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Revised stratigraphy of the Pebble Creek Formation, British Columbia: evidence for interplay between volcanism and mountainous terrain

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Abstract: The Mount Meager volcanic complex hosts rocks from the youngest explosive volcanic eruption in Canada (2360 BP). Products of that eruption constitute the Pebble Creek Formation. We present a revised stratigraphy based on field work from the 2000 and 2001 field seasons. This stratigraphy is based on volcanic and related deposits described by Hickson et al. (1999). New stratigraphic units include reworked fallout, paleolake deposits, a mixed volcanic and rock-avalanche deposit, and an intervolcanic avalanche deposit. The nature and distribution of the Pebble Creek deposits attest to interactions between volcanism and a high-relief landscape hosting a prominent river system.

Résumé : Le complexe volcanique de Mount Meager renferme des roches provenant de la plus récente éruption volcanique explosive au Canada (2360 B.P.). Les matériaux associés à cette éruption constituent la Formation de Pebble Creek. Nous présentons une stratigraphie révisée d'après des travaux effectués sur le terrain pendant les saisons 2000 et 2001. Cette stratigraphie est fondée sur des dépôts volcaniques et des dépôts associés décrits par Hickson et al. (1999). Parmi les nouvelles unités stratigraphiques, mentionnons des retombées remaniées, des dépôts paléolacustres, des dépôts de roches volcaniques et d'avalanche de roches, ainsi qu'un dépôt d'avalanche intervolcanique. La nature et la répartition des dépôts de la Formation de Pebble Creek témoignent des interactions entre le volcanisme et un paysage montagneux sillonné par un important réseau hydrographique.

INTRODUCTION

The Pebble Creek Formation contains a diverse assemblage of deposits reflecting the dynamic interplay between an active volcano and its surrounding environment. At Mount Meager, the environment is dictated by a terrain characterized by rugged, steep topography and is the result of high rates of uplift (Farley et al., 2001) and erosion over the last 2.5 Ma. The resulting stratigraphy includes both primary volcanic deposits and deposits formed by mass wasting and fluvial sedimentary events. Herein, we present a revised stratigraphy and new map of the Pebble Creek Formation based on field work completed during the 2000 and 2001 field seasons.

GEOLOGICAL SETTING

The Mount Meager volcanic complex (Fig. 1) is a composite stratovolcano lying at the northern end of the Garibaldi volcanic belt (Mathews, 1958; Green et al., 1988). Volcanism within the complex spans the last 2.2 Ma (Read, 1978). Exhumed remnants of volcanic stocks and feeders demonstrate a northward younging of volcanism in the complex (Read, 1978). The Pebble Creek Formation comprises deposits from the most recent eruption of the complex and within the Garibaldi volcanic belt (Green et al., 1988; Hickson, 1994). The Pebble Creek eruption is dated at 2360 BP by ^{14}C (Nasmith et al., 1967; Lowden and Blake, 1968, 1978; Anderson, 1975; Rutherford et al., 1975; Mathewes and Westgate, 1980; Evans, 1992; Clague et al., 1995) and glacial varves (Leonard, 1995). The deposits partly fill the Lillooet River valley and mantle slopes north and east of Mount Meager. Read (1978) traced them up to an inferred vent that lies at the base of a large col on the northeast shoulder of Plinth Peak.

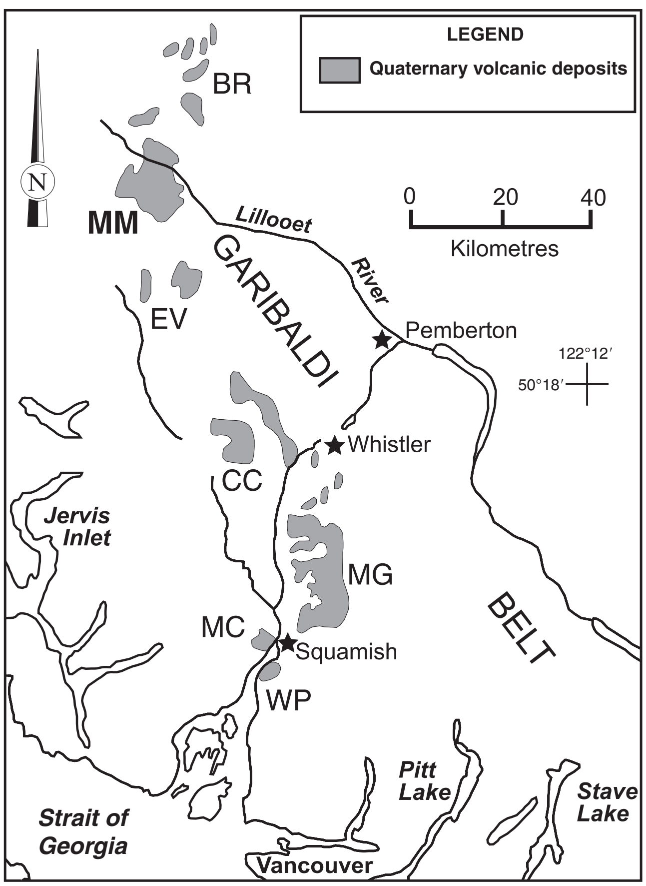

Figure 1. *Location of the Mount Meager volcanic complex (MM). It lies at the northern extent of the Cascade range of volcanoes in Canada, which include Watts Point (WP), Monmouth Creek (MC), Mount Garibaldi (MG), Mount Cayley (CC), Elaho Valley (EV), and Bridge River (BR) volcanic centres and complexes. These volcanoes make up the Garibaldi volcanic belt (*after *Hickson, 1994).*

PEBBLE CREEK FORMATION

The Pebble Creek Formation as defined by Hickson et al. (1999) includes cogenetic volcanic deposits and closely associated rock-avalanche and debris-flow deposits. Volumetrically, dacitic pyroclastic rocks (Stasiuk and Russell, 1989; Stasiuk et al., 1996) make up most of the Pebble Creek Formation. Figure 2 presents a revised distribution of the Pebble Creek Formation based on field work from the 2000 and 2001 field seasons. Pyroclastic deposits include fallout tephra (TF) locally overlain by ignimbrite (PF) and block-and-ash-flow (BA) deposits. A dacite lava flow (VD) is the youngest eruption product. Additional deposits include avalanche deposits (AV), reworked fallout deposits (TF_{RW}), lake-associated deposits (LS), and a hot debris-flow deposit (LA).

VOLCANIC DEPOSITS

Pyroclastic fallout deposits blanket south-facing slopes opposite Mount Meager and north slopes on Plinth Peak (Fig. 2). Pyroclastic flow deposits include ignimbrite (PF) and block-and-ash-flow deposits (BA). Ignimbrite deposits (PF) directly overlie pyroclastic fallout deposits, oxidized and reworked pumice deposits, and till. The uppermost ignimbrite deposit grades into overlying block-and-ash-flow deposits, which reach stratigraphic thicknesses greater than 150 m near Keyhole Falls (Fig. 3, section D). Detailed descriptions of the above deposits are provided by Hickson et al. (1999).

We have mapped the distribution of a new deposit within the Pebble Creek Formation. It features a mixture of two main clast types found in equal proportions. The poorly sorted massive deposit comprises a) Plinth assemblage clasts and b) blocks of Pebble Creek Formation lava. Plinth assemblage clasts are subangular and their surfaces show pre-fragmentation weathering. Pebble Creek Formation blocks are dense to pumiceous lava blocks that reach 1.5 m in diameter; they commonly have breadcrusted surfaces and local internal prismatic joints. Unit BA_M is dominantly matrix supported, but in places is nearly clast supported. It is thicker than 15 m and

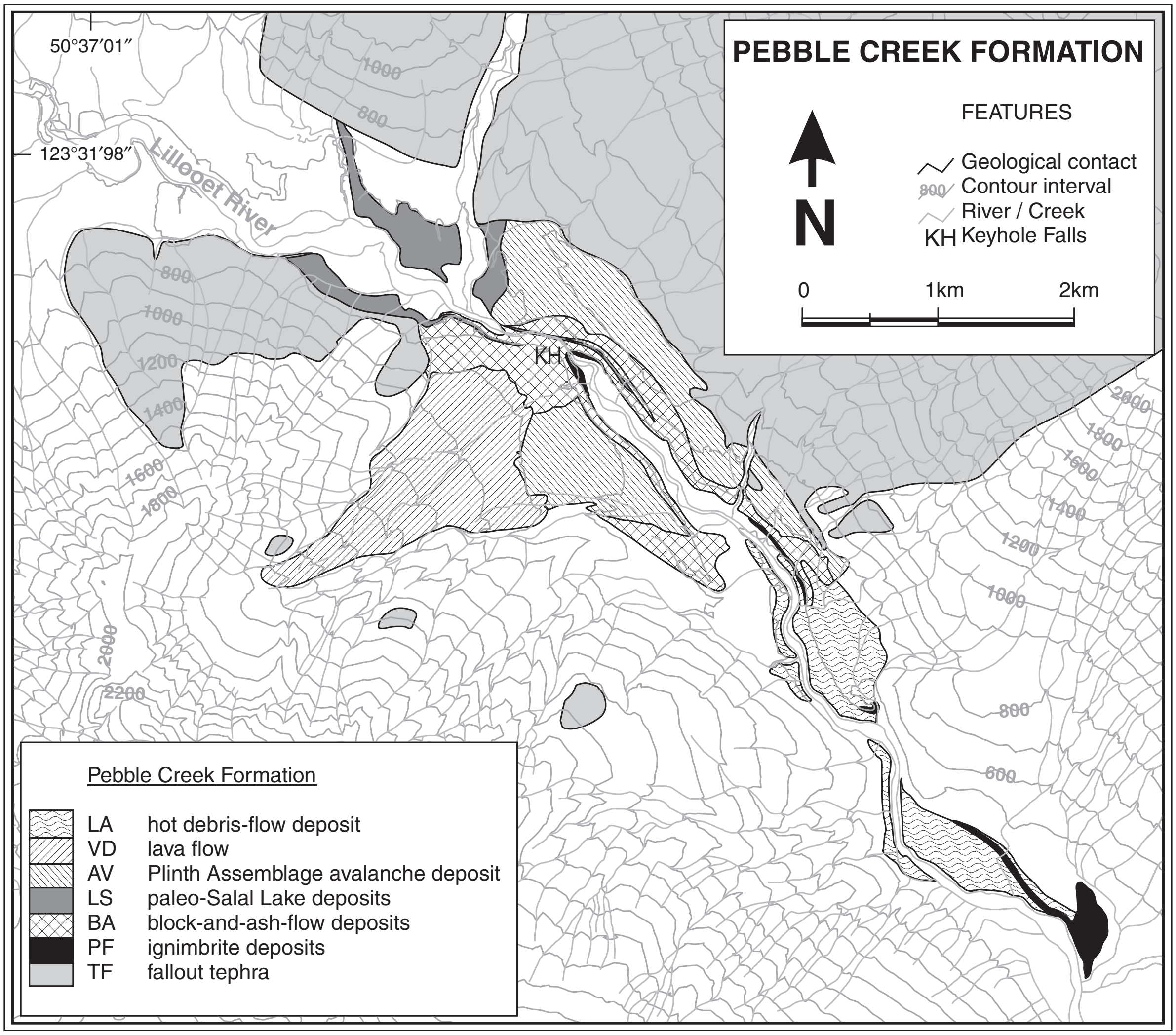

Figure 2. *Geological map showing the distribution of Pebble Creek Formation units in the Mount Meager area. Pyroclastic fall deposits are much more extensive, reaching as far as the Alberta–British Columbia border (Westgate and Dreimanis, 1967). This map represents earlier work by Read (1978), Stasiuk and Russell (1990), Stasiuk et al. (1996), Hickson et al. (1999), and Stewart et al. (2001) and includes revisions based on results of the 2000 and 2001 field seasons.*

appears to lie only on the northwest limb of the pyroclastic apron (Fig. 3, section C). Clast characteristics suggest that this deposit was formed by the simultaneous production and mixing of a cold rock avalanche and hot block-and-ash flow.

NONVOLCANIC CLASTIC UNITS

Rock-avalanche deposits

The slopes surrounding Mount Meager's north flank are covered by poorly sorted, monolithological, rock-avalanche (AV) deposits composed primarily of fragments of plagioclase-quartz-phyric dacite. Their source has been shown to be old volcanic stratigraphy high up on Plinth Peak (Hickson et al., 1999; Stewart et al., 2001). They are massive and form extensive avalanche aprons or small lenses within volcanic strata. They are predominantly matrix supported, but can be clast supported on the margins of larger deposits or in small deposits close to the mountain. Maximum clast sizes range from 55 cm to 240 cm.

The Pebble Creek Formation includes several rock-avalanche deposits composed of Plinth assemblage material, including an intervolcanic (AV_I) and a postvolcanic (AV_P) avalanche deposit. Unit AV_I overlies flood deposits at section D (Fig. 3) and is itself overlain by the latest block-and-ash-flow deposit. It forms a thin lens that is 15 m thick and at least 500 m long.

The largest avalanche unit preserved is unit AV_P, which mimics the geometry of the pyroclastic apron upon which it was deposited. In places, it overlies pyroclastic fallout deposits (TF). Where visible, the contact is a smooth, undulating surface that scours the top of the fallout deposit. Unit

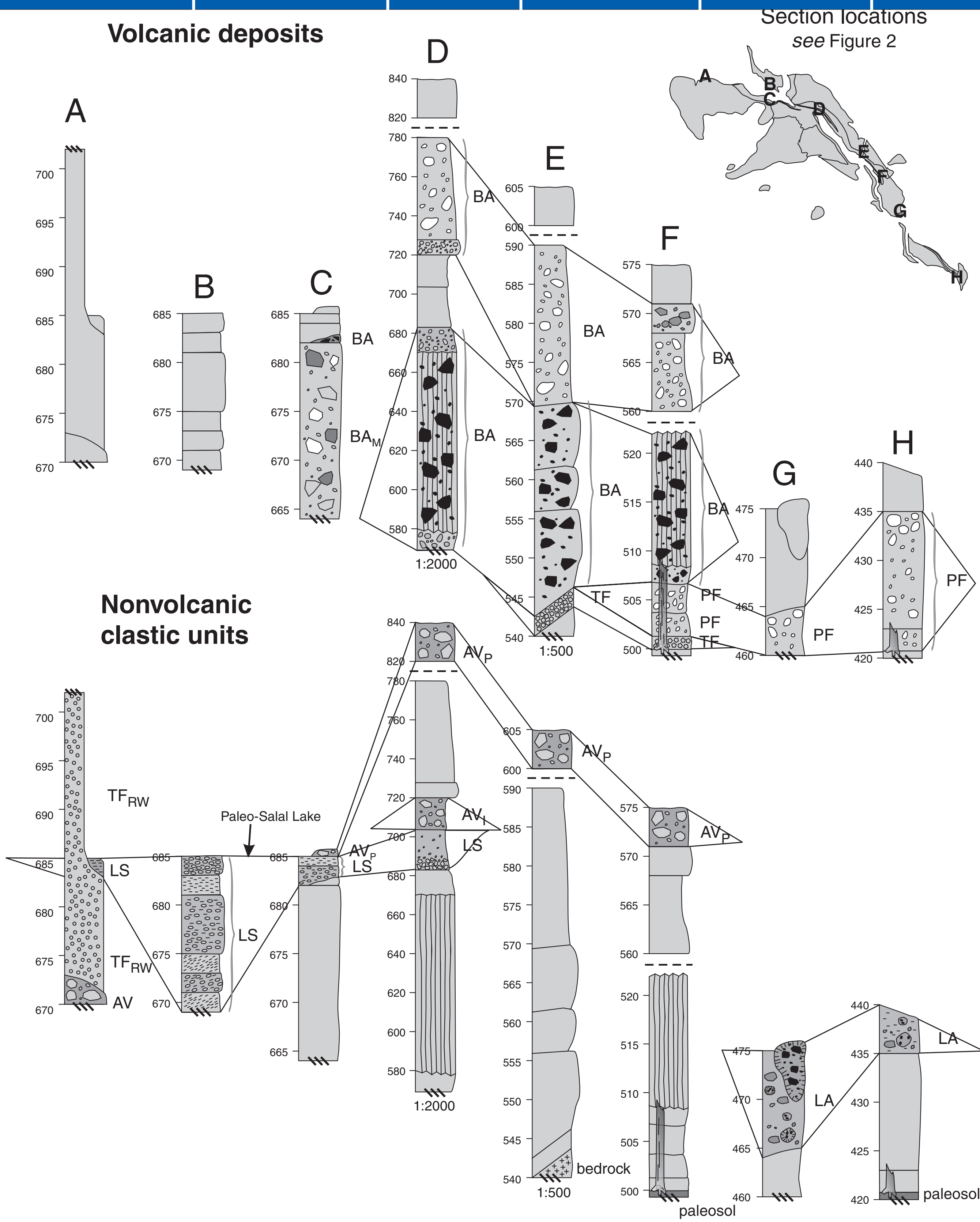

Figure 3. *Comprehensive stratigraphic sections of the volcanic and nonvolcanic Pebble Creek Formation deposits illustrated in map view in Figure 2. Elevations are given in metres to the left of each section. All sections are shown at a 1:415 scale except sections D and E (1:2000 and 1:500, respectively). Sections A, B, C, and D illustrate the highstand mark that can be observed from the paleo-Salal Lake deposits (LS). AV = avalanche deposit; BA = block-and-ash deposit; LA = hot debris-flow deposit; LS = lake-associated deposit; PF = ignimbrite deposit; TF = fallout tephra deposit*

AV_P forms a prominent, 3.8 km wide topographic hump where it intersects steep slopes above Keyhole Falls, opposite Mount Meager (Fig. 2). It overlies most of the volcanic Pebble Creek deposits (Fig. 3, sections C, D, E, and F) and forms a barrier that has diverted local streams laterally along much of its width.

Reworked pumice fallout

On the steep northern slopes of Plinth Peak and along the southern banks of the Lillooet River, deposits of reworked pumice fallout (TF_{rw}) are at least 80 m thick (Fig. 3, section A). They are characterized by weak sorting in crude, reversely graded beds, subrounded to rounded clasts, and interspersed thin lenses of Plinth assemblage avalanche deposits (Fig. 4a). From their upper extent to 800 to 900 m elevation, they lie at critical angles (37°) and lap directly onto primary fallout tephra (TF). Below this, they shallow to 22° in a large apron extending to the margins of the Lillooet River. Underlying Plinth assemblage rock-avalanche deposits are exposed in bluffs along the river (Stevenson, 1947).

Lake deposits

Correlative flood deposits, deltaic, and lakeshore sediments (LS) occur higher in the Pebble Creek Formation. A subhorizontal erosion surface truncating the top of the densely welded block-and-ash flows forms a surface on which clastic sediments were deposited (Fig. 3, section D). This deposit grades from framework-supported angular cobbles and boulders at its base to well sorted pumiceous pebbly sands at its top. Clasts and matrix are a mixture of oxidized Pebble Creek Formation and Plinth assemblage clasts and medium- to fine-grained sand. The deposit extends at least 500 m downstream from Keyhole Falls and correlates upstream with lakeshore deposits found at similar elevations (Fig. 2; Fig. 3, sections A, B, C, and D). It is immediately overlain by the avalanche unit AV_I and represents a hiatus in the accumulation of block-and-ash flows during which river levels overtopped the pyroclastic deposits.

Upriver from Keyhole Falls, aprons of clastic material are distributed along the margins of the valley and form visible benches at 685 m elevation for several kilometres along the shore. These benches are composed of block-and-ash-flow deposits (BA) and reworked pumice (TF_{rw}) farther upstream. Well sorted silt, sands, and pebbly to cobbly sands form thin, laterally continuous beds (LS) on the benches. The beds range from 6 cm silt laminae to >8 m, very well sorted lithic sands with rounded pumice pebbles and lie 15 to 40 m above the present Lillooet River flood level. Pebbles and cobbles in coarser deposits are very well rounded and include granitoid, metamorphic, vesicular basalt, and pumice clasts.

West (upstream) of Keyhole Falls, a gently sloping delta is composed of poorly sorted conglomerate and interbedded, well sorted sand lenses (Fig. 4b). Section B (Fig. 3) illustrates the progression from foreset beds at the base of the exposure through to flat-lying topset beds on top of the bluffs along the Lillooet River. Bedding fabric is defined in the conglomerate

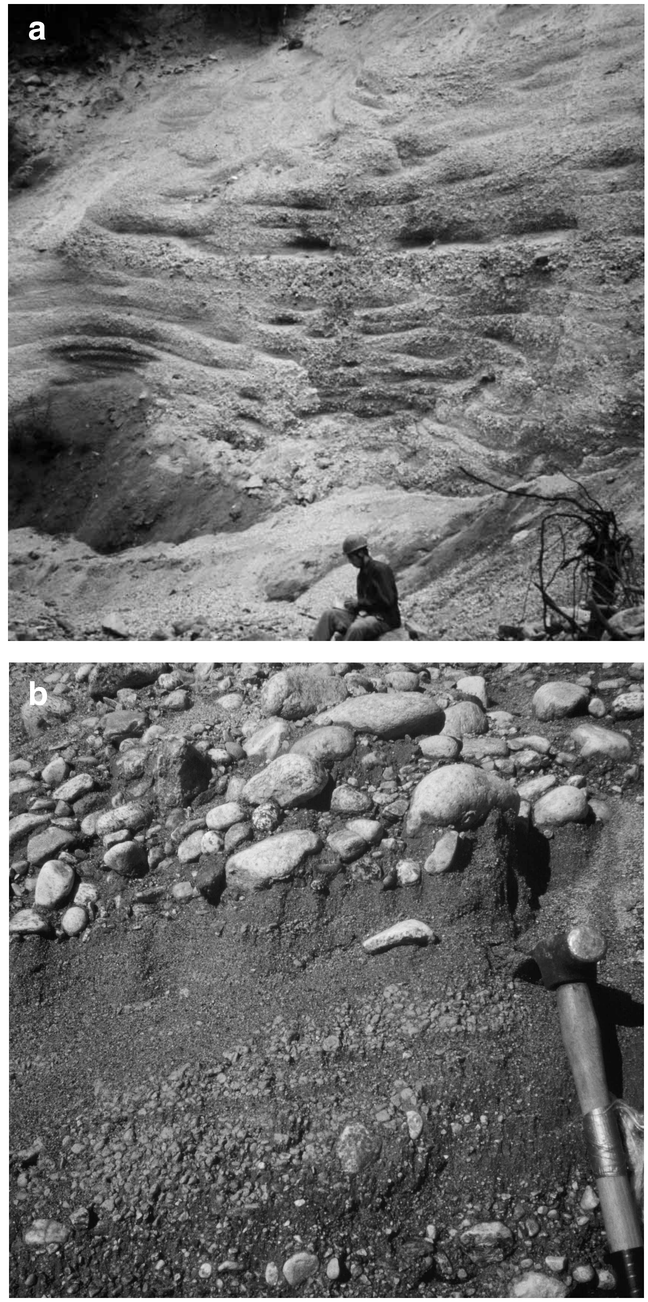

Figure 4. *Outcrop photographs of nonvolcanic units associated with the Pebble Creek Formation.* ***a)*** *Accumulations of primary pyroclastic fall are subject to reworking on steep slopes. On the north slope of Mount Meager, reworked pumice (TF_{RW}) has been accumulated in thicknesses in excess of 80 m.* ***b)*** *Thick conglomerate and pumice-rich sandstone form a large delta (LS) along the shores of the paleo-Salal Lake. Thin beds of similar deposits preserve the lake highstand mark upstream of the volcanic deposits that provided the natural dam to form the lake.*

by flat-lying and imbricated oblate clasts. These clasts are framework-supported, very well rounded cobbles and pebbles identical in composition to those found on the benches mentioned above. Well sorted beds are composed of normally graded lithic or pumice sand. Up to 15 cm of well rounded pumice cobbles can be found in the strata. The delta is cut by a major stream that drains into the Lillooet River. That stream contains the same clast types as those observed in the delta and was likely the source of the deltaic sediments.

Thick, massive beds of poorly sorted, reworked, Pebble Creek Formation deposits fill the Lillooet River valley below Keyhole Falls. They overlie ignimbrite deposits east (downstream) of the block-and-ash-flow deposits and have been described by Hickson et al. (1999) as products of the sudden release of lake waters built up behind the valley-filling pyroclastic deposits.

DISCUSSION

Many of the deposits described above owe their existence, directly or indirectly, to the eruption event that occurred at 2360 BP. The character of many these deposits and in some cases the deposits themselves are unique to volcanic eruptions occurring in mountainous environments.

The deposits at Mount Meager illustrate the potential impact of high-relief landscapes and alpine drainage systems on the styles of volcanism and the effects of volcanism on mass wasting and fluvial processes. For example, viscous lava flows and domes erupted onto steep slopes may result in brittle failure or the generation of explosive pyroclastic flows. Modern analogous deposits have been observed forming from the Montserrat (Cole et al., 1998) and Mount Unzen (Ui et al., 1999) volcanoes. Block-and-ash-flow deposits at Mount Meager share common characteristics and geometries with deposits at these volcanoes and likely have similar origins.

Pyroclastic events from an explosive eruption may cause erosion and undercutting of the older edifice that produced the eruption. This erosion, coupled with attendant eruption seismicity and ground deformation, can result in partial collapse of the edifice and formation of cold rock avalanches. For example, rock-avalanche deposits (AV) at Mount Meager are found within and directly overlying volcanic deposits. Unit BA_M is distinct because it is the product of a combination of mass wasting and volcanic events. It contains cold rock material derived from the older edifice as well as hot Pebble Creek pyroclastic material.

Narrow mountainous valleys provide an efficient catchment area for block-and-ash flows and rock avalanches. The steep-sided Lillooet River valley below Mount Meager provided a trap for block-and-ash flows and avalanches during the 2360 BP eruption. These flows built up thick accumulations and welded to form dense deposits that efficiently dammed the flow of the Lillooet River. Lakeshore sedimentary deposits preserve what we believe is a highstand mark for a short-lived paleo-Salal Lake that built up behind this dam during the course of the eruption.

The Lillooet River and surrounding drainage systems undergo flood cycles from the buildup and failure of natural dams produced by avalanche processes (Evans, 1986, 1992; Bovis and Jakob, 2000). The short time scale over which the large volumes of Pebble Creek pyroclastic deposits accumulated allowed for the buildup of what we define as the 'paleo-Salal Lake' west of the existing Keyhole Falls. Flood levels of that lake apparently overtopped the pyroclastic flows at least twice. The second of these event resulted in failure of the natural dam, and a large canyon was cut back into the pyroclastic apron. This canyon apparently cut as deeply as pre-eruptive drainage levels and transected 3 km of the eastern limb of the pyroclastic deposits. This failure generated a hot, sediment-laden outburst flood (forming unit LA) as the lake drained through and cut into the pyroclastic apron.

We have presented new deposits in the Pebble Creek Formation that demonstrate the close interplay of volcanic, rock-avalanche, and fluvial processes in a mountainous environment. Many of these processes occur individually either during volcanic eruptions outside mountainous environments, or in mountainous regions where volcanism is absent. When both these conditions are met, each process may be amplified by feedback between the contributing environments. The cumulative potential energy provided by tectonic uplift and igneous processes can increase the number and intensity of hazards present in such environments.

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