Geology and geochemistry of the Kamloops Group (Eocene) in its type area, Kamloops, British Columbia

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Abstract

The city of Kamloops is the type locality of the eponymous Kamloops Group, a package of early Eocene (ca. 52 Ma) volcanic and lesser sedimentary rocks. In its type area, the Kamloops Group is divided into the Tranquille Formation and the overlying Dewdrop Flats Formation, each of which is separated into a number of members. Field, petrographic, and whole rock major, trace, and rare earth element data indicate that many members have comparable compositions and volcanic facies whereas others differ at different geographic locations. This difference may reflect that different locations may have been fed by different feeder vents. The volcanic rocks range from basaltic andesite to dacite; minor rhyolite occurs west of the type area in the Mount Savona Formation. The most common rock type is andesite and although some andesites have high-Mg and adakite-like geochemical features (high Sr/Y, La/Yb) these terms should not be used to imply the type of mantle contribution to this volcanic pile (e.g., slab melting). Rather, petrographic and geochemical evidence support that some of these rocks were derived from garnet-free mantle melts that mingled with garnet-free lower crust. The geochemical features are consistent with amphibole, pyroxene, and plagioclase control resulting from mantle melts mixing with lower crust.

Keywords: Kamloops Group, Eocene, volcanism, petrography, geochemistry

1. Introduction

The Kamloops Group (Eocene) of south-central British Columbia forms a portion of a discontinuous belt of graben-fill volcanic and sedimentary rocks that extends from Challis, Idaho to eastern Alaska (Fig. 1). In British Columbia, this belt overlies older accreted terranes of the intermontane region and the edge of Ancestral North America (Fig. 1; Nelson et al., 2013). Outcropping in spatially separated areas, rocks of the belt have been referred to as the Sloko Group (includes Bennet Lake and Mount Skukum volcanic complexes) and the Endako, Ootsa Lake, Kamloops, Princeton, and Penticton groups (e.g., Ickert et al., 2009; Fig. 1). The available radiometric age data indicate that volcanism occurred between 56 and 46 Ma (e.g., Ickert et al., 2009; Bordet et al., 2014).

Although the timing of Kamloops Group volcanism coincides with major global tectonic change including mantle plumes, ridge subduction, and continental collision (e.g., Gaina and Jacob, 2018) and climate change (e.g., Zachos et al., 2001), the response and/or contribution of volcanism remains unknown. In addition, the tectonic drivers of the volcanism remain controversial (Breitsprecher et al., 2003; Haeussler et al., 2003; Morris and Creaser, 2003; Bordet et al., 2014; Dostal et al., 2019; Stern and Dumitru, 2019). The Kamloops Group also appears to be underexplored for mineral deposits. For example, although an epithermal bedrock deposit was suggested as the source of placer gold in the Tranquille River and Watching Creek (Knight and McTaggart, 1988; Chapman and Mileham, 2016), which run through the type area of the Kamloops Group, such a deposit remains undiscovered. Low-sulphidation epithermal Au-Ag deposits are known in other areas of Eocene volcanism including the Skukum volcanic complex, Yukon (Love et al., 1998), the Camelsfoot Range in southern British Columbia (Blackdome mine; Schroeter, 1987), in the southern boundary region of British Columbia (Dufresne, 2015; Höy et al., 2021), and in the Republic and Toroda grabens of the Colville Group in Washington State (Ashley et al., 1990). Non-metallic mineral deposits commonly associated with Eocene rocks in southern British Columbia include coal, diatomaceous earth, kaolinite and bentonite, industrial zeolites, precious opals, and aggregates (Simandl et al., 1996; Read, 2000; Northcote, 2022).

We initiated this study, comprising bedrock mapping, geochemistry, and geochronology, to provide an understanding of the volumes, duration, and architecture of volcanism in the Kamloops Group. The volcanic and structural framework will also help assess the potential for mineralization, in particular for epithermal mineral deposits. This report presents petrographic data and summarizes geochemical data from the Kamloops Group type area, which is in the lands of the Tk'emlúps te Secwépemc First Nation, in Secwepemcúlucw, the traditional territory of the Secwépemc.

2. Study area

The type area of the Kamloops Group covers approximately 23 by 18 km (~400 km^2) near Kamloops (Fig. 2; Ewing,1981a, b, c, 1982; Van Wagoner, et al., 2021a). In the type area, the

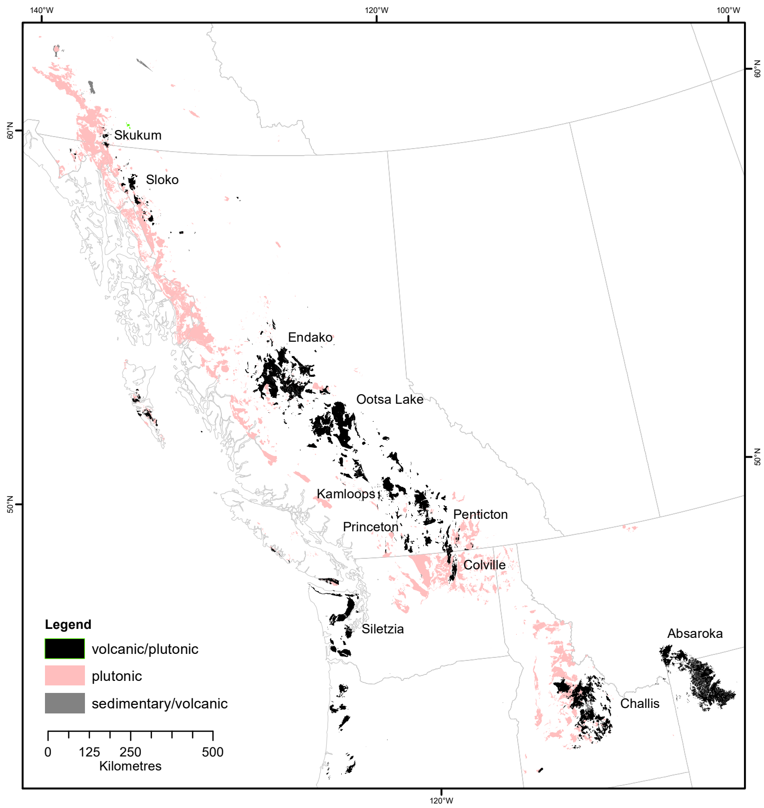

Fig. 1. Distribution of early Eocene (56-46 Ma) volcanic and plutonic complexes in the Cordilleran orogen of western Canada and northwest United States.

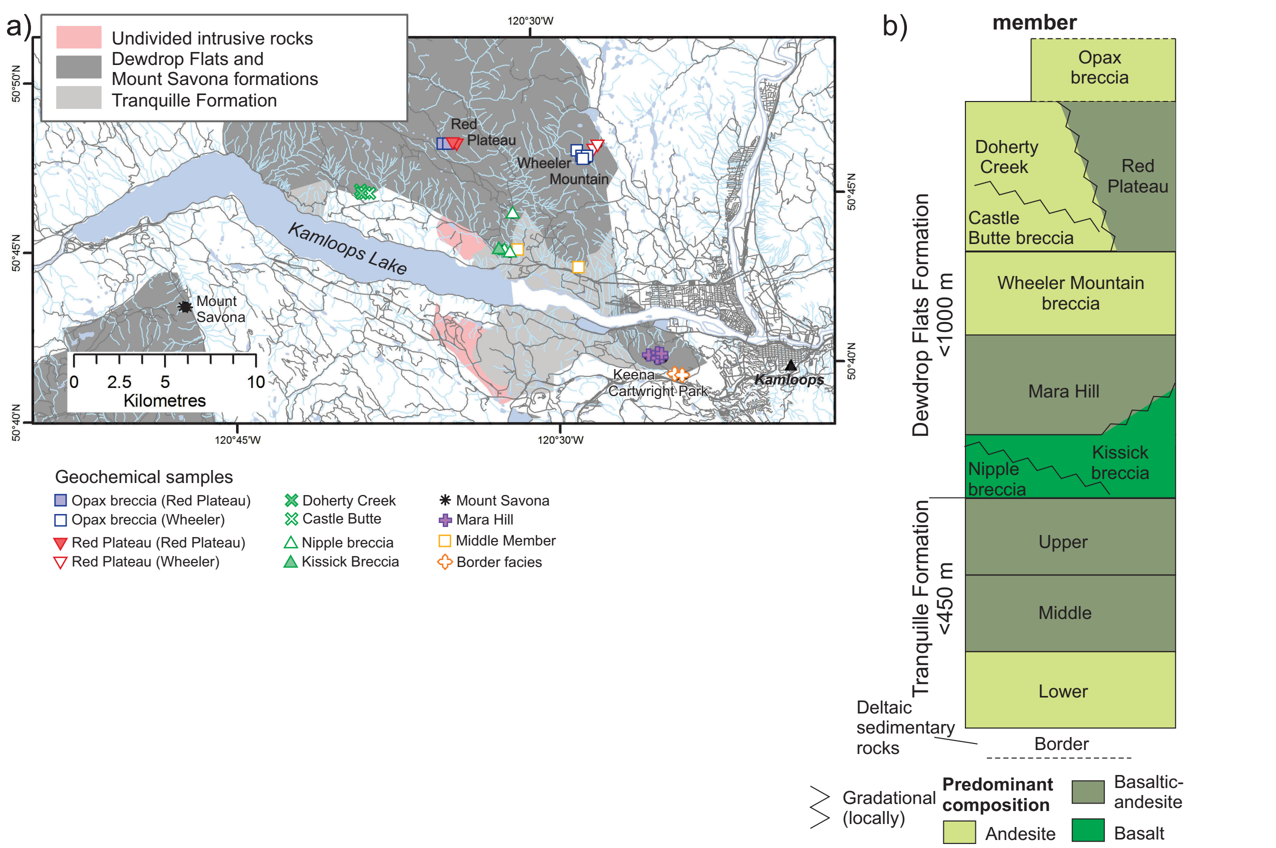

Fig. 2. a) Geological map of volcanic and lesser sedimentary rocks of the Kamloops Group, simplified after Ewing (1982). **b)** Generalized stratigraphy of the Kamloops Group (simplified after Ewing, 1981a).

rocks overlie the Nicola Group (Triassic) and are bounded on all but the north side by Nicola Group exposures. To the north, the Kamloops Group rocks continue outside the type area, forming a rectangular block that is ~25 by 16 km. For comparison with other volcanic complexes, Crater Lake (Oregon) has a diameter of ~9 km, the base of Mt. Shasta (California) has a diameter of ~10 km, and the Long Valley Caldera (California) is ~32 by 16 km (~500 km^2).

Ewing (1981a, b) divided the Kamloops Group in its type area into the lower Tranquille and the upper Dewdrop Flats formations, along with a number of informal members (Fig. 2b). The age relationships between the formations and members remains uncertain because most volcanic units are laterally discontinuous, contact relationships are rarely exposed, and volcanic facies (e.g., hyaloclastite) are not diagnostic of a particular member and are repeated throughout the sequence. In addition, some of the members have different mineralogical and geochemical characteristics at different locations.

The Kamloops Group volcanic rocks were deposited in subaerial to lacustrine environments. Subaqueous facies include pillowed flows, pillow breccias, and hyaloclastites. Interbedded with these subaqueous rocks, and more abundant near the top of the sequence, are subaerial pahoehoe and ‘A’ā flows with well-developed autobreccias, and cryptodomes with brecciated margins (Ewing 1980, 1981a, b, c, 1982; Van Wagoner et al., 2021a). Individual flows are up to several m thick, and flow sequences are up to about 600 m thick (Ewing, 1981a). Pyroclastic deposits are primarily phreatic and phreatomagmatic. Moderately to highly welded felsic tuffs are interbedded with lacustrine shales.

3. Description of sampled units

Samples were collected from north of Kamloops Lake, at Kenna Cartwright Park in the city of Kamloops, and at Mount Savona, which is 7.5 km southeast of the town of Savona and 30 km west of the Kamloops Group type area (Fig. 2). Petrographic details are summarized in Table 1.

3.1.Tranquille Formation

The Border facies (Fig. 2b) was interpreted by Ewing (1981a, b) to be at the base of the Tranquille Formation. It is exposed in the northern portion of Kenna Cartwright Park where it is in fault contact with the Kissick breccia (Fig. 2). There, the Border facies includes lenses of altered ash (bentonite), massive flows, hyaloclastite, and a reversely graded andesitic tuff breccia, interpreted as a phreatomagmatic airfall deposit (Figs. 3a-c; Van Wagoner et al., 2021a). These flows typically contain microcrysts of plagioclase and differ from other flows in the sequence by a paucity of mafic phenocrysts and pervasive alteration of plagioclase to clay minerals.

The middle member was sampled at two localities north of Kamloops Lake and is characterized by large compact pillowed flows that grade vertically and laterally to pillow breccias and hyaloclastite (Fig. 3d; Van Wagoner et al., 2021a).

3.2. Dewdrop Flats Formation

North of Kamloops Lake, the Nipple breccia forms a belt about 3.5 by 1.5 km that is the remnant of a phreatomagmatic cone and associated flows (Fig. 2). It is thickest in the northern part of the exposure where it forms a cone of vesicular to scoriaceous pyroclasts, representing a vent area (Fig. 4a). Flows from this area thin to the south. These rocks have large phenocrysts (up to 3-4 mm) of olivine, pyroxene, ±plagioclase and contain the freshest olivine in the study area (Fig. 4b).

The Kissick breccia is the name given to andesitic breccias that occur throughout the central part of the type area. These include a variety of hyaloclastite breccias, as well as breccias that formed by phreatic and phreatomagmatic eruptive processes (Van Wagoner et al., 2021a). At Kenna Cartwright Park, the Kissick breccia forms a ridge of phreatomagmatic breccias that are cored by feeder dikes and plugs (Fig. 4c), whereas at a locality north of the Kamloops Lake, where it was sampled, the unit forms the brecciated margin of a dome (Figs. 4d, e; Van Wagoner et al., 2021a).

The Mara Hill member at Kenna Cartwright Park forms a series of subaerial pahoehoe lava flows. These flows are generally 1.5 to 3 m thick but thin to anastomosing pahoehoe toes that are 3 to 20 cm thick with well-defined chill margins. These flows are distinguished from others in the type area by flow top features that include small tumuli, inflation cavities, and lava tubes (Fig. 5a) and a lack of flow-top autobreccias.

The Castle Butte breccia comprises basaltic-andesite vesicular flows and flow breccias (Fig. 5b). Within the Castle Butte breccia is a discontinuous lens of water-lain shale and sandstone beds, overlain by a 5 m thick, vaguely bedded felsic phreatomagmatic, crystal-lithic-vitric lapilli tuff, which in turn is overlain by hyaloclastite. The tuff beds are internally massive, moderately welded (Figs. 5c-f), and are the most felsic units sampled from the type area.

The Doherty Creek member comprises a series of ‘A’ā flows, flow breccias, and hyaloclastite breccias (Fig. 6a). These rocks are mineralogically similar to the Nipple breccia except that most of the olivine is entirely altered to smectite ±iddingsite and oxides (Figs. 6b-d).

The Red Plateau member was investigated on Red Plateau and on Wheeler Mountain. In both areas, the Red Plateau member is a series of ‘A’ā flows and flow breccias, but each location is mineralogically distinct. On Wheeler Mountain, the member comprises basaltic to basaltic andesite flows, flow breccias, and hyaloclastic breccias that are commonly plagioclase-phyric and rarely clinopyoxene-phyric (Figs. 7a, b). In contrast, at Red Plateau the member is more intermediate in composition (basaltic andesites and andesites) and includes hornblende as a phenocryst and microcryst phase, comprising up to about 5% in one sample (Fig. 7c). In addition, the rocks at Red Plateau typically show extensive textural evidence for complex magma chamber processes, and the only equilibrium phase appears to be clinopyroxene microcrysts. Plagioclase phenocrysts commonly have zoned, unaltered cores, surrounded by a coarse- to fine-sieve texture or dusty zone followed by an overgrowth

Table 1. Petrographic description of units sampled for geochemistry.

Formation	Member	Location	Rock type and volcanic features	Petrography
Mount Savona		Mount Savona	Rhyolitic flows and pyroclastic flows and airfall deposits	Lithic-vitric-crystal tuff with juvenile tuff fragments (to 4 cm) in a matrix of crystal vitric tuff containing 1% blocky shards and broken microlites of sanidine. The tuff fragments are similar to the matrix, but also contain compacted pumice forming a eutaxitic texture. The flow is sparsely feldspar (5%), hornblende- and biotite-phyric (3%), and flow banded due to alignment of feldspar phenocrysts.
Dewdrop Flats	Opax breccia	Red Plateau	Andesitic flow breccias and flows	Sparsely to highly vesicular. Sparsely plagioclase-phyric with <5% pyroxene and pseudomorphs of olivine microcrysts. Clinopyroxene microcrysts are euhedral to subhedral and commonly zoned. Plagioclase phenocrysts are anhedral with sieve textures, embayed edges, or rounded. Groundmass plagioclase microlites form trachytic texture.
		Wheeler Mountain	Andesitic to dacitic vesicular flow and an in situ vitric breccia	The flow is vesicular (25%), with rare skeletal plagioclase and clinopyroxene microlites in glassy to felty cryptocrystalline groundmass of plagioclase and acicular opaques with interstitial glass and clinopyroxene. The breccia is petrologically identical but is glassy and non-vesicular. Angular fragments <1 mm to several cm, commonly with oxidized rims. The rims and some entire fragments are composed of isotropic volcanic glass that contains microlites of feldspar and mafic minerals.
	Red Plateau	Red Plateau	Basaltic andesite to andesitic ‘A’ā flows and flow breccias	Flows predominantly hornblende- (5%) and plagioclase- (10-15%) phyric; rare olivine (euhedral to subhedral to 0.25 mm (<1%) pseudomorphed by calcite and clay minerals. Clinopyroxene a microcryst and groundmass phase. Larger microlites are euhedral to anhedral and locally rimmed by corona of smaller crystals. Matrix glassy to hyalo-ophitic, with glass and pyroxene filling spaces between felty to trachyitic network of plagioclase microlites. In one flow, groundmass with microphenocryst beads primarily of euhedral to subhedral pyroxene and droplets and crystals of opaques. One ‘A’ā flow autobreccia sample scoriaceous with opal filling the vesicles.
		Wheeler Mountain	Basaltic andesite ‘A’ā flows and flow breccias	Flows are plagioclase-phyric and rarely clinopyroxene-phyric. Plagioclase phenocrysts (3-5%) are 0.3 to 3 mm, embayed, zoned, and contain melt inclusions. The groundmass is hypocrystalline with microlites of skeletal to subhedral plagioclase forming a moderate trachytic texture. Minor interstitial pyroxene, and <1% opaque minerals.
	Doherty Creek	North of Kamloops Lake	Basaltic andesite flows, flow breccias, and hyaloclastite breccia	Flows and flow breccias with 1-3mm euhedral-subhedral clinopyroxene (~7%), up to 0.5 mm euhedral to anhedral olivine phenocrysts (5%), and 0.5-1.5 mm broken and deformed plagioclase phenocrysts. The groundmass is hypocrystalline with microlites of skeletal plagioclase. Hyaloclastite breccia fragments are mineralogically similar, but matrix is largely fresh glass with incipient palagonite alteration along cracks and crystal margins.
	Castle Butte breccia	Castle Butte	Basaltic andesite flows and flow breccias, hyaloclastite, water-lain shale and sandstone, and a felsic phreatomagmatic crystal-lithic-vitric lapilli tuff	Andesitic flows are vesicular with phenocrysts and glomerocrysts (3-5%) of clinopyroxene and rare olivine pseudomorphed by iddingsite and smectite, in a pilotaxitic groundmass of randomly oriented plagioclase. Felsic tuff of magmatic vitric lapilli and pumice (45-55%), cognate andesitic fragments (~15%), and pyrogenic crystals (primarily feldspar; 5-7%) in fine ash matrix.
	Mara Hill	Kenna Cartwright Park	Subaerial basaltic andesite pahoehoe flows	Flows 1.5-3 m thick, locally thin to 3-20 cm thick pahoehoe toes. Aphyric to sparsely plagioclase phyric.

Table 1. Continued.

	Kissick breccia	North of Kamloops Lake	Basaltic andesite monolithic breccia at margin of a small dome that resulted from a mixture of magmatic and autoclastic processes.	Hypocrystalline to glassy with microlites of plagioclase (30%) forming a trachytic texture. The fragments are angular to subrounded, <0.5 mm to several cm, with smaller fragments forming the matrix breccia.
		Kenna Cartwright Park	Andesitic pillow, flow and phreatomagmatic breccias forming the remnants of cones	Breccia fragments are aphyric, microcrystalline to glassy.
	Nipple breccia	North of Kamloops Lake	Basaltic andesite, phreatomagmatic scoria cone, lava flows, and flow breccias	Typically olivine-, pyroxene-, plagioclase-phyric (3-15%). Olivine phenocrysts are euhedral to subhedral, up to 3 cm and zoned to highly embayed. Clinopyroxene euhedral to anhedral, 3-4 mm, rarely zoned. Largest plagioclase phenocrysts are zoned and display sieve textures. Groundmass glassy with microlites (3%) of plagioclase and lesser pyroxene and olivine. Microlites exhibit a trachyitic texture, commonly broken.
Tranquille	Middle	North of Kamloops Lake	Basaltic andesite, pillowed flows, pillow breccias, and hyaloclastite	Pillowed flows up to 2.5 m in diameter. Flows are aphyric to micro-plagioclase phyric. Flow margins and hyaloclastite are glassy and commonly altered to palagonite.
	Border facies	Kenna Cartwright Park	Basaltic andesite to andesite, ash (bentonite), massive flows, hyaloclasite breccias, and andesitic lapilli tuff-tuff breccia (phreatomagmatic airfall)	Flow margins and hyaloclastite fragments are glassy to hypocrystalline with microlites of plagioclase forming a trachytic texture. Flow interiors have an interstitial texture. Mafic phases are commonly altered to chlorite and calcite. Plagioclase is commonly altered to sericite.

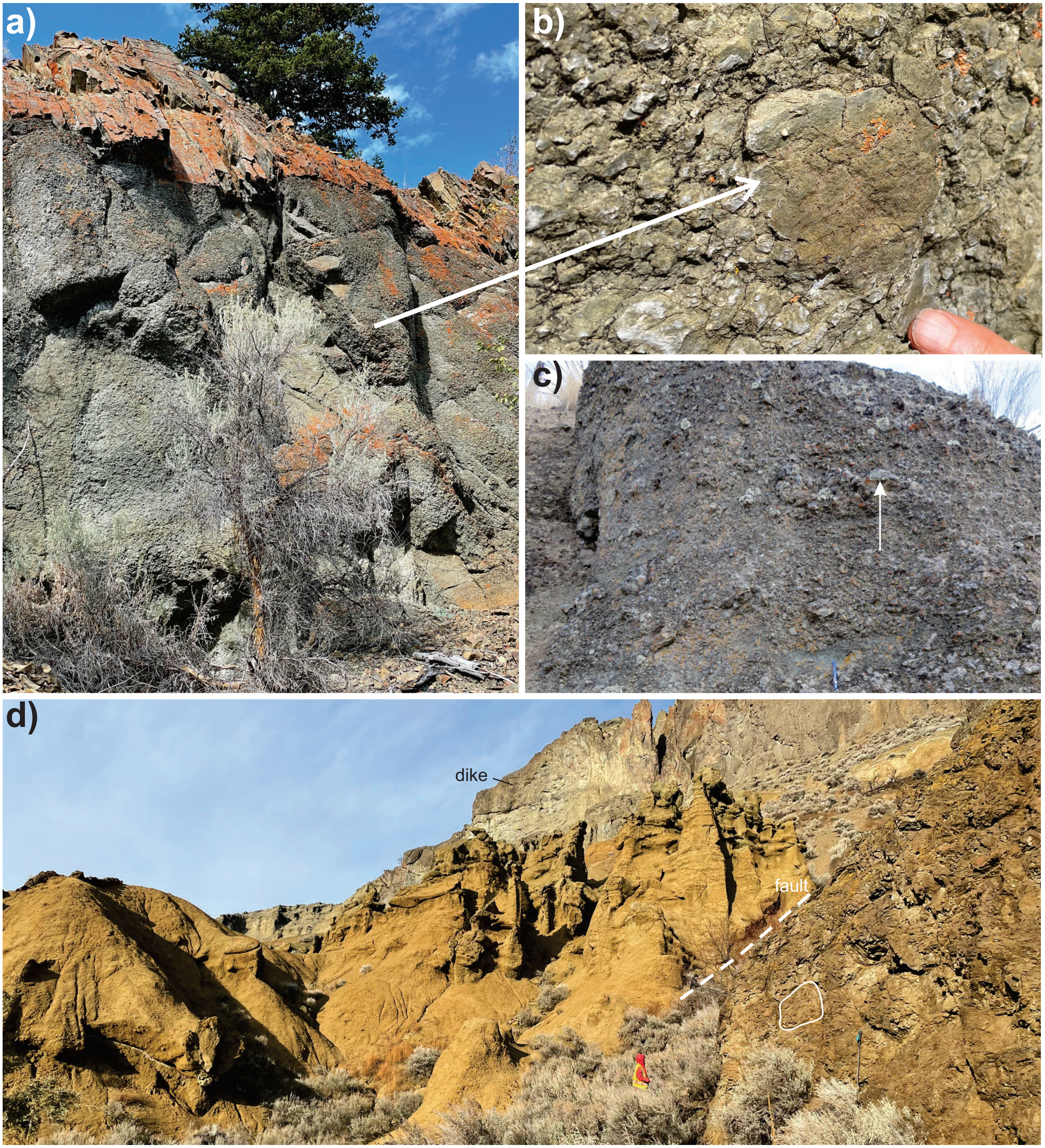

Fig. 3. a) Tranquille Formation, Border facies monolithic massive andesitic lapillistone, Kenna Cartwright Park. **b)** Close up of a) showing small bomb in a matrix of angular to subangular lapilli. **c)** Border facies lapilli tuff breccia forming a series of reversely graded beds. The arrow marks one bed. Individual fragments are primarily angular, Kenna Cartwright Park. **d)** Tranquille Formation middle member pillowed flows on right (one pillow outlined) in fault contact with upper member pyroclastic tuffs, lahars, and epiclastic sedimentary rocks that are cut by a mafic, northeast-trending, vertical dike.

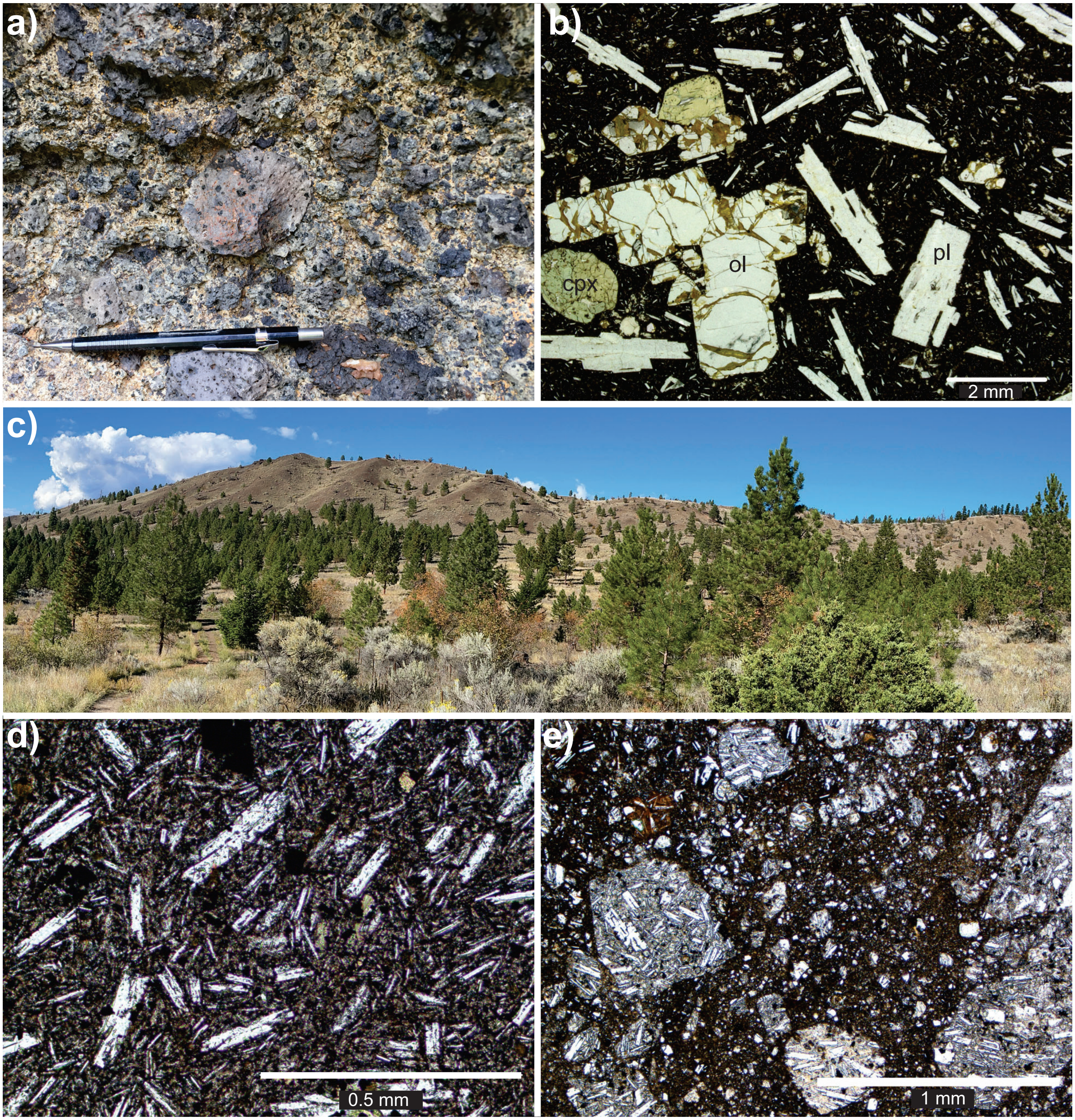

Fig. 4. a) Nipple breccia vesicular to scoriaceous magmatic pyroclasts, north of Kamloops River. **b)** Pyroclast in the Nipple breccia showing euhedral and subhedral olivine (ol), clinopyroxene (cpx), and plagioclase (pl) phenocrysts and microlites in a hypocrystalline groundmass. Plane polarized light. **c)** Ridge of the Kissick breccia at Kenna Cartwright Park. **d)** Photomicrographic from a dome that is part of the Kissick breccia north of Kamloops Lake showing microlites of plagioclase and interstitial opaque and mafic minerals in a cryptocrystalline groundmass. Cross polarized light. **e)** Kissick breccia at the margin of the dome in d). The fragments are monolithic, angular to subangular, hypocrystalline to glassy, with microlites of plagioclase forming a trachytic texture. The matrix is of smaller fragments. Cross polarized light.

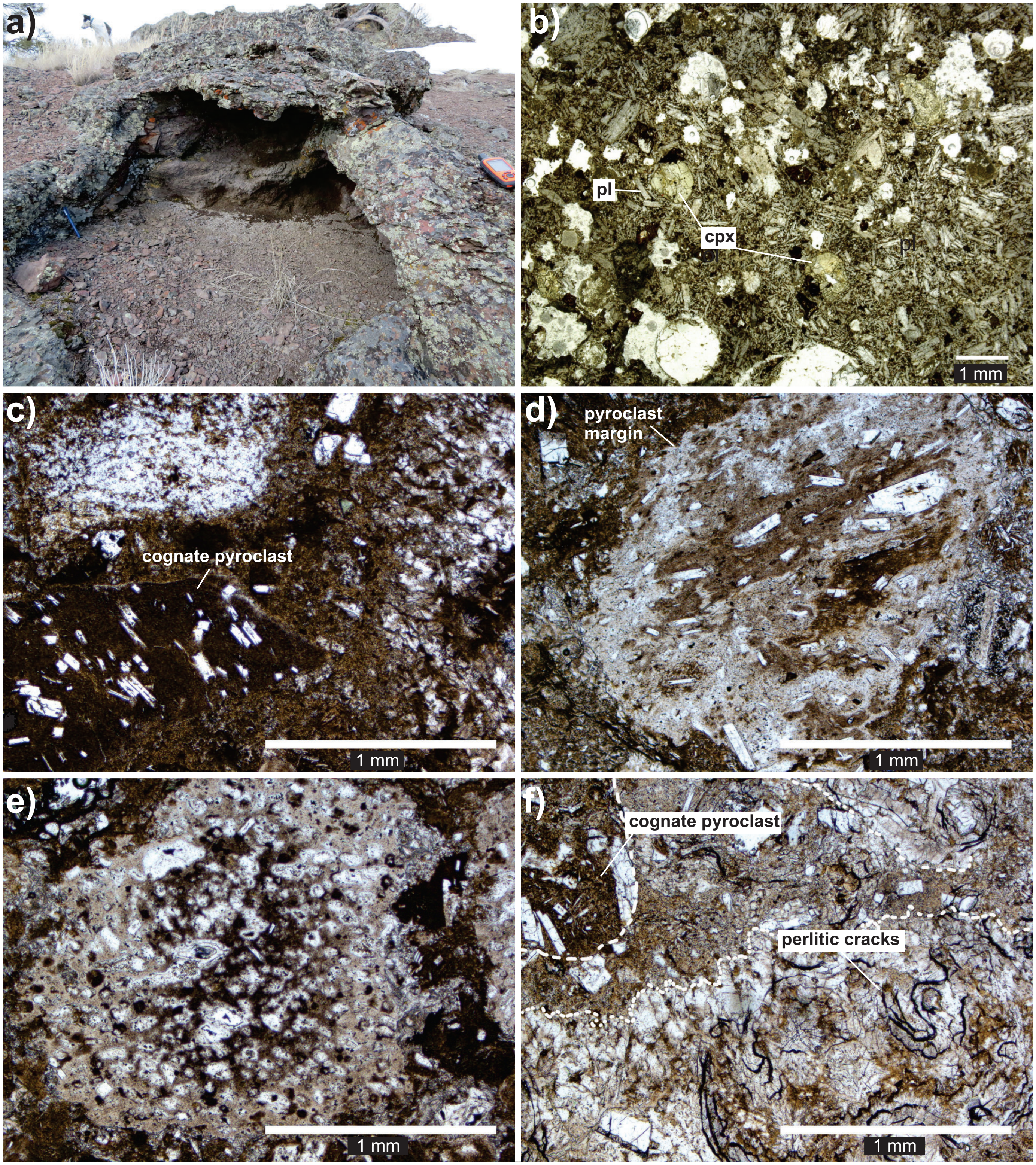

Fig. 5. a) Mara Hill member pahoehoe flow top with drain-away ledge in cavity beneath upper crust, Kenna Cartwright Park. **b)** Castle Butte member basaltic andesite autoclastic flow breccia showing a pilotaxitic groundmass texture and phenocrysts of clinopyroxene (cpx), plagioclase (pl), and oxides, north of Kamloops Lake. Clear circular shapes in the section are amygdules that are filled with calcite and analcime. Plane polarized light. **c)** Castle Butte member tuff, angular cognate pyroclast with skeletal plagioclase laths, north of Kamloops Lake. Plane polarized light. **d)** Castle Butte member tuff with magmatic pyroclast showing delicate margins and aligned plagioclase microlites, north of Kamloops Lake. Plane polarized light. **e)** Castle Butte member tuff pumice pyroclast, north of Kamloops Lake. Plane polarized light. **f)** Castle Butte member tuff vitric pyroclast, outlined in white, showing perlitic cracks, north of Kamloops Lake. Plane polarized light.

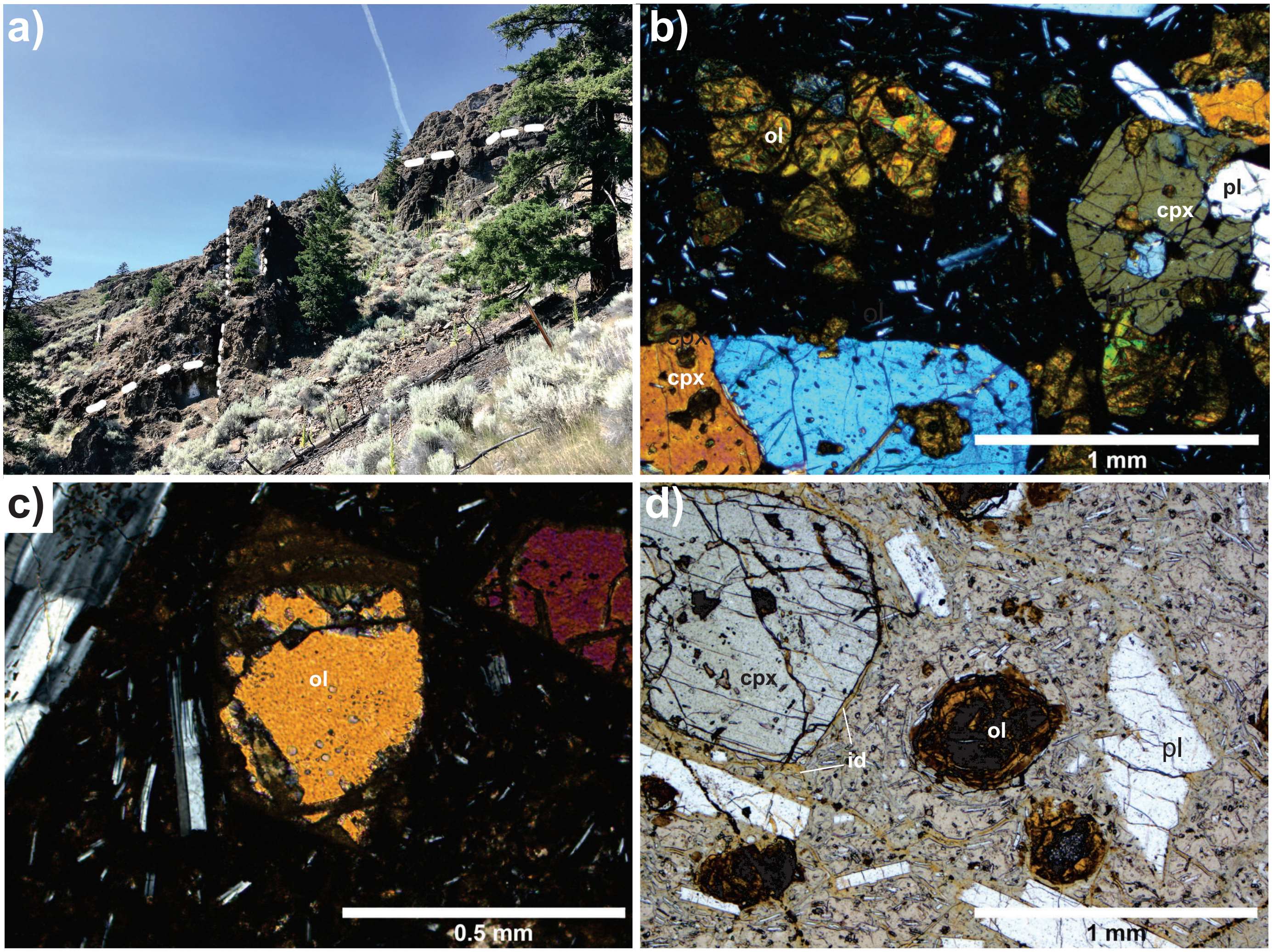

Fig. 6. Doherty Creek member, north of Kamloops Lake. **a)** Gently dipping flows and flow breccias highlighted by thick dashed line, cut by a near-vertical dike outlined by dashed lines. **b)** Fresh clinopyroxene (cpx), a glomerocryst (right) of clinopyroxene, plagioclase (pl) and altered olivine (ol), upper left. Cross polarized light. **c)** Rare fresh core of olivine. Cross polarized light. **d)** Glassy fragment of hyaloclastite, exhibiting incipient iddingsite (id) alteration along cracks and margins of phenocrysts. Cross polarized light.

rim (Fig. 7d). Amphibole (hornblende) includes both embayed and resorbed crystals, some with an inner ring of crystals and fluid inclusions (Fig. 7e). Amphibole is commonly surrounded by thick opacitic rims that have almost completely replaced the original mineral (Fig. 7c), and pyroxene microcrysts are locally surrounded by a beaded corona of micron-sized crystals (Fig. 7f).

The Opax breccia occurs near the top of Red Plateau and at the peak of Wheeler Mountain. On Red Plateau, the breccia comprises mainly andesitic flow breccias that are sparsely plagioclase-phyric and plagioclase and clinopyroxene (<1%) micro-phyric, with rare olivine that is pseudomorphed by iddingsite, clay minerals, and calcite (Figs. 8a, b). Like the underlying Red Plateau member, the large plagioclase phenocrysts display sieve textures, embayed edges and overgrowth rims (Fig. 8a). At Wheeler Mountain, the Opax breccia is andesitic to dacitic and comprises a vesicular hypocrystalline flow (Fig. 8c) and a vitric monolithic in situ hydrothermal breccia (Figs. 8d, e). The breccia at Wheeler Mountain lacks hornblende and clinopyroxene microcrysts and the disequilibrium textures observed in the feldspars at Red Plateau.

3.3. Mount Savona Formation

At Mount Savona, the Mount Savona Formation is considered the lateral equivalent of the Dewdrop Flats Formation (Ewing, 1981b). There, volcanic rocks include a rhyolitic flow (Figs. 9a, b) and tuffs (Figs. 9c, d). The flow is massive and feldspar-phyric with microcrysts of euhedral to subhedral hornblende and biotite. Flow banding is defined by the alignment of the long axes of hornblende and feldspar. (Figs. 9a, b). The tuffs are thinly bedded lithic-vitric-crystal tuffs with flow banding and massive crystal tuffs (Figs. 9c-e).

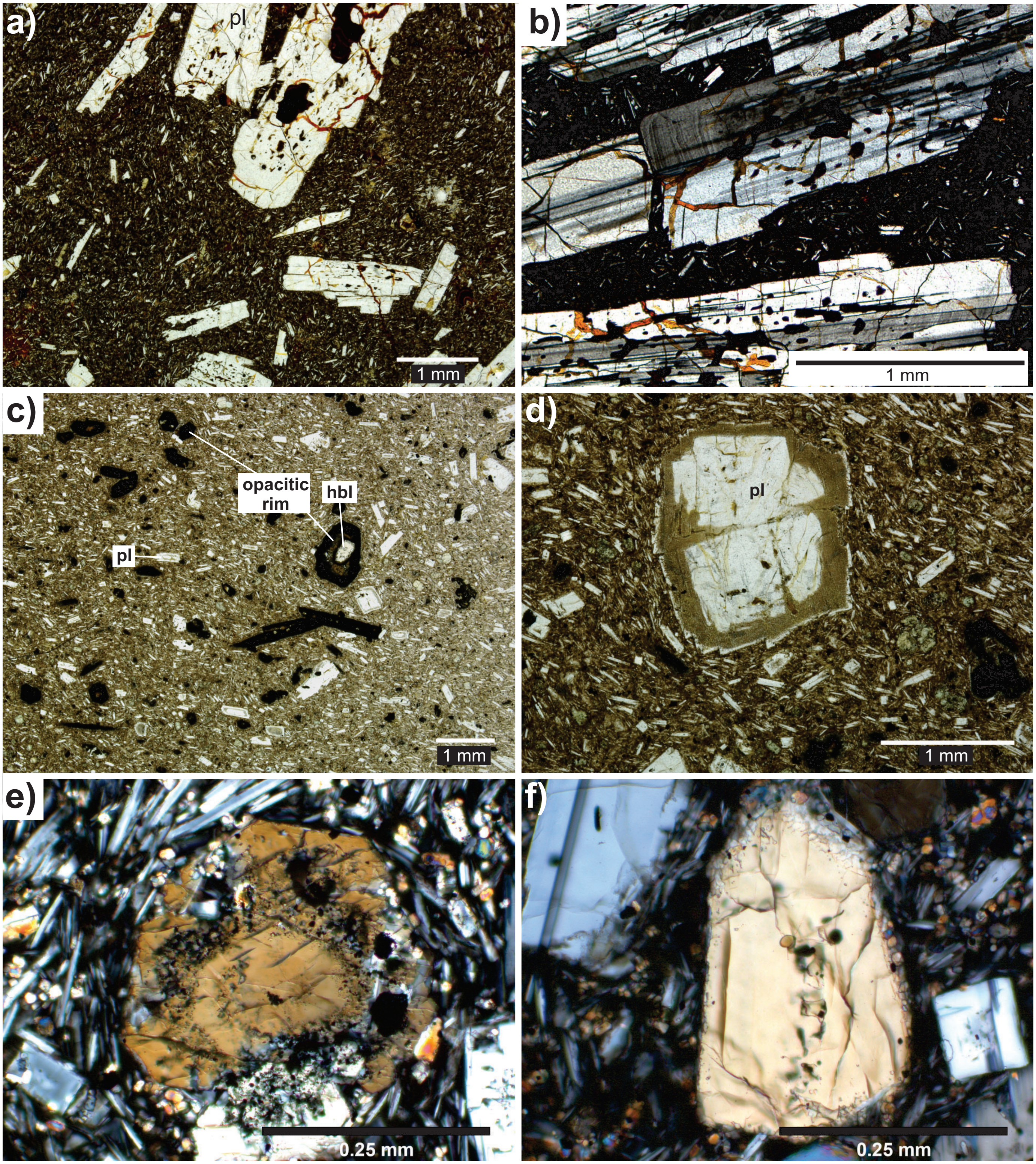

Fig. 7. a) Red Plateau member partially resorbed plagioclase exhibiting coarse sieve, or resorption texture. Groundmass includes plagioclase crystals, and microlites forming a trachytic texture, Wheeler Mountain. Plane polarized light. **b)** Red Plateau member with zoned plagioclase in the hypocrystalline groundmass, Wheeler Mountain. Cross polarized light. **c)** Red Plateau member with hornblende (hbl) surrounded by opacitic rims, Red Plateau. Plane polarized light. **d)** Red Plateau member zoned plagioclase with a fine sieve texture or dusty zone at the margin and a discontinuous overgrowth rim of annealed plagioclase, Red Plateau. Plane polarized light. **e)** Red Plateau member, originally euhedral amphibole that is partially resorbed with an internal ring of mineral and melt inclusions, Red Plateau. Cross polarized light. **f)** Red Plateau member clinopyroxene with melt, fluid, and mineral inclusions. The clinopyroxene crystal is rimmed by a corona of smaller euhedral to subhedral clinopyroxene crystals that also form a spotted texture in the groundmass, Red Plateau. Cross polarized light.

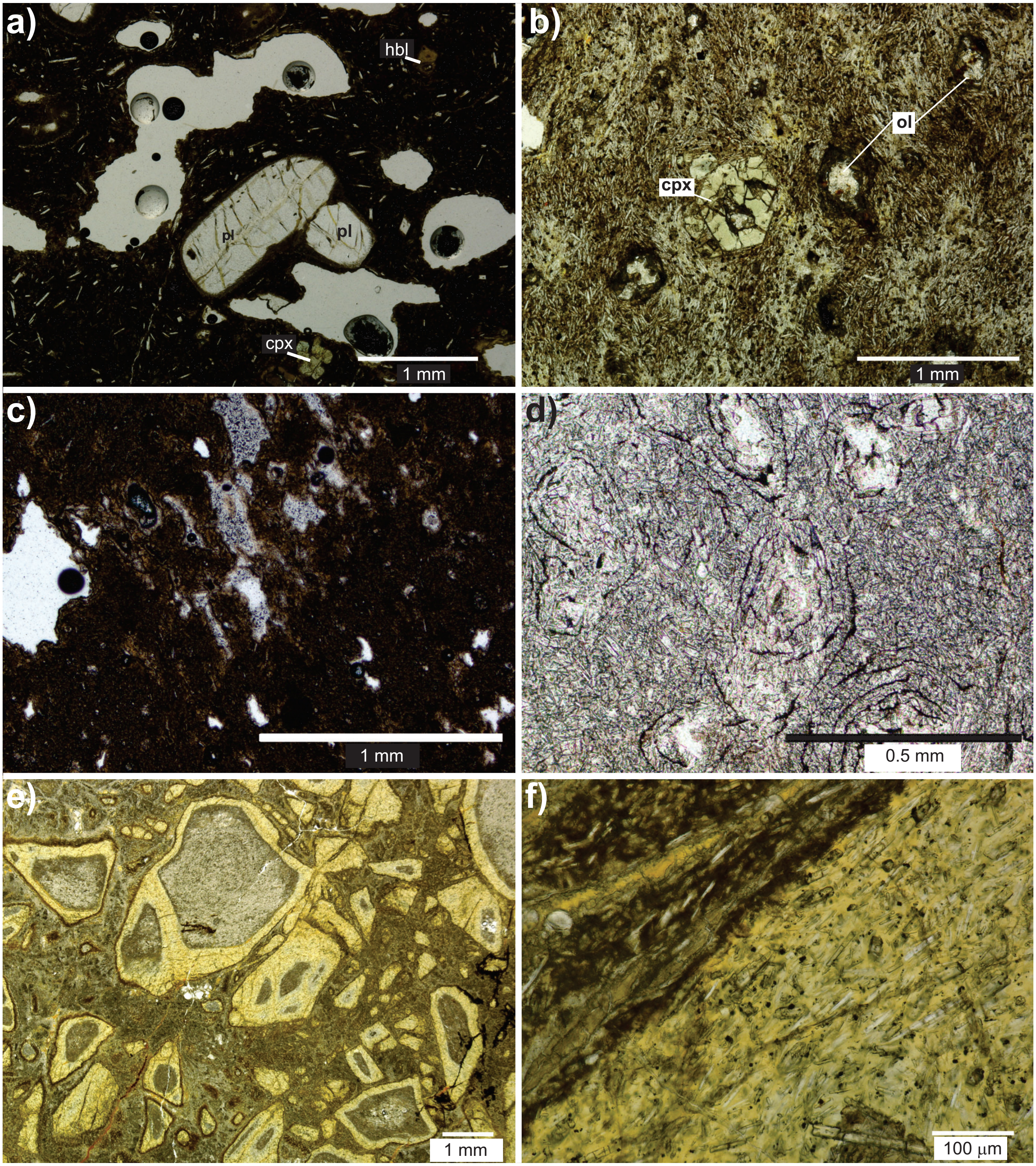

Fig. 8. Opax breccia. **a)** Vesicular andesitic flow showing rounded and resorbed plagioclase with sieve texture, a phenocryst of clinopyroxene with embayed margins, and a microlite of hornblende, Red Plateau. Plane polarized light. **b)** Euhedral clinopyroxene, plagioclase microlites forming a trachytic texture, and olivine completely altered to clay minerals and calcite (bright cores), Red Plateau**.** Plane polarized light. **c)** Vesicular, hypocrystalline flow showing very fine plagioclase microlites, Wheeler Mountain. Plane polarized light. **d)** Volcanic glass with perlitic cracks, Wheeler Mountain. Plane polarized light. **e)** Vitric breccia showing angular clasts with oxidized rims and fresh glassy margins. **f)** Closeup of e) showing microlites in a glassy matrix, Wheeler Mountain. Plane polarized light.

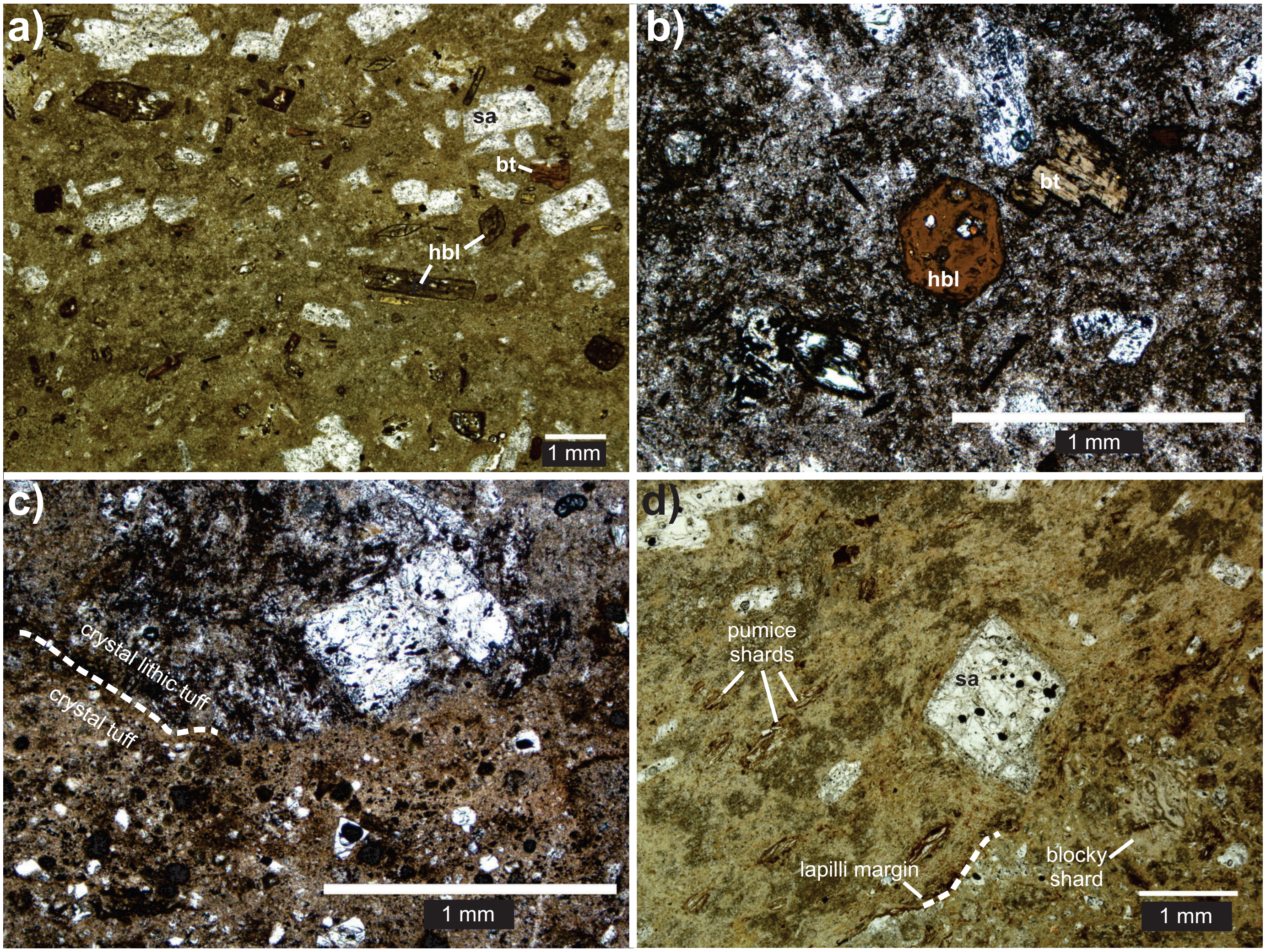

Fig. 9. Mount Savona Formation volcanic rocks. **a)** Rhyolite flow showing the main phenocryst phases of sanidine (sa), hornblende, and biotite (bt). **b)** Rhyolite flow containing euhedral biotite with mineral inclusions and euhedral hornblende. **c)** Contact between two tuff beds. **d)** Lithic fragment of a vitric-crystal tuff within a lithic-vitric-crystal tuff.

4. Geochemistry

Samples for whole rock geochemistry were collected from selected members of the Tranquille and Dewdrop Flats formations in 2019 and 2020. Massive flow units were sampled, except one of the samples from the Castle member is a heterolithic lapilli tuff that contains cognate mafic lapilli, and one sample from the Mount Savona Formation is a crystal-lithic tuff. In the case of monolithic breccias, larger fragments with minimal internal brecciation were sampled. The Mara flows from Kenna Cartwright Park (Fig. 2) were sampled in the most detail (Fig. 10). The complete dataset is provided in Van Wagoner et al. (2021b).

4.1. Methods

Clean, alteration-free samples were submitted to Activation laboratories, Ancaster, Ontario, for whole rock major, trace, and rare earth element analysis. At Actlabs, samples were crushed, mechanically split, and pulverized using mild steel. Major element oxides were determined using inductively coupled plasma optical emission spectroscopy (ICP-OES) and trace and rare earth element concentrations were determined using fusion inductively coupled plasma mass spectrometry (ICP-MS). Measurement precision was determined from duplicate analyses and accuracy was determined using certified standards provided by Actlabs and blind samples of the British Columbia Geological Survey till standard (Van Wagoner et al., 2021b). All major elements were recalculated to 100% volatile-free.

5. Results

The rocks in this study (n=32) have loss on ignition (LOI) from 1.41 to 13.12%, (average=4.2%) and geochemical data are plotted as volatile free at 100% (Fig. 10). One sample from the Red Plateau member at Wheeler Mountain was removed from the plots because the volatile-free SiO_2 (~45 wt.%) and MgO (2 wt.%) are too low and the sample consistently plots as an outlier. The rocks range from high-K calc-alkaline basalt to

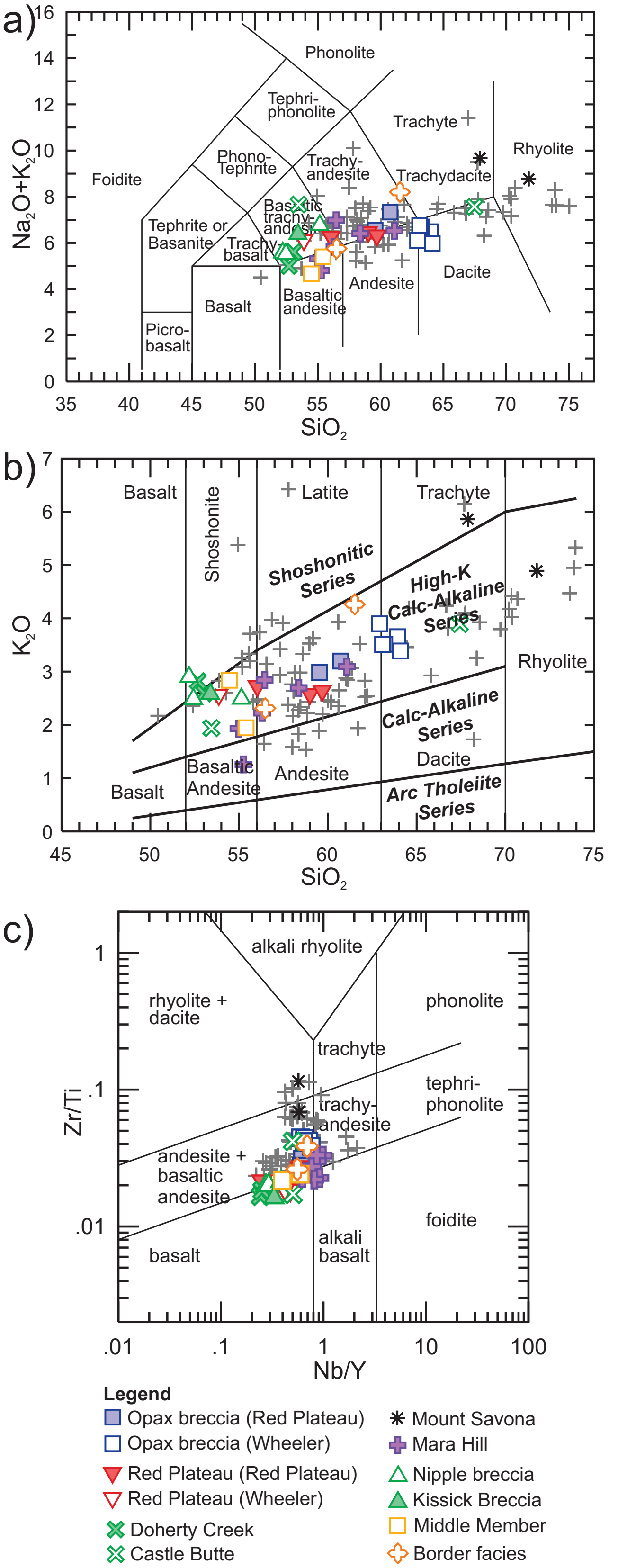

Fig. 10. a) Total alkali-silica diagram (wt.%) after Le Bas et al. (1986). Major elements calculated at 100% LOI free. **b)** SiO_2 vs. K_2O (wt.%). Fields are after Peccerillo and Taylor (1976). **c)** Nb/Y vs. Zr/Ti c diagram, after Pearce, 1996 (after Winchester and Floyd, 1977).

rhyolite with most being basaltic-andesite to andesite (Fig. 10). The most mafic rocks are from the Nipple breccia, Doherty Creek, Castle Butte, and Kissick breccia members of the Dewdrop Flats Formation, and a pillow flow from the middle member of the Tranquille Formation. The most felsic rocks are from the Mount Savona Formation west of the Kamloops Group type area. The rocks display tight trends between SiO_2 and MgO, CaO, Fe_2O_3, TiO_2, Al_2O_3, and P_2O_5 (Fig. 11). The rocks have Mg# from 30 to 63; the highest Mg#=63 is from the Nipple member and is slightly below the threshold of primitive arc magmas (Mg#=65; Fig. 12; Kelemen et al., 2003).

Relative to chondrite, the rocks are uniformly light rare earth element (LREE) enriched ($(La/Yb)_N$=6-21), with no Eu anomalies, and relatively flat middle to heavy REE ($(Dy/Yb)_n$; Fig. 13). Relative to primitive mantle, all rocks are enriched in the large ion lithophile elements (LILE), particularly fluid-mobile Ba, K, and Pb, and to a lesser extent U and Sr. The rocks have negative anomalies of some high field strength elements (HFSE; Nb, Ta. P, and Ti). The most felsic samples from Mount Savona Formation have the most pronounced negative Ti anomalies (Fig. 13c)

6. Discussion

Volcanic facies within most members of the Kamloops Group in its type area are similar at different geographic locations. However, the Red Plateau and Opax breccia members on Red Plateau are petrographically and geochemically distinct from the same members on Wheeler Mountain (Figs. 7, 8, 10, 11). The Opax breccia member at Wheeler Mountain is overall more felsic than at Red Plateau, is much finer grained, lacks clinopyroxene and olivine microlites, and has plagioclase phenocrysts with disequilibrium textures. Inversely, the Red Plateau member at Red Plateau is slightly more felsic than at Wheeler Mountain (Figs. 7, 8, 10, 11) and has hornblende and plagioclase phenocrysts with disequilibrium textures. This may indicate that each geographic location represents a unique volcanic centre.

The Castle Butte member tuffs are the most felsic rocks in the type area. Outside the type area, the Mount Savona Formation volcanic rocks comprise a felsic volcanic centre, but their contribution to tuffaceous beds elsewhere in the Kamloops Group is unclear.

The basaltic rocks have low-Mg (Mg#<65) and none of the rocks are primitive andesite (Fig. 12; Kelemen et al., 2003). Some of the Kamloops Group rocks are consistent with high-Mg andesites (Mg#50-60; Fig. 12; Kelemen et al., 2003) and some have adakitic compositions (Fig. 12; Richards and Kerrich, 2007). The terms high-Mg andesite and adakite have traditionally appealed to a tectonic process, such as slab melting (Kelemen et al., 2003; Kerrich and Richards, 2007; Zhang et al., 2019). Because the Kamloops Group volcanic rocks cover a broad compositional span that transcends the definitive fields (Fig. 12), it is best to call the rocks andesite with high-Mg or adakite-like. This terminology removes genetic connotations. The low-Mg basalts and the broad overall compositional span

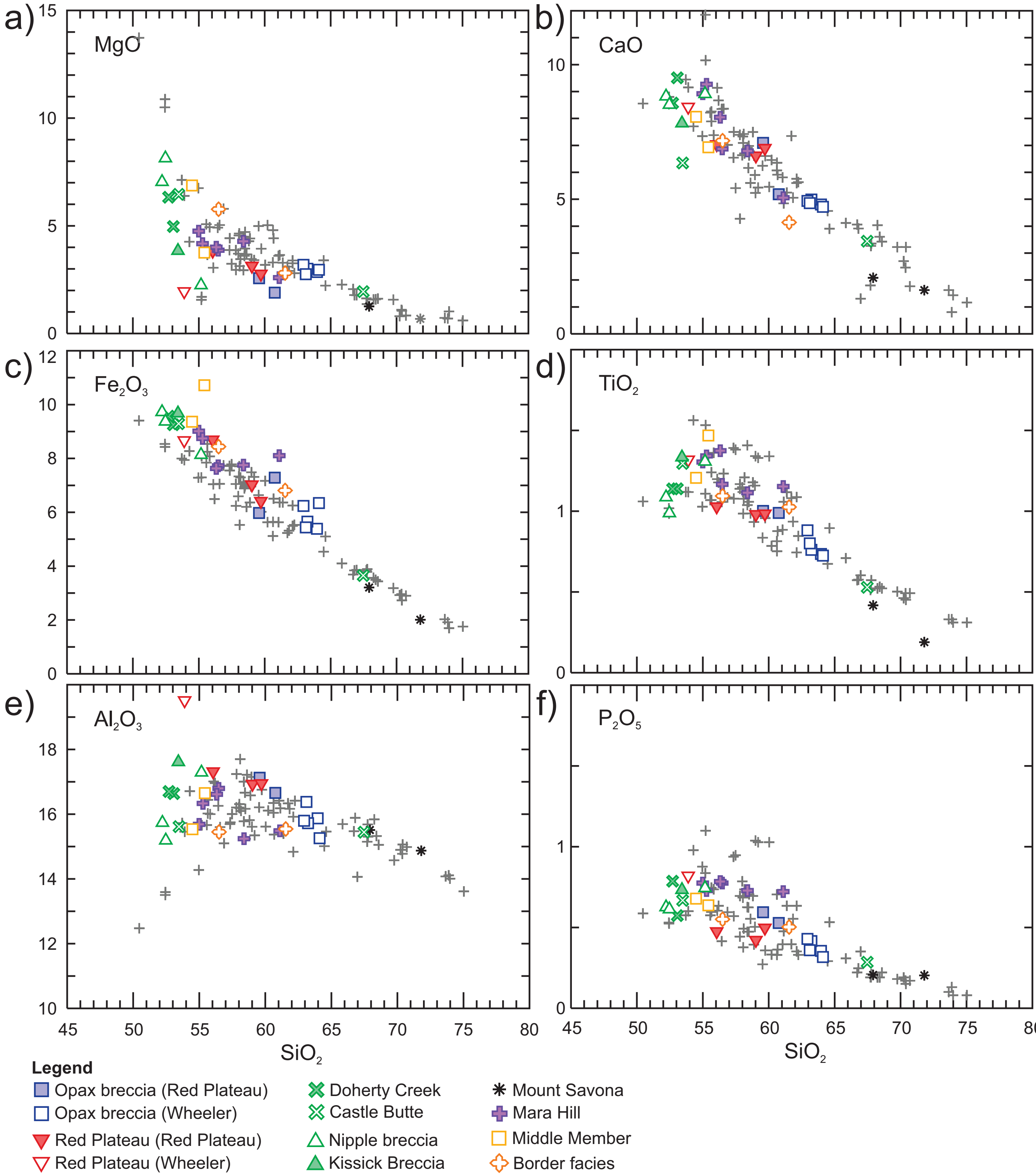

Fig. 11. Harker diagrams (wt.%). SiO_2 vs. **a)** MgO, **b)** CaO, **c)** Fe_2O_3, **d)** TiO_2, **e)** Al_2O_3, and **f)** P_2O_5.

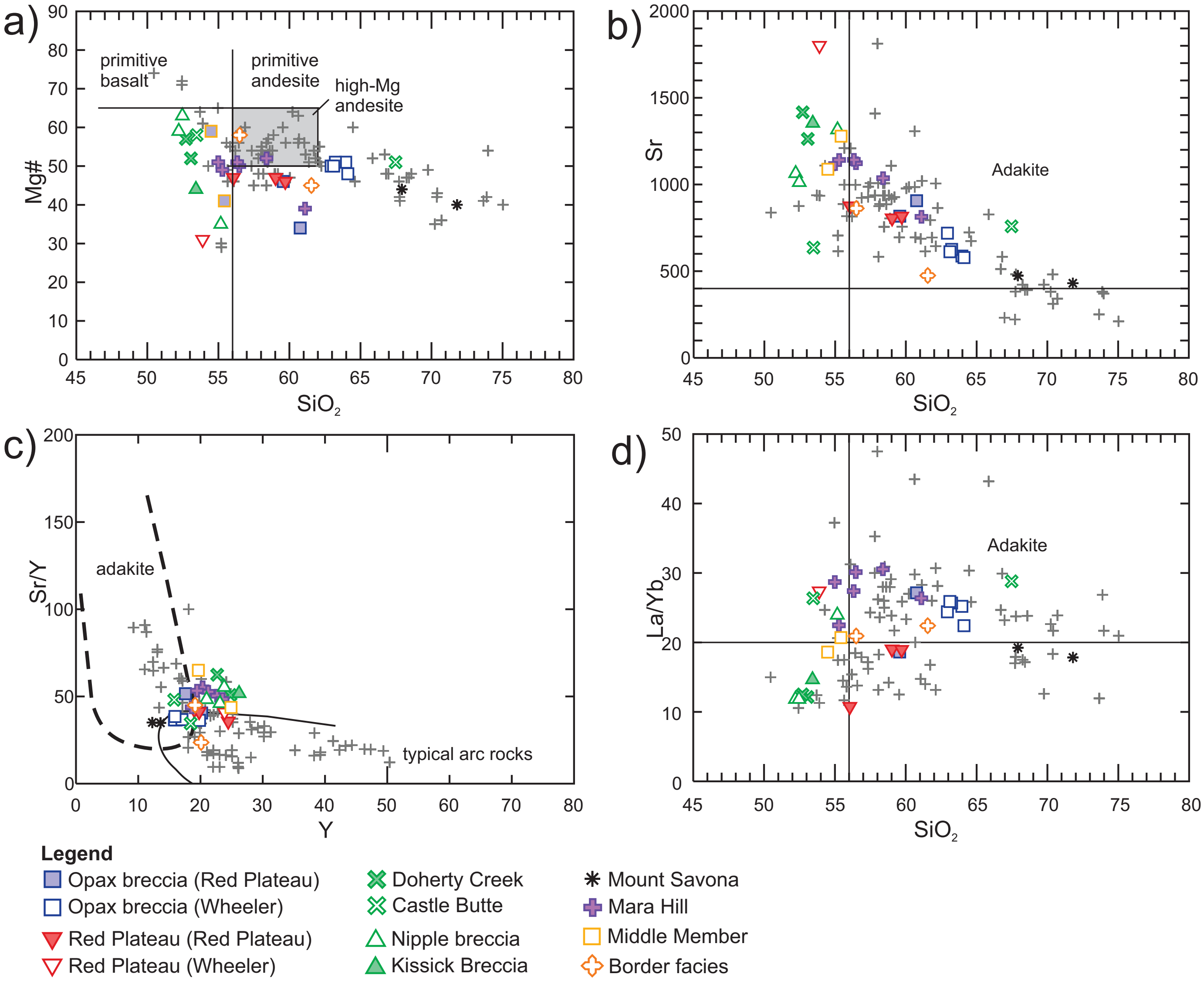

Fig. 12. a) SiO_2 (wt.%) vs. Mg#. Primitive basalt and andesite and high-Mg andesite fields from Kelemen et al. (2003). **b)** SiO_2 (wt.%) vs. Sr (ppm). **c)** Y vs. Sr/Y (ppm). **d)** SiO_2 (wt.%) vs. La/Yb. Adakite fields and typical arc field from Richards and Kerrich (2007).

indicate the volcanic rocks were likely derived from mantle magmas that hybridized with lower crust. This interpretation is supported by petrographic observations of common disequilibrium textures in phenocrysts (Figs. 7, 8a).

Many of the volcanic rocks in the Kamloops Group have plagioclase phenocrysts with disequilibrium textures (Figs. 7c, d). Such textures have been attributed to the injection and mixing of a mafic magma into a more felsic magma reservoir, particularly in andesites with high-Mg (Maro and Caffe, 2016; Conway et al., 2020; Beier et al., 2017). Parental magma mixing is also consistent with the opacitic rims that surround hornblende (Fig. 7c), which can be attributed to melt degassing or dehydration during decompression or ascent, temperature increase, and/or oxidation of the melt (e.g., Plechov et al., 2008). Similar opacitic rims textures occur in rocks from the 1956 eruption of the Bezymyannyi volcano in Kamchatka, caused by heating of the magma chamber due to injection of new magma, which triggered the eruption (Plechov et al., 2008).

Chondrite-normalized (La/Sm)n increases with increasing SiO_2, whereas (Dy/Yb)n remains relatively flat (Fig. 13). The (Dy/Yb)n is controlled by different minerals (e.g., garnet, amphibole, pyroxene) in the melt source or during fractional crystallization but the ratio does not describe the shape of the normalized middle to heavy REE pattern, which is better explained by Dy/Dy*($Dy/Dy^* = Dy_n/[La_n^{4/13} * Yb_n^{9/13}]$; n=chondrite normalized; Davidson et al., 2013). The shape of the normalized Kamloops Group middle to heavy REE is entirely consistent with amphibole and pyroxene control and follow a trend similar to other arcs (Figs. 13a, b; Fig. 14a).

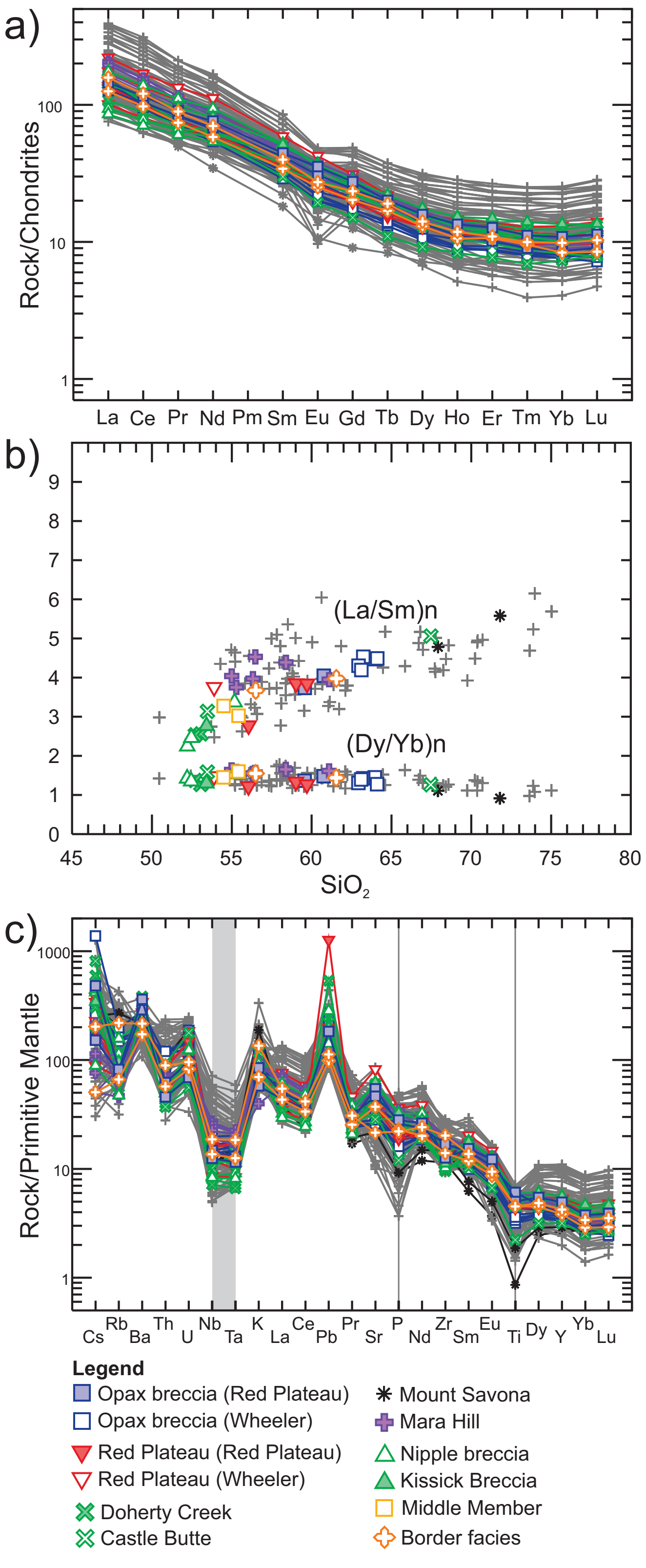

Fig. 13. a) Chondrite normalized rare earth elements. **b)** SiO_2 (wt.%) vs. chondrite normalized (La/Sm)n and (Dy/Yb)n. **c)** Primitive mantle normalized trace elements. Vertical grey bar and lines mark Nb-Ta, P, Ti anomalies. Normalizing values are from Sun and McDonough (1989).

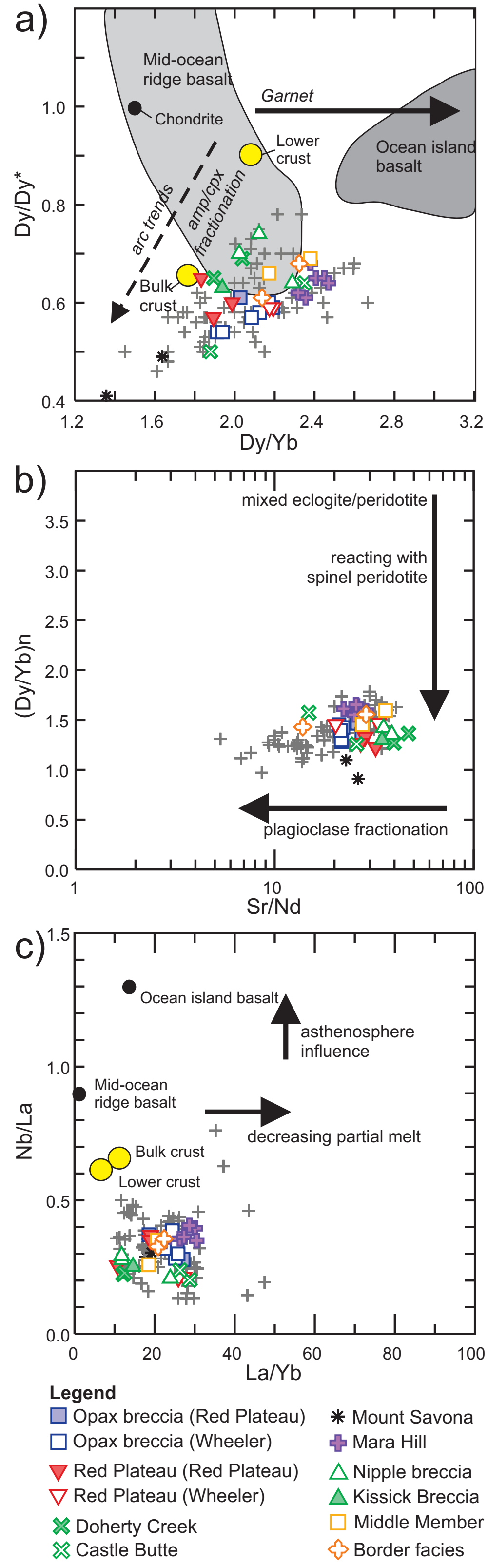

Fig. 14. a) Dy/Yb vs. Dy/Dy*. Modified after Davidson et al. (2013). **b)** Sr/Nd vs. chondrite normalized (Dy/Yb)n. Modified after Kelemen et al. (2003); chondrite from Sun and McDonough (1989). **c)** La/Yb vs. Nb/La. Mid-ocean ridge and ocean island basalt values from Sun and McDonough (1989) and crustal values from Rudnick and Fountain (1995).

There does not appear to be any garnet control on the REE, indicating that eclogite was not in the melt source, and that the parental melts were not derived from nor interacted with garnet-bearing lower crust (Figs. 14a, b). Overall, the Kamloops Group geochemistry appears to be controlled by amphibole and pyroxene and possibly by plagioclase fractionation, which explains the overall trend to lower Sr/Nd (Fig. 14c). The more mafic rocks contain the highest Sr concentrations (Fig. 12a), indicating the melt source was low in plagioclase, which would have withheld Sr during melting. This is supported by the overall lack of negative Eu anomalies in the chondrite normalized REE (Fig. 13a).

The primitive mantle normalized trace elements have negative Nb, P, and Ti anomalies (Fig. 13c) that are consistent with melts derived from a subduction-modified mantle source. The Nb/La are well below asthenosphere-derived melts, supporting a lithospheric source (Fig. 14c). Van Wagoner et al. (2021a) and others (e.g., Morris et al., 2000) contended that the Eocene magmas are not derived directly from concomitant subduction processes (cf. Ickert et al., 2009), but rather from mantle and crust that was previously subduction modified. In the Kamloops area this could be Triassic-Jurassic subduction related to the Nicola arc, or overprinting Cretaceous subduction and accretion processes. Due to the parental magma hybridization, further geochemical modelling is required to determine what mantle source was the end-member to mix with lower crust. Regarding the lower crustal end-member, geophysical evidence indicates there is a sliver of Ancestral North America near the base of the lower crust in the Kamloops area (Cook, 1995). However, whole rock Nd isotopic evidence indicates the volcanic rocks in the Savona area are juvenile (Dostal et al., 2019), supporting a mainly Quesnel terrane lower crust end-member. The petrographic and geochemical properties of the Kamloops Group volcanic rocks in this study provide an indication that bulk-rock geochemistry may not be indicative of either direct mantle melting processes or the tectonic process that caused the melting.

7. Summary

In the type area, the Kamloops Group volcanic rocks have a compositional range from basaltic andesite to dacite. The most common rock type is andesite and some have high-Mg and adakite-like geochemical features. The combination of common disequilibrium textures in plagioclase phenocrysts and geochemistry of the rocks indicate the magmas resulted from mixing of eclogite-free mantle melts with garnet-free lower crust. The geochemistry should not be used independently for tectonic discrimination as the crustal and mantle end-members require further identification.

Ongoing work for this study includes further lithostratigraphic mapping and geochemistry, high-precision geochronology, and measuring phenocryst-hosted melt inclusions in Eocene volcanic complexes in southern British Columbia. Collectively this information will help untangle the volcanogenic evolution of the Eocene volcanism, help identify volcanic centres that may control the loci of epithermal gold deposits. and estimate the contributions of volatile gases (e.g., CO_2, SO_2) to the early Eocene atmosphere.

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