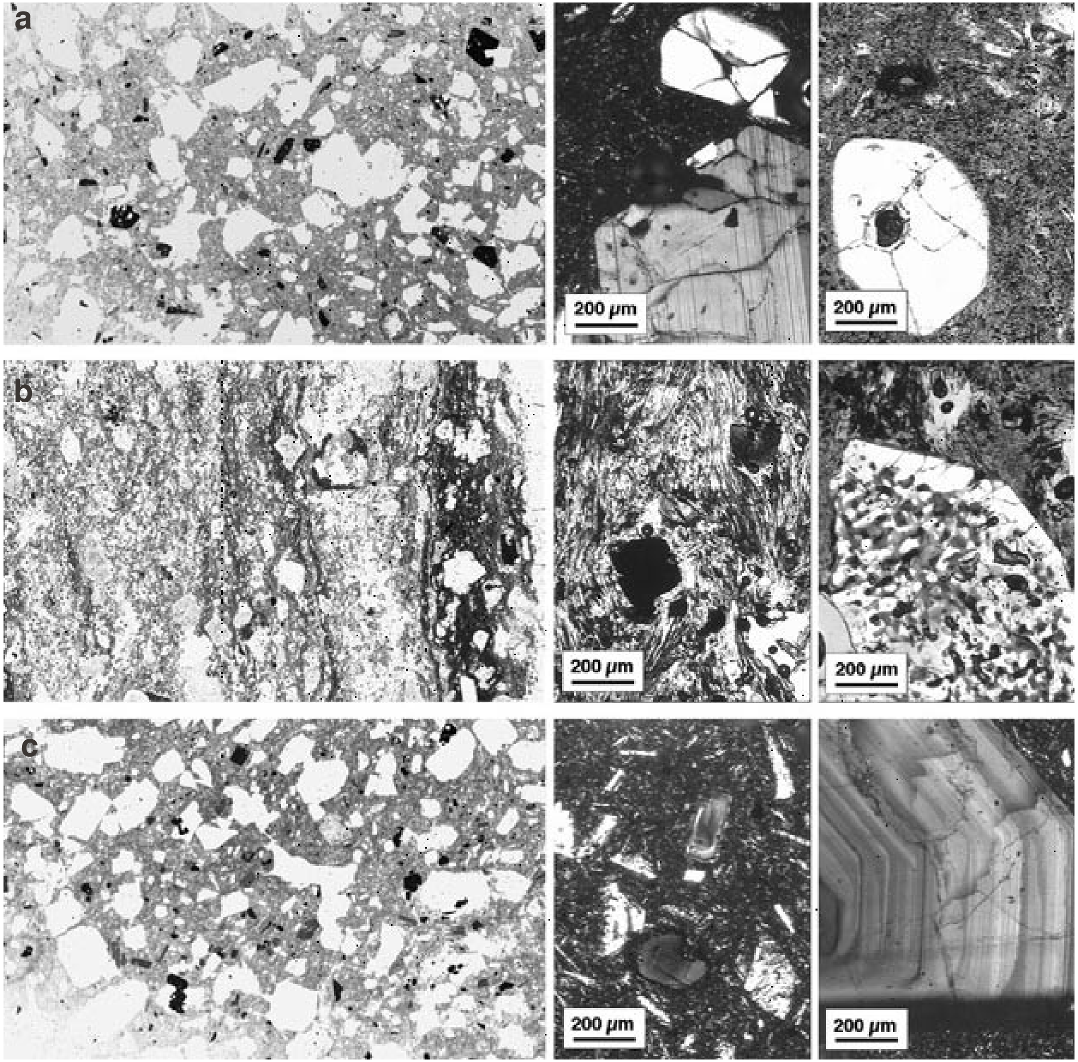

Figure 7. Digitally scanned images of thin sections under plane-polarized (ppl) and crosspolarized (cpl) light (sections are 4 cm by 2.5 cm). Images are of thin sections from **a**) cold Plinth avalanche deposit (ppl), showing rounded quartz and euhedral plagioclase phenocrysts (cpl) and a quartz phenocryst with amphibole inclusion in devitrified matrix (ppl); **b**) Hot Pebble Creek block-and-ash flow (ppl), showing flattened vesicles in a welded block and a sieve-textured (resorbed) coarse, euhedral plagioclase grain (ppl); and **c**) hot Plinth block-and-ash flow (ppl), showing microphenocryst-rich matrix (cpl) and a distinctly zoned and unresorbed plagioclase phenocryst (cpl).

Table 1. Summary of properties of avalanche deposits produced by mass wasting or volcanic processes. Deposits at Mount Meager include rock avalanches derived from Plinth Peak (Evans 1992; Hickson et al, 1994) and Merapi-type, block and ash flows (Stasiuk et al., 1996). Deposit types share mesoscopic similarities but are distinguished by several finer-scale diagnostic features (see text).

Description	Rock avalanche	Pyroclastic block-and-ash avalanche	Pyroclastic block-and-ash avalanche	Diagnostic[2]
Origin	mass wasting	lava dome/flow collapse	lava dome/flow collapse	
Source	Plinth Formation	Pebble Creek eruption	Plinth eruption	
Unit	[1]Av_{bx}	[1]PCf_{bx}	PLf_{bx}	
Age	< 2360 BP	2360 BP	> 21 ka	
Lithology	monolithological; >90% clasts are dacite of the Plinth Formation	monolithological; >95% clasts are dacite of the Pebble Creek Formation	monolithological; >90% clasts are dacite of the Plinth Formation	
Clasts[3]	porphyritic (Pl, Qtz, Bit)	porphyritic (Pl, Bit, Hbl); glassy, vesicular	porphyritic (Pl, Qtz, Bit)	
Sorting	none	none	none	
Internal structure	none	minor clast alignment	none	P
Induration	unconsolidated	unconsolidated to welded	unconsolidated to partly indurated	X
Clast shape	angular	angular and subrounded	angular and (sub)rounded	P
Clast surface	rough, fractured	smooth to rough	smooth	O
Clast features	joint-bounded surfaces	breadcrust-textured surface	radially oriented joints	X

1 Unit designations are *after* Hickson et al. (1999).
2 X-strong; O-weak; P-possible.
3 Minerals abbreviations: plagioclase (Pl), quartz (Qtz), biotite (Bit), hornblende (Hbl).