Volcanic stratigraphy of the Cambrian-Ordovician Kechika group, Pelly Mountains, south-central Yukon

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Campbell, R.W. and Beranek, L.P., 2017. Volcanic stratigraphy of the Cambrian-Ordovician Kechika group, Pelly Mountains, south-central Yukon. *In:* Yukon Exploration and Geology 2016, K.E. MacFarlane and L.H. Weston (eds.), Yukon Geological Survey, p. 25-45.

ABSTRACT

Volcanic rocks occur throughout the lower Paleozoic passive margin successions of western Canada. The tectonic significance of post-breakup magmatism is uncertain, however, some volcanic rocks are spatially associated with margin-parallel normal faults. At the plate-scale, such magmatism is consistent with asymmetric rift models for passive margins, including those with lineaments or transform-transfer zones that form at high angles to the rifted margin. A two-year project was conducted to define the stratigraphy of post-breakup volcanism in the Pelly Mountains, south-central Yukon, and test genetic relationships with the adjacent Liard Line lineament. Field studies targeted Cambrian-Ordovician volcanic strata of the Kechika group in the Quiet Lake map area (NTS 105F). Observed lithofacies are indicative of submarine volcanic edifices and sediment-sill complexes that develop during continental extension. Analogous margin-parallel extension is recognized along the length of the Canadian Cordillera, but the influence of the Liard Line on Cambrian-Ordovician magmatism requires further testing.

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INTRODUCTION

The ancestral Pacific margin of western North America (Fig. 1) was created during the protracted rifting of Rodinia (*e.g.*, Bond *et al.*, 1984, 1985). An initial Neoproterozoic rifting event in the Canadian Cordillera is in part recorded by the Franklin LIP and Windermere Supergroup (Heaman *et al.*, 1992; Colpron *et al.*, 2002). The Hamill and Gog groups are the inferred products of the final stage of continental break-up within the southern Canadian Rocky Mountains and the Selkirk and Purcell mountains, southeastern British Columbia (Fig. 1; *e.g.*, Bond *et al.*, 1985; Devlin and Bond, 1988; Nelson *et al.*, 2013). In this region, the timing of final rifting is constrained by late Ediacaran (*ca.* 570 Ma) volcanic rocks of the Hamill Group (Colpron *et al.*, 2002). The rift to post-rift transition did not occur until at least the Early Cambrian based on Tommotian to Atdabanian (Terreneuvian to Cambrian Series 2) fossils in the Gog Group and McNaughton Formation (Bond *et al.*, 1985; Magwood and Pemberton, 1988; Hein and McMechan, 1994) and thermal subsidence trends (*e.g.*, Bond and Kominz, 1984). Ediacaran to Lower Cambrian strata similarly record the establishment of shallow-water Mackenzie platform and deep-water Selwyn basin in eastern Yukon and adjacent Northwest Territories (Fig. 1; *e.g.*, Gordey and Anderson, 1993; Moynihan, 2014).

Magmatism along the western Laurentian margin did not cease with continental break-up and remains an outstanding problem in Cordilleran geology. For example, Upper Cambrian-Ordovician volcanic rocks observed along the length of the North American Cordillera (*e.g.*, Goodfellow *et al.*, 1995; Lund *et al.*, 2010; Millonig *et al.*, 2012; Pigage *et al.*, 2012) are seemingly inconsistent with simplistic models for post-breakup, passive margin sedimentation (*e.g.*, Aitken, 1993). Goodfellow *et al.* (1995) suggested a spatial association between lower Paleozoic volcanic rocks and margin-parallel normal faults that define the western extent of the basin to the basin-platform transition zone (Fig. 2; Hayward, 2015). Early Paleozoic volcanism in the region has therefore been linked to periodic extension (*e.g.*, Fritz *et al.*, 1991; MacIntyre, 1998; Pyle and Barnes, 2003). For example, Marmot Formation rocks in the Misty Creek Embayment, Northwest Territories (Fig. 1) are associated with a "steer's head" rift profile (Cecile *et al.*, 1982,1997; Leslie, 2009). Menzie Creek formation volcanic rocks in the Anvil district, central Yukon (Fig. 1), are adjacent to sedimentary exhalative (SEDEX) base-metal deposits (Faro, Grum, Vangorda and others) and probably related to local faulting (*e.g.*, Pigage, 2004; Cobbett, 2016). Early Paleozoic faults allowed volumetrically small, incompatible element-enriched, low degree partial mantle melts to erupt onto the surface or crystallize in the upper crust (Goodfellow *et al.*, 1995; Millonig *et al.*, 2012).

The inferred volume of early Paleozoic magmatism is minor compared to that associated with continental breakup and no other major tectonic event is recorded within Cambrian-Ordovician rocks along the ancient Pacific margin (*e.g.*, Bond *et al.*, 1984; Devlin and Bond, 1988; Cecile and Norford, 1993). Periodic, Late Cambrian to Ordovician volcanism is therefore unlikely to result from subduction or plume-related magmatism. Instead, post-breakup magmatism is consistent with asymmetric rift models for passive continental margins (*e.g.*, Lister *et al.*, 1986, 1991). Such models combine lithospheric-scale detachment faults and related low-angle shear zones with crustal thinning to achieve continental breakup. In most versions of this model, the hanging wall of the detachment fault, termed the upper-plate, undergoes less extension and is dominated by upper crust. Conversely the footwall, termed the lower-plate, undergoes a greater degree of extension and is more dominated by lower and middle crust (Fig. 3; *e.g.*, Lister *et al.*, 1986). Along the length of a rifted margin, upper and lower-plate segments are separated by lithospheric-scale transform-transfer faults (*e.g.*, Lister *et al.*, 1986). Such structural zones may provide a pathway for mantle-derived melts (*e.g.*, Corti *et al.*, 2002). Asymmetric rifting processes have been applied to the Paleozoic Cordilleran margin to explain the control of lithospheric-scale structures on extension and regional paleogeography (Fig. 2; *e.g.*, Cecile *et al.*, 1997; Lund, 2008).

In order to understand the implications of post-breakup magmatism along the Cordilleran margin, a field project was designed to characterize the physical stratigraphy of Cambrian-Ordovician volcanic rocks in the Pelly Mountains, south-central Yukon. These rocks form part of the Cassiar terrane, a parautochthonous fragment of ancestral North America (Fig. 1) that underwent at least 430 km of dextral displacement along the Tintina fault (Gabrielse *et al.*, 2006). Our fieldwork targeted outcrops of the Kechika group (informal) in the Pass Peak (105F/9) and Cloutier Creek (105F/10) map areas of the Quiet Lake 1:250 000 sheet, south of the Tintina Trench and community of Ross River. Cecile *et al.* (1997) interpreted that a northeast-trending, transform-transfer zone named

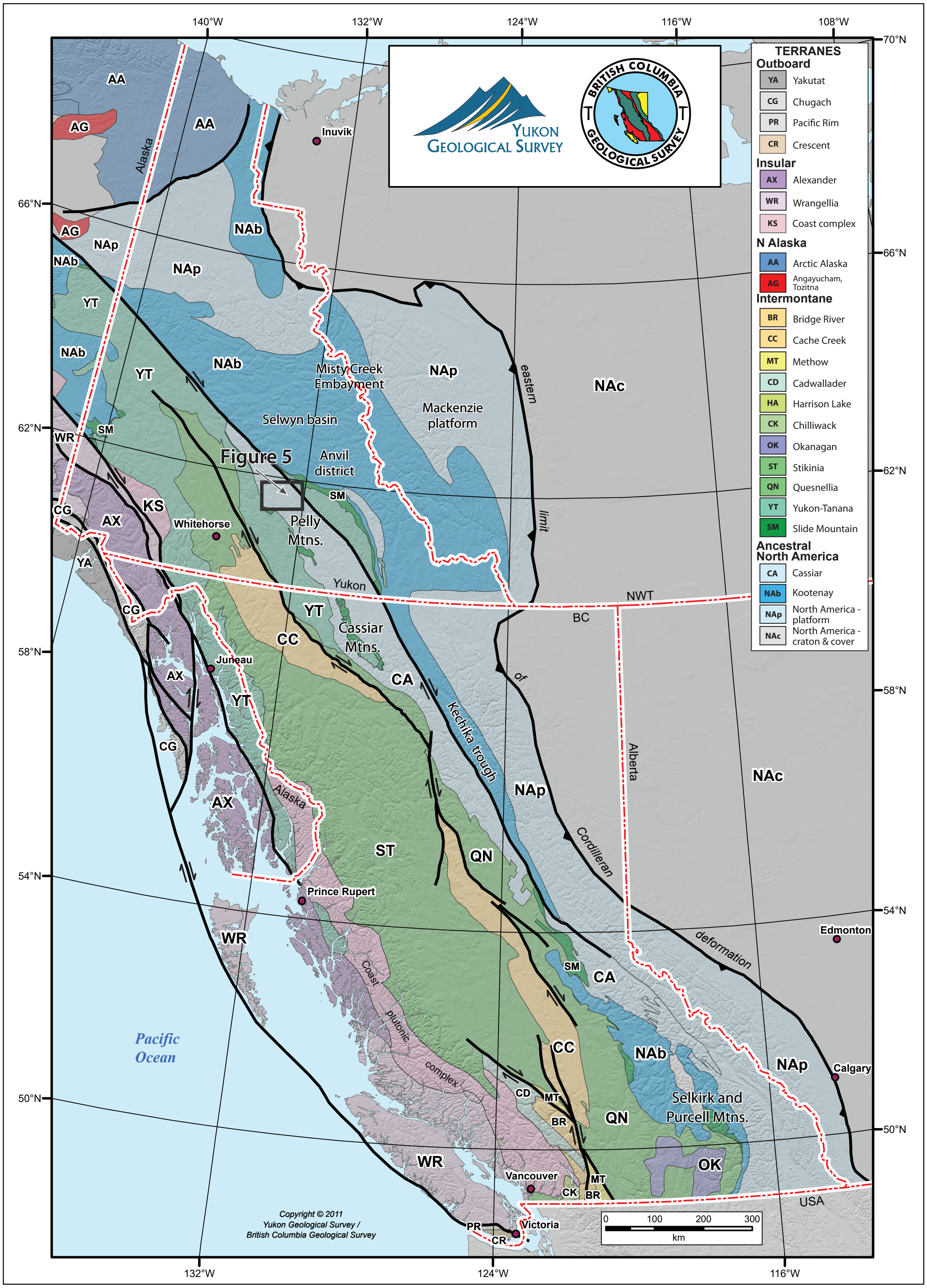

Figure 1. Terrane map of the Canadian Cordillera (modified from Colpron and Nelson, 2011).

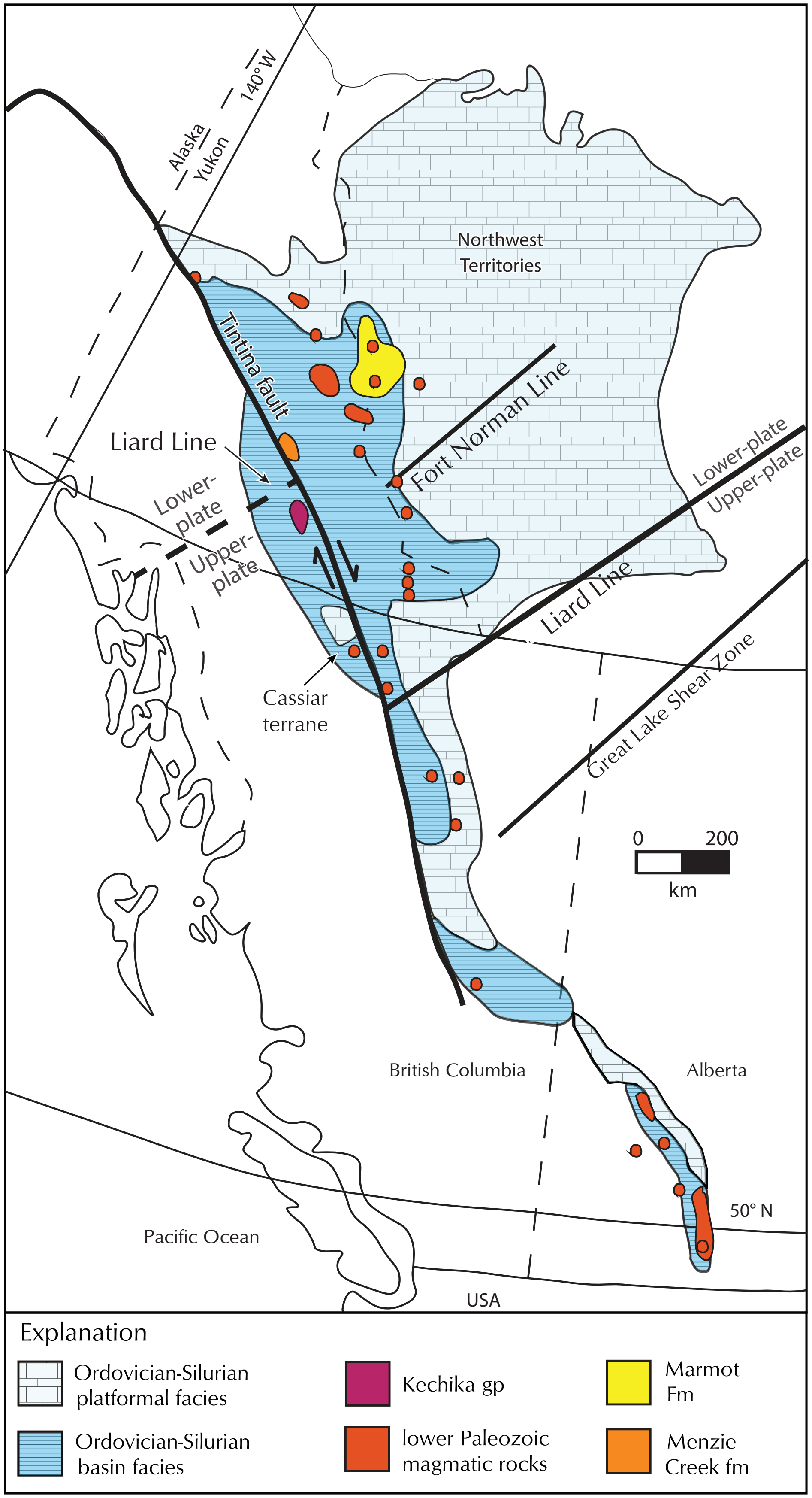

Figure 2. *Distribution of major faults, lower Paleozoic igneous rocks and Ordovician-Silurian paleogeography in the Canadian Cordillera (modified from Goodfellow et al., 1995; Cecile et al., 1997). The division between the northern lower-plate and the southern upper-plate is an inferred ancestral transfer fault, the Liard Line, which is offset in the west due to dextral movement along the Tintina fault.*

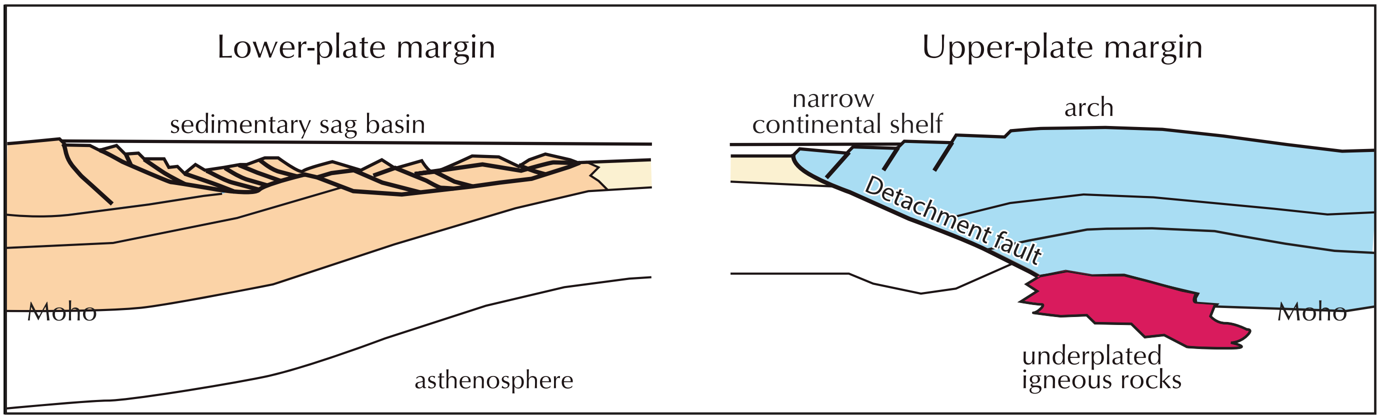

Figure 3. *Schematic cross section of an asymmetric rift system (modified from Lister et al., 1991; Lund, 2008).*

the Liard Line is present in the Pelly Mountains, placing most of the southern Cassiar terrane within an upper-plate setting (Fig. 2). The Liard Line is likely a reactivated ancient basement structure (Hayward, 2015) that also controlled the northern margin of the Proterozoic Muskwa basin (Lund, 2008) and recent neotectonic activity in the northern Cordillera (Audet *et al.*, 2016). Because the Liard Line is spatially associated with Neoproterozoic and Eocene alkaline magmatism in southeastern Yukon (Pigage and Mortensen, 2004), a long-term objective of this study is to understand its influence on Kechika group volcanism in the Pelly Mountains.

GEOLOGICAL FRAMEWORK

KETZA GROUP

The Ketza group consists of upper Neoproterozoic to Lower Cambrian rocks that are the oldest exposed units of the Cassiar terrane in the Quiet Lake map area (Figs. 4 and 5a; Tempelman-Kluit, 2012). The basal Pass Peak formation is 200-700 m thick and comprises green to tan shale, siltstone, and quartzite. The overlying McConnell River formation is 600-800 m-thick and consists of calcareous mudstone and siltstone, carbonate lenses with archaeocyathid-bearing mounds, and black pyritic slate (Tempelman-Kluit, 2012). The late Early Cambrian archaeocyathid mounds are also recognized within post-rift successions of the southern Canadian Cordillera (*e.g.*, Devlin, 1989). In the Cloutier Creek map area, the upper contact of the Ketza group near the Ketza River Mine (Fig. 5b) is poorly exposed and structurally deformed. A distinct mid-Cambrian fossil gap between upper Ketza and lower Kechika group strata suggests the presence of an unconformity (Tempelman-Kluit, 2012).

A similar mid-Cambrian unconformity has been inferred within the Cassiar terrane of the Cassiar Mountains and the Kechika trough of the northern Canadian Rocky Mountains (Fig. 1; *e.g.*, Gabrielse, 1963; Taylor and Stott, 1973; Gabrielse *et al.*, 2006). In the Cassiar Mountains, the contact between the Lower Cambrian Rosella Formation and Upper Cambrian to Ordovician Kechika group is obscured by faulting (Gabrielse, 1963; Fritz *et al.*, 1991). In the Canadian Rockies, Middle to Late Cambrian deposition occurred within an active horst and graben system named the Kechika graben (*e.g.*, Gabrielse and Taylor, 1982; Post and Long, 2008). This graben later evolved into the Kechika trough (Post and Long, 2008).

KECHIKA GROUP

The Kechika group (Fig. 4; Beranek *et al.*, 2016) is an Upper Cambrian to Ordovician succession of four formations that Tempelman-Kluit (2012) described as laterally equivalent and interfingered. The four formations from northeast to southwest (Fig. 5a,b) comprise the Ram, Cloutier, Groundhog, and Gray Creek formations (Tempelman-Kluit, 2012) and occur as narrow, northwest-trending, discontinuous belts across the Pelly Mountains. The Groundhog, Cloutier and Ram formations are discontinuously capped by the Magundy formation (Fig. 4).

Tempelman-Kluit (2012) defined the Groundhog formation as at least 800 m-thick and consisting of thinly bedded, “darker, non-calcareous phyllite or slate” as opposed to the “orange or buff platy limestone and phyllite” of the Ram formation and the volcanic tuff of the Cloutier formation. Our fieldwork has instead shown that Groundhog formation strata are characterized by interbedded argillaceous shale, silty limestone, tuffaceous

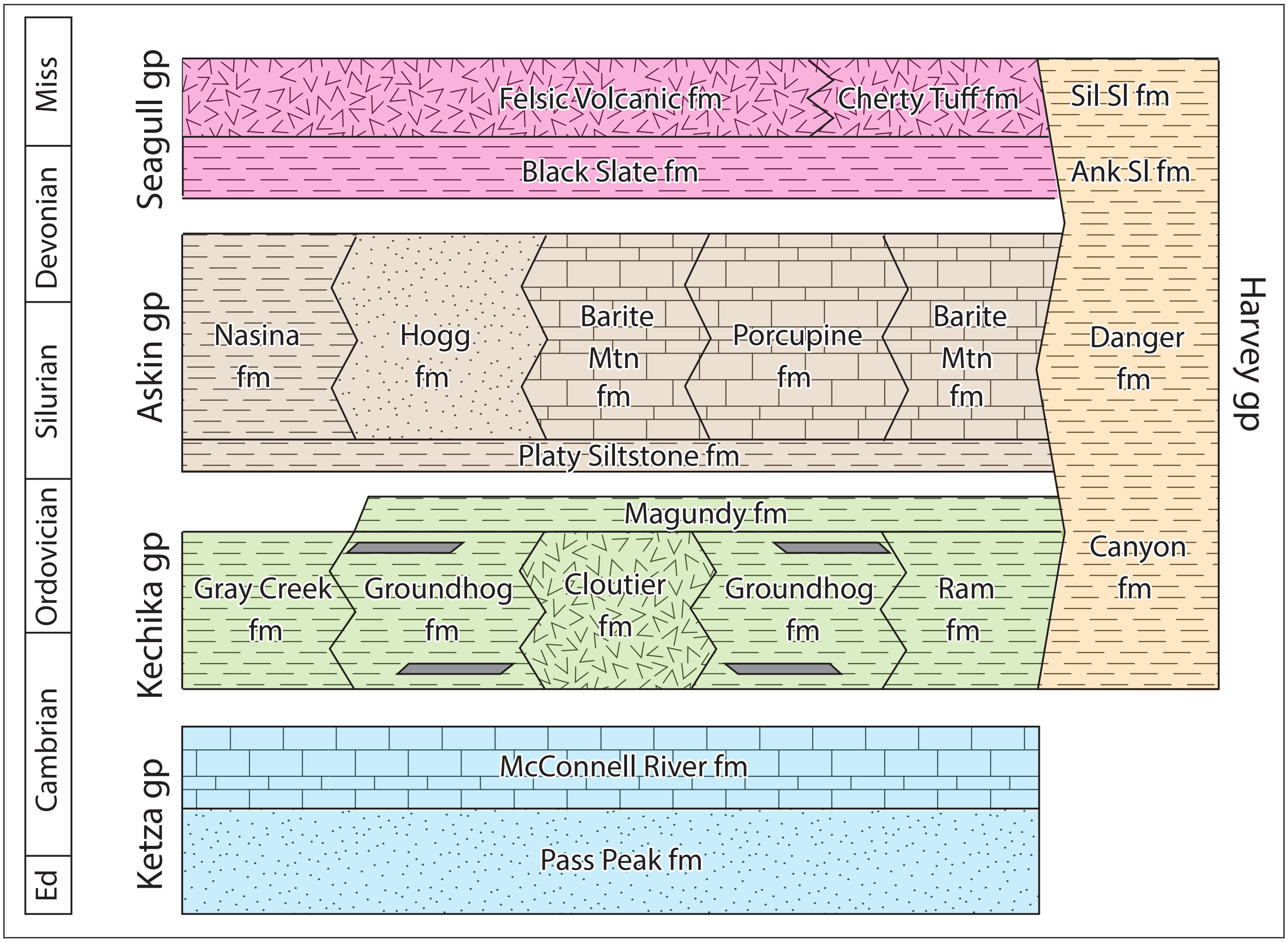

Figure 4. *Paleozoic stratigraphy of the Pelly Mountains compiled by Tempelman-Kluit (2012). Abbreviations: Ank=Ankerite; Ed=Ediacaran; fm=formation; gp=group; Miss=Mississippian; Mtn=mountain; Sil=Siliceous; and Sl=Slate. Grey polygons in Kechika group represent mafic sills.*

shale (phyllite) to sandstone, and lapilli tuff. Silty limestone occurs throughout the Groundhog formation, but tuffaceous rocks are generally restricted to the middle to upper part of the sequence.

Massive basalt and gabbro sills that are 0.5 to 30 m-thick occur throughout the Groundhog formation and typically show intrusive contacts with enclosing fine-grained clastic rocks. Up to 20 m-thick sections of volcanic and volcaniclastic rocks occur within the Groundhog and Magundy formations in the northern Quiet Lake map area, especially near Ram Creek and south of Mt. Green (Fig. 5b). Volcanic and volcanogenic sedimentary lithofacies include massive amygdaloidal basalt, lapilli tuff, monomictic volcanic breccia, sediment-matrix (volcanic and sedimentary lithic) breccia, and polymictic (volcanic and sedimentary clast) conglomerate (Appendix 1).

The Cloutier formation is 500 to 1000 m-thick and comprises resistant, mafic volcanic and volcaniclastic rocks that vary in lateral extent (Tempelman-Kluit, 2012). Primary volcanic facies include massive vesicular to amygdaloidal basalt, pillow basalt, and sediment-matrix basalt breccia (Appendix 1). Volcanogenic sedimentary facies include lapilli tuff, tuffaceous shale (phyllite) to sandstone, monomictic volcanic breccia, monomictic volcanic conglomerate and polymictic (volcanic and sedimentary clast) conglomerate (Appendix 1). These facies are intercalated with fine-grained argillaceous and calcareous rocks (comparable to those that define the Groundhog and Ram formations, respectively) and black shale (Appendix 1).

The Magundy formation is up to 400 m-thick and mostly consists of recessive graphitic shale with minor quartz sandstone, massive basalt, and tuff comparable with those of the Cloutier formation (Gordey, 1981; Tempelman-Kluit, 2012). Ordovician graptolites provide an upper age constraint for the Magundy formation (Gordey, 1981; Tempelman-Kluit, 2012).

The Ram formation is at least 1000 m-thick and crops out between the Tintina and St Cyr faults. The depositional age of the Ram formation is constrained by Late Cambrian and Early Ordovician trilobite fossils (Tempelman-Kluit, 2012). The Gray Creek formation is a 400 m-thick unit that consists of greenstone, quartz mica schist, and siltstone that Tempelman-Kluit (2012) related to more metamorphosed equivalents of the Cloutier, Pass Peak, and Nasina formations (Askin group), respectively.

Magmatic equivalents of the Groundhog and Cloutier formations in the Pelly Mountains are recognized elsewhere in the Cassiar terrane. In the Cassiar Mountains, Gabrielse (1963) mapped greenstone units that are similar to the mafic sills within the Quiet Lake map area (Tempelman-Kluit, 2012). In the Glenlyon area of central Yukon, minor amphibolite has been interpreted as high-grade equivalents of the Kechika group sills (*e.g.*, Black *et al.*, 2003; Gladwin *et al.*, 2002).

ASKIN GROUP

Shallow-marine strata of the Askin group (Fig. 4) comprise part of the Silurian and Early Devonian Cassiar platform (*e.g.*, Gabrielse, 1963; Cecile *et al.*, 1997; Tempelman-Kluit, 2012). A basal 100-500 m-thick unit of dolomitic siltstone (Platy Siltstone formation) locally contains mafic to intermediate volcanic rocks (Orange Volcanics member). Our field observations suggest that the Orange Volcanics member near Ram Creek and Mt. Green (Fig. 5b) contains pillow basalt and intermediate volcanic breccia. This basal unit is overlain by four formations (Porcupine, Barite Mountain, Hogg and Nasina formations; Fig. 4) with gradational to angular discordant contacts and rapid facies and thickness changes (Tempelman-Kluit, 2012). The Grey Limestone formation caps these four formations.

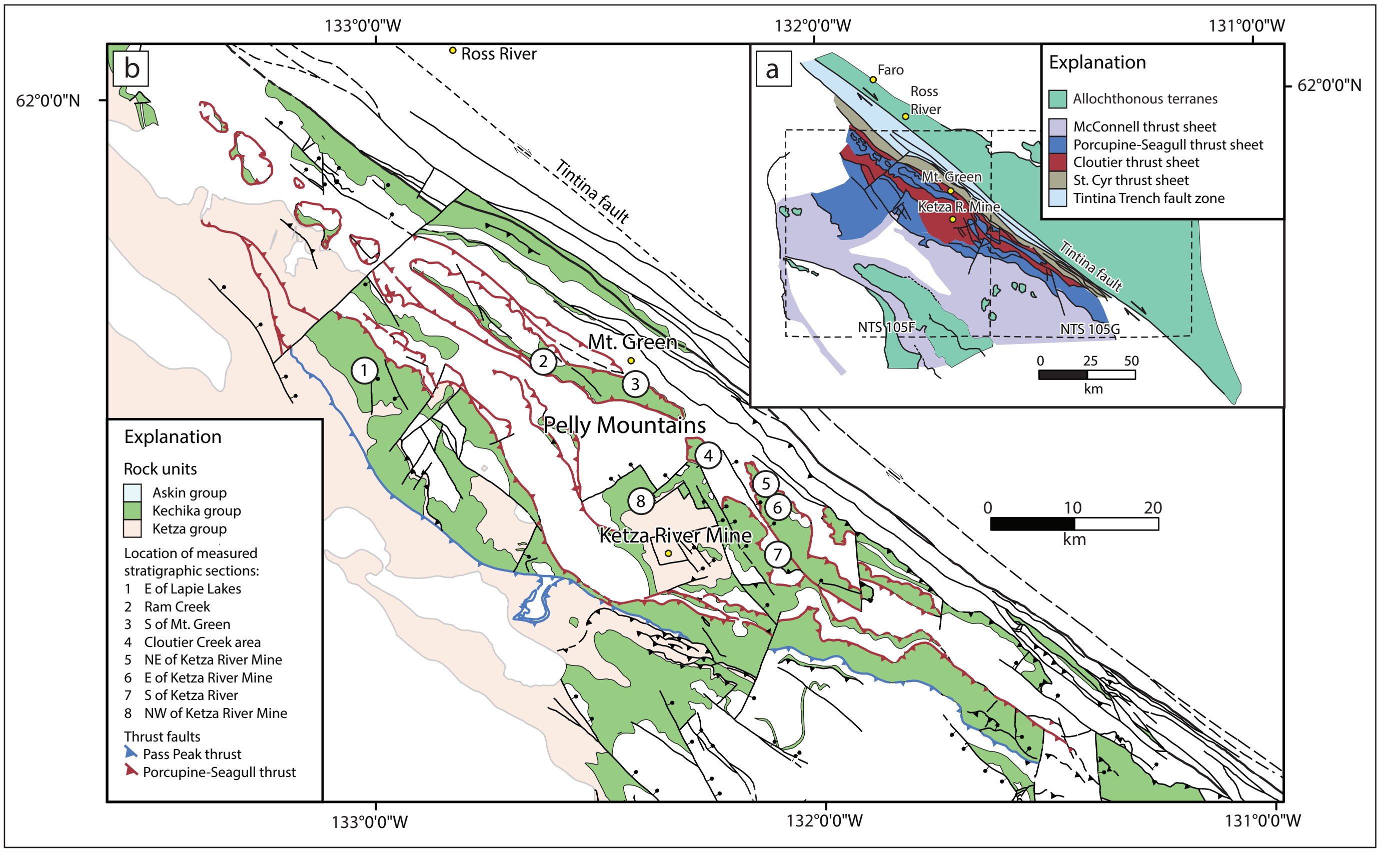

***Figure 5. (a)** Distribution of thrust sheets within the Quiet Lake (NTS 105F) and Finlayson Lake (NTS 105G) map areas, Pelly Mountains, south-central Yukon (modified from Tempelman-Kluit, 2012). **(b)** Distribution of Ketza, Kechika and Askin group rocks in the Pelly Mountains (modified from Tempelman-Kluit, 2012). Measured stratigraphic sections on map are displayed in Figure 6.*

FIELD STUDIES

Lower Paleozoic rocks of the Pelly Mountains crop out within four structural-stratigraphic zones that from west to east comprise the McConnell, Porcupine-Seagull, Cloutier, and St. Cyr thrust sheets (Fig. 5a). Seven of the stratigraphic sections (Figs. 6.1-6.7) discussed below occur within the Porcupine-Seagull thrust sheet, whereas one stratigraphic section (Fig. 6.8) occurs within the overlying Cloutier thrust sheet. The locations of field sites are shown in Figure 5b and sequentially numbered therein from northeast to southwest. Facies associations and estimated thicknesses are documented through stratigraphic measurement and description. Volcanic and intrusive rocks were systematically sampled for whole-rock geochemistry, Nd-Hf isotope geochemistry, and zircon U-Pb geochronology to constrain the genesis and crustal-mantle sources of early Paleozoic magmatism.

GROUNDHOG FORMATION STRATIGRAPHY

East of Lapie Lakes - Figure 6, location 1

This section is exposed along a series of northeast-trending ridges immediately east of Lapie Lakes and the South Canol Road in the western Pass Peak map area (base of section: zone 08V 603248E 6843697N NAD83). Although exposure is patchy and complex folding is common, 50% of the outcrop throughout >200 m-thick section consists of interbedded steel-grey argillaceous and calcareous shale (phyllite; Fig. 7a,b) with rare 5-30 cm fine sandstone beds. Roughly 40% of the exposure consists of resistant, 1 to >30 m thick basaltic to gabbroic sills. Rare (<10% of outcrop), up to 2 m-thick lapilli tuff beds form resistant units within the shale.

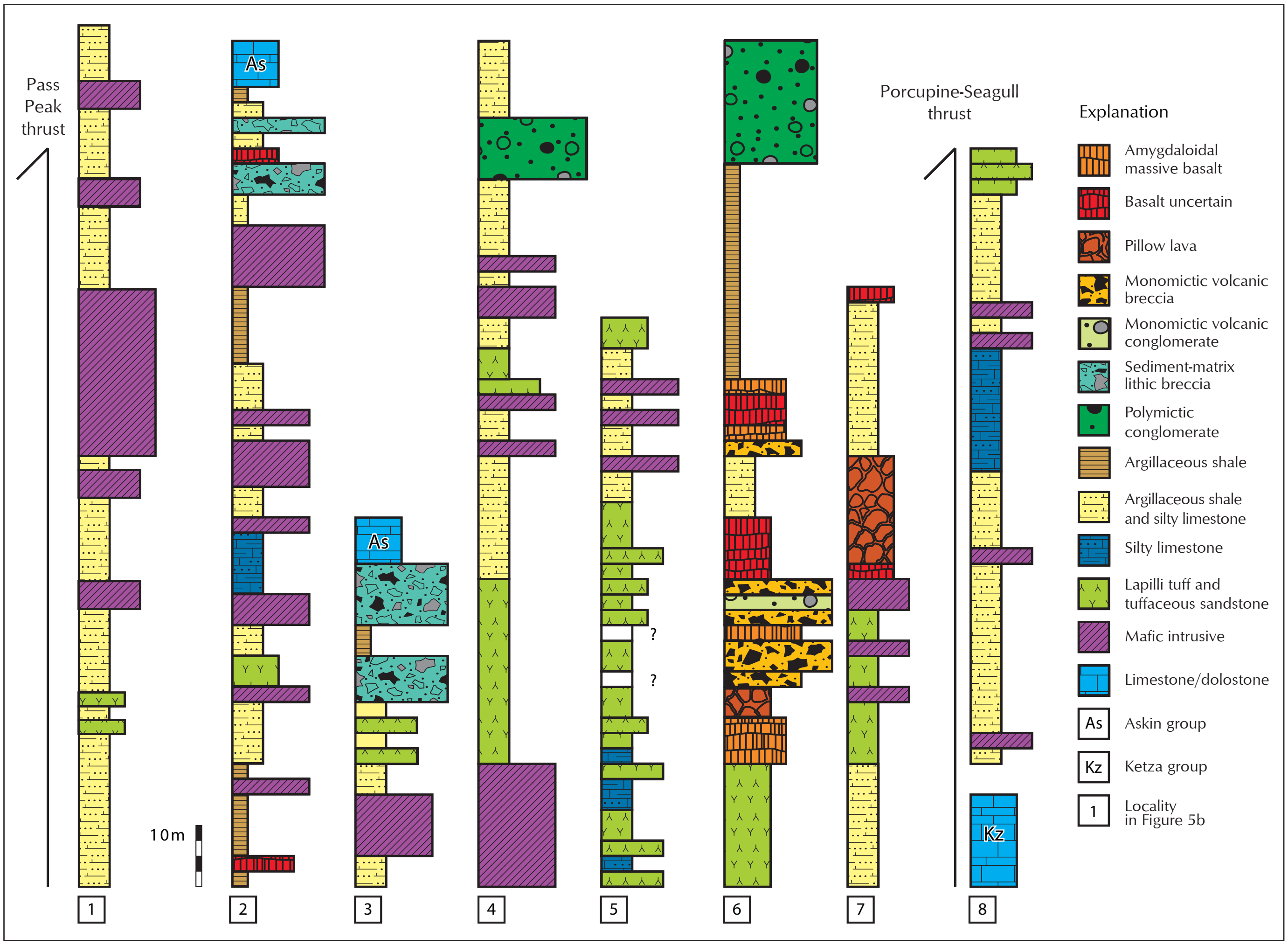

Figure 6. *Measured stratigraphic sections of the Kechika group, Pass Peak and Cloutier Creek map areas, Pelly Mountains, south-central Yukon.*

Ram Creek - Figure 6, location 2

Exposures of the upper Groundhog formation were examined along a northwest-trending ridge near the headwaters of Ram Creek in the northern Pass Peak map area (base of section: zone 08V 626236E 6844619N NAD83). The section is >130 m-thick and features two distinct components. The basal 60% of the section consists of steel grey to black argillaceous and tuffaceous shale (phyllite), with medium-bedded silty limestone and 1 to >10 m-thick massive amygdaloidal basalt to gabbro sills (Fig. 7c). Volcanic and volcaniclastic rocks are intercalated within the upper 40% of the section and mostly consist of massive basalt, monomictic volcanic breccia, and sediment-matrix (volcanic and sedimentary lithic) breccia (Fig. 7d-f). These rocks are interbedded with metre-thick units of grey shale, limestone and poorly exposed black shale of the Magundy formation. The overlying Askin group at this location consists of volcaniclastic breccia and dolomitic sandstone of the Orange Volcanics member of the Platy Siltstone formation.

South of Mt. Green - Figure 6, location 3

Groundhog and Magundy formation strata were examined along a northeast-trending ridge ~3 km south of Mt. Green in the northwest Cloutier Creek map area. The basal contact of the Groundhog formation is a thrust fault that places Kechika group rocks on top of the Devonian-Mississippian Black Slate formation (base of section: zone 08V 0636780E 6843033N NAD83). This section is at least 50 m-thick and lithologically similar to that exposed in the Ram Creek area. The basal 50% consists of interbedded steel-grey argillaceous and calcareous shale (phyllite) and >10 m-thick gabbro intrusion. The upper 50% consists of monomictic volcanic breccia, sediment-matrix (volcanic and sedimentary lithic) breccia (Fig. 7g) and lapilli tuff (Fig. 7h).

Cloutier Creek area - Figure 6, location 4

Groundhog formation rocks were examined ~8 km north of the Ketza River Mine, along a northwest-trending ridge between Cloutier Creek and the Ketza River, in the central Cloutier Creek map area (base of section: zone 08V 645712E 6834820N NAD83). This section is at least 150 m-thick and consists of a gabbroic stock (mapped as Cloutier formation) that intrudes >20 m of interbedded tuffaceous shale (Fig. 8a), thin to medium-bedded silty limestone (Fig. 8b), tuffaceous sandstone (Fig. 8c), and interbedded steel-grey argillaceous to calcareous shale (phyllite). Several metre-thick gabbroic sills occur throughout the succession. The erosional top of the section consists of green, polymictic (volcanic and limestone clast) conglomerate.

Northwest of Ketza River Mine - Figure 6, location 8

A succession of Groundhog formation strata overlies the Ketza group ~6 km northwest of the Ketza River Mine in the southern Cloutier Creek map area (base of the Groundhog formation: 08V 637814E 6829108N NAD83). Ketza group strata at this location comprise archaeocyathid-bearing limestone, silty limestone and pyritic mudstone. The contact with the overlying Groundhog formation is poorly exposed and the Ketza group shows evidence of structural duplication and local faulting. The Groundhog formation is >100 m-thick and consists of interbedded steel-grey shale and silty limestone units (Fig. 8d,e) that are intruded by 0.5-2 m-thick, typically amygdaloidal, basalt to gabbro sills (Fig. 8f; >10% of the total outcrop). Strongly deformed and complexly folded tuffaceous green phyllitic shale and lesser fine-grained sandstone comprise the top of the section (<10% of sequence).

CLOUTIER FORMATION STRATIGRAPHY

Northeast of Ketza River Mine - Figure 6, location 5

This section is >90 m-thick and exposed along a ridge ~6 km northeast of the Ketza River Mine, near peak 6762 in the eastern Cloutier Creek map area (base of the section: 08V 652511E 6831507N NAD83). The basal 70% of the section consists of tuffaceous shale (phyllite), normally graded beds of coarse to fine-grained volcanic sandstone (Fig. 8g), and lapilli tuff (Fig. 8h). The tuffaceous rocks are locally intercalated with medium-bedded limestone. The upper 30% of the section consists of complexly folded, massive amygdaloidal basalt sills that are interbedded with steel-grey argillaceous and calcareous shale (phyllite) and lapilli tuff.

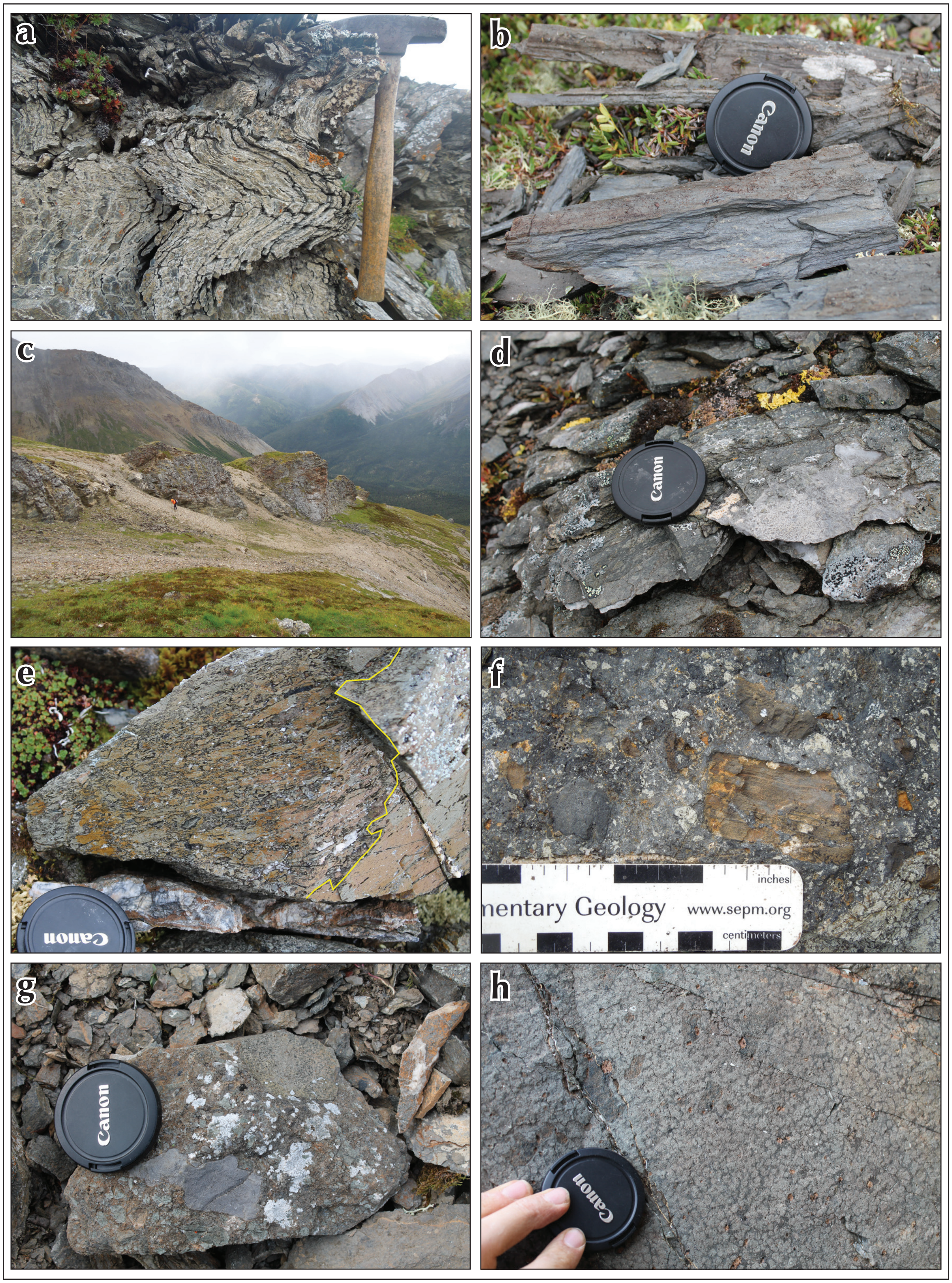

Figure 7. *Field photographs of Kechika group units at field localities 1-3.* ***(a)*** *tight folding of grey-shale, east of Lapie Lakes, Pass Peak map area;* ***(b)*** *steel-grey argillaceous shale;* ***(c)*** *resistant 8 m-thick gabbroic sill within shale, Ram Creek, Cloutier Creek map area;* ***(d)*** *sediment-matrix lithic (limestone and tuffaceous rock) breccia;* ***(e)*** *massive amygdaloidal basalt in contact with sediment-matrix volcanic and sedimentary lithic breccia (contact outlined in yellow)* ***(f)*** *sediment-matrix volcanic and sedimentary lithic breccia;* ***(g)*** *sediment-matrix lithic (limestone, shale, mafic tuff, amygdaloidal basalt) breccia, south of Mt. Green, Cloutier Creek map area; and* ***(h)*** *lapillistone to lapilli tuff with rounded lapilli clasts.*

Figure 8. *Field photographs of Kechika group units at field localities 4-6.* ***(a)*** *Interbedded tuffaceous shale and silty limestone, near Cloutier Creek, Cloutier Creek map area* ***(b)*** *medium-bedded silty limestone;* ***(c)*** *green tuffaceous sandstone;* ***(d)*** *interbedded steel-grey argillaceous shale and silty limestone, northwest of Ketza River Mine, Cloutier Creek map area;* ***(e)*** *thin to medium-bedded silty limestone;* ***(f)*** *intrusive contact of 2 m-thick amygdaloidal basalt sill;* ***(g)*** *irregular lapilli clasts in graded tuffaceous sandstone and shale, northeast of Ketza River, Cloutier Creek map area; and* ***(h)*** *lapilli tuff with elongate lapilli clasts.*

East of Ketza River Mine - Figure 6, location 6

This 140 m-thick section is exposed along a southwest-trending ridge ~10 km east of the Ketza River Mine (base of section: zone 08V 654218E 6829014N NAD83). The basal part of the sequence consists of 2 to 10 m-thick units of vesicular to amygdaloidal massive basalt (Fig. 9a), vesicular pillow basalt (Fig. 9b), sediment-matrix basalt breccia (Fig. 9c), and up to 8 m-thick units of monomictic volcanic breccia (Fig. 9d) and monomictic volcanic conglomerate (Fig. 9e). The top of the succession is variably deformed and consists of black shale, limestone and up to 2 m-thick massive basalt lava flows that are capped by granule to cobble polymictic (mafic-intermediate volcanic and limestone clast) conglomerate (Fig. 9f).

South of Ketza River - Figure 6, location 7

At least 90 m of Cloutier formation strata are exposed along a north-trending ridge at the headwaters of the Ketza River in the southern Cloutier Creek map area (base of section: zone 08V 654352E 6823223N NAD83). The basal 70% of this sequence consists of interbedded steel-grey argillaceous and calcareous shale (phyllite), 1 to 3 m-thick basalt to gabbro sills, and up to 3 m-thick beds of lapilli tuff. The upper 30% consists of a 20 m-thick sequence of pillow basalt (Fig. 9g,h) and sheared mafic rocks that are intercalated with silty limestone and argillaceous shale.

PRELIMINARY ANALYTICAL RESULTS

Preliminary lithogeochemical results indicate that Kechika group rocks have Ocean Island Basalt-like (OIB) affinities (Fig. 10a; Sun and McDonough, 1989) that are typical of some alkali basalt to foidite rocks in the Canadian Cordillera (Fig. 10b) and around the globe (Winchester and Floyd 1977; Sykes, 1978; Pearce 1996). High-precision zircon U-Pb studies have determined Late Cambrian and Early Ordovician crystallization ages for gabbro in the Pass Peak map area (work in progress).

STRATIGRAPHIC INTERPRETATION

Four principal lithofacies (basaltic, volcanogenic sedimentary, limestone-argillite, intrusive rock) are recognized within the Cloutier and Groundhog formations (Appendix 1). Volcanic and proximal volcanogenic lithofacies of the middle to upper Cloutier formation and parts of the upper Groundhog and lower Magundy formations are consistent with a submarine vent proximal succession. The lower Cloutier formation and much of the Groundhog formation may comprise part of a sediment-sill complex based on the prevalence of concordant mafic rocks that intruded into, or were erupted onto, wet marine sediment (*e.g.*, Einsele, 1986; Batiza and White, 2000).

BASALTIC FACIES ASSOCIATION

The basaltic facies association is related to the eruption of primary volcanic products. Basaltic lithofacies consist of massive amygdaloidal to vesicular basalt, pillowed basalt and peperite (Appendix 1). The massive amygdaloidal to vesicular basalts are predominantly sills, but some lava flows are locally recognized. The vesicular nature of flows and sills is caused by fluid exsolution, which can occur due to a decrease in the depth of the magma or through crystallization (Cas and Wright, 1988). Pillowed lava flows are consistent with subaqueous volcanism and most common within low effusivity systems (Moore, 1975; Batiza and White, 2000). Sediment-matrix basalt breccia lithofacies, with lapilli-sized, amoeboid to angular-shaped clasts, are interpreted as fluidal peperite units that formed through the interaction of basaltic lava and fluid-saturated sediment during emplacement (*e.g.*, Skilling *et al.*, 2002).

VOLCANOGENIC SEDIMENTARY FACIES ASSOCIATION

Volcanogenic sedimentary rocks are interpreted to have formed by the reworking of primary volcanic units. Volcanogenic sedimentary facies mostly include monomictic volcanic breccia, monomictic volcanic conglomerate, sediment-matrix volcanic and sedimentary lithic breccia, polymictic volcanic and limestone clast conglomerate, lapilli tuff and tuffaceous shale to sandstone (Appendix 1).

Monomictic volcanic breccia units consist of lapilli to bomb-sized, irregular-shaped, basaltic clasts. These strata likely represent resedimented hyaloclastite units that form due to the rapid cooling and fragmentation of basaltic lava during interaction with water (*e.g.*, Batiza and White, 2000; Simpson and McPhie, 2001). Fragmentation processes can also occur due to the expansion of volatiles (Fisher and Schminke, 1984). Hyaloclastite units with bomb-sized fragments occur adjacent to pillow basalt and are inferred to represent pillow breccia, a deposit formed by the gravitational or mechanical detachment of pillows (*e.g.*, Batiza and White, 2000; Simpson and McPhie, 2001). Hyaloclastite units are typical of shallow-water deposits and/or within areas of steep relief such as seamount flanks (Batiza and White, 2000).

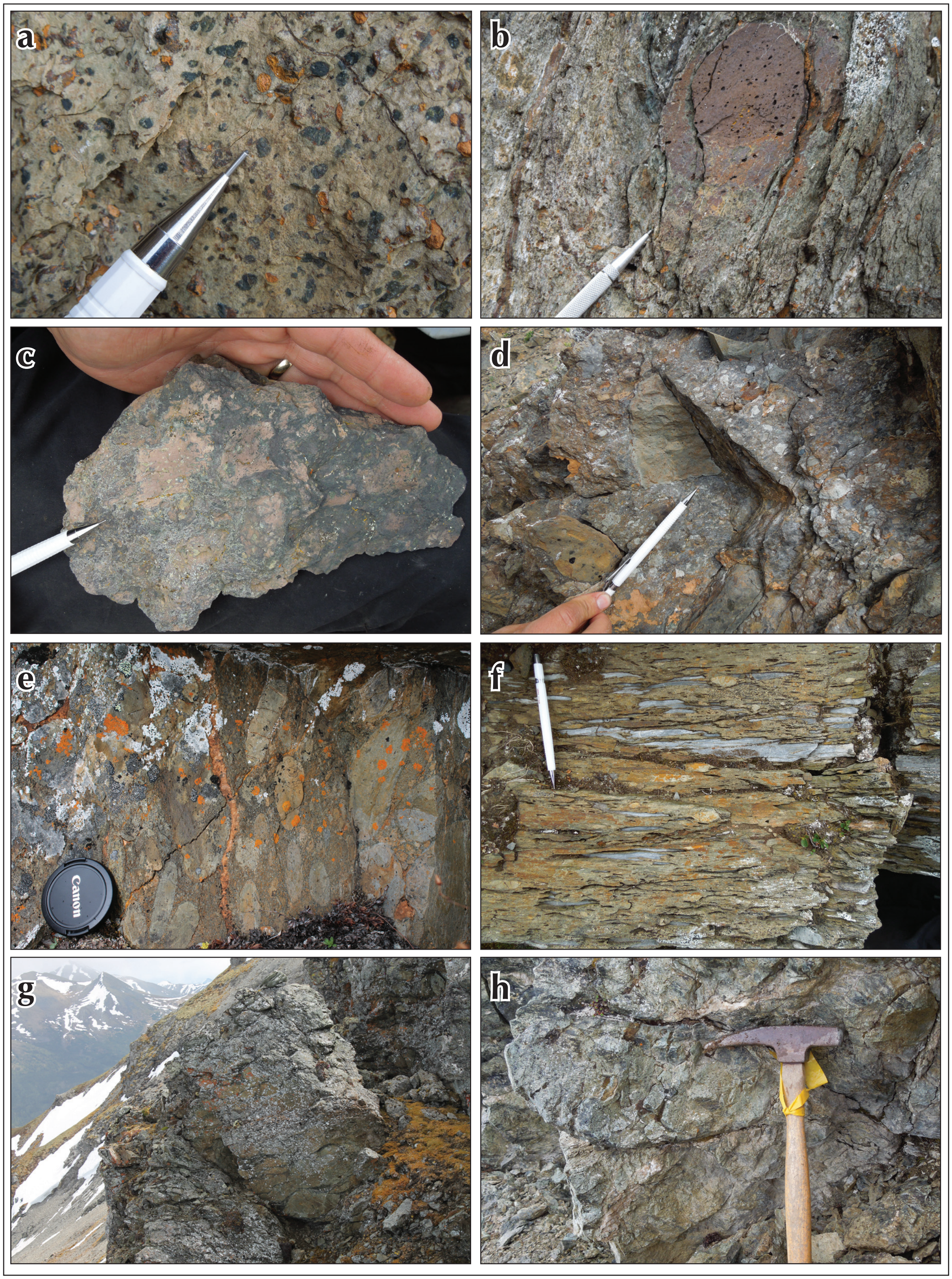

Figure 9. *Field photographs of Kechika group units at field localities 7 and 8.* ***(a)*** *Amygdaloidal (chlorite) massive basalt, east of Ketza River Mine, Cloutier Creek map area;* ***(b)*** *vesicular pillow basalt;* ***(c)*** *sediment-matrix basalt breccia (fluidal peperite) consisting of amoeboid to angular-shaped, lapilli-sized fragments in volcaniclastic matrix* ***(d)*** *monomictic basalt breccia (hyaloclasite) with angular, lapilli to bomb sized fragments in volcaniclastic matrix;* ***(e)*** *monomictic volcanic conglomerate;* ***(f)*** *sheared polymictic limestone and mafic-intermediate volcanic conglomerate;* ***(g)*** *part of a 20 m-thick sequence of pillow basalt, south of Ketza River, Cloutier Creek map area; and* ***(h)*** *pillow basalt.*

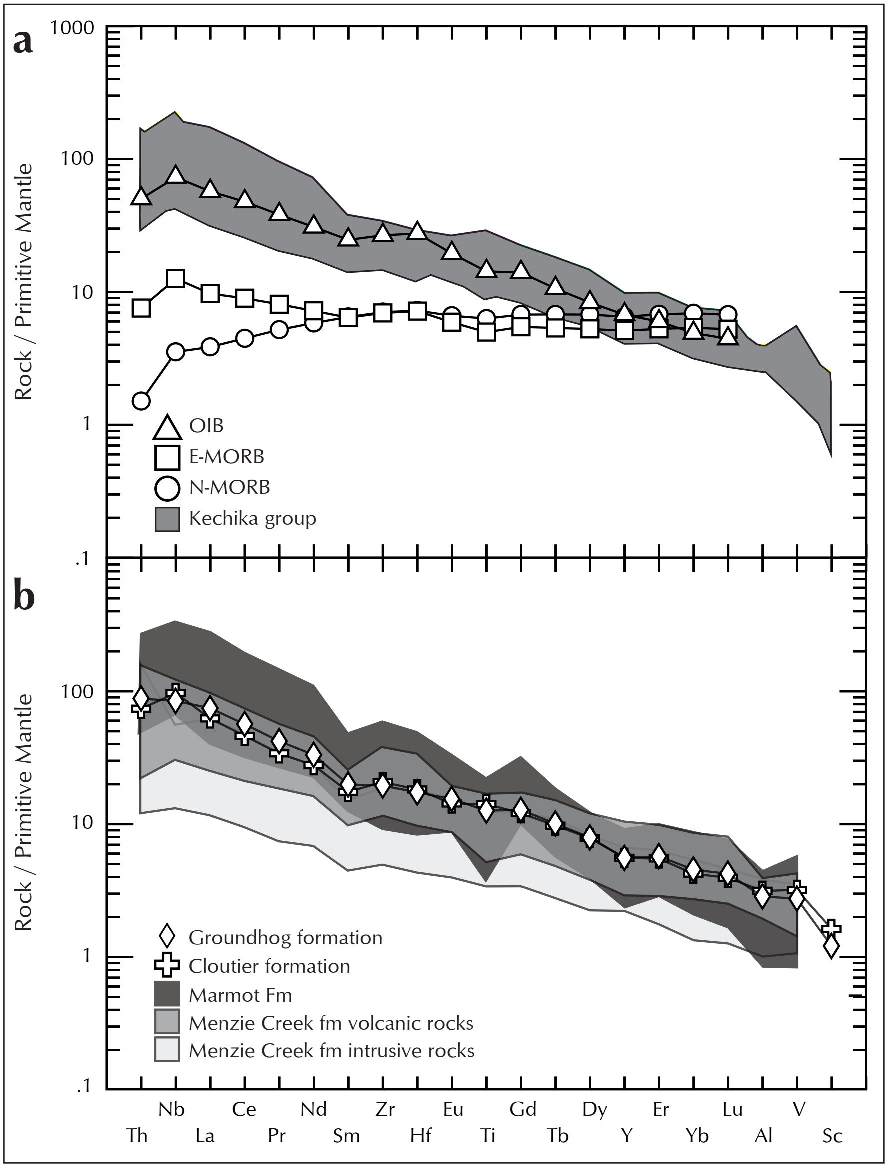

Figure 10 *Primitive mantle-normalized multi-element plots of mafic rocks from the Kechika group and global magmatic system.* ***(a)*** *Range of values from Kechika group (this study) and the global averages of ocean-island basalt (OIB), normal and enriched mid-ocean ridge basalt (E-MORB and N-MORB; Sun and McDonough, 1989); and* ***(b)*** *average values of Cloutier and Groundhog formation (this study), range of values from the Marmot Formation (Leslie, 2009) and range of values from the Menzie Creek formation (Pigage, 2004). Primitive-mantle normalising values are from Sun and McDonough (1989) and McDonough and Sun (1995).*

Sediment-matrix lithic breccia and polymictic conglomerate units contain rock fragments that are representative of underlying volcanic, volcaniclastic, and marine sedimentary strata. For example, the limestone-bearing conglomerate units have clasts that are comparable to exposures of blue-grey carbonate and limy clastic rocks within the Cloutier and Groundhog formations. The large clast sizes and locally sourced material indicate proximal reworking and deposition with limited transport. These coarse-grained units were likely caused by slope collapse processes and may be unrelated to volcanic processes (e.g., McPhie and Cas, 2015).

Tuffaceous rocks are inferred to record both pyroclastic and epiclastic processes (e.g., Fisher and Schminke, 1984). Tuffaceous sandstone and shale are indicative of epiclastic processes, especially when beds show evidence for normally graded bedding (e.g., Cas and Wright, 1988). Tuffaceous shale, often interbedded with argillaceous and calcareous layers, likely formed through the deposition of "relatively dilute suspensions of ash" in the water column during periods of low volcanic activity (e.g., McPhie and Cas, 2015).

LIMESTONE-ARGILLITE FACIES ASSOCIATION

The limestone-argillite facies likely resulted from the suspension sedimentation of mud, silty carbonate and volcanic ash below wave-base. Interbedded steel-grey argillaceous shale and blue-grey to tan silty limestone are the most common facies. Black shale with rare limestone occurs near the top of the Groundhog and Cloutier formations. Metre-thick, medium-bedded limestone units are intercalated within the tuffaceous-rich successions. Silty limestone predominates over argillaceous shale for tens of metres near the base of the Kechika group.

INTRUSIVE ROCKS

Intrusive rocks of the Kechika group are associated with the emplacement of magma within shallow or unconsolidated sedimentary strata. The intrusive rocks consist of tabular, 1 to 30 m-thick basaltic to gabbroic rocks that are concordant with bedding. Gabbroic rocks are dark grey to green, with coarse porphyritic pyroxene (altered to chlorite) and more rarely plagioclase. The intrusive contacts are typically irregular and often display chill margins and baked contacts with enclosing shale units that are 10s of centimetres thick.

The geochemical similarities of Kechika group units support the interpretation that intrusive rocks (mostly in the Groundhog formation) were subvolcanic feeders to coeval extrusive rocks (mostly in the Cloutier formation). Metre-thick to tens of metres thick sills within the Groundhog and lower Cloutier formations are inferred to represent part of a sill-sediment complex (*e.g.,* Einsele, 1986). Such complexes occur in areas of thick unconsolidated (wet) sediment, although intrusive, not peperite contacts, predominate within the Kechika group sills. Sill-sediment complexes can form during the rifting of thinned continental crust and are frequently associated with transform-transfer zones (*e.g.*, Einsele, 1986; Naylor *et al.*, 1999).

REGIONAL CORRELATIONS AND FUTURE WORK

Based on the available geochemical results (Fig. 10a), our working hypothesis calls for Kechika group magmatism to have resulted from the low-degree partial melting of a mantle source with fertile components (*e.g.*, Fitton, 1987; Pearce 1996; Niu *et al.*, 2011), perhaps due to periodic extensional faulting along the Cordilleran margin (work in progress). Although no direct field evidence is yet recognized for Cambrian-Ordovician faults in the Pelly Mountains (Tempelman-Kluit, 2012), the Kechika group is characterized by lithofacies and geochemical signatures that are analogous to coeval mafic rocks within the Selwyn basin and Misty Creek Embayment (Fig. 10b), which are demonstrably linked to local extension (*e.g.*, Pigage, 2004; Leslie, 2009). These correlations imply that similar post-breakup, rift-related processes occurred to the north and south of the Liard Line during the early Paleozoic. Similar to the Kechika group, Menzie Creek formation rocks in the Anvil district are overlain by younger volcanic rocks that may be related to the reactivation of pre-existing structures along the Cordilleran margin (Beranek *et al.*, 2016; Cobbett, 2016). The influence of the Liard Line on Paleozoic magmatism in south-central Yukon remains an open question and requires future testing.

Potential analogues for Kechika group volcanism include syn to post-breakup rocks associated with the Orphan, Fogo, and Newfoundland Seamounts in the Grand Banks area, offshore Newfoundland (Pe-Piper *et al.*, 2007, 2013). The Newfoundland continental margin is a magma-poor, hyperextended, asymmetric rift margin that evolved from Late Triassic to mid-Cretaceous time (*e.g.*, Peron-Pinvidic *et al.*, 2007; Brune *et al.*, 2014). This margin has volcanic centres with OIB-like, alkaline mafic rocks that were emplaced into extended continental crust (Jagoutz *et al.*, 2007; Pe-Piper *et al.*, 2013). The seamounts are generally linear features that are bounded by margin-parallel extensional faults. In the case of the Orphan and Fogo Seamounts, volcanic centres are spatially associated with the Charlie Gibbs fracture zone and Southwest Grand Banks transform margin, respectively (Pe-Piper *et al.*, 2007). These structures are major transfer zones that are at high angles to the rifted margin, analogous to the Liard Line in the Canadian Cordillera.

ACKNOWLEDGEMENTS

This project is supported by the GEM (Geo-mapping for Energy and Minerals) program at Natural Resources Canada, Yukon Geological Survey, and NSERC Discovery Grant program. Will Tompson of TransNorth Turbo Air provided excellent helicopter support. Rosie Cobbett provided thoughtful and constructive comments that improved this manuscript.

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Appendix 1. *Principal lithofacies of the Kechika group, Pass Peak and Cloutier Creek map areas, Pelly Mountains, south-central Yukon.*

Lithofacies	Thickness and lateral extent	Characterization	Contact/relationship and associated lithofacies	Interpretation
Basaltic facies association				
Amygdaloidal massive basalt	1-5 m-thick	Aphyric to 25% porphyritic (dark green 1-5 mm), up to 25% vesicular-amygdaloidal (1-5 mm quartz-chlorite-carbonate).	Conformable contacts with overlying pillow basalt; intercalated and overlain by other volcanic and volcanogenic facies; irregular, baked contacts with enclosing shale.	Coherent basalt lava; mostly sills represented by upper and lower baked contacts ± rare sediment-matrix basalt breccia (peperite). Rare lava flows likely also present (*e.g.*, Batiza and White, 2000).
Pillow lava	2-20 m-thick	50% aphyric, 50% porphyritic (dark green 1-5 mm); rarely vesicular; 0.1-0.5 m lobes closely-loosely packed.	Conformably overlies or grades into massive basalt; locally interpillow matrix of shale; overlain at outcrop scale by monomictic volcanic breccia or shale.	Subaqueous pillowed lava flows (*e.g.*, Moore, 1975), most common within low effusivity magmatic systems (Batiza and White, 2000).
Sediment-matrix basalt breccia	Limited extent	>25% lapilli sized amoeboid to angular basalt clasts; very poorly sorted, massive.	Intercalated with massive basalt and monomictic to sediment-matrix volcanic breccia.	Fluidal to blocky peperite; *in situ* disintegration of coherent magma due to mingling with unconsolidated to poorly consolidated sediment (Skilling *et al.*, 2002).
Volcanogenic sedimentary facies association				
Monomictic volcanic breccia	Up to 8 m-thick	>30% lapilli- to bomb-sized, angular basalt clasts (1 cm to 16 cm); very poorly sorted, massive.	Overlies massive and pillow basalt facies; intercalated with volcanic breccia and conglomerate.	In-situ to wholly to partly resedimented hyaloclasite (Batiza and White, 2000); ±pillow basalt breccia due to detachment of pillows by mechanical/gravitational means (*e.g.*, Simpson and McPhie, 2001).
Monomictic volcanic conglomerate	Up to 2 m-thick	Rounded to sub-angular, granule to cobble-sized volcanic clasts (25%); very poorly sorted, massive.	Intercalated within monomictic volcanic breccia and sediment-matrix lithic breccia.	Resedimented volcanic conglomerate formed by proximal reworking and transport of unstable volcanic facies.
Sediment-matrix volcanic and sedimentary lithic breccia	20 m-thick	Up to 70% angular to subrounded, granule- to cobble-sized (0.5 to >20 cm) clasts of amygdaloidal basalt, dark green (chloritic) tuff, grey-black shale and blue-grey limestone; very poorly sorted, massive.	Underlain by tuff, shale and sills; intercalated with black shale; irregular contacts with massive basalt.	Resedimented volcanic breccia formed through gravity-driven collapse of volcanic facies and erosion of underlying sedimentary facies.

***Appendix 1** continued.*

Lithofacies	Thickness and lateral extent	Characterization	Contact/relationship and associated lithofacies	Interpretation
Polymictic volcanic and limestone clast conglomerate	20 m-thick	Up to 30% granule to boulder-sized, rounded to subangular; blue-grey limestone and mafic-intermediate volcanic clasts.	Intercalated with volcanic strata and shale of the Cloutier formation and tuff, sills and shale of the Groundhog formation.	Reworking and transport of underlying volcanic and sedimentary facies.
Lapilli tuff	0.1 to 3 m-thick beds and lenses	Up to 30% pale to dark green (chlorite) lapilli clasts; often elongate, irregular to wispy to rounded (0.1-3 cm); within dark grey, resistant, sandy to phyllitic volcaniclastic matrix; 1 m-thick beds of normally graded lapillistone.	Forms solitary beds within limestone-argillite facies and tuffaceous sequences.	Formed through pyroclastic processes and/or epiclastic processes (*e.g.*, Fisher and Schminke, 1984).
Tuffaceous shale to sandstone	>50 m-thick sequences; laterally continuous over 10s of metres	Mostly green-orange, tuffaceous shale-siltstone and rare fine-medium sandstone; finely laminated to thinly bedded; normally graded beds of sandstone.	Intercalated with >3 m-thick, laminated to thinly bedded limestone, m-thick (steel-grey) phyllite and lapilli tuff.	Suspension and turbidity current sedimentation of volcanic-derived and limestone-argillite units, most likely below wave base.
Limestone-argillite facies association				
Argillaceous shale	<1 to >2 m-thick	Finely laminated, grey-steel to black argillaceous shale.	Typically interbedded with silty limestone; dominates lower and middle parts of Groundhog and Cloutier formations.	Suspension sedimentation of clay and volcanic ash; likely below wave base.
Silty limestone	<1 to >2 m-thick	Finely laminated to medium-bedded, blue-grey to tan limestone.	Typically interbedded with argillaceous shale; m-thick beds intercalated with tuffaceous shale and sandstone.	Suspension sedimentation of silt and carbonate mud.
Intrusive rocks				
Mafic intrusive	0.5 to 30 m-thick; continuous over 100s of metres	Coherent, dark grey-green, fine (basalt) to coarse-grained (gabbro) intrusive rocks; tabular, concordant bodies; contacts are irregular and baked; coarse porphyritic chlorite/pyroxene and more rarely plagioclase in thicker intrusions; 0.1-0.5 mm quartz-chlorite amygdales found in m-thick bodies.	Predominantly emplaced within limestone-argillite facies.	Concordant and tabular nature of bodies infers they are sills; may be comparable to sediment-sill complexes where thick packages of unconsolidated sediment prevent coherent magma movement through fracture propagation, therefore resulting in magma spreading laterally through the sediment (Einsele, 1986; Batiza and White, 2000).