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Facies architecture of a continental, below-wave-base volcaniclastic basin: the Ohanapecosh Formation, Ancestral Cascades arc (Washington, USA)

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ABSTRACT

The >800-m-thick, Oligocene Ohanapecosh Formation records voluminous sedimentation of volcanic clasts in the Ancestral Cascades arc (Washington State, USA). Most volcaniclastic beds are dominated by angular pumice clasts and fiamme of andesitic composition, now entirely devitrified and altered. All beds are laterally continuous and have uniform thickness; fine sandstone and mudstone beds have features typical of low density turbidity currents and suspension settling; erosion surfaces, cross-beds and evidence of bi-directional oscillatory currents (i.e. wave ripples and swaley and hummocky cross-stratification) are almost entirely absent. We infer that the setting was subaqueous and below wave-base.

The abundance of angular pumice clasts, crystals and dense volcanic clasts, and extreme thickness of several facies suggest they were derived from magmatic volatile-driven explosive eruptions. The extremely thick beds are ungraded or weakly graded, and lack evidence of hot emplacement, suggesting deposition from subaqueous, water-supported, high-concentration volcaniclastic density currents. Some of the thickest beds contain coarse, rounded dense clasts at their base and are interbedded with accretionary-lapilli-bearing mudstone; these beds are interpreted to be deposits from subaqueous density currents fed by subaerial pyroclastic flows that crossed the shoreline. Shallow basaltic intrusions and mafic volcanic breccia composed of scoria lapilli indicate the presence of intra-basinal scoria cones that may have been partly subaerial.

The range in facies in the Ohanapecosh Formation is typical of below-wave-base, continental (lacustrine) basins that form in proximity to active volcanic arcs, and includes eruption-fed and resedimented facies. Extreme instantaneous aggradation rates are related directly to explosive eruptions, and sediment pathways reflect the locations of active volcanoes, in contrast to conventional sedimentation processes acting in non-volcanic environments.

INTRODUCTION

The Oligocene Ohanapecosh Formation (Washington State, USA) has been a key reference in the literature on subaqueous explosive volcanism (Fiske, 1963; Fiske et al., 1963). The highly influential work of Fiske (1963) explored general concepts of the nature of explosive eruption-fed subaqueous volcaniclastic density currents – then called “subaqueous pyroclastic flows” – and related them to sources, and transport and depositional processes. Despite the widespread extent of the Ohanapecosh

Formation in the central Cascades (>400 km^2), and mapping of various sections, the depositional processes and paleo-environment remain debated, in part due to incomplete exposure. This voluminous volcaniclastic succession is basaltic to andesitic in composition, and records the northernmost eruptive activity of the Ancestral Cascades arc (Sherrod and Smith, 2000; du Bray et al., 2006; du Bray and John, 2011).

We use facies analysis and the facies architecture of this succession to reassess the eruption styles and paleo-environments of eruption, transport and deposition. We focus on the range of volcanic and sedimentary processes that can reasonably be inferred for voluminous pumice-rich units deposited in a quiet water environment. These processes include subaqueous deposition from subaerial pyroclastic flows that entered water, and subaqueous resedimentation of unconsolidated pumice-rich aggregates. Previous interpretations are re-evaluated.

Our facies analysis demonstrates the Ohanapecosh Formation to represent a water-filled depocenter supplied almost entirely by volcanoes. Current understanding of non-volcanic basins (e.g. Johnson and Baldwin, 1996; Stow et al., 1996) cannot be applied directly to basins supplied by active volcanoes, because particle types, particle supply rates, transport and deposition processes, facies (especially bed thickness) and aggradation rates differ substantially. Using evidence from the Ohanapecosh Formation, we discuss the facies characteristics of strongly volcanic-influenced, basin successions, and how they differ from non-volcanic basins.

Definitions and methods

The bed thickness nomenclature follows Ingram (1954), and “extremely thick” is added for beds >10 m thick. “Breccia” is used as a non-genetic term to describe any clastic facies composed of angular clasts coarser than 2 mm (Fisher, 1961b); the term "matrix" is used broadly for interstitial clasts <2 mm.

Most components of the Ohanapecosh Formation are volcanic, and we follow the nomenclature of McPhie et al. (1993) to describe these rocks. In this paper, volcanic clast-rich rocks are grouped into the broad term "volcaniclastic"; facies generated by explosive eruptions are called "pyroclastic". "Pumice" is used for highly vesicular (>60 vol.%) volcanic fragments that are intermediate to felsic in composition, whereas "scoria" clasts are less vesicular (<60 vol.%) and mafic in composition. Aligned lenticular clasts are called "fiamme" (Bull and McPhie, 2007) and most appear to have been pumice clasts that compacted during diagenesis, partly or fully losing their initial porosity.

U/Pb analyses on zircons by LA-ICP-MS were performed on an Agilent 7500cs quadrupole ICPMS with a 193 nm Coherent Ar-F gas laser and the Resonetics M50 ablation cell at the University of Tasmania (Australia). Rocks were crushed in a Cr-steel ring mill to a grain size <400 microns; zircons were paned, separated from magnetic heavy minerals and hand-picked under the microscope. The selected zircon crystals were glued into epoxy and finally polished and cleaned (electronic suppl.).

GEOLOGICAL SETTING OF THE OHANAPECOSH FORMATION

Volcanism and tectonic setting of the Ancestral Cascades arc

Subduction of the Pacific plate under the North American plate began in the Paleozoic era and is still continuing today (Dickinson, 2009). During the Cenozoic, the extremely long (>1,250 km) Ancestral Cascades arc developed on the Paleozoic and Mesozoic continental terranes of western North America. Uncertainties regarding the magmatism of the Ancestral Cascades arc (45-4 Ma; du Bray and John, 2011), and the early Cenozoic history of southern Washington are partly due to loss of the geological record by erosion in response to regional uplift of the northern Cascades (e.g. McBirney, 1978; Hammond, 1979; Reiners et al., 2002), and burial under Miocene and Quaternary volcanoes (Schuster, 2005; Hildreth, 2007).

From the Eocene to the middle Oligocene, regional extension and transtension affected the northwestern part of the North American continent (Frizzell et al., 1984; Tabor et al., 1984; Johnson, 1985; Tabor et al., 2000). In southern Washington, major transcurrent faults offset the pre-Tertiary continental basement, in response to oblique subduction beneath the North American plate (Bonini et al., 1974; Johnson, 1984; Johnson, 1985; Armstrong and Ward, 1991; Blakely et al., 2002). From 57 to 43 Ma (Cheney and Hayman, 2009), these faults promoted the formation of separate basins that have distinct sedimentation and deformation histories (Johnson, 1984; Johnson, 1985). The fills of these basins comprise the middle to late Eocene Puget Group, and Renton, Spiketon and Naches formations, which are partially conformably overlain by the Ohanapecosh Formation (Tabor et al., 2000). The Ohanapecosh Formation records the northernmost, early magmatism of the Ancestral Cascades arc in southern Washington (Tabor et al., 1984; Johnson, 1985; du Bray and John, 2011).

The contact of the Ohanapecosh Formation with the underlying volcaniclastic and siliciclastic Puget Group, and Spiketon and Renton formations is everywhere conformable and commonly gradational (Fiske et al., 1963; Gard, 1968; Simmons et al., 1983; Vance et al., 1987). In contrast, the contact with the underlying Naches Formation is an unconformity (Johnson, 1985; Vance et al., 1987; Tabor et al., 2000).

The middle to late Eocene Summit Creek Sandstone (~43 to 37 Ma; Vance et al., 1987) consists of various sandstone units conformably underlying the Ohanapecosh

Formation in the areas from the eastern side of White Pass to the Naches River to the east (Ellingson, 1972; Vance et al., 1987; Hammond, 2005).

The Ohanapecosh Formation

The mostly volcaniclastic, pumice- and fiamme-rich Ohanapecosh Formation (Fiske et al., 1963) is early to middle Oligocene in age (36 to 28 Ma, mostly dated by fission tracks in zircons; Tabor et al., 2000). However, these dates include samples from a much wider area than the volcaniclastic facies described by Fiske et al. (1963) and this study. In addition, criteria to discern the Ohanapecosh Formation are subtle and its facies are poorly defined amongst the various generations of mappers, therefore it is commonly grouped with other formations into the broad name of Tertiary volcaniclastic units. The Ohanapecosh Formation was thought to be ~3 km thick (Fiske et al., 1963), exposed over >400 km^2 in an area >700 km^2 (Schuster, 2005) throughout Mt Rainier National Park and its surroundings, and is the basement upon which Mt Rainier volcano was built (Fig. 1). Coherent facies possibly related to the Ohanapecosh Formation occur at a few places (Fiske et al., 1963; Wise, 1970; Swanson, 1996; Swanson et al., 1997; Hammond, 2011 unpubl. data), and numerous younger dykes intrude the formation (Fiske et al., 1963).

The Ohanapecosh Formation *sensu lato* has been recognized from the Snoqualmie area (north) to Columbia River Gorge (south to Mt St Helens and Mt Adams), and from Mt Rainier and Lake Tapps (northwest) to Little Naches River area (east) (Fig. 1; e.g. Fisher, 1961a; Fiske et al., 1963; Gard, 1968; Wise, 1970; Ellingson, 1972; Simmons et al., 1983; Frizzell et al., 1984; Evarts et al., 1987; Schasse, 1987; Vance et al., 1987; Smith, 1989; Swanson, 1996; Swanson et al., 1997; Tabor et al., 2000; Hammond, 2005; Schuster, 2005; Hammond, 2011 unpubl. data). Northeast of Mt

Rainier, the Ohanapecosh Formation contains sedimentary units derived from a granitic-metamorphic basement, bordering the northern end of the Cascade volcanic arc (Hammond, 1979). A crystalline basement source in eastern Washington and Idaho was suggested by Winters (1984) for feldspathic sandstone that occurs in the Ohanapecosh Formation southeast of Packwood.

In the Mt Rainier National Park area, the Ohanapecosh Formation is overlain with an unconformable contact by the Oligocene (25-27 Ma) Stevens Ridge Member, which is the lower part of the Fifes Peak Formation (Vance et al., 1987; Tabor et al., 2000; Hammond, 2011 unpubl. data). This member is composed of multiple 5- to >100-m-thick quartz-bearing rhyolitic ignimbrites, whereas the Fifes Peak Formation is dominated by basaltic and andesitic lavas (Fiske et al., 1963). At Backbone Ridge, southeast of Mt Rainier (Fig. 2), the top of the Ohanapecosh Formation is eroded, and clasts of the Ohanapecosh Formation and tree trunks occur in the base of the lowest ignimbrite of the Stevens Ridge Member (Fiske et al., 1963). In the Mt Rainier National Park, the Stevens Ridge Member was originally defined as a formation by Fiske et al. (1963). However, Tabor et al. (2000) found a gradational boundary between it and the overlying Fifes Peak Formation, and consequently re-defined the Stevens Ridge Formation as a Member of the Fifes Peak Formation. The Fifes Peak Formation covers large areas around Mt Rainier, at Fifes Peak and Tieton (Warren, 1941; Fiske et al., 1963; Swanson, 1965, 1966, 1978; Schasse, 1987; Vance et al., 1987; Tabor et al., 2000; Hammond, 2005, 2011 unpubl. data). In southern Washington, the Ohanapecosh Formation is unconformably overlain by the early Miocene Eagle Creek Formation (Wise, 1970), composed of very poorly sorted conglomerate containing pumice fragments, thin-bedded sandstone and pebble conglomerate, and paleosols. These Tertiary formations are mostly covered by thick lavas and volcaniclastic aprons of the modern Cascades arc volcanoes (Mt Rainier, Goat Rocks, Mt Adams, Indian Heaven and Mt St Helens; Fig. 1; Crandell, 1976; Hildreth, 2007).

Previous work on facies of the Ohanapecosh Formation

The volcaniclastic facies of the Ohanapecosh Formation in the Mt Rainier area were studied extensively by Fiske (1963) and Fiske et al. (1963, 1964). Various processes and origins have been proposed (Fiske, 1963; Fiske et al., 1963; Winters, 1984; Stine, 1987; Vance et al., 1987; Swanson, 1996; Swanson et al., 1997). The formation is mainly composed of andesitic and dacitic volcaniclastic facies; minor lavas, “arkose” and “sandstone” are present locally (Wise, 1970; Winters, 1984; Stine, 1987; Vance et al., 1987). The main volcanic clasts consist of pumice, crystals and dense andesite. Broken and unbroken accretionary lapilli are common in a few facies. Fossils of wood, leaves and poorly preserved benthic shells ("ostracods, gastropods, and perhaps even Foraminifera"; Fiske, 1963) are locally present, but not diagnostic of a marine versus lacustrine environment.

The “thick” beds (Fiske, 1963) are well defined and laterally extensive (>hundreds of m), and 3 to 60 m thick (average thickness of 10 m). No welding textures or columnar joints were documented. The “thin” beds (Fiske, 1963) are well defined, laterally extensive over tens of meters, commonly normally graded, and mostly 50-60 cm thick. Some “thin” beds are internally stratified, but sole marks, slump structures and cross laminae are uncommon. Bed pinch-out structures were documented locally southeast of Packwood (Winters, 1984; Stine, 1987). No major faults were identified in previous studies of the Ohanapecosh Formation.

Fiske (1963), followed by Wise (1970), proposed that most of the formation was erupted and emplaced subaqueously, in quiet water such as a lake or sheltered embayment of the sea, thus representing the depocenter of underwater volcanoes. The quiet subaqueous depositional setting was inferred on the basis of: the laterally extensive, uniform-thickness bed geometry, internal grading, and the complete absence of unconformities, erosion surfaces and large-scale cross beds. The absence of typically marine fossils suggested a lacustrine rather than marine environment. However, more recent interpretations have assumed - on the basis of weak or incorrect evidence - a subaerial environment of deposition, such as a fluviatile and alluvial apron in which lakes were minor, shallow and temporary (Frizzell et al., 1984; Winters, 1984; Stine, 1987; Vance et al., 1987; Swanson, 1996; Swanson et al., 1997; Tabor et al., 2000).

The Ohanapecosh Formation is intruded by numerous silicic dykes and sills that are related to the Miocene Tatoosh and Snoqualmie plutons (Fiske et al., 1963; Johnson, 1985; Tabor et al., 2000). The dykes are commonly <10 m wide. The Ohanapecosh Formation is locally altered at contacts with the largest sills (>>10 m thick). The formation is well indurated and has a secondary mineral assemblage consistent with low-grade regional metamorphism (zeolite facies). All original glass and most original ferromagnesian and plagioclase phenocrysts have been replaced by secondary minerals. The alteration has been attributed to higher temperature and pressure associated with deep burial and contact metamorphism from intrusions (Fiske et al., 1963).

INTERNAL STRATIGRAPHY OF THE OHANAPECOSH FORMATION

In the studied area (Fig. 2), the Ohanapecosh Formation records deposition of almost exclusively volcaniclastic facies. This study subdivides the Ohanapecosh Formation into three main associations that each consists of similar volcaniclastic facies: the Chinook Pass association, the White Pass association and the Johnson Creek association.

The Chinook Pass association comprises >350-m-thick volcaniclastic sequences exposed at Cayuse and Chinook Passes and at Cougar Lake (Fig. 3; electronic suppl.). The total thickness of the association is unknown. The Chinook Pass association is characterized by pale green, extremely thick, pumice and fiamme-rich beds of intermediate composition, interbedded with multiple, laterally continuous, thin to thick beds that have similar aspects.

The White Pass association is >800 m thick and exposed in the road cuts of White Pass and Backbone Ridge, as well as on the slope from near the Ohanapecosh Campground up to the Backbone Ridge road (Fig. 4; electronic suppl.). The chiefly volcaniclastic White Pass association consists of dark to pale green, thin to extremely thick, pumice- and fiamme-rich beds of mafic and intermediate composition. A mafic component is common, whereas it has not been found in the other two associations of the formation. Thin to thick, fine sandstone and mudstone beds are common.

The Johnson Creek association is exposed in scattered road outcrops to the southeast of Packwood (electronic suppl.). The dark green volcaniclastic facies are mostly similar to those in the Ohanapecosh Campground and Backbone Ridge sections (White Pass association), but beds are thinner and show rare cross-laminae and channel-like features. Rare fine grained siliciclastic facies have been reported (Winters, 1984; Stine, 1987).

Ohanapecosh Fault

In the White Pass section at the bottom of Ohanapecosh River Valley, two units are used as stratigraphic markers (Fig. 4): an extremely thick (>15 m) bed of red fiamme breccia (unit 143, White Pass section) and a white, 5-m-thick, quartz-rich, matrix-supported volcanic breccia (unit 147, White Pass section). The red fiamme breccia (unit 143) probably correlates with the red fiamme breccia of the Stevens Ridge Member of the Fifes Peak Formation outside the logged area at Backbone Ridge (Fig. 4). At the base of White Pass (bed 147, top of the White Pass section), after more than 200 m of intervening hidden exposures from bed 143, there is a poorly exposed, white, 5-m-thick bed of quartz-rich, fine ignimbrite that is also attributed to the Stevens Ridge Member. This outcrop of the Stevens Ridge Member and numerous beds higher in the stratigraphy are not shown on any geological maps (Fiske et al., 1963; Schuster, 2005; Hammond, 2011 unpubl. data).

On the basis of stratigraphic correlations in the Stevens Ridge Member and the White Pass association (Fig. 4), we infer that a major north-south fault separates the White Pass and Backbone Ridge sections. This fault follows the Ohanapecosh River Valley and is here named the Ohanapecosh Fault (Fig. 4). Its exact location and dip are unknown, but it doubles ~500 m of stratigraphy. The Ohanapecosh Fault accounts for repetition of the red fiamme breccia and quartz-rich fine ignimbrite in the Stevens Ridge Member (Fifes Peak Formation; Fig. 4). On the basis of the White Pass and Backbone Ridge sections, Fiske et al. (1963) proposed a thickness of ~3 km for the entire Ohanapecosh Formation. The fault repetition proposed here decreases the maximum thickness of the formation to >800 m (Fig. 4), because the Ohanapecosh Fault increases the apparent thickness of the White Pass association between White Pass and Backbone Ridge (Fig. 4; electronic suppl.).

New U/Pb in zircon dates

Zircons in the lowermost and uppermost beds of the White Pass association have been dated at 31.9 ±1.4 Ma and 25.94±0.31 Ma, respectively (Fig. 4; electronic suppl.). U/Pb analyses of zircons by LA-ICP-MS of a pumice-rich bed in the Cayuse Pass section gave an age of 29.69±0.68 Ma (Fig. 3; electronic suppl.). These dates restrict the Ohanapecosh Formation to a time interval of ~6 million years, and to be overall younger than previously thought (Vance et al., 1987; Tabor et al., 2000). However, these former studies used samples from a wider area, and a very broadly defined Ohanapecosh Formation. In addition, former ages are essentially derived from fission tracks on zircons, which is a much less accurate technique than the U/Pb by LA-ICP-MS analyses reported here. Method accuracy may explain why the age of the uppermost bed in the Ohanapecosh Formation (this study) is younger than the published fission track age of the overlying Stevens Ridge Member from the Fifes Peak Formation (Vance et al., 1987).

COMPONENTS OF THE OHANAPECOSH FORMATION

A dominant intermediate composition of the fiamme, pumice and dense clasts is suggested by abundant plagioclase and minor ferromagnesian phenocrysts. A minor part of the succession is mafic in composition (probably basaltic) and characterized by abundant ferromagnesian and rare feldspar phenocrysts in scoria and dense clasts. Pumice clasts and fiamme (Table 1) are ubiquitous throughout the Ohanapecosh Formation. Fiamme have their long axes oriented parallel to bedding, and they are considered to be former pumice clasts, now compacted. Scoria clasts are present in the White Pass association. Numerous types of dense clasts occur in the Ohanapecosh

Formation. The dense clasts are rich in feldspar and ferromagnesian crystals, but lack quartz, which reflects their mafic to intermediate compositions. The dense clasts are aphyric to moderately porphyritic and variably altered. The matrix (<2 mm) now includes crystal fragments (partly to fully altered, mostly feldspar, with minor ferromagnesian minerals). Apart from crystals, matrix is similar in color and texture to the preserved clasts, which strongly suggests that the original components were all volcanic, and had the same bulk composition. Rim-type accretionary and armored lapilli (Schumacher and Schmincke, 1991) were found in a few very thin beds, and can reach 20 mm across. They are absent in the thick to extremely thick beds. Plant fossils and casts of leaves and silicified tree fragments were found at various places, but in minor quantities.

FACIES IN THE OHANAPECOSH FORMATION

The Ohanapecosh Formation is composed of 13 major facies, most of them being volcaniclastic and composed entirely of volcanic clasts. The volcaniclastic facies were distinguished on the basis of bed thickness, grading, componentry, grain size and composition. A full description of the facies in the Ohanapecosh Formation is presented in Table 2, and additional field data and complete logs are added as an electronic supplement. The grain size distribution of selected facies was calculated by image analysis and functional stereology (Jutzeler et al., 2012), and will be presented in a further study.

Coarse-grained, extremely thick facies occur everywhere in the Ohanapecosh Formation, and make a large part of the Chinook Pass and White Pass associations, where they are interbedded with thinner and finer grained facies. Most of the volume of the Chinook Pass association consists of tabular and laterally continuous, extremely thick beds (up to >40 m) of normally graded fiamme-dense clast breccia (facies 1; Fig. 5), normally graded dense clast-fiamme breccia (facies 2; Fig. 6), normally graded fiamme breccia (facies 3; Fig. 7) and reversely graded fiamme breccia (facies 4; Fig. 8), which are mostly composed of fiamme and pumice clasts, crystal fragments and dense clasts; some facies have a basal sub-facies rich in coarse, dense, angular to sub-rounded volcanic clasts. Rare polymictic breccia-conglomerate (facies 7) occurs in the White Pass section.

In the White Pass association, the graded or massive volcanic breccia (facies 5; Fig. 9) and massive volcanic breccia (facies 6; Fig. 10) are very thick to extremely thick, laterally continuous, clast- or matrix-supported, and consist of variable amounts of fiamme, pumice clasts, dense clasts, and crystal fragments. In the Chinook Pass association, an unusual very thick (>3 m) succession of reversely to normally graded pumice breccia (facies 8; Fig. 11) occurs. It is extensive over >100 m and composed of six main beds of pumice breccia that are intercalated with tens of beds of mudstone.

Most of the very thin to medium thickness beds in the Ohanapecosh Formation are fine sandstone and mudstone (facies 9; Fig. 12). They occur as m-thick groups, are laterally continuous, uniform in thickness, lack cross-bedded structures and commonly contain wood and accretionary lapilli. They are interbedded with the thicker facies. Voluminous successions of basaltic scoria breccia (facies 11; Fig. 13) occur in the White Pass association, and can be associated with vesicular basalt (facies 12), which is rarely found in the Chinook Pass association. Other minor facies include normally graded dense clast breccia to fiamme breccia (facies 10), flow-banded dacite (facies 13), thin to very thick beds of relatively well-sorted, massive mafic sandstone (facies 14), fine, dense clast volcanic breccia (facies 15), and thinly to thickly bedded, normally or reversely graded fiamme mudstone (facies 16).

INTERPRETATION AND DISCUSSION

Origins of clasts in the Ohanapecosh Formation

The high abundance of relatively fine (mostly <10 cm) pumice clasts and fiamme, and crystal fragments in most volcaniclastic facies (Table 1) strongly suggests that these components were produced by explosive eruptions and are thus considered to be pyroclasts. Free broken crystals are interpreted as pyroclasts derived from the same magmas as the pumice clasts and fiamme (Table 1). Scoria clasts are the most abundant components in the basaltic scoria breccia (facies 11) and massive mafic sandstone (facies 14), and are also considered to be pyroclasts. Most dense clasts of the Ohanapecosh Formation contain microlites and phenocrysts that attest to their volcanic origin (Table 1) and have intermediate to mafic compositions. Angular dense clasts that occur with abundant pumice clasts or fiamme are possibly pyroclasts. The origins of sub-angular to rounded dense volcanic clasts cannot be resolved because these clasts were abraded prior to and/or during final deposition. The matrix other than crystals is interpreted to be mostly made of fine, originally glassy pyroclasts. Rare beds of dark grayish brown fine sandstone to mudstone (facies 9) that contain wood chips and leaves are probably partly derived from decay of organic components. A few beds of fine sandstone to mudstone (facies 9) in the Johnson Creek association contain abundant non-volcanic feldspar crystals that reflect continental erosion (Winters, 1984).

Depositional setting

Poorly preserved fossils "ostracods, gastropods, and perhaps even Foraminifera" described by Fiske et al. (1963) indicate a subaqueous depositional setting for the Ohanapecosh Formation. In addition, the Ohanapecosh Formation includes several very thinly to thickly bedded facies (facies 9, 14, 15) in which beds are planar and laterally continuous, and that lack cross-stratification, erosional surfaces or paleosols. The overall absence of cross-beds, erosional surfaces and paleosols precludes a subaerial to shallow water setting. Most clasts - including pumice - in the Ohanapecosh Formation are angular, which suggests minimum residence in a subaerial or shoreline environment. We agree with Fiske (1963) that these bed characteristics strongly constrain the depositional setting of most of the formation to below wave base (Fig. 14).

The Ohanapecosh Formation was probably deposited in a deep lake, or a protected sea embayment because of its setting close to the continental margin (e.g. McBirney, 1978; Johnson, 1985; Dickinson, 2009). The relatively common occurrence of wood chips and leaves in the very thin to thickly bedded facies (facies 8, 9 and 16; Table 1) indicates proximity to land. Lakes are likely to produce scarce carbonaceous facies (Platt and Wright, 1991), have shores with gentler gradients, and wave action is much weaker than in conventional marine settings, reducing coastal erosion and limiting the abundance of well-rounded clasts (e.g. Manville, 2001). Lacustrine environments in active tectonic areas, such as an intra-continental rift, can be deep (i.e. >500 m) and subside rapidly so that subsidence compensates for the high accumulation rates of volcaniclastic facies (e.g. Baltzer, 1991; Gaylord et al., 2001). The lack of facies indicative of shoreline processes, such as coarse conglomerate, well sorted pebbly sandstone, cross-bedded sandstone, evidence of bi-directional oscillatory currents (i.e. wave ripples and swaley and hummocky cross-stratification), mega-breccia from large-scale failure events, and abundant coastal shell fragments (e.g. Busby-Spera, 1985; White and Busby-Spera, 1987; Busby-Spera, 1988; Allen, 2004b; Allen et al., 2007) precludes a volcaniclastic apron environment. We infer that the Ohanapecosh Formation accumulated on a quiet, below-wave-base, very low-gradient slope. The presence of accretionary lapilli in fine sandstone to mudstone (facies 8) is not an indicator of the depositional environment, as they can be robust enough to withstand sedimentation and resedimentation in water (e.g. Boulter, 1987).

The upper part of the Ohanapecosh Formation is poorly exposed and the presence or the absence of the planar thinly bedded facies, partial indicators of a subaqueous environment, is unknown. The overlying Fifes Peak Formation was deposited subaerially (Fiske et al., 1963), after an episode of erosion and deformation (Fiske et al., 1963; Hammond, 2011 unpubl. data). It is possible that a shallow water or subaerial setting existed during the last stage of deposition of the Ohanapecosh Formation. However, the volume of potentially shallow to subaerial facies is minor compared to the total thickness and extent of the Ohanapecosh Formation.

Transport and depositional processes

The lithofacies characteristics suggest that most of very thick to extremely thick clastic facies were produced by high concentration, subaqueous volcaniclastic density currents (Fig. 14, Table 3). In contrast, most very thin to thick beds show better sorting and grading, consistent with deposition from low-concentration density currents and vertical settling from suspension, and are discussed separately below. However, lithofacies analysis in the Ohanapecosh Formation remains difficult because the finest (<2 mm) clasts were destroyed during diagenesis, preventing description of the total grain size distribution.

Very thick to extremely thick beds

Most facies of the Ohanapecosh Formation consist of very thick to extremely thick tabular beds with sharp bases that are distinctly graded or massive, and are typical of deposits from high-concentration density currents in general (Lowe, 1982; Mulder and Alexander, 2001; Kokelaar et al., 2007; Piper and Normark, 2009; Sumner et al., 2009; Talling et al., 2012). Such currents can have hot volcanic gas (pyroclastic flows *sensu stricto*) or water as the interstitial fluid. Although composed primarily of pyroclasts, all facies in the Ohanapecosh Formation lack textures related to hot state deposition, such as welding, columnar joints and gas segregation pipes (Cas and Wright, 1991). Also, pumice clasts are typically angular and indicate that clast-to-clast interaction was more limited than is typical of pyroclastic flow transport (e.g. Dufek and Manga, 2008; Manga et al., 2011). Further, the internal textures and organization of the very thick to extremely thick beds are uniform everywhere in the >400 km^2 area of exposure, indicating that throughout this area, the transport and depositional processes were also uniform. Therefore, the density currents must have propagated for several to tens of km in the below-wave-base setting. There are no examples known of laterally extensive subaqueous pyroclastic flow deposits *sensu stricto*, and theoretical arguments imply that gas-supported phases under water should be replaced quickly by water, by condensation of the gas phase during cooling (Legros and Druitt, 2000; Freundt, 2003; Head and Wilson, 2003; Dufek et al., 2007; Allen et al., 2008). Notable exceptions may include very proximal, submarine inner-caldera environment (Busby-Spera, 1986) and where subaerial pyroclastic flows rather push than enter a water body (Legros and Druitt, 2000) where flat shore occur.

On this basis, we infer that the Ohanapecosh Formation volcaniclastic density currents were water-supported, rather than hot gas-supported.

The term “subaqueous volcaniclastic density current” is used for the density currents that produced the very thick to extremely thick facies in the Ohanapecosh Formation (Table 3); the term is intended to imply that the density currents were water-supported, high concentration and composed of volcanic particles and is inclusive of all the triggering mechanisms (eruption-fed versus resedimentation) and source settings (subaerial versus subaqueous). The apparently abundant matrix and poor sorting in the extremely thick facies suggest deposition from a type of volcaniclastic density current in which the particle concentration was very high and turbulence was suppressed.

Very thin to thick beds

Very thin to thick beds in the Ohanapecosh Formation are laterally continuous and have a uniform thickness, which suggests deposition from a combination of suspension settling and low density turbidity currents. Low density pumice clasts and very fine particles can be temporarily suspended in the water column. Settling involves discrete particle fallout and/or vertical density currents, minimal particle interaction and typically produces very good hydraulic sorting (Rubey, 1933; Cashman and Fiske, 1991; Wiesner et al., 1995; Manville et al., 2002; Burgisser and Gardner, 2006). In the reversely to normally graded pumice breccia (facies 8) at Chinook Pass, the lateral continuity of the pumice-dominated beds, presence of mudstone interbeds and the sub-rounded shape of the pumice clasts (Fig. 11; Table 3) suggest that the pumice clasts settled from pumice rafts (Fig. 14a; e.g. White et al., 2001; Manville et al., 2002).

Beds of fine sandstone and mudstone (facies 9) in the Ohanapecosh Formation are interpreted to be deposits from low density turbidity currents (turbidity currents *sensu stricto*; Bouma, 1962; Lowe, 1982; Shanmugam, 2002) or suspension in the water column (Fig. 14; Table 3). Conventional low density turbidity currents *sensu stricto* are defined by their high degree of turbulence and lack of cohesion; they can transport a relatively low concentration (<10 vol.%) of mostly fine-grained (<2 mm) clasts under water (Lowe, 1982; Mulder and Alexander, 2001; Piper and Normark, 2009) and commonly produce regular successions of relatively thin (up to a few m) beds that are massive or graded (Bouma, 1962; Lowe, 1982; Shanmugam, 2002).

Eruption-fed versus resedimented pyroclastic facies

Distinguishing between eruption-fed and resedimentation-driven processes of initiation of subaqueous volcaniclastic density currents is an ongoing challenge (Fisher and Schmincke, 1984; McPhie et al., 1993; White, 2000; White et al., 2003). Piper and Normark (2009) concluded that there is no simple relationship between the characteristics of subaqueous density current deposits and the initiating processes. Subaerial explosive eruptions may generate a wide range of eruption-fed subaqueous facies, including subaqueous volcaniclastic density current deposits and suspension deposits (e.g. Sparks et al., 1980; Yamada, 1984; Whitham and Sparks, 1986; Whitham, 1989; Cas and Wright, 1991; Carey et al., 1996; Mandeville et al., 1996; White et al., 2001; Manville et al., 2002; Freundt, 2003; Dufek et al., 2007). The lower, concentrated part (“basal underflow”) of subaerial pyroclastic flows may be dense enough to enter a body of water and transform into water-supported subaqueous volcaniclastic density current; the much more dilute overriding ash cloud and pyroclastic surges can travel over water for some distance (e.g. White, 2000; Freundt, 2003; Edmonds and Herd, 2005; Dufek et al., 2007). Pumice-forming, explosive eruptions can also occur from sea-floor vents, producing density currents underwater (Fiske, 1963; Kokelaar, 1983; Kano, 2003; White et al., 2003; Allen and McPhie, 2009). Furthermore, subaqueous volcaniclastic density currents can originate from resedimentation of saturated aggregates (Allen and Freundt, 2006).

The presence of pumice clasts in submarine water-supported volcaniclastic density current deposits implies that the pumice clasts were denser than water when entrained in the current. The pumice clasts available for transport in subaqueous volcaniclastic density currents can be: (1) sufficiently hot on contact with water to ingest water immediately and sink (Cas and Wright, 1991; Allen et al., 2008), (2) already sufficiently waterlogged (Allen and Freundt, 2006), and/or (3) low-vesicularity types that are denser than water. Pumice clasts with a vesicularity <60 vol.% will sink because their density is greater than that of water, regardless of the vesicles being gas- or water-filled (Manville et al., 1998; White et al., 2001; Manville et al., 2002). (Cas and Wright, 1991). Pumice clasts of intermediate composition commonly have vesicularities <60 vol.% (e.g. Whitham, 1989; Allen, 2004a).

Assessing the source and the transport processes on the basis of deposit characteristics is especially difficult for pyroclast-rich facies in which there is no evidence of hot emplacement (e.g. Cas and Wright, 1991), as in the case for volcaniclastic units in the Ohanapecosh Formation. The characteristics used herein to infer a pumice-forming, explosive eruption-fed origin for volcaniclastic density current deposits include abundant pumice clasts and crystals fragments that reflect a single magma composition, and very thick to extremely thick sedimentation units that reflect large eruption volumes (Table 3). On the other hand, resedimentation events are expected to involve diverse clast compositions, thus generating deposits that are strongly polymictic. Resedimentation processes affect pre-existing unconsolidated deposits, and each resedimentation event is likely to remove only a portion of the pre-existing deposits. Thus, the volumes (and thicknesses) of single beds derived from resedimentation events are predicted to be smaller in comparison to eruption-fed beds, especially in cases involving felsic and intermediate explosive eruptions.

Eruption-fed units in the Ohanapecosh Formation

The normally graded fiamme-dense clast breccia (facies 1), normally graded dense clast-fiamme breccia (facies 2), normally graded fiamme breccia (facies 3), reversely graded fiamme breccia (facies 4) and some beds of graded or massive volcanic breccia (facies 5) are all characterized by extreme bed thickness, massive aspect and a high abundance of pyroclasts of similar composition. These facies are interpreted to be explosive eruption-fed products (Fig. 14; Table 3).

In the reversely to normally graded pumice breccia (facies 8), pumice clasts are sub-rounded, and dense clasts are absent. The distinctive grading of facies 8 is consistent with saturation grading (Fig. 11). Waterlogging of pumice clasts a few cm in diameter is immediate when the pumice clasts are still hot, whereas it can take up to several months if the pumice clasts are cold and highly vesicular (Whitham and Sparks, 1986; Manville et al., 1998; White et al., 2001; Bryan et al., 2004). Therefore, facies 8 is probably eruption-fed, but the complex grading and presence of mudstone (likely to consist originally of glassy ash) and accretionary lapilli interbeds indicate that the pumice clasts sank progressively in batches from rafts (Fig. 14).

In the White Pass section, a succession of upward arching, normally graded and well sorted beds of basaltic scoria breccia (facies 11) that includes impact sags (Fig. 13a; Table 2) is interbedded with fine sandstone and mudstone (facies 9) that contains accretionary lapilli. The succession is interpreted to be the remnant of a scoria cone, probably produced by a combination of strombolian and surtseyan activity (Kokelaar, 1986; White, 2001), and most beds are considered to be eruption-fed, or slightly resedimented on the steep slopes of the volcanic cone (Fig. 14c). Units of vesicular basalt (facies 12) beneath the scoria cone facies are probably related to shallow intrusions or small lavas.

Resedimented units in the Ohanapecosh Formation

The polymictic breccia-conglomerate (facies 7) is likely to be resedimented, because it contains rounded clasts that were abraded in an above wave-base environment, and occurs in a bed that is only 3 m thick. Some of the beds of basaltic scoria breccia (facies 11) are likely to represent short-distance resedimentation on the scoria cone (Fig. 14). The graded or massive volcanic breccia (facies 5), massive volcanic breccia (facies 6) and some of the beds of fine sandstone and mudstone (facies 9) are not diagnostic of a single initiation process, and can be either eruption-fed or resedimented, and both alternatives probably occur (Fig. 14).

Setting of source volcanoes

The abundance of pyroclasts in the Ohanapecosh Formation attests to its origin from explosive eruptions (Table 3). The laterally continuous, very thin to thick beds imply deposition in a subaqueous environment. However, the setting of source vents is difficult to constrain for most facies although both subaerial and subaqueous vents are possible, and may have co-existed; a chiefly subaerial setting of source volcanoes is preferred. The most efficient ways to introduce voluminous pumice and dense clasts to a subaqueous setting are by subaerial pyroclastic flows crossing the shoreline

(Whitham, 1989; Cas and Wright, 1991; Allen and Smith, 1994; Kurokawa and Tomita, 1998; Legros and Druitt, 2000; Allen et al., 2003; Freundt, 2003; Allen et al., 2012), or alternatively by subaqueous explosive eruptions (Busby-Spera, 1986; Allen and McPhie, 2009). Subaqueous eruptions are not likely to have been persistent throughout the millions of years of the Ohanapecosh Formation, and known facies derived from subaqueous explosive eruptions (Cas and Wright, 1991; Kano, 2003; Allen et al., 2008; Allen and McPhie, 2009) are not represented in the Ohanapecosh Formation. The vents of intra-basinal subaqueous volcanoes would rapidly reach the water surface, considering the growth of the volcanic edifice and minor wave erosion in a quiet lake environment, filling the basin and producing distinctive above wave-base facies at its top. In addition, the many facies of the Ohanapecosh Formation imply multiple sources, thus many of them would not be positioned in the basin, but at its rim. It is more likely that most of the vents associated with the Chinook Pass association were subaerial, because rare intercalated facies contain rounded clasts resedimented from above wave-base environments (polymictic breccia-conglomerate, unit 58 in the Chinook Pass section; facies 7). Pumice-rich facies interpreted to originate from pumice rafts, and accretionary lapilli occur together in unit 60 of the Chinook Pass section (facies 8; Table 3), both of which imply the existence of a subaerial eruption plume. In addition, the basal dense clast breccia in the three extremely thick, fiamme-rich facies (facies 1–3) include coarse sub-rounded dense clasts that could have been collected at the shoreline, although such rounded clasts may have been previously transported under water from the shore (such as facies 7) and picked-up by the newly arriving density currents. These facies (1, 2, 3, 7, 8) all occur interbedded in the Chinook Pass association, and all other intercalated facies are in conformable contact and contain similar clast types, suggesting a similar source.

Hence, the entire Chinook Pass section is most likely to have been chiefly generated by subaerial pyroclastic flows that crossed a shoreline and transformed into water-supported volcaniclastic density currents. In addition, the pumice rafts represented by unit 60 (facies 8) probably formed immediately before or after a climactic eruption represented by extremely thick beds of reversely graded fiamme breccia (facies 4; units 59 and 61, respectively). We infer that the broadly similar, extremely thick beds of the fiamme-rich facies (facies 1–4) in the other associations have the same origin.

Some features in facies 1–4 deserve particular consideration. The pumice clasts are distinctly angular and there is abundant matrix (<2 mm), at least in the middle and upper sub-facies. Pumice clasts transported in pyroclastic flows are quickly rounded (e.g. Dufek and Manga, 2008; Manga et al., 2011) so the angular clasts imply that transport by this mode was short. The poor sorting suggests that transport of pumice clasts in water-supported density current was relatively short because in general this transport mode results in relatively good grading and sorting (White, 2000). Thus, the distance between the vents and the deposition site was probably short, and the source volcanoes were nearby. The apparent abundance of matrix in facies 1–4 also suggests that the pyroclastic flows were not very expanded when they crossed the shoreline (e.g. Cas and Wright, 1991).

The Ohanapecosh Formation basin

Chinook Pass association

The Chinook Pass association comprises volcaniclastic facies from one main source, because most clasts have similar mineralogy and composition, and the beds have been deposited by similar types of subaqueous volcaniclastic density currents. Most of the thickness of the Chinook Pass association (~70% of the exposed sections) is dominated by extremely thick, tabular and laterally continuous beds that originated from subaerial pyroclastic flows (normally graded fiamme-dense clast breccia, facies 1; normally graded dense clast-fiamme breccia, facies 2; normally graded fiamme breccia, facies 3; reversely graded fiamme breccia, facies 4). Each extremely thick bed in the Chinook Pass association was probably related to a magma eruption volume of 0.1 to >10 km^3. These extremely thickly bedded facies are interbedded with facies composed of much thinner beds (e.g. facies 5, 9 and 15). Such a transition from single eruption-fed beds to multiple, compositionally similar but much thinner beds may record voluminous deposition from a large-scale explosive eruption, followed by syn- to post-eruptive resedimentation of more proximal, upslope deposits into deeper water (Fig. 15). The latter is preferred for the Chinook Pass association, because most facies in the Chinook Pass association consist of the same coarse components, suggesting that following the main eruptive events, parts of the eruption-fed deposits upslope were resedimented in the Chinook Pass association. The relatively thinly bedded intervals probably also include deposits that are unrelated to eruptions, and instead represent the "background" sedimentation.

White Pass association

The White Pass association comprises volcaniclastic facies from at least two main sources. One source produced voluminous and widespread pumiceous volcaniclastic facies of intermediate composition that occur in very thin to extremely thick, planar and laterally continuous beds (graded or massive volcanic breccia, facies 5; massive volcanic breccia, facies 6; fine sandstone and mudstone, facies 9). Whether these source volcanoes were subaqueous, subaerial or both, and whether some beds of the facies are eruption-fed could not be determined from facies characteristics. However, the abundance of beds, most of them polymictic, strongly suggest that many beds are derived from resedimentation, and that resedimentation processes greatly contributed to the filling of the basin. The second source generated small-volume, basaltic, very thinly to thickly bedded volcaniclastic facies (fine sandstone and mudstone, facies 9; massive mafic sandstone, facies 14; basaltic scoria breccia, facies 11). These facies were generated by intrabasinal, weakly explosive, basaltic eruptions and resedimentation, from one or more shallow-water or subaerial vents (Figs 14, 16).

In modern subaqueous basins, maximum bed thickness and maximum coarseness occur close to the main transport path and in a medial position relative to the source (e.g. Trofimovs et al., 2006). Distal and lateral equivalents are thinner and finer grained. Strong differences in grain size and average bed thickness that occur between sections in the White Pass association (Fig. 4; Fig. 15) could reflect two settings in relation to the sediment transport path, or intercalation of proximal and distal deposits of two volcanic sources respectively. The White Pass section contains the coarsest and thickest beds of the White Pass association (up to 25 m; massive volcanic breccia, facies 6). This section is interpreted to record deposition centered on the main sediment transport path at a medial position from the source, in a low-gradient basin. In the lower part of the White Pass section, stacks of facies 5 are overlain by stacks of facies 6, which reflects an increase in thickness (electronic suppl.) and coarseness (Fig. 4; electronic suppl.) of the beds. Such a dramatic change may result from progradation (Busby-Spera, 1988), or from different sources and/or pathways of sedimentation. In comparison, beds present in the Ohanapecosh Campground and Backbone Ridge sections are overall thinner and finer grained (fine sandstone and mudstone, facies 9; fine, dense clast volcanic breccia, facies 15; normally or reversely graded fiamme mudstone, facies 16). These sections were probably situated in more distal and/or lateral positions compared to the main sediment transport path recorded in the White Pass section. These facies variations suggest a main broad westward direction of sediment transport in the White Pass association.

The two sections of the White Pass association from each side of the Ohanapecosh Fault include multiple beds of basaltic scoria breccia (facies 11; Fig. 13). These beds are interpreted to broadly correlate. The thick sequence of basaltic scoria breccia containing fine sandstone and mudstone (facies 9) with accretionary lapilli and intrusions of vesicular basalt (facies 12) in the White Pass section indicate proximity to a subaerial to shallow water scoria cone, whereas the thinner sequences of basaltic scoria breccia in the Ohanapecosh Campground and Backbone Ridge sections probably formed at a greater distance from the vent(s).

Johnson Creek association

The Johnson Creek association consists of very similar facies to the Backbone Ridge section of the White Pass association, and is therefore interpreted in a similar way. It is chiefly composed of thin to very thick beds of pumice fragments of intermediate composition (graded or massive volcanic breccia, facies 5; normally or reversely graded fiamme mudstone, facies 16). These facies probably accumulated in a distal and/or lateral environment with respect to the coarser and thicker facies in the White Pass association. A broadly westward direction of sedimentation was proposed by Winters (1984) on the basis of minor beds of fine sandstone and mudstone containing clasts derived from pre-Tertiary basement rocks.

Basin architecture and duration

The Ohanapecosh Formation provides a good example of the complexity possible in subaqueous volcaniclastic basins (Figs 15, 16). The age of the lowermost (31.9 ±1.4 Ma) and uppermost (25.94±0.31 Ma) beds in the White Pass association constrain the >800 m of volcaniclastic sediments to have been sedimented during ~6 million years. An average sedimentation rate of 65-120 m/my can be estimated considering the two beds are separated by 500 m in the stratigraphy (Fig. 4)..The three associations are close enough (<10 km) to be part of a single, wide basin. However, the lithofacies of the Chinook Pass association are different from those in the White Pass association and Johnson Creek association. The difference could be explained by supply from different volcanic sources, and/or by the presence of two sub-basins within a larger basin. The poor exposure between the studied sections precludes a better understanding of the stratigraphic relationships between the depocenters.

Sources of the Ohanapecosh Formation

The regional extent (>400 km^2) and >6 million years in duration of the Ohanapecosh Formation (Tabor et al., 2000; Schuster, 2005; this study), the presence of the remnants of at least one scoria cone in the White Pass association (facies 11, Fig. 13), and the variations in clast mineralogy (Tables 1, 2) all imply that volcaniclastic sediments were supplied from multiple volcanic edifices (Fiske, 1963; Vance et al., 1987; this study). The major eruption centers that fed the Ohanapecosh Formation have not been identified. Lavas or shallow intrusions that could be marking the locations of source vents for the volcaniclastic facies are uncommon and not obviously related to the volcaniclastic facies. Minor lavas within the eastern and northeastern part of the formation (sensu lato) are contemporaneous (Hammond, 2011 unpubl. data). Coherent andesite units found in the area southeast of Packwood

(Swanson, 1996; Swanson et al., 1997) and at Indian Bar (Fiske et al., 1964) were identified as possible sources of the Ohanapecosh Formation, however nearby volcaniclastic facies could not be directly correlated to these units. The flow-banded dacite (facies 13) at Cougar Lake is probably contemporaneous with the Ohanapecosh Formation, and reflects emplacement of an intrabasinal lava or dome.

The Mt Aix caldera, 20 km southeast of Chinook Pass (Fig. 1), is a plausible source of the Ohanapecosh Formation. The age of the caldera-forming eruption (24.7 Ma; Hammond, 2005) is too young compared to the Ohanapecosh Formation, and it produced a rhyolitic ignimbrite (Bumping River tuff). Silicic calderas can be long-lived and commonly form after a period of volcanism involving less evolved (andesitic) magma (e.g. Bailey et al., 1976; Bacon, 1983). Thus, pre-caldera volcanic activity at the vicinity of the Mt Aix caldera could have been a source of the Ohanapecosh Formation. With the exception of the White Pass example, it remains unclear whether or not the mafic intrusions (vesicular basalt, facies 12) were a source of the Ohanapecosh Formation. The White Pass and Chinook Pass associations (Fig. 15) comprise facies that reflect filling of the basin primarily during eruptions and the immediate post-eruptive period of resedimentation (e.g. Busby-Spera, 1988; Smith, 1991).

The Ancestral Cascades arc in Washington

Extending over more than >400 km^2 in Washington, the Ohanapecosh Formation records an important part of the northern tip of the Ancestral Cascades arc (45–4 Ma, du Bray and John, 2011) during the Oligocene. The depocenter could have formed as a far-field response to the regional extension farther to the northeast during the Eocene (Johnson, 1984; Johnson, 1985; Vance et al., 1987; Cheney and Hayman, 2009; Evans, 2010), and thus extend the time and area affected by this regional extension event.

The remnants of magmatic activity are more abundant in Washington for the late Oligocene to Miocene period, suggesting a peak of volcanic activity around 25 Ma (e.g. du Bray and John, 2011). However volumetric comparisons should be subject to caution, considering how volcaniclastic deposits are relatively poorly preserved and much less studied in comparison to lavas and intrusions, as exemplified with the few contributions on the Ohanapecosh Formation. Thus, the importance and volume of volcaniclastic deposits are likely to be wrongly minimized (e.g. du Bray et al., 2006). In central Washington, several volcanic centers and intrusions were emplaced after the deposition of the Ohanapecosh Formation, and confirm the continuation of the magmatism in the Ancestral Cascades arc in central Washington. The relationship between the Ohanapecosh Formation and its overlying formations (in particular the Fifes Peak Formation) remains poorly understood and they are likely to be part of different eruptive cycles. Volcanic rocks to the northeast were mostly grouped into the Fifes Peak Formation (Fiske et al., 1963; Tabor et al., 2000; Hammond, 2011 unpubl. data), and important late Oligocene to Miocene volcanic centers include the Mount Aix caldera (late Oligocene), Timberwolf Mountain volcano (late Oligocene), Fifes Peak volcano (Oligocene-Miocene) and Tieton volcano (Late Miocene), and intrusions include the Tatoosh pluton (Late Miocene), Bumping Lake granite (Oligocene) and White River pluton (Miocene) (Fig. 1; Fiske et al., 1963; Swanson, 1966; Hammond, 2005, 2011 unpubl. data). The relationship of the Oligocene-Miocene Snoqualmie plutons in central Washington with the Ancestral Cascades arc remains unclear (du Bray and John, 2011).

In Washington and Oregon, 45 million years of Ancestral and modern Cascades arc magmatic activity has been concentrated in a relatively narrow segment of continental crust (Sherrod and Smith, 2000; Schuster, 2005) indicating that the volcanic front has remained in more-or-less the same position relative to the subduction zone. This apparent stability could be responsible for the Ohanapecosh basin remaining an active depocenter for ~6 million years, and for the largely intact preservation of the basin fill. This long-lived basin strongly suggests the Ohanapecosh Formation to chiefly record explosive activity and erosion from multiple volcanic centers, principally to the east, north and south of the studied area. In contrast, the southern segment of the Ancestral Cascades arc from Nevada to California migrated westwards in response to slab roll-back (Colgan et al., 2011) throughout the Oligocene, Miocene and Pliocene. Volcaniclastic basins also formed in the southern segment of the arc (Busby, 2012), but they were relatively short lived (e.g. <1.5 million years; Busby et al., 2006), accumulated thicker sediment piles (10 and 4 km during very fast basin subsidence, respectively; Busby et al., 2005; Busby et al., 2006), and were substantially disrupted by fault active during and after filling (Busby and Bassett, 2007). The differences between the two segments of the Ancestral Cascades arc have been attributed to the presence of a long-lived slab tear in the Farallon plate (Colgan et al., 2011).

Characteristics of deep subaqueous volcaniclastic basins

The Ohanapecosh Formation lacks shallow water facies, implying sedimentation in a relatively deep lake, or in a basin subsiding at the same rate as filling. In addition, the Ohanapecosh basin had a low gradient, because the succession does not include any slide and slump-related facies. Therefore, the Ohanapecosh Formation had a similar setting to other below-wave-base, deep, quiet basins (e.g. Johnson and Baldwin, 1996;

Stow et al., 1996), but it consists of very different and distinctive facies. Deep, quiet, non-volcaniclastic basins comprise turbidites and suspension-settled facies that may relate to sediment dispersal via submarine fans (e.g. Johnson and Baldwin, 1996; Stow et al., 1996; Talling et al., 2012). Single events (flood, landslide, earthquake, etc.) that produce density currents can introduce huge volumes (up to 100 km^3) of sediments (Talling et al., 2012). Single turbidites range in thickness of a few cm to ~10 m, depending on their proximity to source, and are typically composed of <2-mm-particles, relatively well sorted and commonly graded (Piper and Normark, 2009; Talling et al., 2012).

Non-volcanic detritus in the Ohanapecosh Formation (i.e. organic matter and fine sandstone and mudstone of continental origin; part of facies 9) is minimal (< a few vol.%), and implies that the depocenter was almost exclusively supplied by volcanic processes. Andesitic explosive eruptions were the principal supplier of sediment, and this sediment was delivered by means of eruption-fed subaqueous volcaniclastic density currents, and by resedimentation events. Each extremely thick bed was probably related to a magma volume of 0.1–10 km^3 erupted more-or-less instantaneously. From our zircons ages, the average sedimentation rate in the White Pass association is 65–120 m/my, which is comparable to accumulation rates at 30 km offshore Montserrat island (90 m/my; Expedition 340 Scientists, 2012) and in some conventional siliciclastic environments (e.g. Sadler, 1981). Eruptions and syn-eruptive resedimentation events are rapid, producing extreme instantaneous aggradation rates (m to tens of m per hour/year). Single subaqueous volcaniclastic density currents must be more voluminous and/or prolonged and more concentrated than single turbidity currents because their deposits are much thicker, less well sorted, less well graded and in most cases, coarser than conventional turbidites. Wide variations in pyroclast density, size and shape produce facies that cannot be generated by other mechanisms. In active volcanic arc settings, the eruption-fed sediment supply is controlled by eruption frequency, style and magnitude. Sediment dispersal pathways are related to the locations of active volcanoes. In addition, explosive volcanic eruptions disperse large volumes of pyroclasts over wide areas, eliminating any sediment from other sources. In some cases, pyroclasts are introduced independently of established surface pathways, such as by settling of pumice from pumice rafts, or settling of accretionary lapilli and ash from the atmosphere to the water column over large areas (facies 8 and 9).

CONCLUSIONS

The >400 km^2 Ohanapecosh Formation (Washington State, USA) is an Oligocene volcaniclastic succession generated by volcanism in the Ancestral Cascades arc. The formation is mainly composed of andesitic volcaniclastic facies and was deposited over ~6 million years. The thickness of the formation in the studied area is >800 m, and part of the succession has been repeated by an inferred fault in the Ohanapecosh River Valley. Three associations have been defined on the basis of lithofacies characteristics and area of distribution. Multiple sources, eruption styles, and transport and depositional processes are necessary to explain the extent and diversity of the volcaniclastic lithofacies. However, the depositional setting remained subaqueous and below wave-base, and the environment of deposition was low-energy, such as within a continental basin. The lack of lenticular conglomerate and well-sorted cross-bedded sandstone typical of shoreline settings suggests the original basin was larger than the preserved remnants. The most abundant facies (by volume) are extremely thick (up to

50 m), internally massive or graded, and composed of andesitic pyroclasts. They were deposited from eruption-fed, water-supported, subaqueous volcaniclastic density currents generated by pyroclastic flows that crossed the shoreline.

Below-wave-base deposition in basins associated with active subaerial volcanoes differs from that of non-volcanic basins. The supply of sediments is controlled by the frequency, style and magnitude volcanic eruptions, and sediment pathways are influenced by the locations of active volcanoes. The instantaneous accumulation rate of deposits from single explosive eruption-fed events in a volcanic arc basin is likely to be much higher than in a non-volcanic environment, even though the average accumulation rate may be similar or lower. The longevity and overall good preservation of the Ohanapecosh basin possibly reflects the relative stability of the northern Cascades arc compared with the extension-affected southern Cascades arc.

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FIGURES

Fig. 1

Regional geological map of the Ancestral Cascades arc, simplified from Schuster (2005) . The Ohanapecosh Formation is part of the Tertiary volcaniclastic formations.

Fig. 2 Local geological map of the Ohanapecosh Formation in the Mt Rainier area; simplified and slightly modified after Schuster (2005) and Fiske (1964). Logged locations are white dots with letter. Thick black lines are boundaries between the lithological associations of the Ohanapecosh Formation: Chinook Pass association (A), White Pass association (B); Johnson Creek association (C). Dips are in the range 20–45° (Fiske et al., 1963). O.C. for Ohanapecosh campground.

Fig. 3 Stratigraphy of the Chinook Pass association of the Ohanapecosh Formation at Cayuse Pass (locality a in Figure 2) and Chinook Pass (localities b, c, d and e in Figure 4). The proportions of clasts and matrix in representative samples of facies were estimated in the field, and on polished rock slabs and thin sections in the laboratory (Jutzeler, 2012). The log gives the mean clast diameter (i.e. most common long-axis dimension of clasts) on the horizontal scale (in mm); some beds have separate mean clast size for pumice clasts and fiamme (P) and dense clasts (D); isolated clasts on right-hand side give outsized clast dimensions (i.e. maximum dimension of the coarsest clast). Logs are in direct upward continuity from left to right. Log locality (bold letter) refers to Figure 2; unit number (italic type), facies number (bold type) and stratigraphic thickness (plain type) are given on the left-hand side of logs; units (or group of units in thin facies) were separately numbered from base to top of the logs. Pie diagrams give vol.% of different clast types from image analysis (field and rock slabs): white for pumice clasts and fiamme, black for dense clasts, gray for matrix (<2 mm), including crystal fragments. See electronic suppl. for complete logs. For clarity, dykes and intrusions are not shown in the stratigraphic logs. Dates are from U/Pb analyses on zircons by LA-ICP-MS; ages in brackets suggest caution, as only one grain of zircon was used (see electronic suppl.).

Fig. 4 a) Simplified stratigraphic log of the Ohanapecosh Formation and Stevens Ridge Member (Fifes Peak Formation) using sections at White Pass (1; localities l, m, n and o in Figure 2), Ohanapecosh Campground (2; locality h in Figure 2) and Backbone Ridge (3; localities i, j and k in Figure 2). Only dominant facies are indicated; **b)** Inferred Ohanapecosh Fault; the faults repeats ~500 m of the White Pass association (Ohanapecosh Formation) and the Stevens Ridge Member (Fifes Peak Formation). The Stevens Ridge Member was dated at 25-27 Ma by Hammond (2011 unpubl. data). See electronic supplement for complete logs and U/Pb geochronology.

Fig. 5 Facies 1 - Normally graded fiamme-dense clast breccia; **a)** Middle part of facies 1 (unit 40) with porphyritic fiamme (black) and dense clasts (white and gray) in a gray matrix; **b**) Basal facies 1 (unit 40, Cayuse Pass section) composed of dense clasts, rare fiamme and feldspar crystal fragments (white) in a green matrix; **c)** Typical stratigraphic log of facies 1 in unit 40, Cayuse Pass section. Dense clast (D), fiamme (F), pumice clast (P), scoria (Sc), feldspar crystal (xl), cement (cem), accretionary lapilli (al), mudstone (m); graphic log features and key as in Figure 3.

Fig. 6 Facies 2 - Normally graded dense clast-fiamme breccia. **a**) Base of normally graded dense clast-fiamme breccia (facies 2, unit 42, Cayuse Pass section) with sub-rounded dark gray dense clasts in a gray matrix. This basal sub-facies is very similar to the basal part of the normally graded fiamme-dense clast breccia (facies 1); **b**) Stratigraphic log, unit 42, Cayuse Pass section. Graphic log features and key as in Figures 3 and 5.

Fig. 7 Facies 3 - Normally graded fiamme breccia. **a**) Base of unit 57 (Chinook Pass section) in the Chinook Pass association. Abundant fiamme (pale green), minor dense clasts (dark gray and black) in matrix; **b**) Stratigraphic log, unit 57, Chinook Pass section. Graphic log features and key as in Figures 3 and 5.

Fig. 8 Facies 4 - Reversely graded fiamme breccia. **a**) Unit 61 (Chinook Pass section) overlying units 60a, 60b, 60c (reversely to normally graded pumice breccia, facies 8) at Chinook Pass; top of unit 61 is not seen. Note the lateral continuity of the thin beds and the knife sharp-contacts; **b)** Middle of unit 61 at Chinook Pass, with numerous fiamme and pumice clasts (dark), rare dense clasts (white and pale gray) and feldspar crystal fragments (white) in a pale matrix; **c**) Typical stratigraphic log of facies 4, unit 61, Chinook Pass section. Graphic log features and key as in Figures 3 and 5.

Fig. 9 Facies 5 - Graded or massive volcanic breccia; **a**) Tube pumice clasts and dense clasts in a fine (<0.2 mm) matrix (unit 5, White Pass section); **b**) Clast-supported facies 5 at Indian Bar; pumice clasts and fiamme (dark), dense clasts and feldspar crystals (white); **c**) Facies 5 at the base of the Ohanapecosh Formation (unit 5, White Pass), dark fiamme, pumice clasts and dense clasts supported in a pale matrix; **d**) Typical stratigraphic log of two beds of facies 5 in the White Pass section. Graphic log features and key as in Figures 3 and 5.

Fig. 10 Facies 6 - Massive volcanic breccia; **a**) Coarse volcanic breccia, White Pass section (unit 62), composed of fine pumice clasts and fiamme (black) and dense clasts, including a poorly vesicular basalt clast (bas); **b**) Typical stratigraphic log of facies 6. Graphic log features and key as in Figures 3 and 5.

Fig. 11 Facies 8 - Reversely to normally graded pumice breccia. **a)** Unit 60b, Chinook Pass section. Note the reverse grading in pale gray pumice clasts in the lower unit, and dark gray interbeds of mudstone; **b**) Reversely graded pumice clasts and mudstone interbeds in facies 8 at Chinook Pass (unit 60); **c)** Sub-rounded pumice clasts (unit 60b); white zeolite cement fills interstices between pumice clasts; **d)** Two detailed logs of laterally continuous units (60b and 60c) of facies 8 in the Chinook Pass section. Log A is >80 m to the east of log B. The lines link the main parts of the two sections that can be traced in the field. Graphic log features and key as in Figures 3 and 5.

Fig. 12 Facies 9, Chinook Pass association (a, b) and White Pass association (c, d) - Fine sandstone and mudstone. **a**) Succession of parallel-bedded facies 9 in lower Cayuse Pass; **b**) Laminated facies 9 at Cougar Lake. Accretionary lapilli occur in these beds. **c)** Beds of fine sandstone and mudstone (arrows, unit 78, White Pass) interbedded with graded or massive volcanic breccia; **d)** Succession of very thin beds and laminae of fine sandstone and mudstone (facies 9, unit D11 at Backbone Ridge); fossil leaves were found in these beds. Key as in Figure 5.

Fig. 13 Facies 11 - Basaltic scoria breccia. **a)** Thick, well bedded basaltic scoria breccia (facies 11, lateral equivalent of bed 137) at White Pass. Note the upward arch in the beds, interpreted to be primary dip. Cliff face (140-160°) is parallel to the general bedding strike of the Ohanapecosh Formation. White circles for interpreted impact sags, arrow for mafic sill. Inset gives a detailed view of an interpreted impact sag; **b)** Unit 22 in the Ohanapecosh Campground section, with normally graded beds of monomictic dark basaltic scoria clasts and pale-gray cement; **c**) Scanned slab of facies 11 (unit 137 in the White Pass section), dark gray basaltic scoria clasts in pale matrix and white zeolite cement; **d)** Stratigraphic log of unit 137, White Pass section. Graphic log features and key as in Figures 3 and 5.

Fig. 14 Inferred depositional processes in the Ohanapecosh Formation. **a**) Subaerial magmatic gas-driven, pumice-forming explosive eruption (A) followed by collapse of the eruption column and creation of magmatic gas-supported pyroclastic flow towards water body (B). Coastal steam explosion (C) due to contact of hot pumice with water (e.g. Cas and Wright, 1991; Freundt, 2003; Dufek et al., 2007). Accretionary lapilli may form in subaerial eruption plumes. Dilute pyroclastic density current flows over the water body (D). Pumice clasts from dilute pyroclastic density currents may stay buoyant and create a pumice raft (E), to eventually generate saturation grading in reversely to normally graded pumice breccia (facies 8). Dense part of the pyroclastic flow enters water and transforms into a subaqueous volcaniclastic density current (F) that deposits very thin to extremely thick, tabular beds (facies 1–5, 8, 9) on the basin floor (G). Background sedimentation (H) produces fine grained thin beds (facies 9); **b)** Mass-wasting processes (K) resediment unconsolidated aggregates, creating subaqueous volcaniclastic density currents (L) that form tabular beds (facies 5–7, 9) on the basin floor (M). Background sedimentation (H) produces interlayers of fine grained thin beds (facies 9); **c**) Same resedimentation process (K) as in b, but in shallower water, such as in the upper part of the White Pass association. Subaqueous volcaniclastic density currents (N) generate tabular beds on the shallow basin floor (O). Shallow intrusions of basalt (P; facies 12) and subaqueous to locally subaerial eruptions (Q) build scoria cone of basaltic scoria breccia (R; facies 11) by subaerial and water-settled fallout; thick proximal facies are affected by resedimentation (S). Scoria cone (R, facies 11) is discordant with general stratigraphy. Background sedimentation and fallout from eruption column produces interlayers (T) of fine grained thin beds (facies 9).

Fig. 15

Simplified stratigraphic logs of the Chinook Pass and White Pass associations showing the contrasts between eruption-fed facies and resedimented facies. See Figures 3 and 4 and electronic supplement for complete logs.

Fig. 16

Reconstruction of the Ohanapecosh basin. Active subaerial andesitic volcanoes to the east supply most of the volcaniclastic facies preserved in the Ohanapecosh Formation. The depositional setting for most facies was subaqueous and below wave-base. Local intrabasinal scoria cones are present. The Chinook Pass association and White Pass association probably accumulated in two sub-basins, here separated by the thick gray dashed line. Flow-banded dacite at Cougar Lake not represented. Chinook Pass and Cayuse Pass, CP; Cougar Lake, CL; White Pass, WP; Backbone Ridge, BBR.

TABLES

Table 1 Textural characteristics of clasts in the Ohanapecosh Formation.

Table 2 Lithofacies in the Ohanapecosh Formation.

Table 3 Current type, origin and environment at source of main facies of the Ohanapecosh Formation.

ELECTRONIC SUPPLEMENT

Additional field data

Chinook Pass and White Pass associations; GPS coordinates (WGS 84) of start, intermediary points and end of log section locations in the Ohanapecosh Formation.

Fig. A Complete stratigraphic log of Cayuse Pass section, Chinook Pass association; locality a in Figure 2. Logs are vertically continuous from left to right. Graphic log features and key as in Figures 3 and 5.

Fig. B Complete stratigraphic log of Chinook Pass section, Chinook Pass association; localities b, c and d in Figure 2. Logs are vertically continuous from left to right. Graphic log features and key as in Figures 3 and 5.

Fig. C Complete stratigraphic log of Cougar Lake section, Chinook Pass association; localities f and g in Figure 2. Graphic log features and key as in Figures 3 and 5.

Fig. D Complete stratigraphic log of White Pass section, White Pass association; localities l, m, n and o in Figure 2. Logs are vertically continuous from left to right. Graphic log features and key as in Figures 3 and 5.

Fig. E Complete stratigraphic log of Ohanapecosh campground section, White Pass association; locality h in Figure 2. Logs are vertically continuous from left to right. Graphic log features and key as in Figures 3 and 5.

Fig. F Complete stratigraphic log of Backbone Ridge section, White Pass association, localities i, j and k in Figure 2. Logs are vertically continuous from left to right. Graphic log features and key as in Figures 3 and 5.

Fig. G Typical stratigraphic log of the Johnson Creek association; locality p in Figure 2. Graphic log features and key as in Figures 3 and 5.

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Figure 1

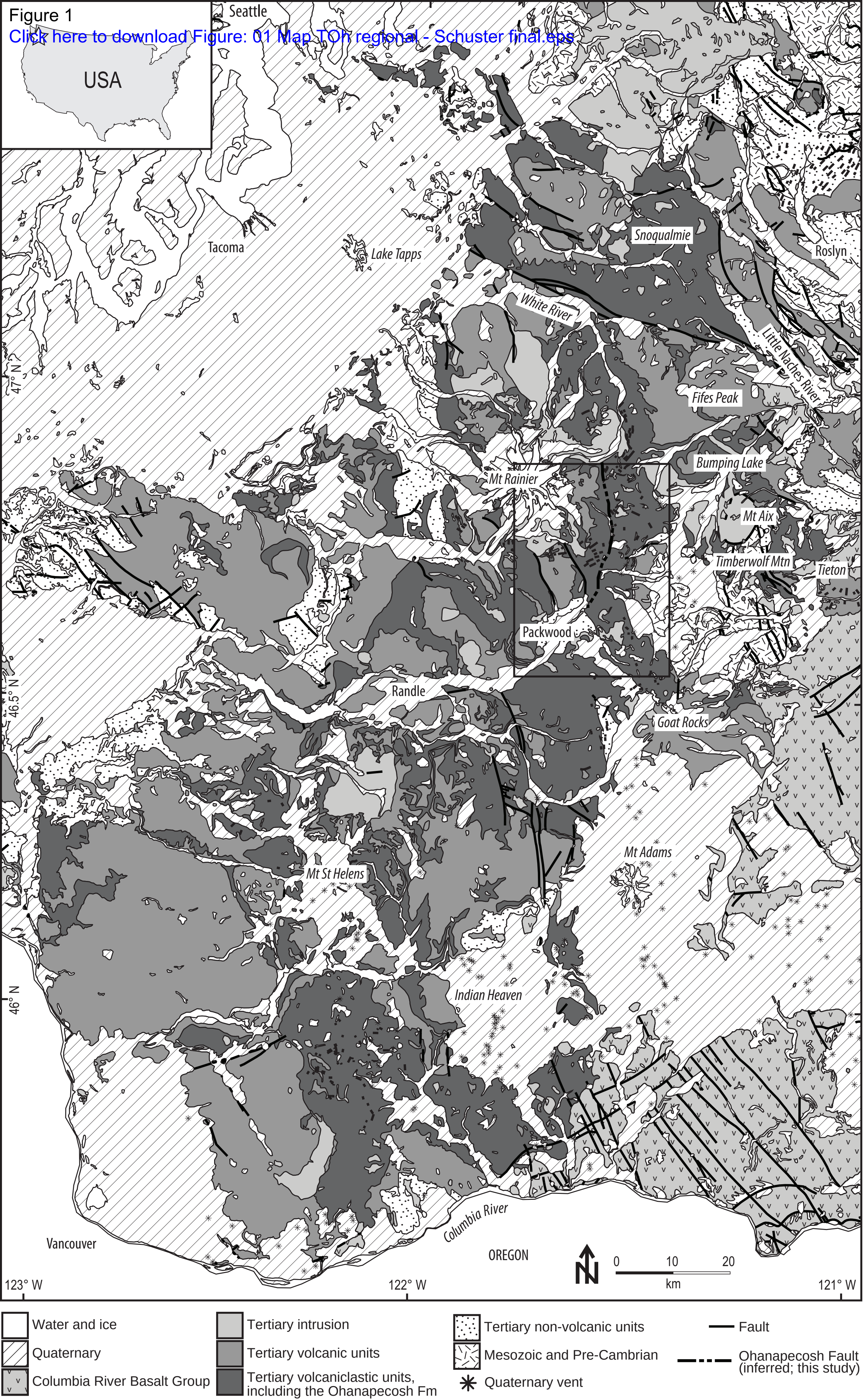

USA
Seattle
Tacoma
Lake Tapps
Snoqualmie
Roslyn
White River
Little Naches River
Fifes Peak
Bumping Lake
Mt Rainier
Mt Aix
Timberwolf Mtn
Tieton
Packwood
Randle
Goat Rocks
Mt Adams
Mt St Helens
Indian Heaven
Columbia River
Vancouver
OREGON
N
0
10
20
km
47° N
46.5° N
46° N
123° W
122° W
121° W
Water and ice
Quaternary
Columbia River Basalt Group
Tertiary intrusion
Tertiary volcanic units
Tertiary volcaniclastic units, including the Ohanapecosh Fm
Tertiary non-volcanic units
Mesozoic and Pre-Cambrian
Quaternary vent
Fault
Ohanapecosh Fault (inferred; this study)

Figure 2

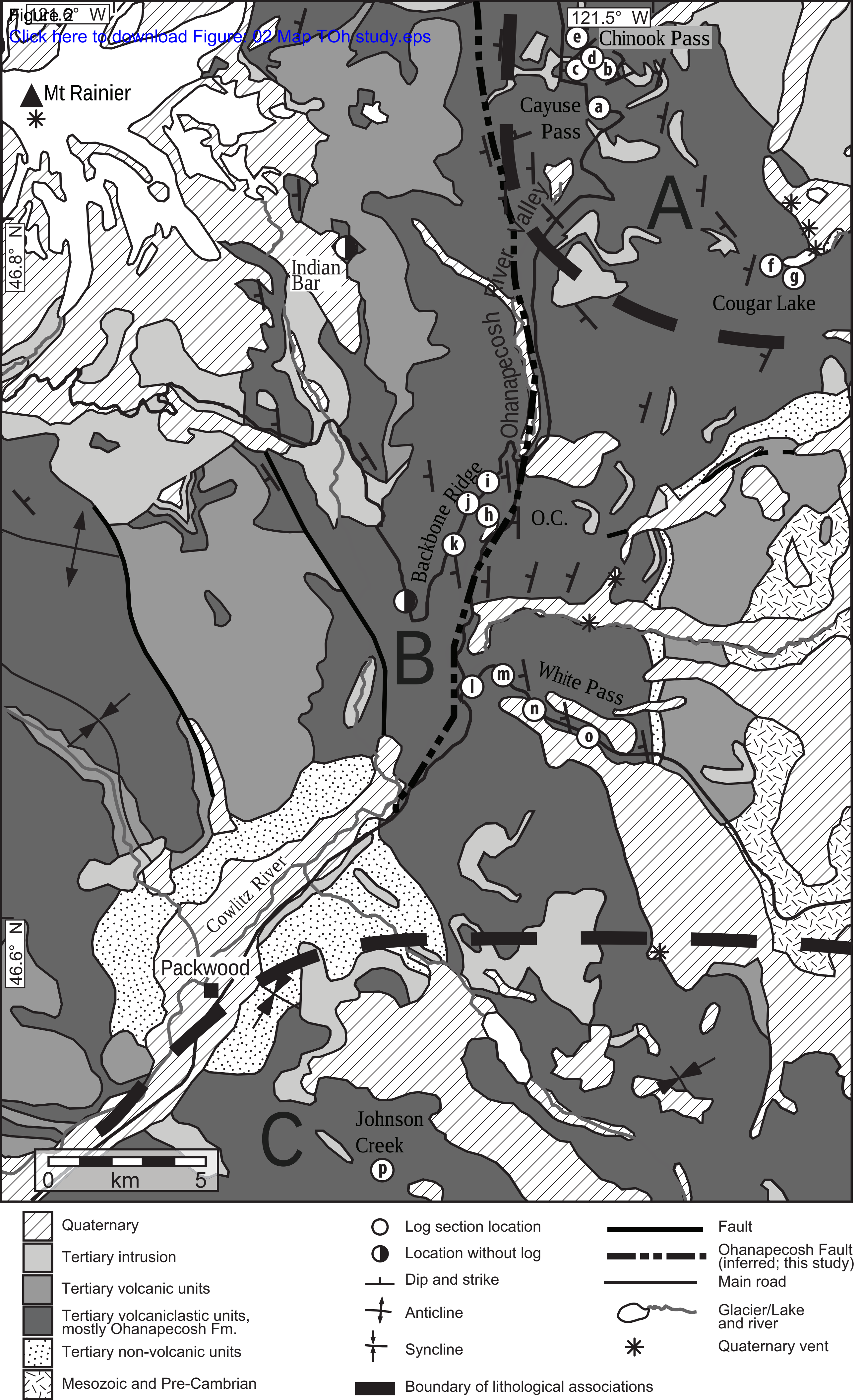
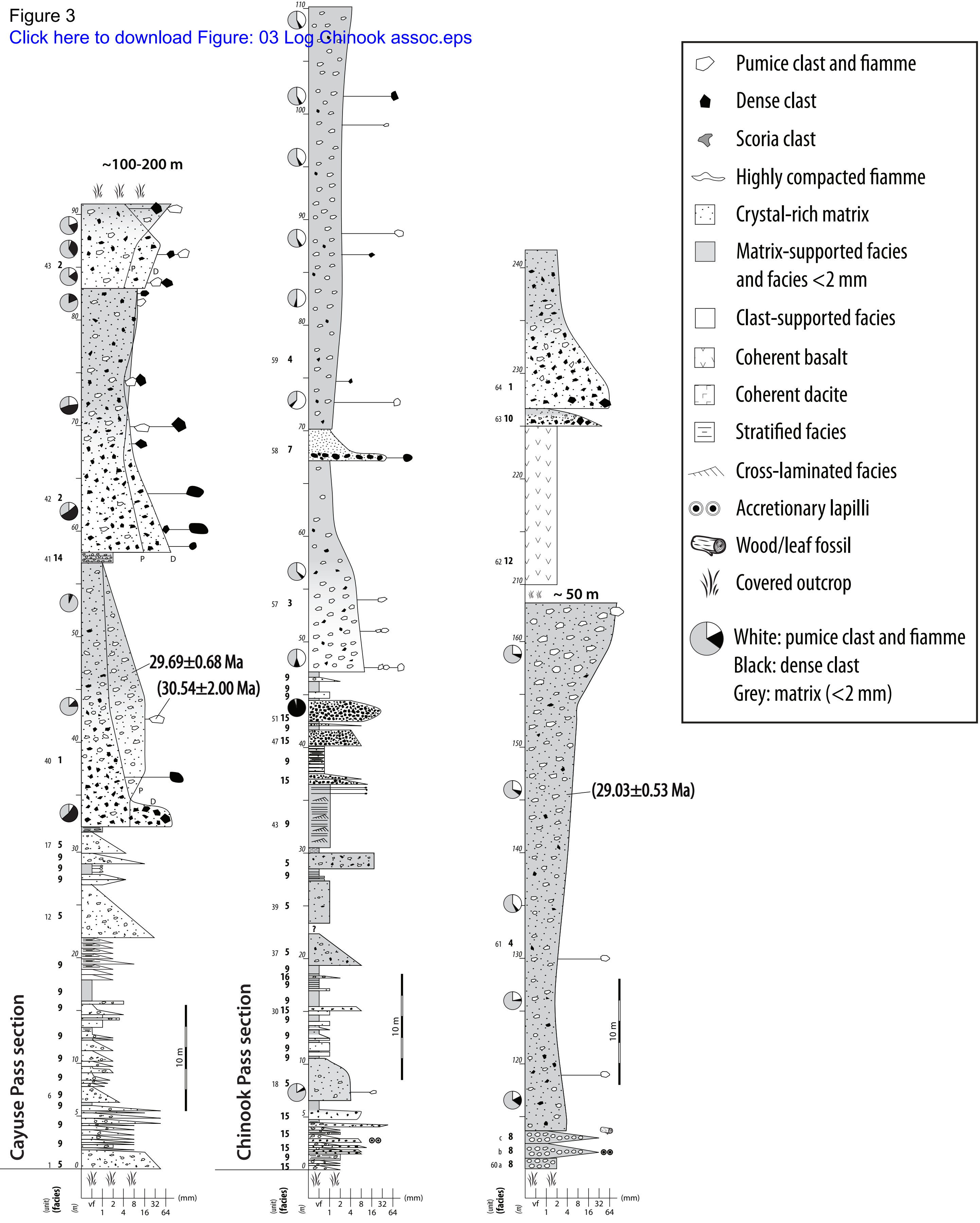
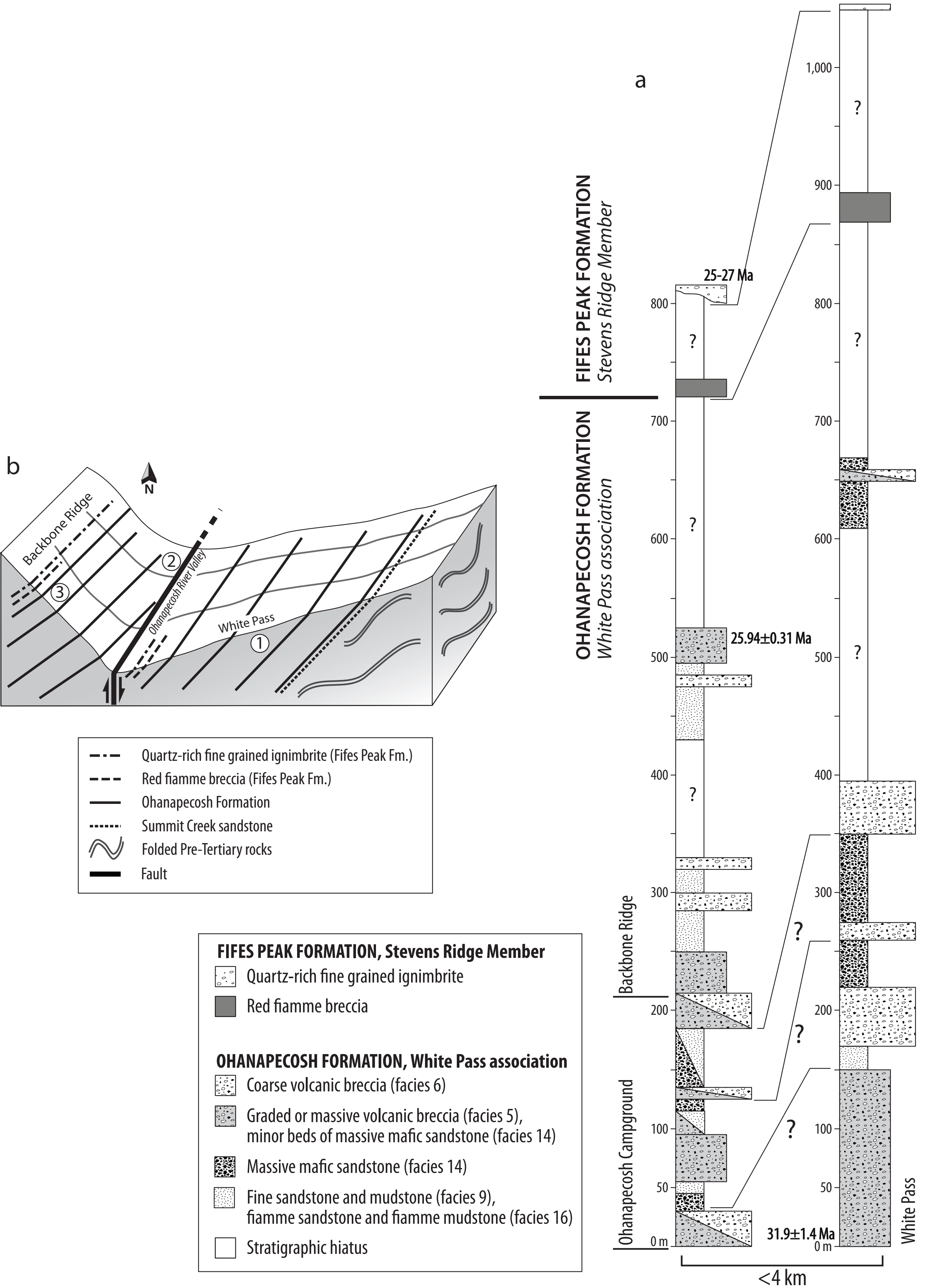
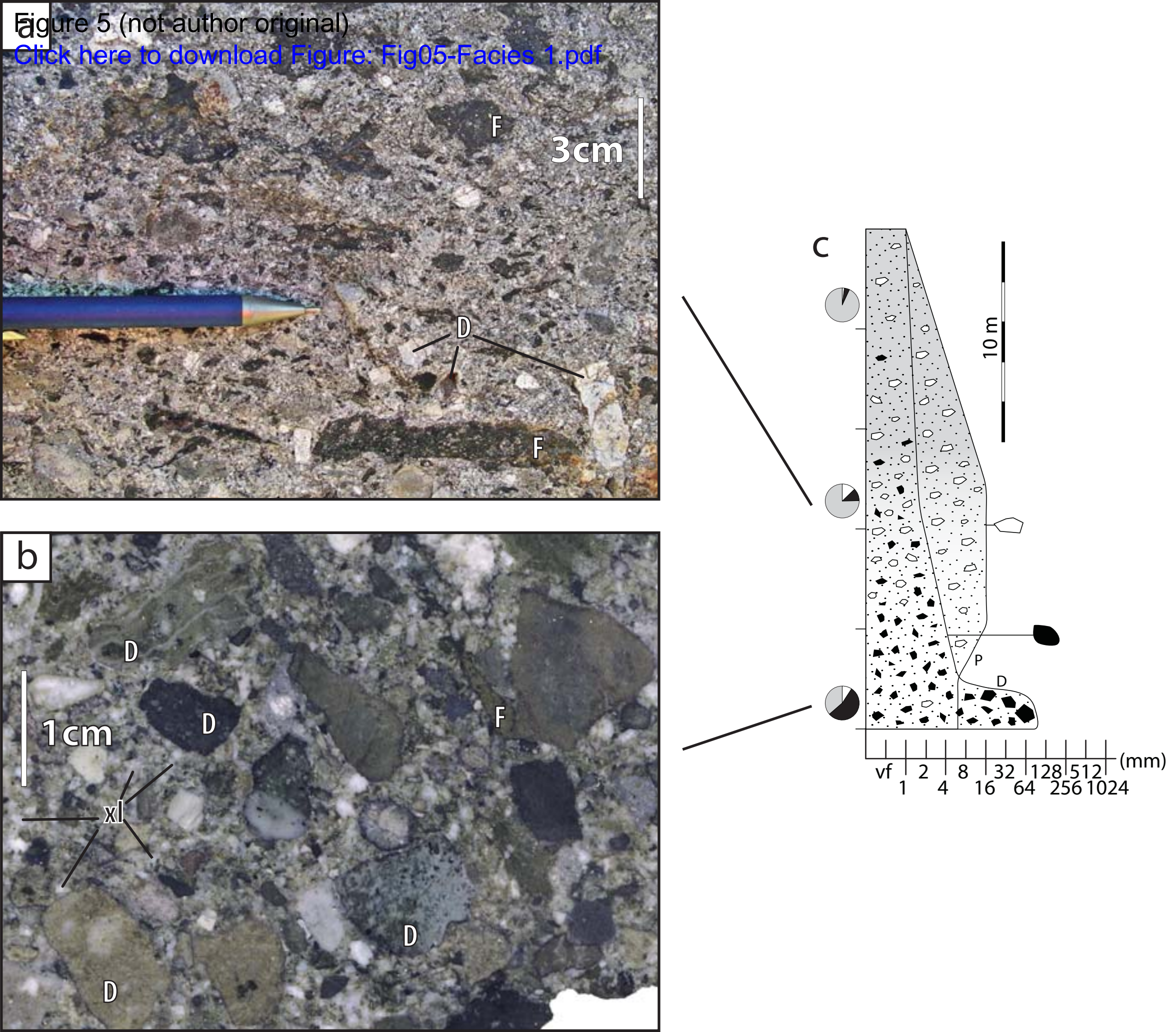
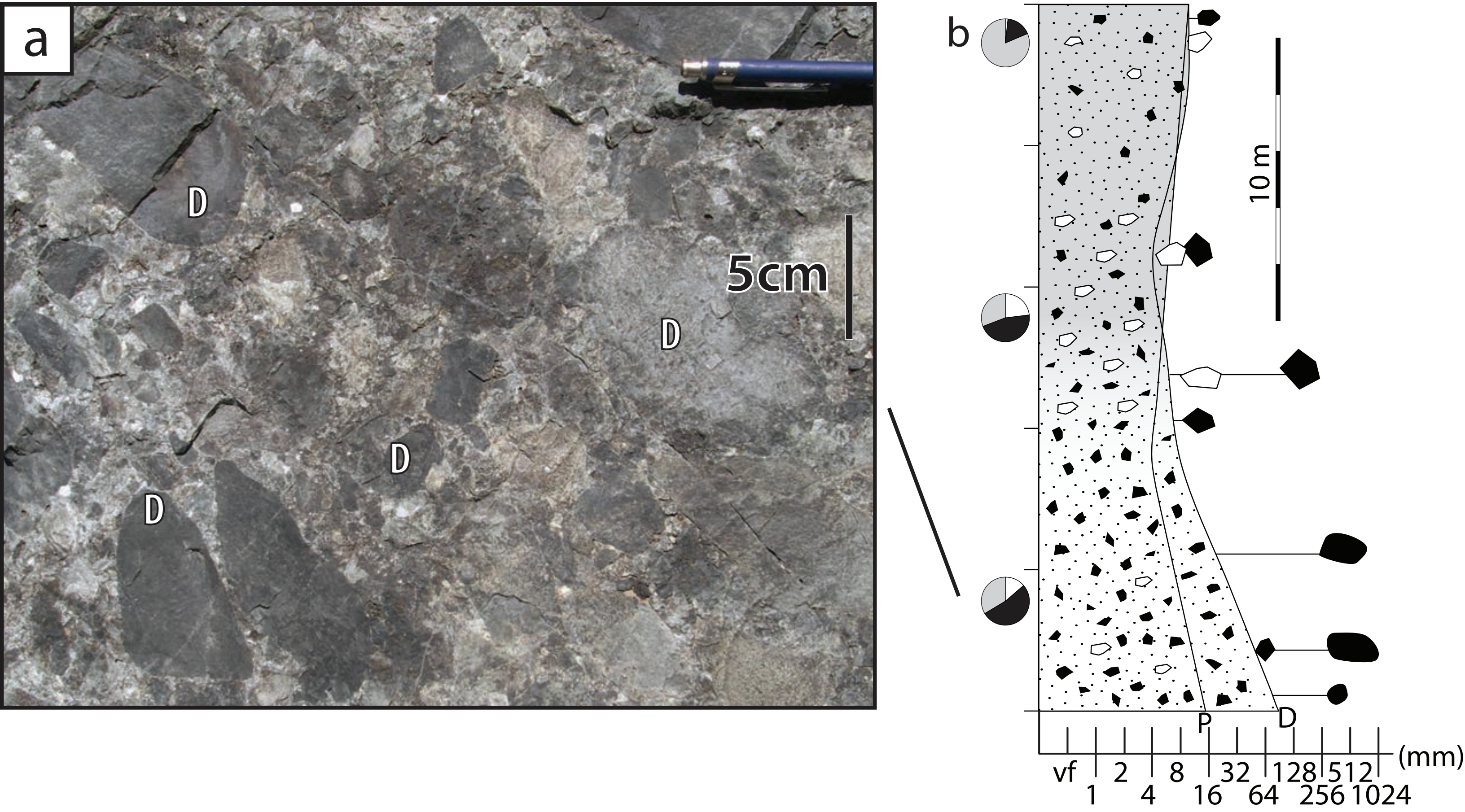

121.7° W
121.5° W
46.8° N
46.6° N
Mt Rainier
Chinook Pass
Cayuse Pass
a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
p
A
B
C
Indian Bar
Ohanapecosh River Valley
Cougar Lake
Backbone Ridge
O.C.
White Pass
Cowlitz River
Packwood
Johnson Creek
0
km
5
Quaternary
Tertiary intrusion
Tertiary volcanic units
Tertiary volcaniclastic units, mostly Ohanapecosh Fm.
Tertiary non-volcanic units
Mesozoic and Pre-Cambrian
Log section location
Location without log
Dip and strike
Anticline
Syncline
Boundary of lithological associations
Fault
Ohanapecosh Fault (inferred; this study)
Main road
Glacier/Lake and river
Quaternary vent

Figure 3


Pumice clast and fiamme
Dense clast
Scoria clast
Highly compacted fiamme
Crystal-rich matrix
Matrix-supported facies and facies <2 mm
Clast-supported facies
Coherent basalt
Coherent dacite
Stratified facies
Cross-laminated facies
Accretionary lapilli
Wood/leaf fossil
Covered outcrop
White: pumice clast and fiamme
Black: dense clast
Grey: matrix (<2 mm)
~100-200 m
29.69±0.68 Ma
(30.54±2.00 Ma)
~ 50 m
(29.03±0.53 Ma)
Cayuse Pass section
Chinook Pass section
10 m
(unit)
(facies)
(m)
vf
1
2
4
8
16
32
64
(mm)
P
D


a
b
FIFES PEAK FORMATION
Stevens Ridge Member
OHANAPECOSH FORMATION
White Pass association
Backbone Ridge
Ohanapecosh Campground
White Pass
25-27 Ma
25.94±0.31 Ma
31.9±1.4 Ma
0 m
50
100
200
300
400
500
600
700
800
900
1,000
?
<4 km
N
Backbone Ridge
Ohanapecosh River Valley
White Pass
①
②
③
Quartz-rich fine grained ignimbrite (Fifes Peak Fm.)
Red fiamme breccia (Fifes Peak Fm.)
Ohanapecosh Formation
Summit Creek sandstone
Folded Pre-Tertiary rocks
Fault
FIFES PEAK FORMATION, Stevens Ridge Member
Quartz-rich fine grained ignimbrite
Red fiamme breccia
OHANAPECOSH FORMATION, White Pass association
Coarse volcanic breccia (facies 6)
Graded or massive volcanic breccia (facies 5), minor beds of massive mafic sandstone (facies 14)
Massive mafic sandstone (facies 14)
Fine sandstone and mudstone (facies 9), fiamme sandstone and fiamme mudstone (facies 16)
Stratigraphic hiatus


a
F
3cm
D
F
b
D
D
F
1cm
xl
D
D
c
10 m
P
D
vf
1
2
4
8
16
32
64
128
256
512
1024
(mm)


a
D
D
D
D
5cm
b
10 m
P
D
vf
1
2
4
8
16
32
64
128
256
512
1024
(mm)

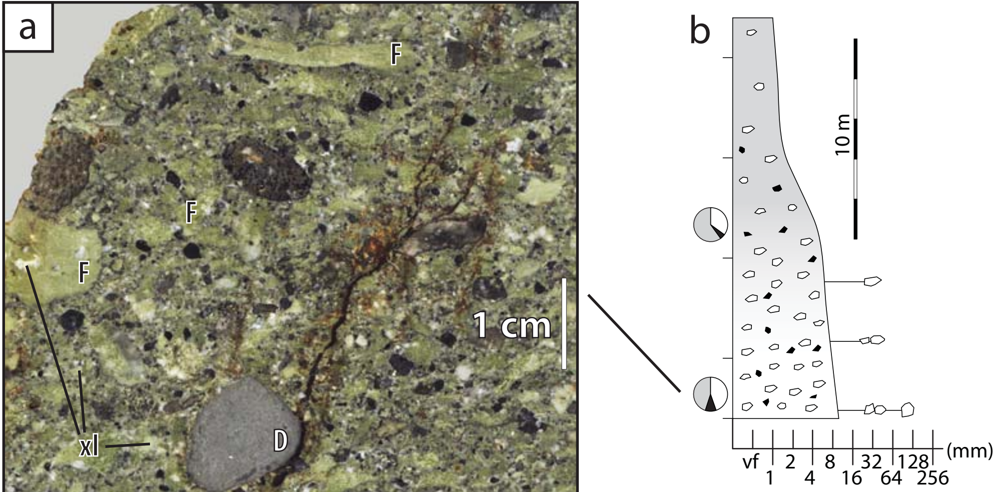
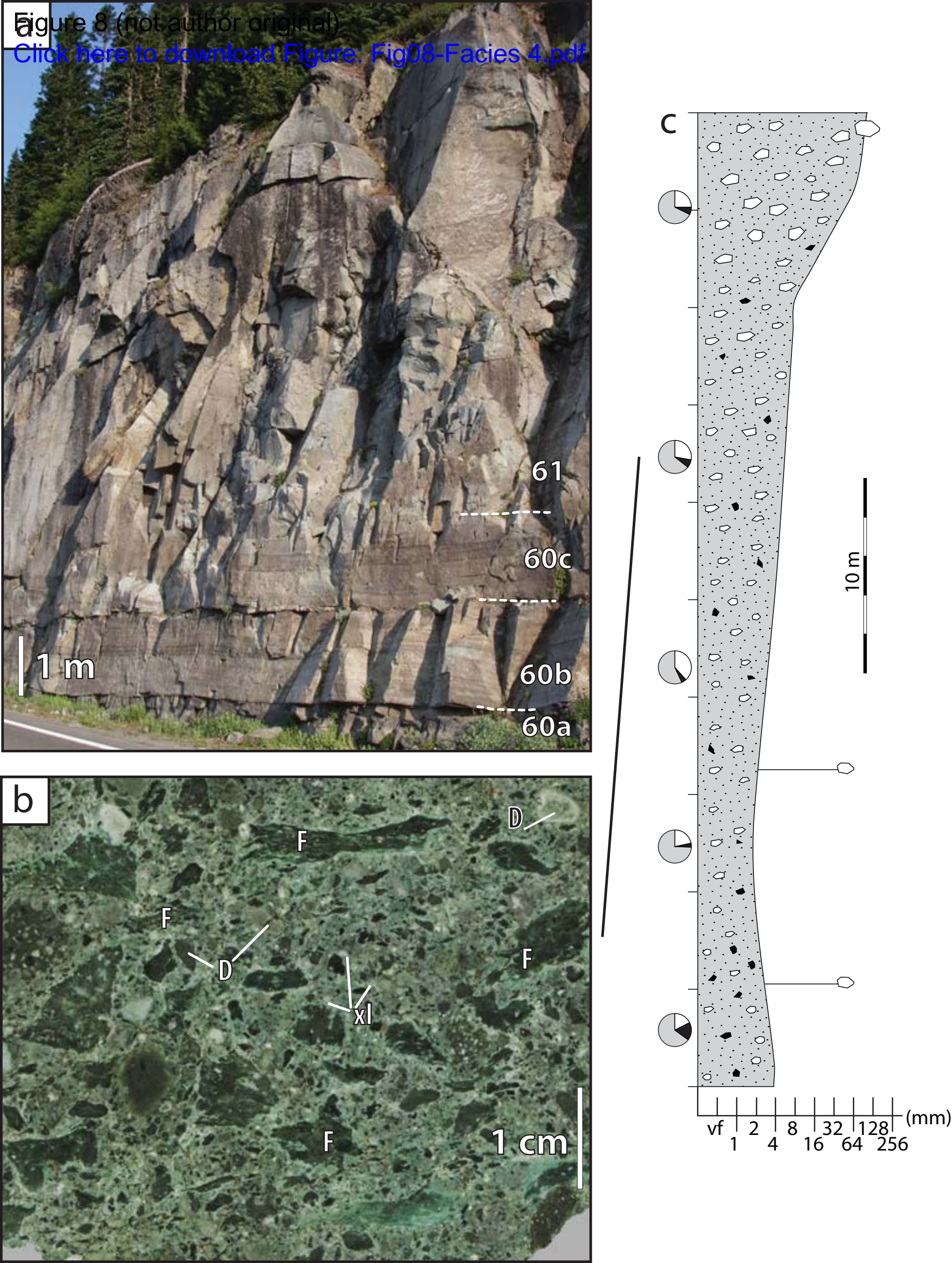
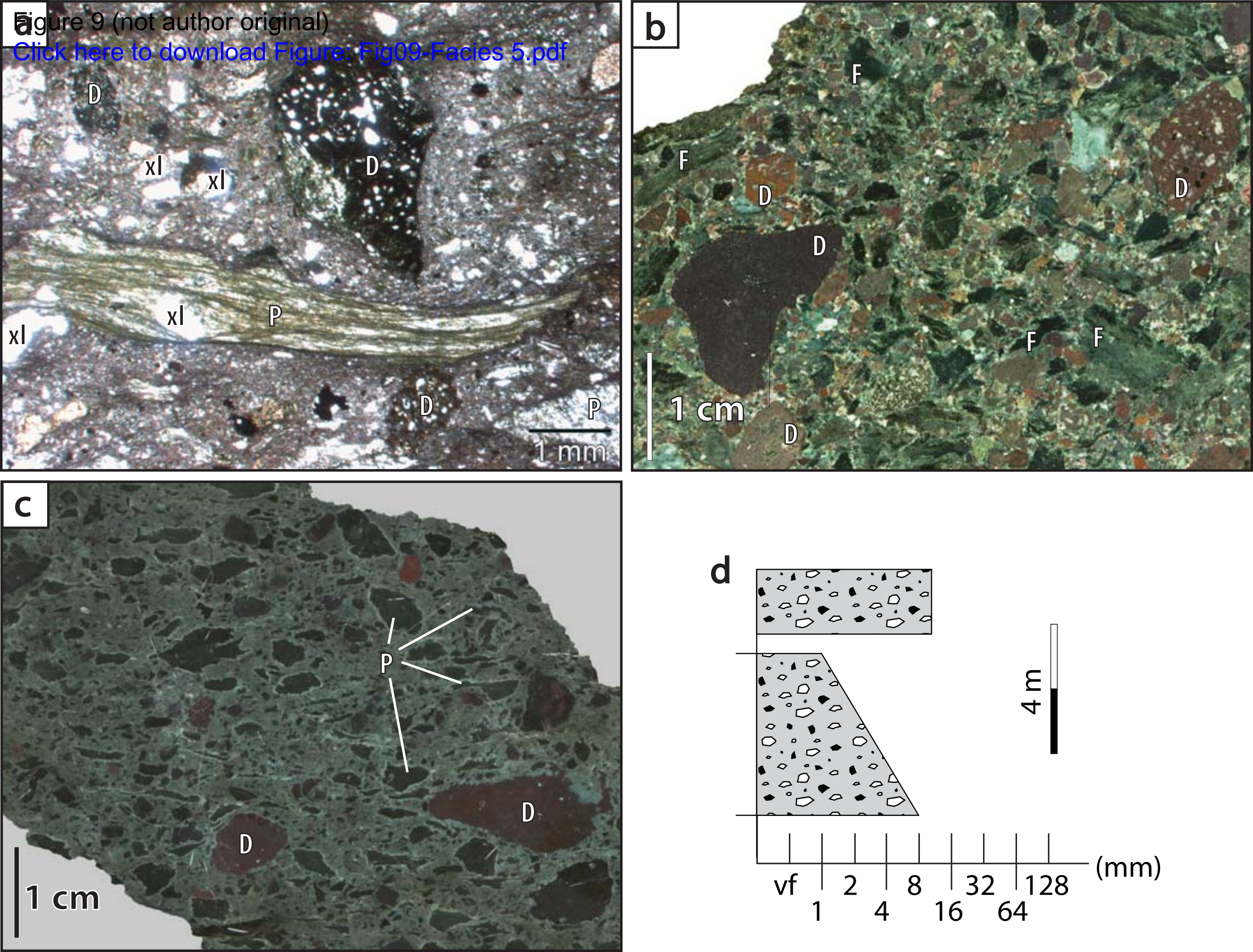
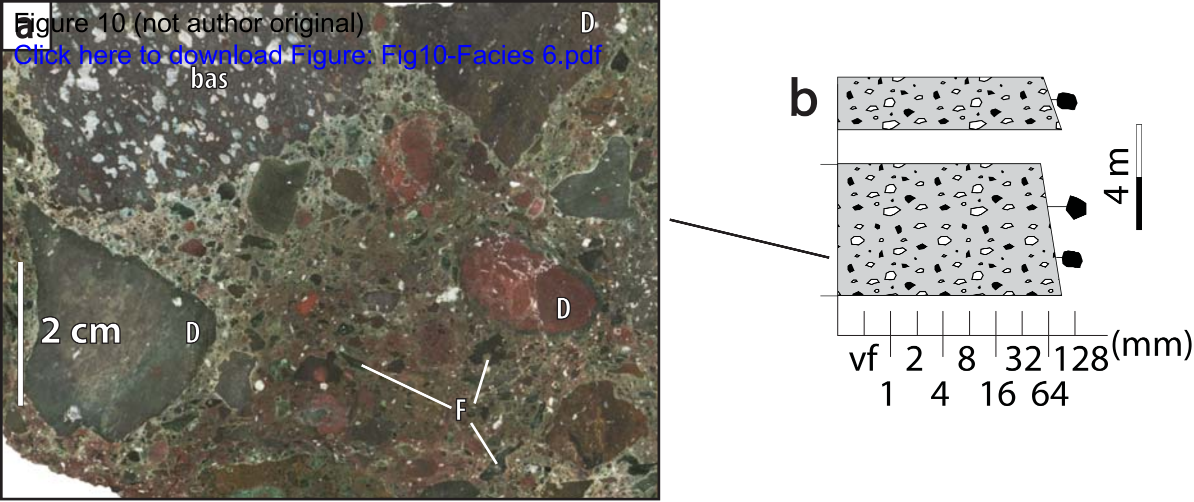
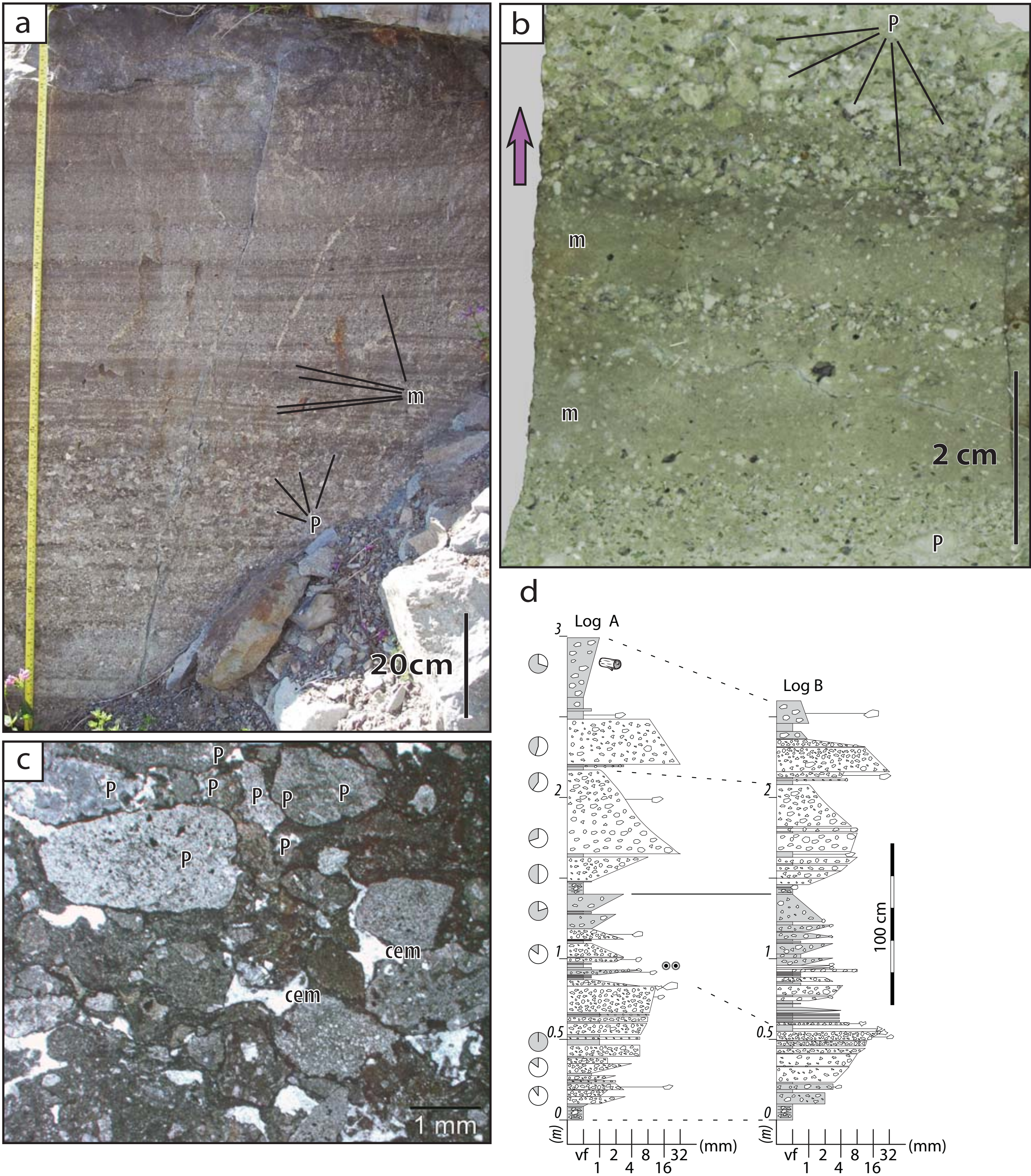

a
F
F
F
xl
D
1 cm
b
10 m
vf
2
8
32
128
1
4
16
64
256
(mm)

Figure 8 (not author original)




a
D
xl
xl
D
xl
P
xl
D
P
1 mm
b
F
F
D
D
D
F
F
1 cm
D
c
P
D
D
1 cm
d
4 m
vf
1
2
4
8
16
32
64
128
(mm)


a
bas
D
D
D
2 cm
F
b
4 m
vf
2
8
32
128
(mm)
1
4
16
64


a
m
P
20cm
b
P
m
m
2 cm
P
c
P
P
P
P
P
P
P
cem
cem
1 mm
d
Log A
Log B
3
2
1
0.5
0
(m)
vf
1
2
4
8
16
32
(mm)
100 cm

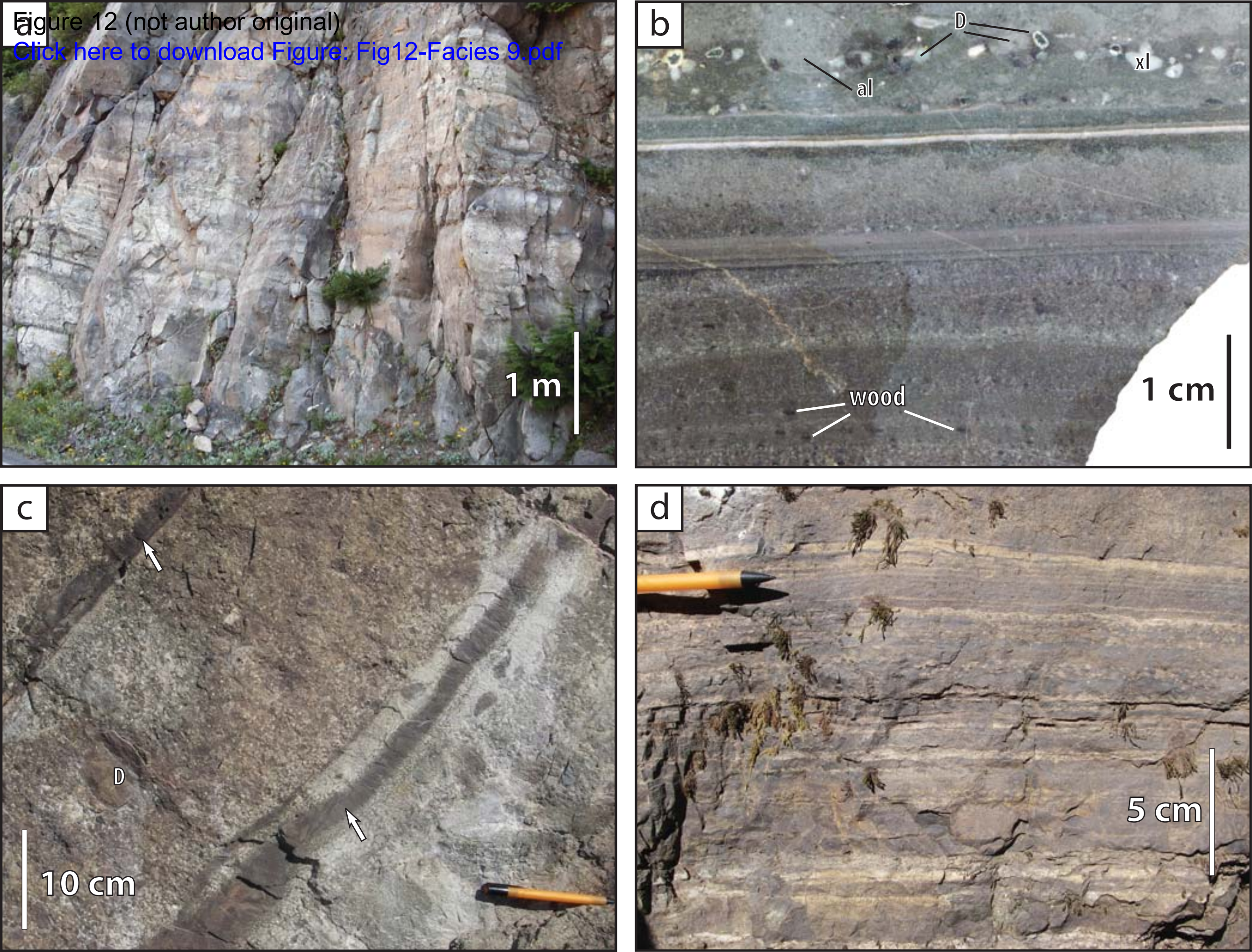
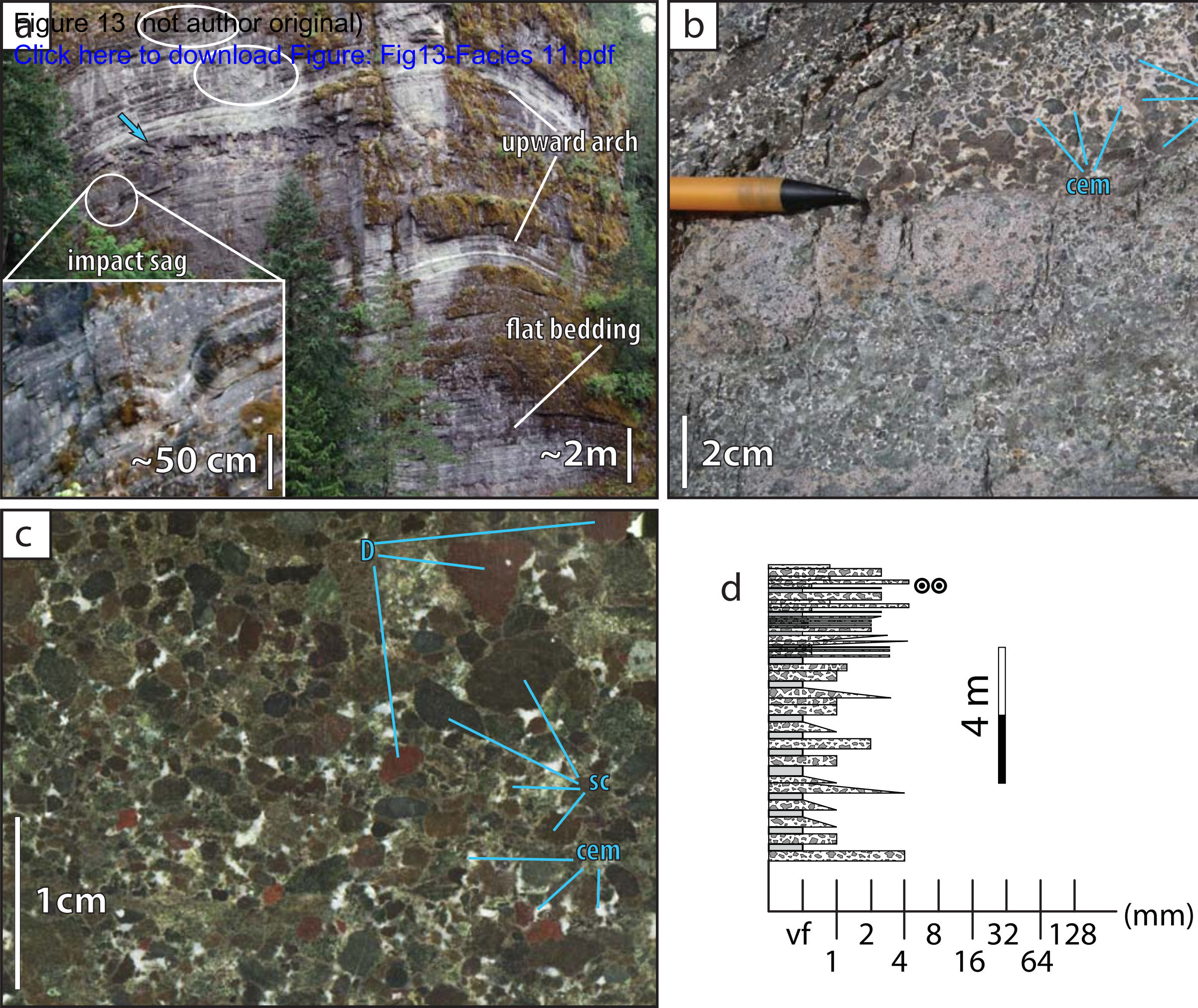

a
1 m
b
D
al
xl
wood
1 cm
c
D
10 cm
d
5 cm

Figure 13 (not author original)



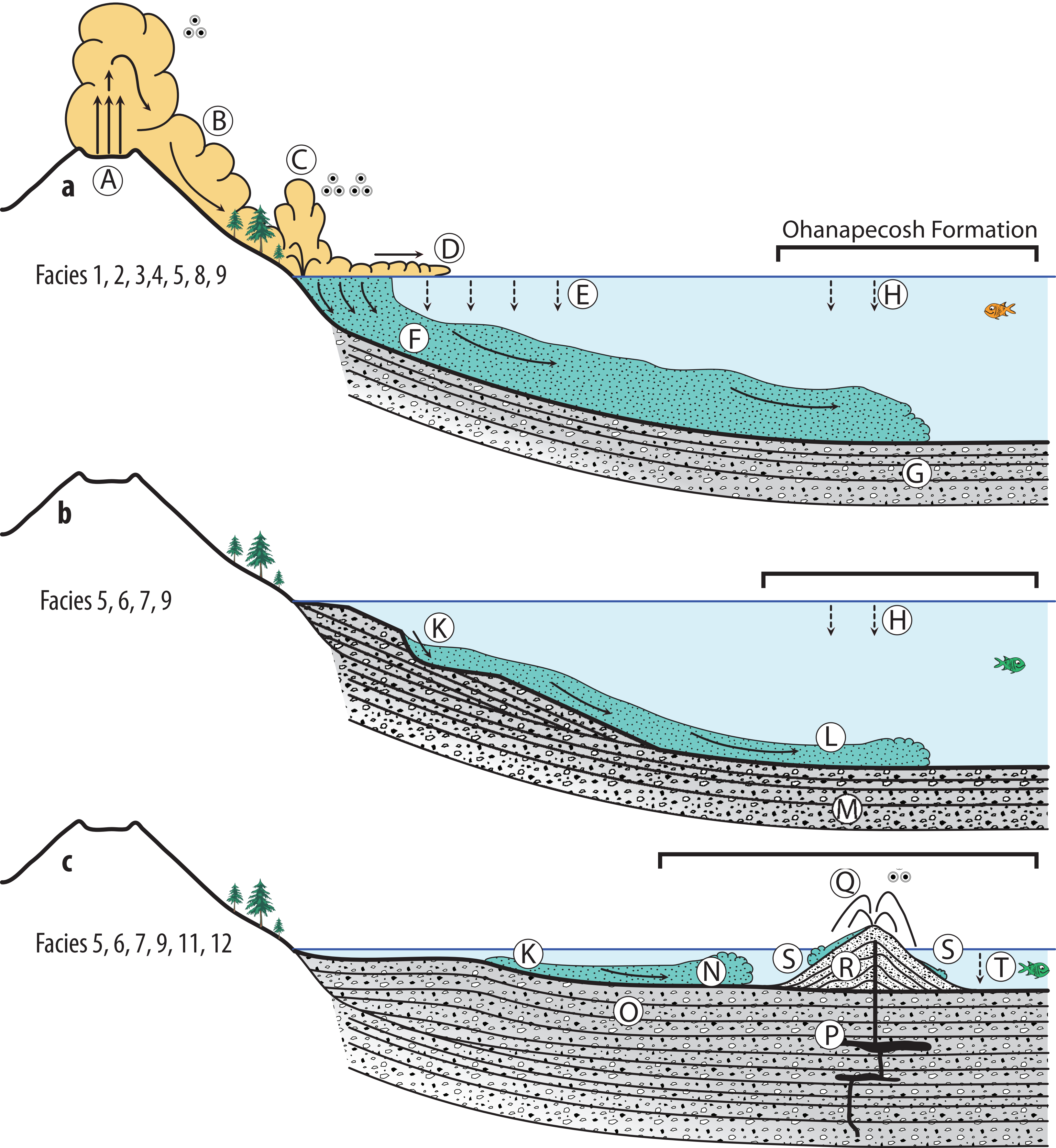
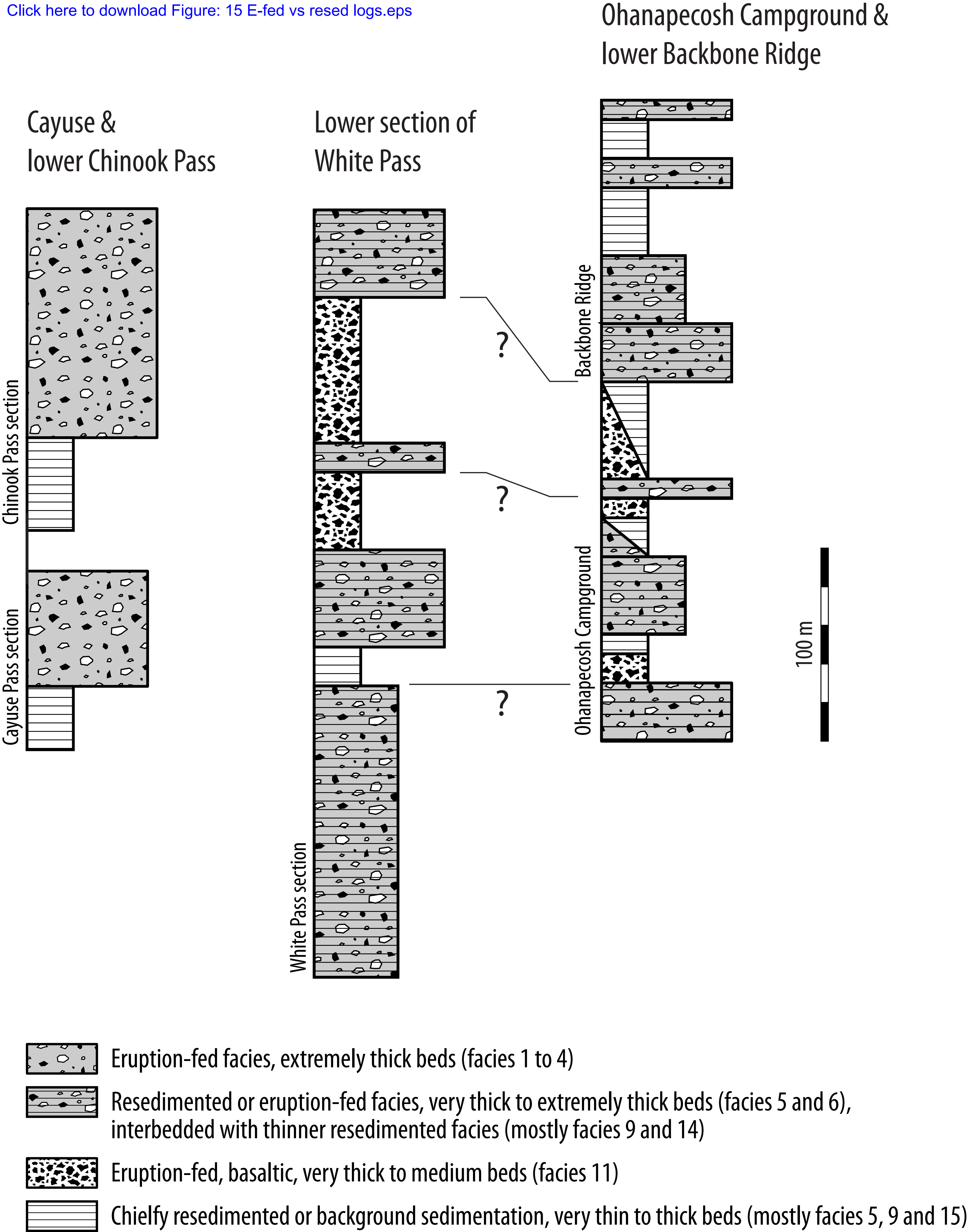

a
A
B
C
D
E
F
G
H
Ohanapecosh Formation
Facies 1, 2, 3,4, 5, 8, 9
b
K
H
L
M
Facies 5, 6, 7, 9
c
Facies 5, 6, 7, 9, 11, 12
K
N
O
P
Q
R
S
S
T

Figure 15


Ohanapecosh Campground &
lower Backbone Ridge
Cayuse &
lower Chinook Pass
Lower section of
White Pass
Chinook Pass section
Cayuse Pass section
White Pass section
Backbone Ridge
Ohanapecosh Campground
?
?
?
100 m
Eruption-fed facies, extremely thick beds (facies 1 to 4)
Resedimented or eruption-fed facies, very thick to extremely thick beds (facies 5 and 6), interbedded with thinner resedimented facies (mostly facies 9 and 14)
Eruption-fed, basaltic, very thick to medium beds (facies 11)
Chielfy resedimented or background sedimentation, very thin to thick beds (mostly facies 5, 9 and 15)

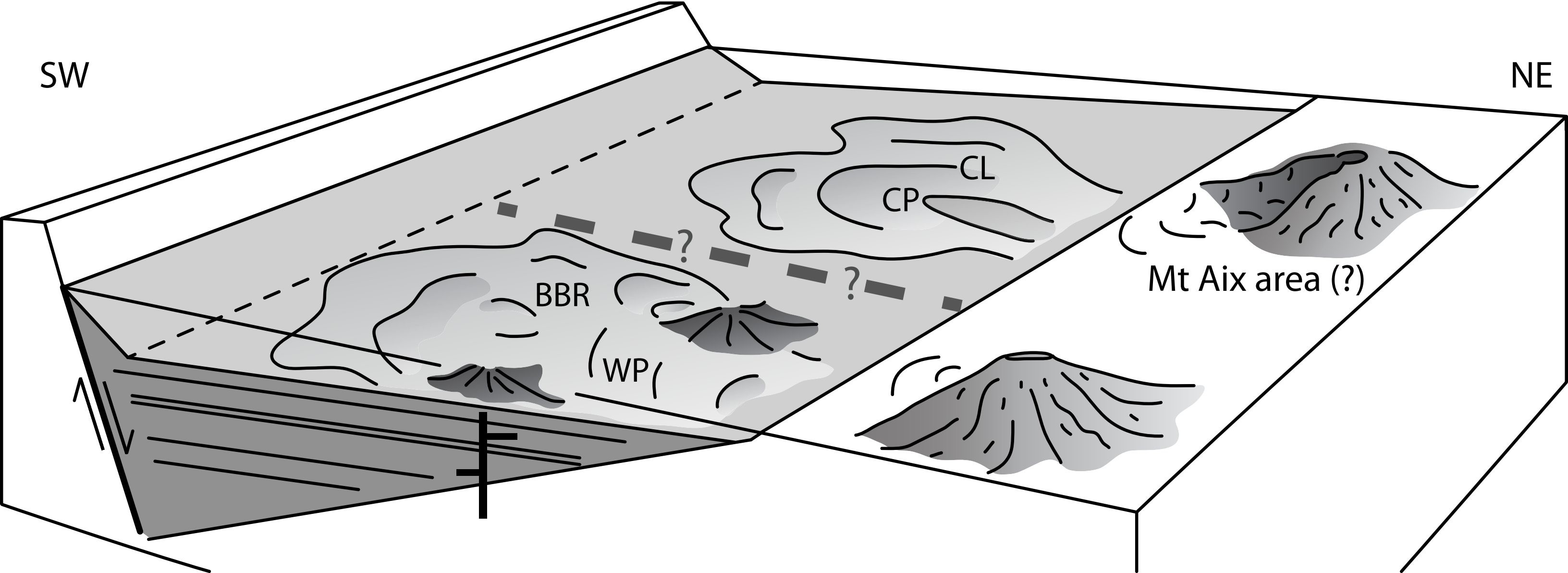

SW
NE
CL
CP
?
?
BBR
WP
Mt Aix area (?)

TABLE 1. CLASTS IN THE OHANAPECOSH FORMATION

Clast type	Color and size	Crystals	Other textures
Pumice and fiamme	1–60 mm; max 300 mm. Pale to dark green to black.	Largely euhedral phenocrysts, 0–20 vol.% in general. Plagioclase and mostly altered ferromagnesians; no quartz. Chinook Pass association: 25-30 vol.% phenocrysts (up to 5 mm) in coarse fiamme; small fiamme aphyric or too small to contain crystals. White Pass association: generally <30 vol.% phenocrysts.	Pumice clasts mostly angular. Former groundmass entirely devitrified, composed of secondary minerals. Aspect ratio of pumice clasts is 1-2.5 on average, maximum 5 for fiamme. Vesicles rarely preserved, round to very elongate (tube pumice, aspect ratio >>100).
Free broken crystals	N.A.	Mostly plagioclase; relics of ferromagnesians (pyroxene, amphibole). No quartz.	Broken on one face to multiple. Free crystal population matches the euhedral phenocryst populations in fiamme, pumice and dense clasts.
Scoria	2–10 mm. Red or dark grey to black.	Altered ferromagnesians common but difficult to distinguish from groundmass, feldspar microlites arranged in a trachytic texture, <1 vol.% plagioclase phenocrysts.	Sub-angular to very angular. Poorly to moderately vesicular (<40 vol.%), rounded to highly contorted vesicles (<0.1–1 mm across) filled with zeolites and other secondary minerals.
Accretionary lapilli	20 mm. Pale to dark gray, core up to 10 mm or absent.	N.A.	Rim-type accretionary and armored lapilli; commonly show multiple rims, and their cores are up to 10 mm (Cougar Lake, Ohanapecosh Campground) or absent (e.g. Backbone Ridge, Ohanapecosh Campground, White Pass). Broken and intact accretionary lapilli occur together.
Dense clasts	<1–1,000 mm. White Pass association: red, dark red, dark green, and dark brown dense clasts Chinook Pass association: white, green or dark green to dark brown aphyric dense clasts; lacks red dense clasts, except where in contact with Miocene Tatoosh sills.	0–50 vol. % plagioclase minor amounts of relic ferromagnesian crystals.	Range from rounded to very angular, but mostly angular.
Plant fossils	<1–20 mm. Black.	N.A.	Leaves, wood, rare >20 cm long silicified trunk fragment was found at lower Cayuse Pass.
Matrix	<2 mm. Pale to dark green, red to dark violet, braun to black.	Fragments of plagioclase crystals (0–15 vol.%) and relics of ferromagnesians.	Former groundmass entirely devitrified, composed of secondary minerals.

Note: N.A. = not applicable

Table 2

TABLE 2. FACIES IN THE OHANAPECOSH FORMATION

Facies	Lithofacies	Typical unit/section; association	Unit thickness; grading		Clast and lithology
1	Normally graded fiamme-dense clast breccia	Cayuse 40, Chinook 64, Cougar Lake CPA	>15 m Normal		Facies 1 is represented by unit 40 at Cayuse Pass, which consists of a >20-m-thick, tabular bed laterally continuous over >400 m (Fig. 5). It overlies a sequence of very thin to thick beds with a sharp contact (Fig. 3). Unit 64 at Chinook Pass is composed of similar facies, but less rich in pumice clasts and fiamme. It is exposed in a 15-m-high cliff (electronic suppl.) that overlies a thick (~1 m) bed of facies 10.
				base	The basal sub-facies consists of 3 m of clast-supported, normally graded polymictic breccia, mostly composed of a variety of coarse dense angular to sub-rounded volcanic clasts (50 vol.%; some with all edges modified), dominated by dark aphyric dense clasts (Fig. 5). The size of the dense clasts gradually decreases upward from 60–80 mm to 6–10 mm, and rare sub-rounded outsized clasts occur (up to 1 m). The other components are abundant feldspar crystal fragments (>10 vol.% of the rock), black moderately porphyritic fiamme and pumice clasts (6–10 mm, 15 vol.%; 15–20 vol.% feldspar phenocrysts) and matrix (<20 vol.%).
				mid	The middle sub-facies (10 m thick) is matrix-supported, normally graded breccia. The volume of dense clasts decreases to 10–15 vol.%, whereas fiamme become abundant (Fig. 5; >15 vol.%); average size is 10-20 mm and rarely up to 400x150 mm. The content of crystal fragments in the matrix remains high (>10 vol.%).
				top	The upper sub-facies is normally graded, matrix-supported breccia (average diameter 6–2 mm, max 20 mm) and occupies the upper third (6–7 m) of the unit. Fiamme are minor (<5 vol.%) and the matrix is up to 90 vol.% and includes 20 vol.% of feldspar crystal fragments. At Cougar Lake, coarse tube pumice clasts (max 30 cm) occur in unit A1. Several m-long altered, tabular clasts (possibly stratified mudstone or coarse fiamme) are present at the top of unit B7. Poorly exposed, laminated or cross-laminated mudstone (>10 m thick) above may be part of the unit.
2	Normally graded dense clast-fiamme breccia	Cayuse 42 CPA	>20 m Normal		Facies 2 is >20 m thick, tabular and laterally continuous over >400 m. Directly overlies a 1-m–thick interval of laminated crystal-rich sandstone (facies 14) with a sharp boundary (Fig. 3). Very similar to facies 1, but rounded dense clasts are coarser and more abundant in this facies (Fig. 6).
				base	The lower sub-facies is <10 m thick. The angular to sub-rounded dense volcanic clasts (dominated by a green aphyric type) are normally graded from 80 to 10 mm in average size and account for 40–60 vol.% (clast-supported). Outsized clasts (up to 1 m) are sub-rounded (Fig. 6), some with all edges modified. Fiamme (up to 15 mm) are relatively abundant (15–20 vol.%). The matrix includes feldspar crystal fragments and dense clasts.
				top	The upper sub-facies is matrix-rich (up to 80 vol.%). Dense clasts (15 vol.%, up to 25 mm), angular pumice clasts (8–10 mm) and small fiamme (<5 vol.%; <4 mm) are also present.
3	Normally graded fiamme breccia	Chinook 57 Cougar Lake B10 CPA	>20 m Normal		Facies 3 is poorly preserved, in tabular, 20-m-thick beds with two gradational sub-facies of similar thickness.
				base	The basal sub-facies is clast-supported in pale-to-dark green fiamme and pumice clasts (Fig. 7; >40 vol.%, 10 mm average, max 30 mm), feldspar crystals fragments (5–10 vol.%) and minor sub-rounded dense clasts (<5 vol.%, up to 15 mm).

				top	The size and abundance of fiamme and pumice clast is smaller than in basal sub-facies (30 vol.%, 2-3 mm average), and this sub-facies is matrix-supported. The size of dense clasts is smaller and their abundance remains similar than the basal sub-facies.
4	Reversely graded fiamme breccia	Chinook 59, Chinook 61 CPA, (WPA)	>40 m Reverse		Facies 4 consists of tabular, 40- to 50-m-thick beds (Fig. 8). A bed at the top of Backbone Ridge (White Pass association) is tentatively included in this facies.
				base	The basal sub-facies contains pale-to-dark green fiamme and pumice clasts (40 vol.%, 2–5 mm), feldspar crystal fragments (>10 vol.%), dense clasts (<5 vol.%) and matrix. The fiamme and pumice clast sizes increase to 10 mm upwards (Fig. 8) and feldspar crystal fragments become more abundant (>15 vol.%).
				top	The upper 10 m of the unit shows a drastic increase in fiamme and pumice clast sizes (average 30-40 mm, max 150 mm). Less than 5 vol.% of dense clasts is found throughout the whole bed.
5	Graded or massive volcanic breccia	White Pass WPA, JCA, (CPA)	mostly 1–5 m, max 15 m Normal, massive; rarely reverse		This facies is made of very thick beds that can be clast-supported or matrix-supported, and dominated by fiamme or dense clasts (Fig. 9). The average grain size decreases from 10 to 4 mm upwards, or shows no change (10 mm). The components are green to dark grey fiamme and pumice clasts (Fig. 9; 30–60 vol.%), very angular dense clasts (10–30 vol.%), feldspar crystal fragments and matrix (20–60 vol.%). The dense clasts are a mixture of red- and dark-grey clasts of probable mafic and intermediate composition. Reversely graded units (southern Packwood, Johnson Creek association; top of the Backbone Ridge section) have similar characteristics except the increase in clast size.
6	Massive volcanic breccia	White Pass WPA, JCA	mostly 1–5 m, max 25 m Massive or normal		This facies occurs at White Pass, Ohanapecosh Campground and Backbone Ridge (White Pass association) and shows slight coarse-tail normal grading in the size of dense clasts (Fig. 10; 60 to 40 mm). Clasts are angular to sub-rounded. Dense clasts (50–70 vol.%), pumice clasts and fiamme (10–20 vol.%), and feldspar crystal fragments together are dominant over matrix (10–25 vol.%). Fiamme are green to dark grey.
7	Polymictic breccia-conglomerate	Chinook 58 CPA	3 m Normal		This facies separates two extremely thick beds of facies 3 and 4; it is poorly preserved. It contains abundant (>60 vol.%) sub-rounded to rounded, poorly porphyritic dense clasts (40 mm average, 200 mm max) at the base of the unit, and grades into fine-grained facies.

8	Reversely to normally graded pumice breccia	Chinook 60 CPA	2.5 m Reverse and normal	Beds of this facies are laterally extensive over >100 m. The main part of the facies consists of pumice breccia chiefly composed of pale yellow to pale brown sub-rounded pumice clasts (average 1 to 10 mm, max 30 mm), with minor fiamme and rare feldspar crystals fragments (<1 mm) and <2 cm, unbroken and broken, rim-type accretionary lapilli (Fig. 11). The mudstone at the top of the units contains wood fragments (<2 cm). The grading of the pumice breccia is laterally continuous over tens of meters, but mudstone interlayers vary in thickness laterally and commonly disappear locally. Unit 60a is poorly preserved and its base is covered by vegetation. The base of unit 60b overlies unit 60a with 20 cm of smooth erosional relief over 3 m laterally. In units 60b and 60c, there are six main beds that are reversely to normally graded and range from clast-supported to matrix-supported (Fig. 11). Most units are interrupted with tens of laminae or very thin beds of mudstone. The upwards continuity in the reverse and normal grading of the pumice clasts in the pumice breccia is continuous, despite the intercalation of mudstone (Fig. 11). The matrix is made of pale yellow to pale brown mudstone of similar color to the sub-rounded pumice clasts. The mudstone matrix is absent in a few places and inter-clast space is filled with calcite and zeolite cement.
9	Fine sandstone and mudstone	Ohanapecosh Formation CPA, WPA, JCA	1 mm – 1 m Massive or normal	Laterally extensive, very thin to thick beds of fine sandstone and mudstone facies are present throughout the Ohanapecosh Formation (Fig. 12). The beds are laterally continuous and uniform in thickness; very rare cm-deep scours and cm-wavelength cross-laminations occur. The beds commonly occur in m-thick groups separating groups of very thick to extremely thick beds. Beds can be dark grey, purple or pale grey and most beds are probably composed exclusively of volcanic components. Crystal content is commonly <10 vol.%, but can reach >20 vol.%. Small pieces of wood (<1 cm) as well as rare accretionary lapilli and armored lapilli are spread throughout the thickness of some of the thin beds or concentrated in layers within very thin beds, especially in the Backbone Ridge section (White Pass association). Wood fragments are present in some beds; the largest fossil wood trunk was found in a pale grey unit at lower Cayuse Pass (Chinook Pass association). In the southern Packwood region (Johnson Creek association), fossil leaves are abundant in a >3-m-thick unit of cross-laminated fine feldspathic sandstone that was interpreted by Winters (1984) to have continental source.
10	Normally graded dense clast breccia to fiamme breccia	Chinook 63, Cougar Lake CPA	1 m Normal	The facies is clast-supported and consists of coarse dense clast breccia at the base (up to 40 cm thick), that grades upwards into fiamme breccia (fiamme 10–40 mm long); it is overlain by massive black sandstone to mudstone.
11	Basaltic scoria breccia	White Pass 137 WPA	<1 m Normal	This facies occurs in thin to thick, normally graded beds, and is composed of very angular scoria clasts (average 2-4 mm, max 10 mm). The scoria clasts are red to dark brown, and contain ovoid to highly contorted vesicles. The abundance of feldspar microlites is variable. The matrix makes up 20–95 vol.%, and the clast-supported varieties have monomodal grain size distribution and are cemented by white zeolites (Fig. 13). In a cliff close to White Pass (unit 137), the gently undulating beds occur in a 70-100-m-thick succession that is discordant to the regional strike. The orientation of beds in the section defines an upward arch (Fig. 13), defining a scoria cone structure. This succession includes scattered <2-m-long depressions in fine-breccia beds that contain 0.5-1 m clasts. The unit 137 is interbedded with a minor amount of beds of facies 9, and a couple of them show high concentration of accretionary lapilli.

12	Vesicular basalt	White Pass CPA, WPA	0.3 m – 3 m	The basalt has sharp contacts and is conformable with bedding. Coherent vesicular basalt contains ellipsoidal vesicles (1-2 cm across) filled by secondary minerals (zeolites). In unit 62 at Chinook Pass, the size of vesicles increases upwards, and the vesicles occur in bands. Large tortuous cavities up to 10 cm long are common in the Cougar Lake section. No associated brecciated facies is present, except for one, poorly preserved outcrop at White Pass (unit 107) where basalt is overlain by mafic volcanic breccia.
13	Flow-banded dacite	Cougar Lake CPA	30 m	Feldspar crystals (>20 vol.%, <1 mm) and flow-banding in this coherent facies contrast with the typically massive Miocene Tatoosh sills. The vertical and horizontal extent of the dacite remains undetermined due to erosion and difficult access, but it is possibly up to 30 m thick and continuous over several hundred meters laterally; the top of the unit is inaccessible. It directly overlies facies 9 with a sharp contact. No flow-banded clasts that could have been derived from this dacite body were found in the Ohanapecosh Formation.
14	Massive mafic sandstone	White Pass WPA	<1 m Massive	Beds of relatively well-sorted, massive mafic sandstone mostly consists of red-oxidized to dark grey, poorly vesicular scoria clasts (>95 vol.%) of probable mafic composition and feldspar crystal fragments (<2 vol.%); fiamme are absent. The cement is composed of zeolites and other secondary minerals. The scoria clasts are made of minor feldspar laths and ferromagnesian phases. The vesicles are ovoid to highly contorted.
15	Fine, dense clast volcanic breccia	Chinook 51 CPA	10 cm – 2 m Normal, or reverse to normal	This facies is normally graded breccia dominated by pale grey, grey and black dense clasts; rare fiamme of similar size are also present. Clast size averages 8-10 mm; largest clasts are 25 mm across. The pale grey clasts contain minor feldspar crystals (<10 vol.%). The proportions of matrix and clasts vary from unit to unit, but dense clasts are commonly >60 vol.%.
16	Normally or reversely graded fiamme mudstone	Cougar B13 CPA, WPA	<1 m Normal or reverse	Normally or reversely graded fiamme mudstone is matrix supported. The average fiamme size is 2–4 mm; coarser fiamme (up to 50 mm) are minor. Rare cross laminae, dense clasts and wood occur.

Note: CPA, Chinook Pass association; WPA, White Pass association; JCA, Johnson Creek association.

Table 3

TABLE 3. INTERPRETATION OF THE OHANAPECOSH FORMATION

Facies	Lithofacies characteristics	Transport process	Current behaviour	Eruption-fed versus resedimented products	Environment at source
1, 2, 3, 4, 5	Extremely thick (>20 m), laterally continuous beds, overall matrix-supported. Commonly dominated by angular pumice clasts; rich in crystal fragments. Facies 1, 2 and 3 have a basal dense clast breccia that is dominated by angular to sub-rounded dense clasts. Facies 5 spans from matrix- to clast-supported (20-60 vol.% matrix).	High-concentration density current, weakly cohesive	Non-cohesive current, deposited under some degree of turbulence. Sub-rounded coarse dense clasts in basal breccia suggest accidental pick-up. Reverse grading in facies 4 probably explained by lower density of larger pumice clasts present in the upper part of the bed, or delayed waterlogging.	Extreme thickness, abundance of angular pumice clasts and crystal fragments suggest products from explosive eruptions, fed directly from voluminous pumice-rich density currents.	Presence of facies 7 and 8, wood and accretionary lapilli in the beds of volcaniclastic sequence of the Chinook Pass association suggests the entire sequence to be mostly derived from subaerial environment. Basal breccia composed of sub-rounded dense clasts suggests resedimentation of clasts abraded in above wave-base environment. Angularity of pumice clasts denotes short subaerial transport.
5, 6	Extremely thick (>20 m), laterally continuous beds that span from matrix- to clast-supported beds (20-60 vol.% matrix), and dominated by pumice clasts and fiamme or dense clasts. Rich in crystal fragments. Normally graded or massive, absence of basal dense clast breccia.	High-concentration density current, moderately cohesive	Absence of dense clast breccia and weak grading suggest a more coherent current behaviour. Sub-rounded coarse clasts in facies 6 indicate weak clast abrasion during transport, or accidental pick-up.	Very thick to extremely thick beds, and abundance of angular pumice clasts and crystal fragments suggest products from explosive eruptions or resedimentation. If eruption-fed, directly fed from voluminous pumice-rich density currents. If resedimented, pumice clasts were previously saturated (e.g. Allen and Freundt, 2006).	Where preserved, angularity of pumice clasts denotes short subaerial transport. Sub-rounded dense clasts suggests at least partial source from above wave-base environment. Presence of wood and accretionary lapilli in other beds of the White Pass association suggests that part of the sequence is derived from subaerial environment.
7	Very thick, normally graded breccia-conglomerate that is dominated by sub-rounded to rounded dense clasts at its base. Pumice clasts and fiamme absent.	High-concentration density current	Strong normal grading in relative thin bed indicates weakly cohesive current.	Relative small thickness and absence of pumice clasts and fiamme suggests deposition from a density current.	Resedimentation of dense clasts previously abraded in above wave-base environment.

8	Thick, laterally continuous, reversely to normally graded, well sorted beds. Dominated by sub-rounded pumice clasts and former glass shards. Numerous very thin mudstone interbeds composed of presumed former glass shards do not interrupt grading in pumice clasts. Accretionary lapilli and wood are present in few mudstone interbeds.	Vertical settling	Distinctive reverse grading and presence of sub-rounded pumice clasts records saturation grading from progressive waterlogging of pumice clasts as a function of their size. Beds with normal grading indicate that the coarsest particles sank faster than the smaller ones, in a type of sedimentation dominated by hydraulic sorting. Interbeds of former glass shards reflect complex sedimentation of fine-grained clasts contemporaneously with the sinking of the pumice clasts. Origins could be abrasion of pumice clasts that formed the raft, ash from disintegration of pyroclastic flows at the shoreline, or fallout of ash from atmospheric ash plumes.	Eruption-fed, and formed in a two-step process: (1) a pumice-forming subaerial explosive eruption deposited pumice lapilli and ash onto the water body, forming pumice rafts (e.g. White et al., 2001), and (2) subsequent waterlogging in pumice rafts and settling of the pumice clasts, ash, wood and accretionary lapilli.	The accretionary lapilli demonstrate the presence of wet, ash-rich clouds (Cas and Wright, 1991); wood indicates source to be at least partially subaerial. The formation of pumice rafts is likely to be associated with deposition of pumice clasts that cooled in the atmosphere (Whitham and Cas, 1991).
9	Relatively thin (<1 m), laterally continuous, normally graded to massive beds. Contains mostly fine-grained (<2 mm) components. Wood, pumice clasts and accretionary lapilli can occur in small amount.	Low density density current; vertical settling	Good grading and fine-grained nature of the beds indicate deposition from low density currents or vertical settling processes.	Vertical settling of explosive eruption-fed products or resedimentation of saturated unconsolidated aggregates.	Subaerial eruption plumes deposited onto water, or resedimentation of unconsolidated aggregate.
11	Normally graded, laterally continuous, clast-supported and dominated by angular scoria clasts and crystal fragments, interbedded with beds of fine sandstone and mudstone (facies 9) that rarely contain accretionary lapilli. Unit 137 in White Pass section shows a scoria cone architecture with impact sags, and is associated with vesicular basaltic intrusions (facies 12). Dip and strike differ from general structure of the Ohanapecosh Formation.	Grain flow, low density density current; vertical settling	Normal grading, and clast-supported facies indicate deposition from overall non-cohesive, dilute density current, vertical settling or grain flow.	Scoria cone, impact sags, accretionary lapilli in mudstone interbeds and scoria-clasts-dominated deposits suggest eruption-fed facies, such as surtseyan. However, slopes on scoria cones are typically unstable and partial resedimentation of loose aggregates over a short distance is probable.	Scoria cone, impact sags and accretionary lapilli indicate subaerial or shallow-water (<30 m) vent environment. Different dips and strikes with other beds of Ohanapecosh Formation denote this facies to be localized and intrabasinal.