Early Proterozoic orogeny and exhumation of Wernecke Supergroup revealed by vent facies of Wernecke Breccia, Yukon, Canada[1, 2]

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Abstract: In the Yukon, the oldest known supracrustal succession, the Wernecke Supergroup, was deposited in a marine basin before 1.71 Ga. The earliest orogenic event to disturb these strata was the Racklan orogeny, which produced folds and fabrics at peak temperatures of 450–550 °C. These features and those of the correlative Forward orogeny are recognized at the surface and in the subsurface throughout much of northwestern Canada. Zones of Wernecke Breccia (hydrothermal breccias, 1.60 Ga) were emplaced into the Wernecke Supergroup after Racklan deformation and metamorphism. Two main types of breccia are recognized: grey sodic breccias and colourful potassic breccias. In the Slab Mountain area, a belt of grey breccias contains abundant megaclasts of country rock including blocks of a subaerial lava succession, the Slab volcanics. These grey breccias are interpreted as a vent facies of Wernecke Breccia, and their emplacement into the stratigraphically lowest unit of the Wernecke Supergroup infers that at least 9 km of exhumation occurred in the core of a major Racklan anticline prior to brecciation. The Slab volcanics are preserved only as clasts in Wernecke Breccia and are interpreted as fragments of a former valley-filling basalt succession which overlay deformed and deeply incised strata of the Wernecke Supergroup.

Résumé : Au Yukon, la plus ancienne succession supracrustale connue, le Supergroupe de Wernecke, a été déposée dans un bassin marin avant 1,71 Ga. L'événement orogénique le plus précoce pour distribuer ces strates a été l'orogène Racklan qui a produit des plis et des textures à des températures de pointe de 450–550 °C. Ces caractéristiques et celles de l'orogène corrélative Forward sont reconnues à la surface et sous la surface dans une grande partie du nord-ouest du Canada. Les zones de brèches de Wernecke (des brèches hydrothermales, 1,60 Ga) ont été mises en place dans le Supergroupe de Wernecke après la déformation et le métamorphisme de l'orogène Racklan. Deux principaux types de brèches sont reconnus : des brèches sodiques grises et des brèches potassiques colorées. Dans la région du mont Slab, une ceinture de brèches grises contient beaucoup de mégaclastes de la roche encaissante incluant des blocs d'une succession de laves subaériennes, les volcaniques Slab. Ces brèches grises sont interprétées comme étant un facies d'évent des brèches de Wernecke et leur mise en place dans l'unité stratigraphique la plus basse du Supergroupe de Wernecke porte à croire qu'au moins 9 km d'exhumation a eu lieu dans le centre d'un grand anticlinal de l'orogène Racklan avant la bréchification. Les volcaniques Slab sont préservées uniquement en tant que clastes dans les brèches de Wernecke et elles sont interprétées comme étant des fragments d'une succession antérieure de basalte qui remplissait les vallées et qui recouvrait les strates déformées et fortement incisées du Supergroupe de Wernecke.

[Traduit par la Rédaction]

Introduction

The western margin of ancestral North America (Laurentia) has long been known for thick successions of supracrustal Proterozoic sediments which record several events of extensional basin formation between ~1.84 Ga and 540 Ma (Young et al. 1979). Basin formation and sedimentation were interrupted by other events, however, including orogenesis, exhumation, magmatism, and hydrothermal activity. Unraveling this long and complex "pre-Cordilleran" history is essential to a better understanding of how Laurentia evolved and how it may have interacted with other continents (e.g., Bell and Jefferson 1987; Moores 1991; Thorkelson et al. 2001*a*, 2001*b*).

In this paper, we examine a key locality, herein called the

Received 8 December 2003. Accepted 21 September 2004. Published on the NRC Research Press Web site at http://cjes.nrc.ca on 27 September 2005.

Paper handled by Associate Editor K. Ansdell.

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[1] This article is one of a selection of papers published in this Special Issue on *The Lithoprobe Slave – Northern Cordillera Lithospheric Evolution (SNORCLE) transect*.
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Can. J. Earth Sci. **42**: 1033–1044 (2005) doi: 10.1139/E04-085

study area, located in a remote part of the Wernecke Mountains of northern Yukon (Figs. 1–3). In the study area, hydrothermal megabreccias crosscut metamorphosed and deformed strata of the Paleoproterozoic Wernecke Supergroup (Delaney 1981; Bell 1986; Thorkelson 2000). These breccias belong to a set of widespread breccia zones (1.60 Ga) known collectively as Wernecke Breccia (Thorkelson et al. 2001*a*). We describe the physical and chemical features of the breccias, show how they constrain the nature and timing of the preceding orogenic events (Racklan orogeny), and propose a model involving exhumation, volcanism, and brecciation.

Stratigraphic framework

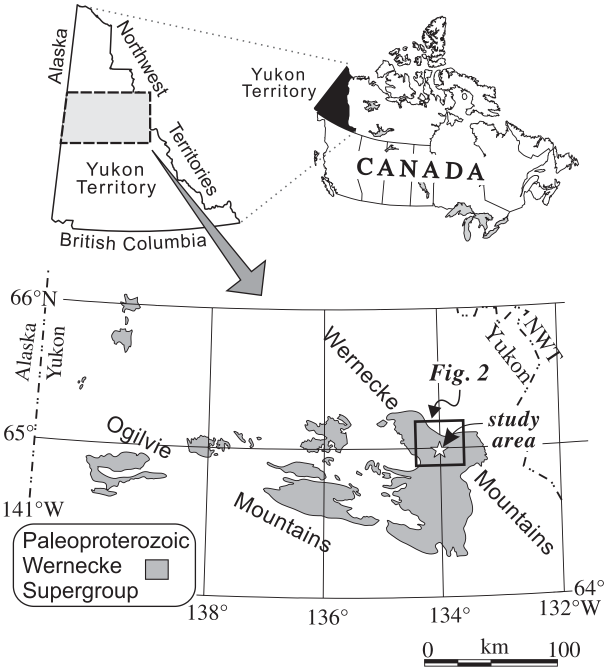
A geological framework for the Proterozoic evolution of northwestern Canada was established by Young et al. (1979), who recognized three unconformity-bounded successions called sequences A, B, and C. More detailed investigations of sequence A (~1.8–1.2 Ga) led Cook and MacLean (1995), Thorkelson (2000), and MacLean and Cook (2004) to expand sequence A into at least three sedimentary successions and three volcanic units, all of which are unconformity bounded. Rock beneath sequence A is nowhere exposed and is presumed to be crystalline basement with ages as young as 1.84 Ga (Thorkelson et al. 2005).

Wernecke Supergroup (Fig. 4), the lowest part of sequence A, was divided by Delaney (1981) into three groups with a combined thickness of at least 13 km (Delaney 1981; Thorkelson 2000). The lowest unit of the Wernecke Supergroup is the Fairchild Lake Group (≥4.6 km). It consists of metamorphosed siltstone, mudstone, sandstone, slate, and minor dolostone. The overlying Quartet Group (3.4 km) is lithologically similar but generally more siliceous, and the highest unit, the Gillespie Lake Group (≥4.7 km), consists primarily of shallow-water, variably stromatolitic, and algal-matted dolostone. The stratigraphic top of the supergroup is nowhere exposed. Whether the Wernecke Supergroup was deposited on a passive margin or in an intracratonic basin is uncertain (Thorkelson et al. 2001*b*). Deformation and metamorphism have converted parts of the Wernecke Supergroup to slate, phyllite, and schist. The Wernecke Supergroup may correlate with the lowest units of the Hornby Bay Assemblage in the Northwest Territories (MacLean and Cook 2004). In the Yukon, the Pinguicula Group, a younger succession within sequence A (ca. 1.38 Ga; Thorkelson et al. 2005), overlies the Wernecke Supergroup with angular unconformity (Wheeler 1954).

Racklan orogeny

Wheeler (1954) recognized a Precambrian orogenic event from the angular unconformity between the Pinguicula and Wernecke successions in the Rackla River area, 50 km south-southeast of the study area. Subsequent work has shown that this interval of deformation, named the Racklan orogeny (Gabrielse 1967; Eisbacher 1978, 1981; Cook 1992), occurred prior to 1.60 Ga (Thorkelson et al. 2001*a*). Brideau et al. (2002) demonstrated that the Racklan orogeny imposed a foliation (at greenschist grade), crenulations, and kink bands on the Wernecke Supergroup before Wernecke Breccia emplacement at 1.60 Ga. Significant deformation after brecciation and before Pinguicula deposition has not been identified. The maximum possible age of the Racklan orogeny is constrained by the age of Wernecke Supergroup deposition, i.e., probably < 1.84 Ga (Fig. 4) (Thorkelson et al. 2001*b*).

Fig. 1. Map showing the distribution of Paleoproterozoic Wernecke Supergroup, Yukon, Canada, and location of the study area.

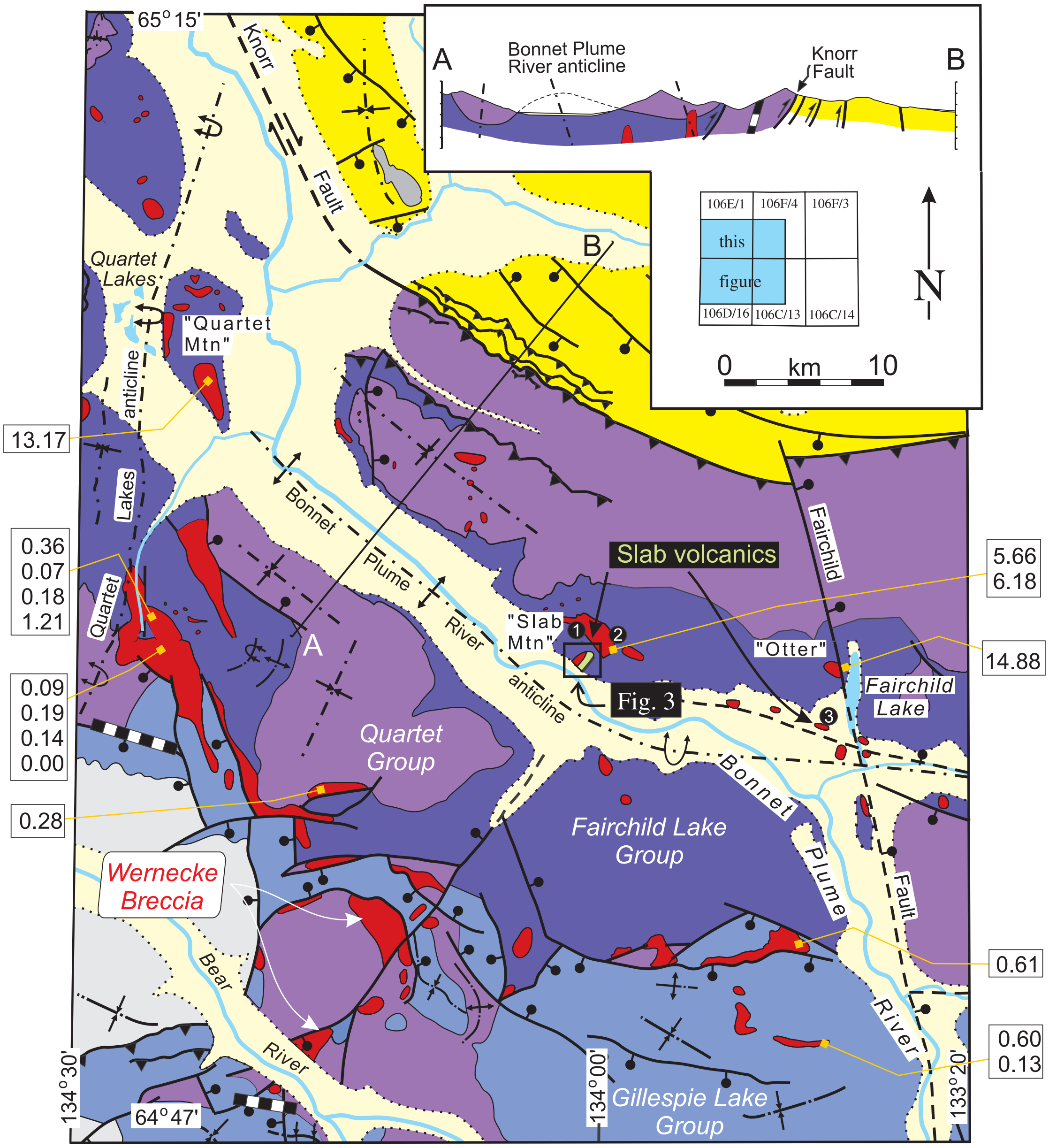


Similar geological relations exist in the Ogilvie Mountains (Fig. 2). Mercier (1989) recognized an unconformity between the Wernecke Supergroup and the overlying lower Fifteenmile Group in the Coal Creek Inlier of the Ogilvie Mountains and named the inferred deformational event the Fifteenmile orogeny. Brideau et al. (2002) equated this event with the Racklan orogeny, based on previous correlations of the lower Fifteenmile Group with the Pinguicula Group (Aitken and McMechan 1992; Abbott 1997). We concur and recommend that the term Racklan orogeny should apply to the pre-1.60 Ga deformational events in both the Wernecke and Ogilvie mountains.

Manifestations in the northern Wernecke Mountains

In the northern Wernecke Mountains, the Racklan orogeny generated at least two sets of major folds and three sets of fabrics and small folds. The major folds are visible on mountainsides and from patterns on 1 : 50 000 scale maps (e.g., Thorkelson et al. 2002). The earlier of the two sets trends north and verges to the east. The most prominent structure of this set in the vicinity of the study area is the Quartet Lakes anticline, which is tight and steeply inclined to overturned (Fig. 2). High-strain zones toward the core of this structure and in related, tight folds led to the local development of phyllite and schist (Thorkelson et al. 2005). These fold-controlled zones of intense deformation are exposed as bands of foliated rock up to 1 km wide (mainly Fairchild Lake Group) that grade into less deformed rock. The second fold set trends east and verges south (Fig. 2). The largest structure of this set is the Bonnet Plume River

Fig. 2. Simplified geology of the region near the study area at Slab Mountain. Three localities of Slab volcanics are indicated by white numbers in black circles. Major folds created by the Racklan orogeny include the Quartet Lakes anticline and the Bonnet Plume River anticline. Values beside the figure are Na_2O/K_2O (wt.%) data from Table 1 (plotted in Fig. 9). Simplified from Thorkelson et al. 2005. Inset includes cross section A–B and location of geological map with respect to National Topographic System maps.



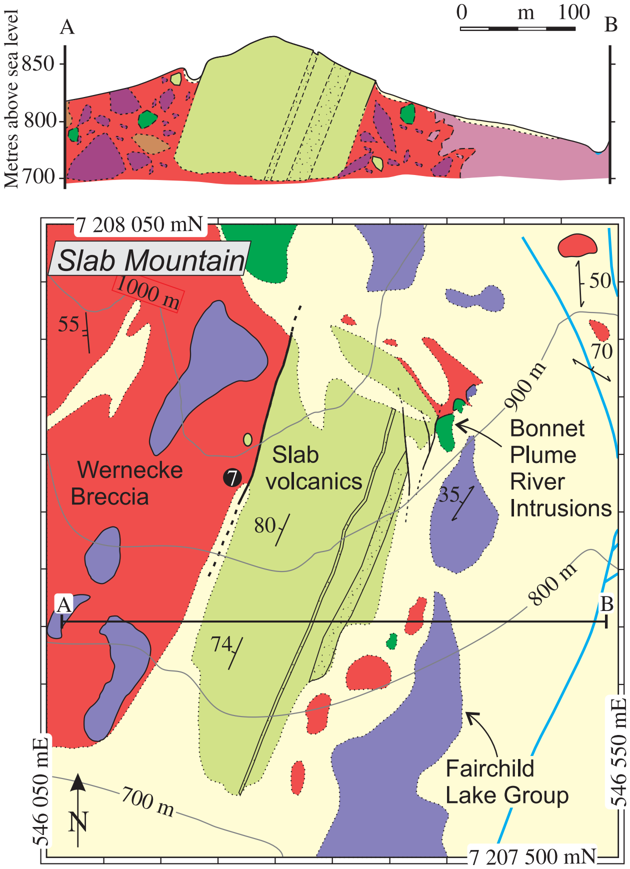
anticline, an open structure that extends for at least 45 km and is flanked by related synclines. The Bonnet Plume River anticline (possibly augmented by the earlier Quartet Lakes structures) probably developed at least 9 km of structural relief before eruption of a subaerial volcanic succession, the Slab volcanics (<1.60 Ga), as discussed later in the text.

The earliest Racklan-generated fabric is a foliation that ranges from a slaty cleavage in the Gillespie Lake and Quartet groups to a phyllitic–schistose fabric in the Fairchild Lake Group. The orientation of this foliation is commonly subparallel to the north-trending Quartet Lakes anticline, and the two features are probably cogenetic. The second fabric is a set of crenulations that locally defines a crenulation cleavage in the Quartet and Fairchild Lake groups (Fig. 5). The third is a set of kink bands superposed on the crenulations. All of these fabrics and structures are crosscut by, and are older than, Wernecke Breccia (1.60 Ga; Thorkelson et al. 2001*a*).

Wernecke Breccia

Wernecke Breccia is a collective term for numerous zones of hydrothermally generated breccia that crosscut the Wernecke Supergroup in the Wernecke and Ogilvie mountains (Figs. 1, 2) (Archer and Schmidt 1978; Bell 1986; Thorkelson and Wallace 1993; Thorkelson et al. 2001*a*, 2005). Individual breccia zones range in area from 0.1 to 10 km^2 (Thorkelson 2000), and many host Fe-oxide–Cu–Au mineral occurrences (Bell and Delaney 1977; Hunt et al. 2005). Titanite from

Fig. 3. Detailed geologic map and cross section of the study area, showing the eastern portion of Slab Mountain. Megaclasts of Fairchild Lake Group (light purple) are within Wernecke Breccia (red). Smaller clasts are not shown. Slab volcanics (light green) contain intercalations of sandstone and conglomerate (pattern). Bonnet Plume River Intrusions are shown in dark green. Location of Fig. 7 is shown. Note small clast of Slab volcanics in Wernecke Breccia near northwest margin of volcanic block. Overburden is shown in yellow. Heavy lines indicate faults, and light lines intrusive contacts. The cross section shows the relationship of Fairchild Lake Group, Slab volcanics, and Wernecke Breccia; and the vertical extent of Slab volcanics and clasts below surface is conjectural.



breccia matrix at Slab Mountain (Fig. 6) was dated at 1595 ± 5 Ma and is considered to be the age of regional breccia formation (Thorkelson et al. 2001*a*). Younger ages of ca. 1270 Ma (monazite; Parrish and Bell 1987) and 1380 Ma (rutile; Thorkelson et al. 2001*a*) have been interpreted as younger metasomatic overprints (Thorkelson et al. 2001*a*, 2005). Clast sizes in the breccia range from < 5 cm up to hundreds of metres and are variably metasomatized. The clasts were derived from the Wernecke Supergroup and, to a minor degree, the Bonnet Plume River Intrusions and Slab volcanics (Figs. 6–8). Country rock adjacent to breccia zones is metasomatised to varying degrees and distances. The alteration is typically characterized by secondary hematite, magnetite, quartz, albite, microcline, chlorite, muscovite, and carbonate (Bell and Delaney 1977; Thorkelson et al. 2001*a*). The contacts between zones of breccia and country rock range from sharp to gradational over distances of hundreds of metres (Bell and Delaney 1977; Thorkelson 2000; Thorkelson et al. 2001*a*).

Fig. 4. Time-stratigraphic column showing major Paleoproterozoic to Mesoproterozoic units and events in the Wernecke Mountains. The Racklan orogeny occurred prior to the undated Slab volcanics, which are older than Wernecke Breccia (1595 Ma). Gp., Group.

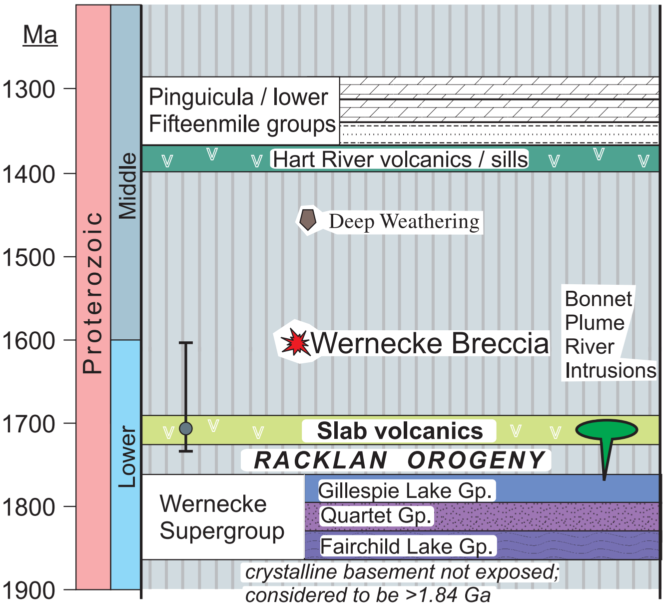
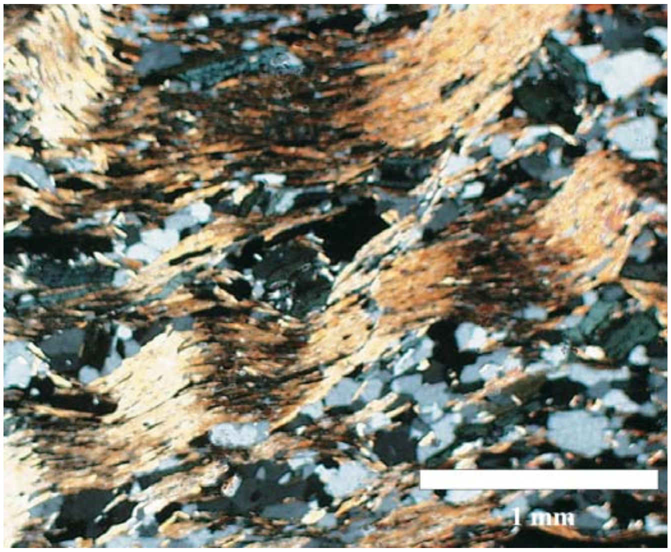


Fig. 5. Photomicrograph of chloritoid–muscovite–chlorite–quartz–schist from Fairchild Lake Group. Original foliation, defined by muscovite, has been superposed by microfolds.



Wernecke Breccia occurs as two visually distinct types, informally named “grey” breccia (Figs. 6, 7) and “colourful” breccia (cf. Laznicka and Gaboury 1988; Lane 1990; Thorkelson et al. 2001*a*). Grey breccia is volumetrically minor and occurs exclusively along the Bonnet Plume River anticline, which extends through the study area (Fig. 2). Colourful breccia has clasts that are altered by potassium feldspar and, to a lesser degree, earthy hematite and is commonly mottled red and pink. The matrix of both breccia types consists of varying proportions of hydrothermally precipitated feldspars, micas,

Fig. 6. Aerial view of Slab Mountain (view to northwest). Examples of Fairchild Lake Group megaclasts are shaded orange. Schist belt east of Slab Mountain consists of chloritoid–quartz–muscovite–chlorite–schist and grades abruptly into deformed metasiltstone lacking strong penetrative fabric. Areas shaded blue represent Bonnet Plume River Intrusions. Slab volcanic megaclast, outlined in white, is surrounded on all exposed sides by Wernecke Breccia. Black outline encloses areas of Wernecke Breccia. Star represents the location of 1.5 m clast of volcanics. Locations of Figs. 7 and 8 are shown as white numbers in black circles.

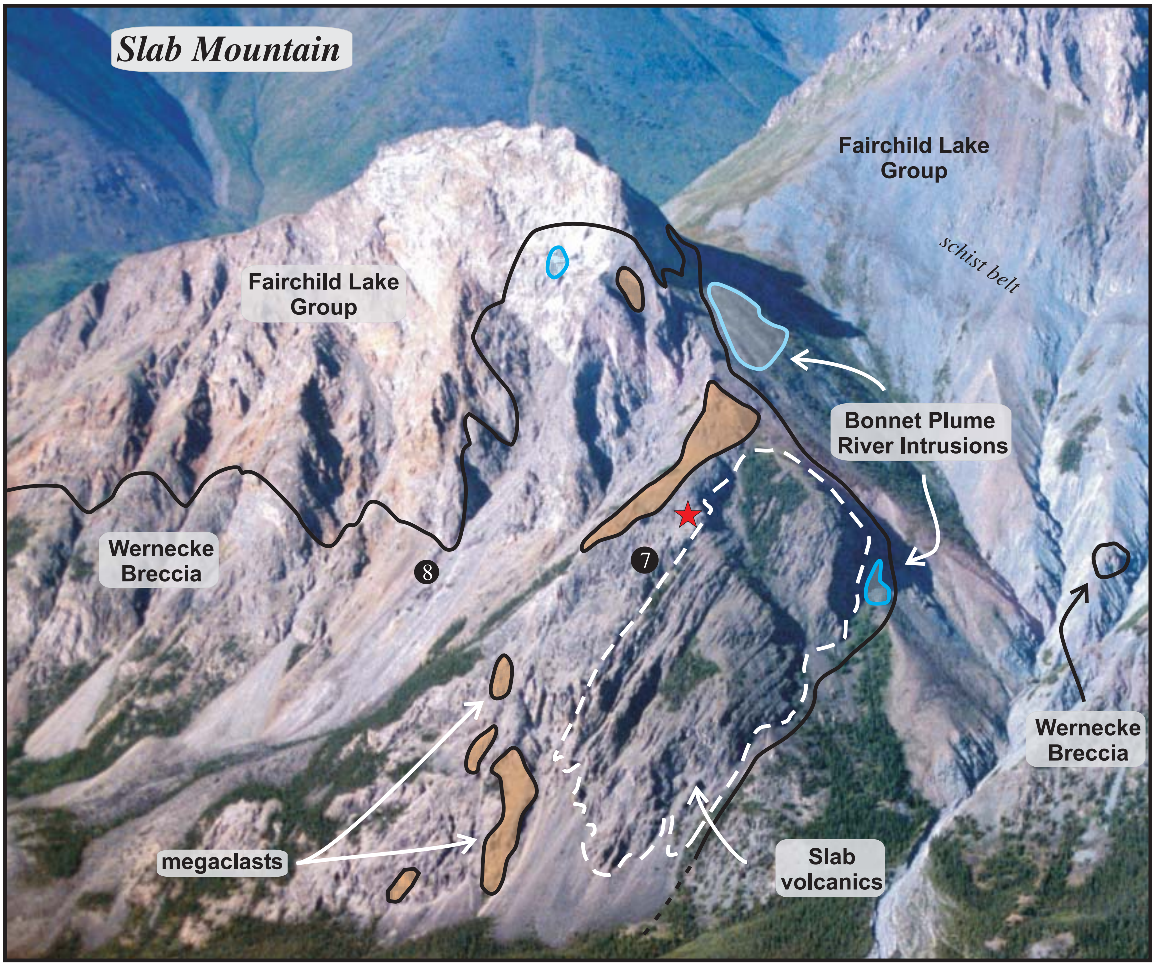


Fig. 7. Fairchild Lake Group megaclasts (circled) in grey-type Wernecke Breccia at Slab Mountain. Orientation of sedimentary layering varies among clasts. View is to the west from the highest (farthest west) lava flow in the Slab volcanic succession (marked in Figs. 3, 6). Geologist (centre left) for scale.

carbonate, quartz, magnetite, and specular hematite. Although the breccia types tend to occur separately, some locations show transitions between them.

Geochemical distinctions

The anomalous nature of the grey megabreccias is highlighted by high sodium concentrations relative to those in the colourful breccia zones. This difference was identified using 20 geochemical analyses reported in Thorkelson (2000) and one additional analysis (Table 1). Three breccia zones with unusually high Na_2O/K_2O ratios form a linear belt along the Bonnet Plume River valley. All are located in zones of grey Wernecke Breccia (Fig. 2) at or near localities where megaclasts of the Slab volcanics occur. Samples that lie outside the belt have lower Na_2O/K_2O ratios.

The sodic nature of the grey breccias is displayed in Fig. 9, in which Na_2O/K_2O and Na_2O/TiO_2 ratios from 20 breccia zones are graphed. TiO_2 is used as a denominator because of its relatively low mobility in aqueous fluids. The Na_2O/K_2O ratios range from 0 to 64, with the majority of samples clustering below 0.2. In this study the data are divided into

Table 1. Selected geochemical data obtained by X-ray fluorescence for 20 Wernecke Breccia zones in the northern Wernecke Mountains, Yukon (data from Thorkelson 2000; Laughton 2004).

Sample No.	TiO_2 (wt.%)	Na_2O (wt.%)	K_2O (wt.%)	Na_2O/K_2O	Na_2O/TiO_2
DT-92-138-1b	0.56	2.00	4.81	0.41	3.54
DT-92-149-8b	0.43	0.15	7.26	0.02	0.36
DT-92-149-7b	0.54	0.04	6.44	0.01	0.07
DT-92-149-6b	0.51	0.09	9.83	0.01	0.18
DT-92-149-5b	0.69	0.83	7.58	0.11	1.21
DT-92-143-1b	0.61	0.05	14.78	0.00	0.09
DT-92-142-5b	0.61	0.12	13.13	0.01	0.19
DT-92-52-4b	0.52	0.07	12.45	0.01	0.14
DT-92-62-2b	0.47	0.00	10.17	0.00	0.00
DT-93-11-3b	0.53	0.15	0.90	0.16	0.28
DT-92-160-3b	0.80	4.54	3.84	1.18	5.66
DT-93-7-1c	0.76	4.72	3.29	1.44	6.18
DT-93-126-1b	0.64	0.39	8.45	0.05	0.61
DT-93-49-1b	0.47	0.29	8.91	0.03	0.60
DT-93-107-2b	1.80	0.24	11.97	0.02	0.13
DT-93-159-1b	0.59	0.28	10.54	0.03	0.47
DT-93-159-3b	0.56	0.25	10.54	0.02	0.44
DT-94-36-1b	0.57	0.15	9.93	0.02	0.26
DT-93-57-1b	0.52	7.79	0.12	63.73	14.88
DT-03-9-1-1c	0.49	6.45	0.13	49.09	13.17

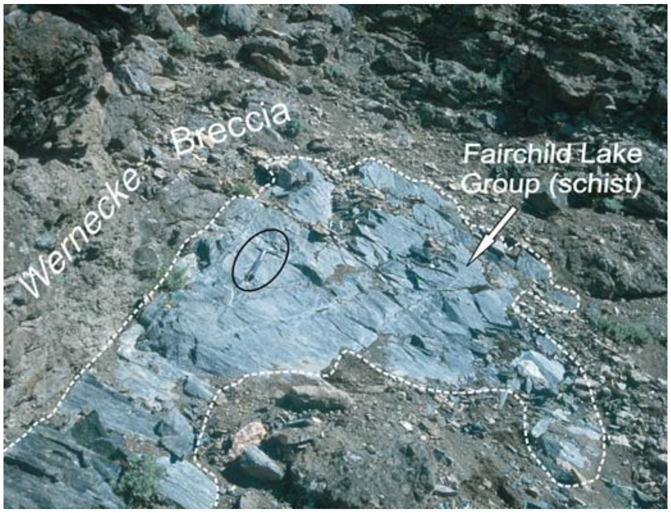
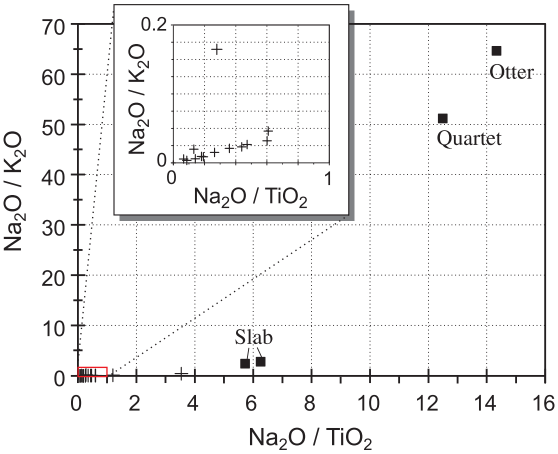


Fig. 8. Photograph of clast of Fairchild Lake Group crenulated, kinked schist (outlined) preserved in Wernecke Breccia at Slab Mountain. Fabrics in schist are truncated by enclosing breccia. Location shown in Fig. 6.

two groups based on low (<1) or high (>1) Na_2O/K_2O ratios. The breccia zones with high Na_2O/K_2O ratios occur at Slab Mountain (average 1.3), Quartet Mountain (64), and the Otter occurrence (49). These high ratios result primarily from high sodium contents (average 5.9 wt.%) and, to a lesser extent, low potassium contents (average 1.8 wt.%). For comparison, the zones that do not occur along the Bonnet Plume anticline average 0.3 wt.% sodium and 9.2 wt.% potassium.

Fig. 9. Bivariate plot of 20 Wernecke breccia samples (data in Table 1; locations of most sample sites shown in Fig. 2). Breccia zones along Bonnet Plume River anticline at Slab Mountain, Quartet Mountain, and Otter mineral occurrence are characterized by higher Na_2O/K_2O ratios. Crosses are values from other breccia zones in the Wernecke Mountains. Inset shows detail of points clustering near the origin.



Volcanic-clast-bearing belt of Wernecke Breccia

The breccia zone at Slab Mountain and the others which occur along the northeast side of the Bonnet Plume River anticline are different from most other breccia zones in the Wernecke and Ogilvie mountains in three main ways. First, they are grey (sodic) breccias. Second, the clast sizes tend to be larger (commonly several metres to tens of metres across;

Figs. 3, 7) than those in other breccia zones (typically <0.5 m). On the south side of Slab Mountain, for example, many clasts of Wernecke Supergroup are greater than 60 m across (Fig. 6). Third, they are the only known breccias to host clasts of the Slab volcanics.

Slab volcanics

The Slab volcanics (informal name) occur only as clasts within Wernecke Breccia (Figs. 2, 3, 6). The presence of volcanic rocks in Wernecke Breccia was first suggested by Bell and Delaney (1977) but remained unconfirmed until Thorkelson and Wallace (1993) described them as part of a regional mapping program. Subsequent descriptions were made by Thorkelson (2000) and Laughton et al. (2002). The volcanics consist of thin (average ~5 m) basaltic lava flows with a few epiclastic interbeds (Laughton et al. 2002). Scoreaceous and pahoehoe flow tops, along with an absence of pillow lava, indicate subaerial deposition (Thorkelson 2000; Laughton et al. 2002; Laughton 2004).

The clasts of the Slab volcanics are the only evidence of an otherwise completely eroded volcanic succession. The subaerial nature of the volcanics and the absence of volcanic rocks within the marine Wernecke Supergroup, despite excellent exposure and detailed stratigraphic analysis (Delaney 1981), strongly suggest that the volcanics were not deposited as part of the Wernecke succession (contrast with Hunt et al. 2005). These relations led Thorkelson (2000) to assign the Slab volcanics to their own stratigraphic position, above the Wernecke Supergroup and below the Pinguicula Group (Fig. 4).

Four occurrences of the Slab volcanics have been recognized at three separate localities in the Wernecke Mountains (Fig. 2). Two occurrences are at Slab Mountain (locality 1; Figs. 3, 6), a third is in a breccia zone on the ridge adjacent to Slab Mountain (locality 2), and a fourth is located ~10 km to the east of locality 2 (locality 3). A possible fifth locality is located 2 km farther east, 1 km southeast of Fairchild Lake (Fig. 2). At locality 1, the largest volcanic block is exposed on the eastern portion of Slab Mountain and is regarded as the main exposure of the Slab volcanics. The exposure is ~160 m × 380 m and is composed of 34 steeply dipping lava flows and a few intercalations of sandstone and conglomerate (Laughton 2004). Approximately 5 m above the uppermost lava flow of the main succession is a 1.5 m aphyric volcanic boulder (Fig. 3; represented by the star in Fig. 6). This boulder is engulfed by breccia and is a clast of lava from the Slab volcanics. Volcanic clasts found in float beneath breccia zones near Slab Mountain suggest that there are additional clasts of the Slab volcanics within Wernecke Breccia.

Locality 2 (Fig. 2) is on the ridge adjacent to Slab Mountain, ~1 km east of the main volcanic succession. At this locality, a fine-grained, amygdaloidal, and locally auto-brecciated fragment of lava measuring 2 m × 3 m is engulfed by breccia (Laughton et al. 2002). At locality 3, the Slab volcanics are exposed in a 150 m high cliff face that is continuous for approximately 500 m. Three separate 50 m wide blocks of dark grey volcanic rocks outcrop along the face. Each block is surrounded by large zones (>70 m) of Wernecke Breccia. An additional 2 m diameter rounded boulder of the Slab volcanics occurs in the breccia at the west end of the outcrop and appears to have been rounded by abrasion (Laughton et al. 2002). In all of these localities the volcanics are clearly megaclasts within Wernecke Breccia.

The former volcanic succession (source of the clasts) must have been at least 160 m thick (the thickness of the succession at Slab Mountain). This thickness and the apparently fluid nature of the constituent, thin pahoehoe lavas suggest that the succession extended laterally for > 1 km. Feeder dykes to the succession have not been located, and the position of the former volcanic centre remains unknown. Medium-grained gabbro and diorite of the 1.71 Ga Bonnet Plume River Intrusions occur at Slab Mountain and elsewhere in the Wernecke Mountains (Thorkelson et al. 2001*b*) but are coarser grained and less tabular than expected for feeder dykes (Fig. 3).

Geology of Slab Mountain and its bearing on orogenesis

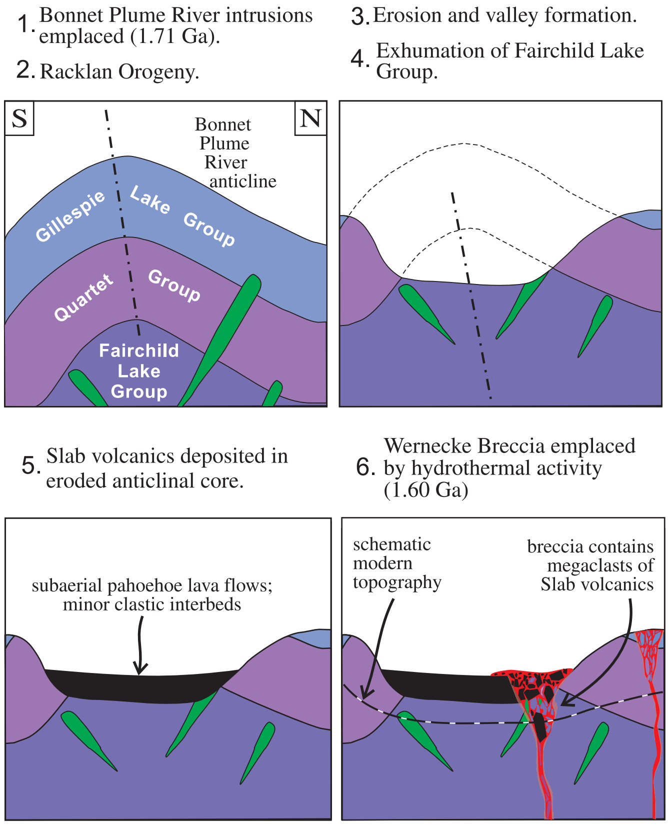
Geological framework

Key geological relationships at Slab Mountain (Hunt et al. 2002) (Figs. 3, 6) provide insight into the style and process of brecciation and constrain the timing and nature of the Racklan orogeny. The breccia zone at Slab Mountain is approximately 1 km × 4 km (Bell and Delaney 1977; Hunt et al. 2002), i.e., a medium-sized breccia zone compared with others in the Wernecke Mountains (Fig. 2). Titanite from the breccia zone yielded an age of 1595 ± 5 Ma (Thorkelson et al. 2001*a*). Clasts in this breccia zone were derived mainly from the Fairchild Lake Group (Fig. 10) and consist of metamorphosed siltstone (some with folds; Fig. 11) and crenulated, kinked schist (Figs. 5, 8). The orientations of structures in the clasts of schist and folded siltstone are random. Clast sizes range up to hundreds of metres (examples shown in Figs. 6, 7). Schist and metamorphosed siltstone of the Fairchild Lake Group host the breccia zone. The schist consists of chloritoid and local garnet porphyroblasts in a foliated groundmass of quartz, chlorite, and muscovite, indicating a peak temperature between 450 and 550 °C (Brideau et al. 2002). The foliation in the schist has been crenulated and subsequently kinked, indicating three separate deformational events. The inclusion of these clasts in the breccia demonstrates that the three phases of deformation recorded in the schist took place prior to brecciation.

Engulfment of volcanic megaclasts

The mechanism by which the volcanic blocks were broken away from their parent succession is likely to have been the force of venting of the hydrothermal fluids and subsequent gravitational collapse. In the prevalent model of Wernecke Breccia formation, brecciation occurred by expansion of hydrothermal solutions (Laznicka and Edwards 1979; Laznicka and Gaboury 1988; Hitzman et al. 1992), possibly leading to venting and discharge of rock material at the surface (Thorkelson et al. 2001*a*). The possibility of surface venting is supported by the work of Browne and Lawless (2001), who compiled data on hydrothermal eruptions and demonstrated that ejection of rocks during geiser-like eruptions is a common occurrence in hydrothermal fields. They noted sev-

Fig. 10. Cartoon showing the progression of Paleoproterozoic to Mesoproterozoic geological events leading to the geological relations of present-day Slab Mountain. (*a*) Inclined, open Racklan folding of Wernecke Supergroup to form the Bonnet Plume River anticline before 1.71 Ga (compare with cross section in Fig. 2; frame postdates earlier Racklan deformation and formation of Quartet Lakes anticline). (*b*) Intrusion of the Bonnet Plume River intrusions, denudation of the Wernecke Supergroup, and incisement of the anticline, 1.71–1.60 Ga. (*c*) Subsequent eruption of the Slab volcanics as valley-filling flows. (*d*) Emplacement of megabreccia at 1.60 Ga. Clasts in breccia are dominantly Fairchild Lake Group, but include Bonnet Plume River Intrusions and Slab volcanics. Note that exhumation removed the upper two units (Gillespie Lake Group and Quartet Group) and part of the lowest unit (Fairchild Lake Group) of Wernecke Supergroup (at least 9 km) from the Bonnet Plume River anticline before volcanism.



eral localities where tens to 100 km^3 of material have been ejected from large hydrothermal explosions, often leaving large maar-like pits surrounded by mounds and fields of rubble with maximum clast sizes commonly ranging from 0.25 to 0.75 km. The vents of explosive hydrothermal systems typically have a diatreme-like geometry, where the open vent (and crater) taper downwards into a narrow neck (Browne and Lawless 2001). Focal depths of hydrothermal vents typically do not exceed 450 m, despite the large volume of material ejected. In the case of the Wernecke breccias, the depth of the breccia zones (>1000 m, based on the vertical extent of breccias exposed on mountainsides), the clast sizes (commonly >50 m in the grey breccias), and the size of the breccia province (nearly 50 000 km^2) all tend to indicate that the hydrothermal system was large compared with modern analogues.

Fig. 11. Isoclinal folds in Fairchild Lake Group siltstone clast within Wernecke Breccia at Slab Mountain. Fold structure is truncated by enclosing breccia. Lens cap (7 cm) for scale.

We propose a model in which the violence of the hydrothermal eruptions in the Slab Mountain area was sufficient to breach the surface, crack large blocks of the Slab volcanics (which may have been the highest unit in the crust), and eject enough material to momentarily create large volumes of open space in the vents and necks. Once broken from the main succession, blocks of the volcanic succession (and the underlying Wernecke Supergroup) apparently tumbled into the vent from above and became enveloped by a steaming mass of milling, settling breccia. According to Bell (1989) and Hunt et al. (2005), collapse may have been partly controlled by dissolution of evaporites. Precipitation of minerals from hydrothermal solutions cemented the breccia mass. Aprons of ejecta probably formed around the vents but were subsequently removed by extensive erosion that occurred after brecciation (Thorkelson et al. 2001*a*).

The volcanic succession that supplied the volcanic clasts probably lay no more than a few hundred metres above the level of the breccia zone exposed at Slab Mountain. (Fig. 10). This scenario is preferred because it is difficult to envisage how a block with the size of the main occurrence could sink more than a few hundred metres into the crust. Open space may have been abundant in the explosion pits and the immediately underlying breccia vents (cf. Browne and Lawless 2001). At greater depths, however, in the neck zones, the space available for megaclasts to settle into would be greatly reduced and, in our view, insufficient to accommodate the continued descent of megaclasts.

In support of this model, we note that down-dropped remnants of eroded cover sequences have been recognized in similar geological environments at other localities. At the Olympic Dam mine in South Australia, Oreskes and Einaudi (1990) and Reeve et al. (1990) described down-dropped fragments of tuffaceous sediments, volcanic conglomerates, and volcanic fragments (centimetres to tens of metres in size) within a hydrothermal breccia that has been correlated with Wernecke Breccia (Thorkelson et al. 2001*a*). As noted for Slab Mountain, these blocks are abundant in the upper portions of the breccia system and represent a since-eroded cover sequence. The breccia zone is considered to have been generated in a near-surface environment where breccias were exposed and eroded (Oreskes and Hitzman 1993). These relations are similar to those in crater facies of kimberlites which contain clasts of cover sequences that are no longer preserved in the stratigraphy (e.g., Hubbard 1967; Cookenboo et al. 1998; McCracken et al. 2000).

An alternative view of the origin of the volcanic megaclasts is that the source rocks existed as a volcanic formation within the Wernecke Supergroup (Hunt et al. 2005). An argument against this option is the lack of volcanic strata exposed anywhere within the Fairchild Lake Group or elsewhere in the Wernecke Supergroup, despite excellent exposure and extensive geological mapping and mineral exploration. Another possibility is that the volcanic clasts originated from a volcanic succession beneath the exposed levels of the Wernecke Supergroup. In this case, the hydrothermal fluids would have had to entrain and transport the volcanic megaclasts upwards for hundreds of metres, or perhaps kilometres, a scenario that we consider implausible.

Constraints on orogenesis

The geological relations in the study area are best explained by a sequence of events in which the Wernecke Supergroup was deformed, metamorphosed, uplifted, denuded, overlain by the Slab volcanic succession, and then hydrothermally brecciated. Three lines of reasoning support this sequence, particularly for the region along the Bonnet Plume River anticline. The first is that the Wernecke Breccia zone at Slab Mountain is a near-surface breccia that crosscuts the Fairchild Lake Group, the lowest unit of the Wernecke Supergroup. This observation requires that at least 9 km of overlying strata were eroded to expose the Fairchild Lake rocks. The second is that the volcanic megaclasts were most likely down-dropped into near-surface vents of Wernecke Breccia along the axis of the Bonnet Plume River anticline. In this interpretation, the Slab volcanic succession lay above the Fairchild Lake Group no more than a few hundred metres above the sites where the megaclasts became lodged. The third is that no clasts of the Gillespie Lake Group or Quartet Group have been identified in the Slab Mountain breccia. If the Slab volcanics were erupted above the Gillespie Lake Group, and if the volcanic megaclast were down-dropped by kilometres into the Fairchild Lake Group, then clasts of the Gillespie and Quartet groups would also be expected in the Slab Mountain breccia. We conclude that the Slab volcanics were deposited after deep erosion of the Wernecke Supergroup. Specifically, the amount of structural relief in the region must have been at least 9 km (nearly as much as it is today) because the stratigraphically higher Quartet and Gillespie Lake groups were subjected to the same deformational events and also host zones of Wernecke Breccia (Fig. 2). Some of that relief may have been generated by an earlier phase of Racklan deformation involving the Quartet Lakes anticline and related structures.

Breccia depth and alkalinity

The foregoing model of vent-facies brecciation sheds light on the differences between the grey and colourful breccia zones. The grey breccias (Slab Mountain, Quartet Mountain, and Otter occurrence; Fig. 2) apparently developed in shallow environments at or very near to the surface and incorporated gravitational fall-back megaclasts. In contrast, the colourful breccias may have formed farther underground and incorporated mainly locally derived wallrock. The sodic nature of the grey breccias (described earlier) likely resulted from processes associated with shallow or surface hydrothermal activity and may reflect the lower temperatures and pressures of formation.

The reason for the higher concentrations of sodium and lower concentration of potassium in breccias that formed nearer to the surface (e.g., at Slab Mountain) may be attributed to feldspar–fluid exchange (Pollard 2001). Experimental studies suggest that Na/K ratios increase in chloride-bearing fluids in equilibrium with two alkali feldspars as temperatures decrease (Orville 1963; Fournier and Truesdell 1973; Truesdell 1984). This may explain the higher Na_2O/K_2O ratio in breccia zones along the Bonnet Plume River anticline which likely occurred under conditions of lower temperature compared with those of other breccia zones in the Wernecke Mountains.

Our correlation of high Na/K ratios with inferred shallow breccia zones differs from an explanation provided by Hitzman et al. (1992). Based on two breccia localities, Hitzman et al. developed a hydrothermal model in which Wernecke Breccia zones display sodic alteration at depth, potassic alteration at higher levels, and sericitic and silicic alteration at very shallow depths. This model differs from the physical and chemical observations presented in this paper for the breccia zone at Slab Mountain. The model presented by Hitzman et al. may not accurately represent the geological conditions at the time of brecciation because it is partially based on the premise that the Wernecke Supergroup was still flat-lying and 4.5 km thick at the time of brecciation. Those conditions contrast with results of stratigraphic and structural studies which have demonstrated that the Wernecke Supergroup is at least 13 km thick and that Racklan deformation and subsequent erosion preceded brecciation (Delaney 1981; Thorkelson 2000). The arguments laid out in this paper call into question the idea that breccias observed higher in Wernecke Supergroup stratigraphy were necessarily emplaced closer to the paleosurface. The reverse relationship apparently occurs in the study area where the stratigraphically lowest unit, Fairchild Lake Group, hosts the shallowest breccia zones.

Implications for landscape morphology

Although the geomorphology of the Wernecke Mountains region in Proterozoic time cannot be deciphered in detail, we offer some suggestions based on the distribution of shallow breccia zones in the study area. The presence of vent-facies breccia zones exclusively along the Bonnet Plume River anticline, but deeper breccia zones in flanking regions, implies that a paleovalley followed the anticline (Fig. 10). This relation may be explained by preferential erosion of cleaved and friable rock of the Fairchild Lake Group relative to the more resistant rock of the Quartet Group and especially the Gillespie Lake Group. A similar situation exists today, with the Bonnet Plume River flowing along the anticlinal axis while flanking areas rise to form mountains more than 1 km above the valley floor (Fig. 2). A paleovalley close to the present Bonnet Plume River valley would have provided a depocentre for the Slab volcanics. As shown in Fig. 10, this model explains why only the grey breccia zones, located along the Bonnet Plume River corridor, show evidence of near-surface conditions.

Regional correlation of Racklan structures

Racklan structures recognized in the subsurface east of the Cordillera are similar to those exposed in the Wernecke Mountains (e.g., Cook and MacLean 1995; Sevigny et al. 1991; Clark and Cook 1992). In the subsurface, possible Racklan structures appear mainly as large broad folds with smaller structural complexities beneath an angular unconformity (Clark and Cook 1992; Dredge Mitchelmore and Cook 1994; Cook and MacLean 1995). Deep-crustal reflection studies combined with gravity and magnetic investigations suggest that Racklan structures were generated from compression of the Wernecke Supergroup against a crustal-scale ramp in the subsurface (Clark and Cook 1992). Line 3 of the Lithoprobe Slave – Northern Cordillera Lithospheric Evolution (SNORCLE) transect (located to the south of the study area but along regional structural strike) shows large-amplitude folds in the subsurface, in strata possibly correlative with the Wernecke Supergroup (Cook et al. 2004).

The Racklan orogeny in the Wernecke Mountains correlates favourably with the intracratonic Forward orogeny in the Northwest Territories to the east (Cook and MacLean 1992, 1995; Rainbird et al. 1996; Abbott 1997; Thorkelson et al. 2001*b*, 2003). Forward deformation is evident from surface exposures and seismic reflection studies. The deformation affected the Paleoproterozoic Hornby Bay assemblage (Kerans et al. 1981), the lower parts of which may be correlative with the Wernecke Supergroup (MacLean and Cook 2004). Similar to the Racklan orogeny, the Forward orogeny involves at least two phases of deformation. An early phase of the Forward orogeny (Cook and MacLean 1995) has been dated at 1663 Ma (Bowring and Ross 1985) and was followed by regional uplift accompanied by partial to complete erosion of the Hornby Bay Group (Cook and MacLean 1995). If Racklan deformation did occur at 1663 Ma, then the Slab volcanics must have been deposited between 1663 and 1595 Ma and could not have been comagmatic with the Bonnet Plume River Intrusions.

Conclusions

Our investigations of Proterozoic rocks in the Wernecke Mountains of the northern Yukon have clarified relations among orogenesis, exhumation, volcanism, and hydrothermal brecciation. At Slab Mountain, the main study site, the Fairchild Lake Group of the Wernecke Supergroup hosts a zone of Wernecke Breccia (1595 Ma). This breccia zone belongs to a subset of Wernecke Breccia which is distinguished from other zones by its grey colour and higher Na/K ratios. These sodic breccias are interpreted as the near-surface (vent) facies of Wernecke Breccia. The breccia zone contains megaclasts of country rock, including a large block (160 m × 380 m) of subaerial lava flows named the Slab volcanics. The volcanic clasts are interpreted as fragments of an inferred volcanic formation that was deposited above the Wernecke Supergroup after Racklan orogeny and exhumation of the Fairchild Lake Group. Apparently, the volcanism followed at least 9 km of erosion in the vicinity of Slab Mountain. At the time of volcanism, the morphology of the land surface may have been similar to what it is today, i.e., rugged topography with the lowest strata exposed in the core of a deeply incised valley. The Racklan orogeny in the Yukon may correlate with the ca. 1663 Ma Forward orogeny in the Northwest Territories. If this correlation is correct, then the age of the Slab volcanics lies between the age of orogenesis and the age of brecciation, 1663–1595 Ma.

Acknowledgments

Funding was provided by the Yukon Geological Survey, Northern Studies Training Program grants to JRL, and Lithoprobe and Natural Sciences and Engineering Research Council of Canada grants to DJT. We thank Richard Ernst for discussions of Proterozoic magmatism, reviewers Larry Aspler and Murray Hitzman for constructive comments, and Associate Editor Kevin Ansdell for helpful suggestions.

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