Geology of the Spanish Lake area, south-central British Columbia

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Abstract

In 2015, the British Columbia Geological Survey initiated a multi-year program to establish a regional stratigraphic framework for the Nicola Group (Triassic), the principal volcano-sedimentary component the Quesnel arc terrane in central and southern British Columbia. Field studies in the Spanish Lake area in 2017 were part of this program, and focused on a predominantly fine-grained sedimentary unit in the eastern part of the Nicola belt. This unit (assemblage one of the Nicola Group) consists mainly of Middle Triassic siltstone and argillite, but also includes pillowed basalt that has geochemical characteristics of mid-ocean ridge basalt, and volcanic sandstone that becomes predominant upsection. Assemblage one forms a northwest-trending belt that dips steeply, youngs to the southwest, and is stratigraphically overlain by Late Triassic Nicola Group assemblages. It, and adjacent Nicola rocks, are on the partially preserved forelimb of a major southwest-verging fold that probably formed in the Middle Jurassic. To the northeast, assemblage one is juxtaposed against Middle Triassic rocks of the Slocan Group, across a fault that postdates the southwest-verging fold. Assemblage one is inferred to represent the remnants of a back-arc basin that formed east of the Nicola arc. The Middle Triassic age of the basin implies that the Nicola arc, although represented mainly by Late Triassic rocks, was initiated during, or before, the Middle Triassic.

Keywords: Nicola Group, Slocan Group, Quesnel terrane, Middle Triassic, Upper Triassic, volcanic arc, back-arc basin, slate, siltstone, volcanic sandstone, pyroxene-phyric basalt

1. Introduction

Quesnel terrane (Fig. 1) is an important metallogenic belt, best known for its prolific porphyry Cu±Au-Mo-Ag deposits. These deposits are part of a Mesozoic arc complex that includes Triassic to Jurassic volcanic and sedimentary rocks, and related calc-alkaline and alkalic intrusions. The Nicola Group (Triassic) is the principal volcano-sedimentary component of this Mesozoic arc complex in central and southern British Columbia. In 2015, the British Columbia Geological Survey initiated a multi-year field-based program to establish a regional stratigraphic framework for the Group. This framework, combined with space-time-composition patterns of associated plutons, will contribute to a better understanding of the architecture of the arc, and improve the geologic framework within which to interpret the settings and controls of mineral occurrences.

Initial investigations in 2015, covered the entire width of Quesnel terrane in the Bridge Lake-Quesnel River area (Fig. 1), and established a preliminary stratigraphic framework for the Triassic rocks that included four informal Nicola Group assemblages and a separate assemblage to the east assigned to the Slocan Group (Schiarizza, 2016). In 2016, the eastern part of the Nicola Group and the adjacent Slocan Group were studied in the Stump Lake-Salmon River area, south of Kamloops (Fig. 1; Schiarizza, 2017). Fieldwork in 2017, in the northeast corner of the large 2015 study area, near the town of Likely, is summarized herein. This work focuses on an eastern, fine-grained sedimentary component of the Nicola Group (assemblage one of Schiarizza, 2016), and its relationship to the main part of the Nicola arc to the west, and the Slocan Group to the east.

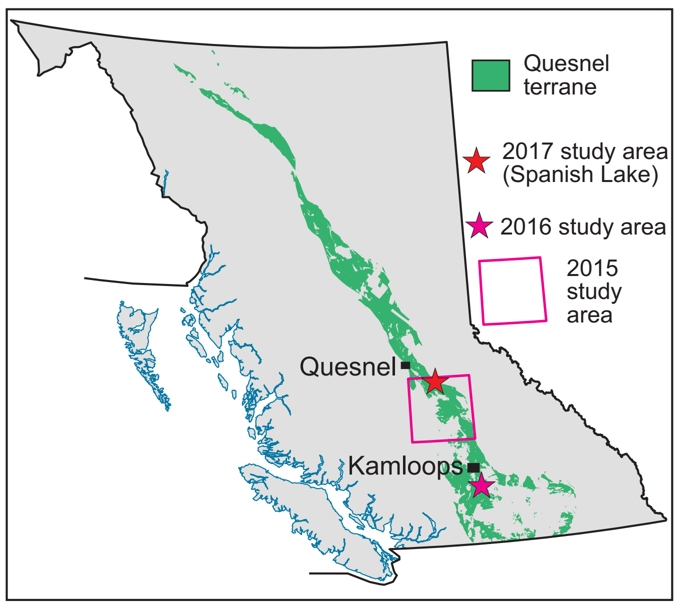

Fig. 1. Distribution of Quesnel terrane in British Columbia, with locations of the areas studied in 2015, 2016 and 2017 for the Nicola stratigraphic framework project.

2. Setting

The Spanish Lake area is on the north side of eastern Quesnel Lake, east of the community of Likely. It is in the Quesnel Highland physiographic province (Holland, 1976), within the traditional territories of the Secwepemc, Esk'etemc, Tsilhqot'in, and Lhtako Dené First Nations. Networks of forestry and logging roads provide easy access to most parts of the area. These originate in Likely, which is connected to 150 Mile House, on Highway 97, by a paved road. Spanish Lake is in the northern part of the Quesnel Lake (93A) NTS map sheet; the geology was described by Campbell (1978), with revisions and updates by Struik (1983, 1988), Rees (1987), Bloodgood (1990), and Panteleyev et al. (1996).

The Nicola Group (Triassic), the predominant component of the Quesnel arc terrane, forms a northwest-trending belt that, in the Likely region, is 25 to 55 km wide (Fig. 2). This belt also includes abundant Late Triassic to Early Jurassic arc intrusions (only the very largest are shown on Fig. 2), and fault-bounded panels of Lower to Middle Jurassic arc-derived siliciclastic sedimentary rocks (Dragon Mountain succession of Logan and Moynihan, 2009). The Nicola Group is flanked to the east by a belt of Triassic sedimentary rocks, mainly black phyllite, siltstone, and quartz sandstone, which is assigned to the Slocan Group (Schiarizza, 2016). These rocks are underlain by a narrow, discontinuous belt of mafic schists (Crooked amphibolite) and, farther east, a wide belt of suspected Proterozoic and Paleozoic quartzites and pelitic schists (Snowshoe Group) that are locally cut by Devono-Mississippian granitic rocks (Quesnel Lake gneiss). Cache Creek terrane, including late Paleozoic to early Mesozoic basalt, chert, limestone, siltstone, and ultramafic rocks, is west of the Nicola belt and is interpreted as an accretionary complex that formed during the subduction that generated the Quesnel magmatic arc. Younger rocks, in and adjacent to the Nicola belt, include Middle Jurassic and Early Cretaceous granitic intrusions, Eocene volcanic and sedimentary rocks, Oligocene-Pliocene conglomerate and sandstone (along the Fraser River), and flat-lying Neogene and Quaternary basalt (Fig. 2).

The Snowshoe Group is part of pericratonic Kootenay terrane, commonly interpreted as a deep-water facies deposited along the western margin of ancestral North America (Colpron and Price, 1995; Nelson et al., 2013). The Quesnel Lake gneiss (Ferri et al., 1999), and age-equivalent volcanic and plutonic rocks of the Eagle Bay assemblage to the south (Schiarizza and Preto, 1987; Paradis et al., 2006), reflect initiation of arc magmatism along the continental margin in the Devono-Mississipian. The Crooked amphibolite, commonly included in Slide Mountain terrane, has been interpreted as oceanic crust that was thrust eastward above pericratonic rocks in the Early Jurassic (Rees, 1987) or Late Permian-Early Triassic (McMullin et al., 1990). The Slocan Group is part of a Triassic siliciclastic basin that was either carried eastward with the Crooked amphibolite on an Early Jurassic thrust (Rees, 1987), or was deposited unconformably above the Crooked amphibolite and the Snowshoe Group after emplacement of the Crooked amphibolite on a Permo-Triassic thrust (McMullin et al., 1990).

The Nicola Group in the Likely region (Fig. 2) is subdivided into four informal assemblages following Schiarizza (2016). Most widespread are Carnian-early Norian volcanic sandstones, with local basalt flows and breccias, assigned to assemblage two. Younger rocks are exposed in the central part of the Nicola belt, reflecting a broadly synclinal architecture. These include a succession of basalt flows and related breccias (assemblage three), and an upper unit (assemblage four) characterized by polymictic conglomerate beds containing hypabyssal and plutonic rock fragments that are intercalated with sandstone, basalt and andesite. The oldest component of the Nicola Group (assemblage one, the focus of fieldwork in 2017) is a Middle Triassic siltstone-sandstone unit juxtaposed against the Slocan Group along the east edge of the Nicola belt (Fig. 2).

3. Geologic units in the Spanish Lake area

The Spanish Lake map area is underlain mainly by four parallel northwest trending units: the Slocan Group and assemblages one, two, and three of the Nicola Group (Figs. 3, 4). Structurally beneath the Slocan Group, in the northern part of the map area, are exposures of Crooked amphibolite, Snowshoe Group, and Quesnel Lake gneiss, which were examined in a cursory manner. Mafic to intermediate dike rocks are prominent locally, but do not form mappable units at the scale of Figure 3.

3.1. Snowshoe Group

The Snowshoe Group is exposed on the eastern edge of the study area (Fig. 3). These rocks are structurally overlain by the Crooked amphibolite to the north and northwest, but may be in direct contact with the Slocan Group across an unexposed contact that marks the south side of the belt (Fig. 3). The Snowshoe Group consists mainly of light grey, light brownish-grey weathered, fine- to medium-grained biotite-muscovite-quartz schist. Locally it includes biotite-muscovite quartzite, which commonly occurs as layers, 1-10 cm thick, separated by micaceous partings (Fig. 5). The Snowshoe Group is not dated here, or anywhere else in the region, but is inferred to be mid-Paleozoic and/or older, because it is cut by Devono-Mississippian granite of the Quesnel Lake gneiss.

3.2. Quesnel Lake gneiss

Two separate bodies of foliated granitic rock crop out in the study area, one in the Snowshoe Group along the east edge of the area, and one structurally beneath the Crooked amphibolite in the northwest. Both units are included in the informal Quesnel Lake gneiss, but they are lithologically distinct. Rees (1987) referred to the eastern body as the 'eastern Quesnel Lake gneiss', and the other, together with other nearby bodies of similar composition (Fig. 2), as the 'western Quesnel Lake gneiss'. The eastern Quesnel Lake gneiss is a moderately to strongly foliated, medium-grained, equigranular rock comprising grey feldspar and quartz, with discontinuous foliae

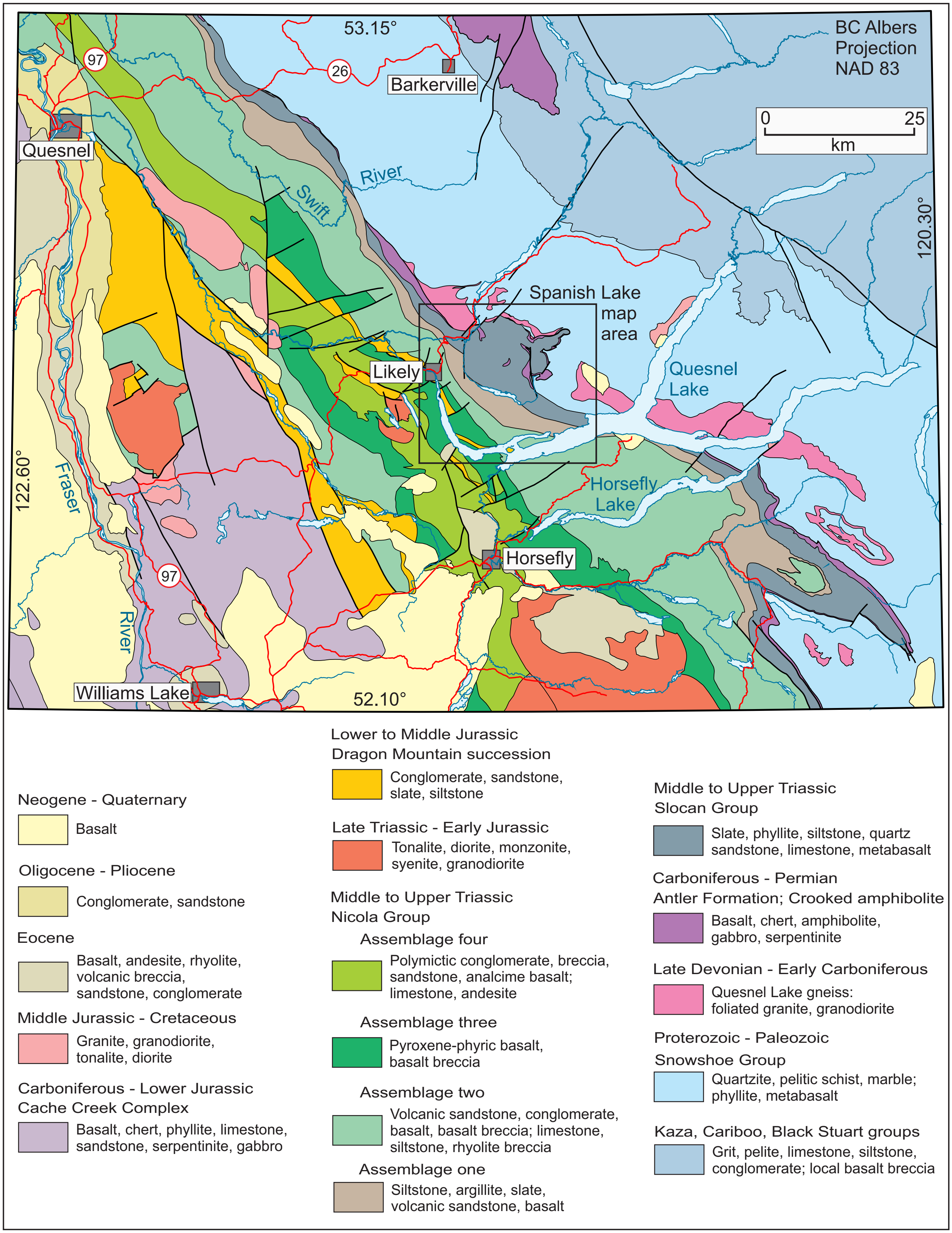

Fig. 2. Geological map of the Likely region, showing location of the Spanish Lake map area. Geology mainly from Logan et al. (2010) and Schiarizza (2016).

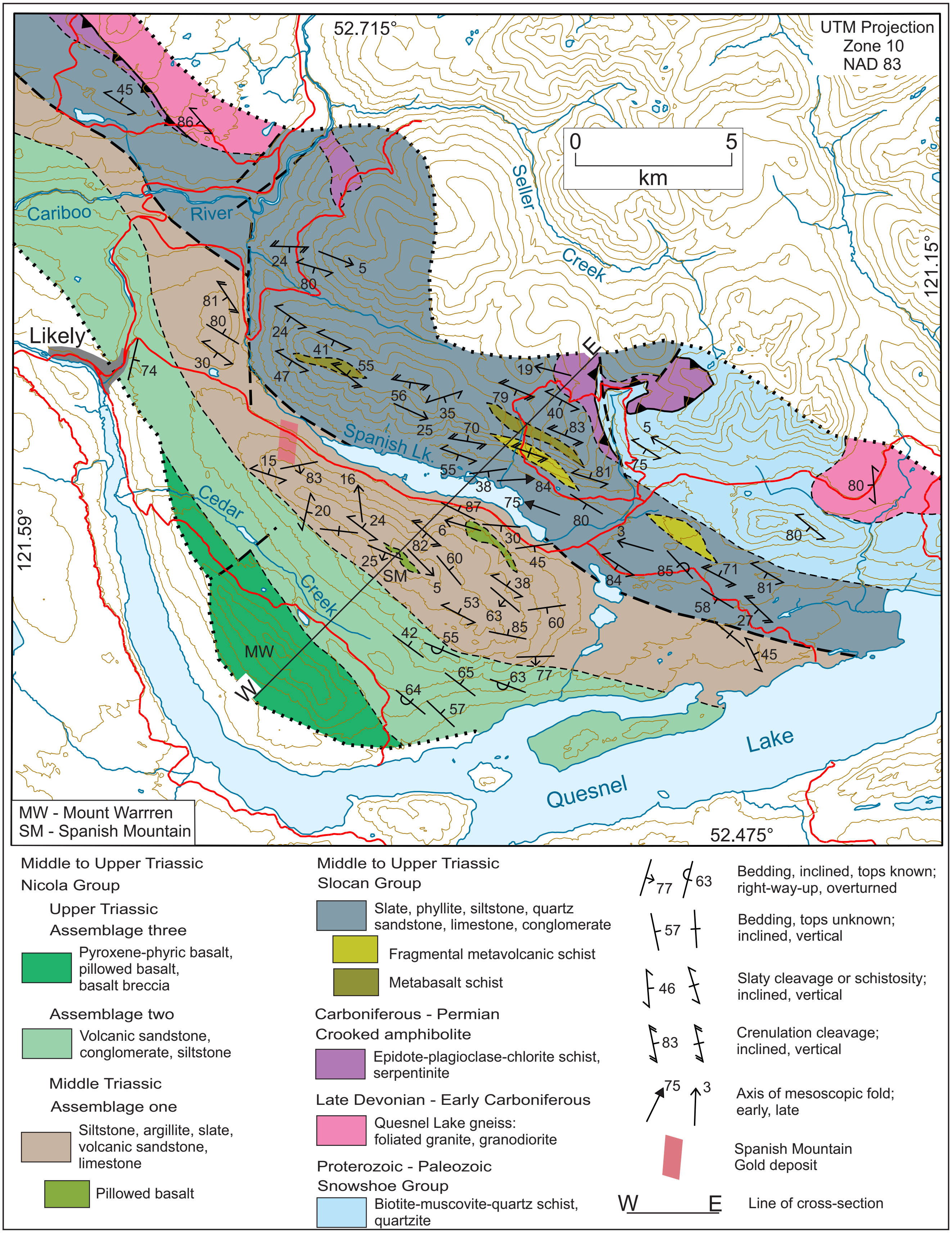

Fig. 3. Geology of the Spanish Lake map area. Geology based on 2015 and 2017 fieldwork, with some information from Rees (1987) and Bloodgood (1990).

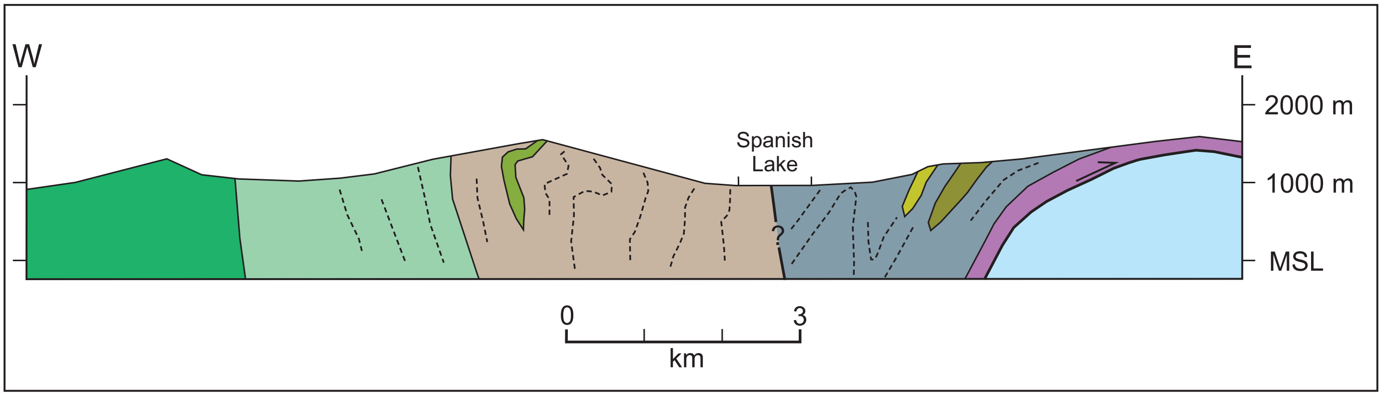

Fig. 4. Schematic vertical cross-section along line E-W shown on Figure 3.

Fig. 5. Platy quartzite, Snowshoe Group, 4.5 km northeast of Spanish Lake.

Fig. 6. Foliated granodiorite, eastern Quesnel Lake gneiss, 11.5 km east-northeast of Spanish Lake.

of biotite and epidote (Fig. 6). In contrast, the western Quesnel Lake gneiss contains large (several cm) augen of K-feldspar enclosed in a strongly foliated, coarse-grained matrix of quartz-feldspar-muscovite-biotite. Ferri et al. (1999) reported a U-Pb zircon crystallization age of 357.2 ±1.0 Ma for a different body of western Quesnel Lake gneiss, just north of the study area.

3.3. Crooked amphibolite

The Crooked amphibolite crops out in several areas scattered across the northern part of the Spanish Lake area, where it forms a narrow unit structurally beneath the Slocan Group, and structurally above the Snowshoe Group and Quesnel Lake gneiss. It consists mainly of medium to dark green chlorite schist (Fig. 7), but locally includes isolated exposures of dark grey-green serpentinite. The predominant schists consist mainly of chlorite and plagioclase, accompanied by various combinations and proportions (trace to abundant) of epidote, biotite, actinolite, quartz, and ankerite. A strong schistosity, defined by oriented chlorite, may be parallel to a lenticular compositional layering (metamorphic segregation), defined

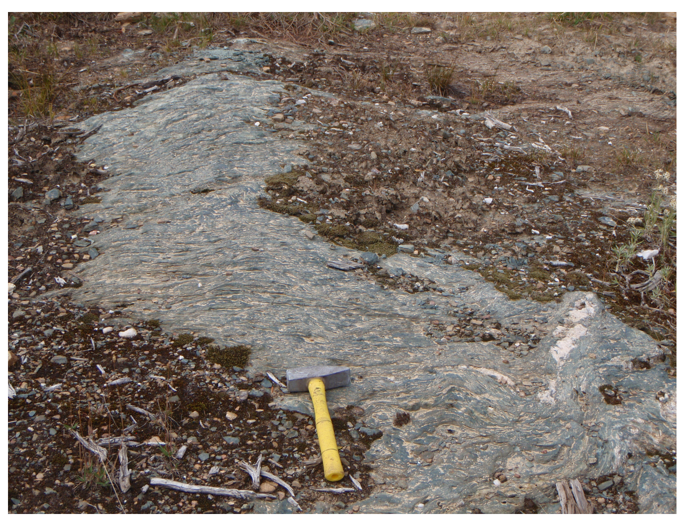

Fig. 7. Chlorite schist, Crooked amphibolite, 3.9 km northeast of Spanish Lake.

by dark chlorite-rich lenses alternating with lighter coloured plagioclase-rich lenses. This compositional layering occurs on a scale of 1 to 5 mm, and may be accentuated by parallel veins and lenses of quartz±epidote and/or ankerite.

The Crooked amphibolite is undated. The predominant chlorite schists have compositions that suggest a mafic volcanic protolith, and analyses presented by Rees (1987) show geochemical signatures that suggest derivation from ocean floor tholeiites. On this basis, and a similar structural relationship to underlying pericratonic rocks, the Crooked amphibolite is correlated with mafic volcanic units of the Antler Formation (Struik and Orchard, 1985) and Fennell Formation (Schiarizza and Preto, 1987) of Slide Mountain terrane, and inferred to be Upper Paleozoic (Rees, 1987).

3.4. Slocan Group

The Slocan Group forms a single continuous belt that extends from southeast to northwest across the Spanish Lake map area (Fig. 3). The Slocan designation follows Schiarizza (2016); the same rocks were mapped as unit uTrp by Struik (1983), the black phyllite unit by Rees (1987), and include unit Tra and part of unit Trb of Bloodgood (1990). The predominant rocks types are phyllite, slate, and siltstone, but the group also includes quartz sandstone, limestone, and volcanic and volcaniclastic rocks. The base of the group was observed at one locality, about 3.5 km northeast of the east end of Spanish Lake, where it rests above the Crooked amphibolite across a contact that dips at a moderate angle to the southwest, more or less parallel to the well-developed schistosity in both units. The southwest contact of the group is an inferred fault that places it against assemblage one of the Nicola Group.

The Slocan Group consists mainly of dark grey to black slate and phyllite, commonly with laminae and thin beds of light grey-weathered siltstone (Fig. 8), and locally with thin- to medium-beds of dark grey slaty siltstone (Fig. 9) or dark grey silty to micritic limestone. Rare intraformational conglomerates contain angular to subrounded fragments, as large as 12 cm, of siltstone and laminated siltstone in a dark grey phyllite matrix (Fig. 10). Locally the phyllite is medium greenish-grey and chloritic, pale grey-green and very siliceous, or pale silvery-green with large orange-weathered ankerite porphyroblasts.

Fine-grained, thin- to medium-bedded quartzose sandstone forms a section several tens of metres thick in the interior part of the Slocan belt, about 4.5 km east-southeast of Spanish Lake (see Fig. 4 of Schiarizza, 2016). A succession of coarser grained siliciclastic rocks occurs on the ridge north of the west end of Spanish Lake, and includes schistose sandstone, gritty sandstone, and small pebble conglomerate (Fig. 11). The clasts are predominantly polycrystalline quartz, plagioclase, and fine-grained sericite-quartz schist (similar in composition and texture to the schistose matrix). Calcareous sericite-quartz

Fig. 9. Dark grey slate with more massive bed of slaty siltstone, Slocan Group, 1 km northeast of the east end of Spanish Lake.

Fig. 8. Dark grey phyllite with light grey siltstone laminae, Slocan Group, north side of Spanish Lake.

Fig. 10. Framework-disrupted intraformational conglomerate containing laminated siltstone fragments in a dark grey phyllite matrix, Slocan Group, 500 m north of the east end of Spanish Lake.

Fig. 11. Gritty metasandstone, Slocan Group, 3 km north of the west end of Spanish Lake.

schist with relict grains and granules of monocrystalline and polycrystalline quartz also occurs in an isolated set of exposures just north of the east end of Spanish Lake. Locally these schists are conglomeratic (Fig. 12), with flattened angular fragments, up to 10 cm long, of mainly pale grey, fine-grained sericite-quartz schist with ovoid grains, ≤1 mm, of polycrystalline quartz, commonly rimmed with calcite. These ovoid grains may be relict amygdules, indicating a felsic volcanic origin for the clasts.

Mafic volcanic rocks map as two lenses within the Slocan Group, one about two km northeast of eastern Spanish Lake, the other on the ridge north of the west end of the lake (Fig. 3). These rocks are pale to medium green plagioclase-actinolite-biotite-chlorite (±epidote±calcite) schists that commonly contain 1-2 mm clots of actinolite-biotite-chlorite that may be altered mafic phenocrysts, and locally contain flattened amygdules (1-5 mm) of quartz±biotite. Logan and Bath (2006) analyzed samples from the eastern lens (their Spanish Lake samples), and showed that they display geochemical characteristics of subduction-generated arc basalt, but are distinct from the arc basalts of the main part of the Nicola belt to the west. Additional samples, from both lenses, were collected in 2017; geochemical results are pending.

Fig. 12. Conglomeratic sericite-quartz schist, with possible felsic volcanic clasts, Slocan Group, 200 m northeast of the east end of Spanish Lake.

Volcaniclastic rocks are mapped in two places, one just south of the eastern volcanic lens, and the other about three kilometres to the east-southeast (Fig. 3). These rocks are mainly plagioclase-quartz-biotite-chlorite-sericite schists that contain coarse (up to 20 cm), flattened, poorly sorted metavolcanic fragments (Fig. 13). The fragments are commonly pale to medium grey-green, and most are similar in composition and texture to the mafic metavolcanic rocks of the two volcanic lenses.

The Slocan Group in the Spanish Lake area is mainly Middle Triassic, based on conodonts extracted from narrow limestone lenses that were sampled at three localities from a generally poorly exposed part of the group, 3 to 5 km east of Spanish Lake. Struik (1988) reported two collections from this area, one Ladinian and the other unrefined Middle Triassic, and Panteleyev et al. (1996) report a collection that is late Anisian-early Ladinian (sample 87MB-01-02). Struik (1988) also reported an unrefined Triassic age for a collection from Beehive Island, just offshore in Quesnel Lake, near the southwest margin of the unit.

Fig. 13. Schist with volcanic fragments, Slocan Group, 1.3 km north of the east end of Spanish Lake.

3.5. Nicola Group

Rocks underlying the southwest half of the Spanish Lake map area are included in the Nicola Group, and are assigned to three units following the nomenclature of Schiarizza (2016). These are, from northeast to southwest, assemblage one, assemblage two, and assemblage three.

3.5.1. Assemblage one

Assemblage one forms a northwest trending belt that is in fault contact with the Slocan Group to the northeast, and is overlain by assemblage two to the southwest, across a steeply dipping, locally overturned, stratigraphic contact. Assemblage one consists mainly of siltstone, but also includes argillite, slate, feldspathic sandstone, limestone, and basalt.

The predominant rock type is medium to dark grey siltstone that typically occurs as thin (1-10 cm) planar to lenticular beds separated by phyllosilicate partings and/or thin interbeds of dark grey slate (Fig. 14). Some intervals of dark grey slaty siltstone are not distinctly bedded, but may contain poorly defined laminae or thin beds. Dark grey argillite is also common, and occurs as thin (1-4 cm) lenticular beds separated by dark greenish-grey chloritic partings, or as thicker indistinctly bedded units with an imperfect slaty cleavage, and rusty porphyroblasts of ankerite and/or pyrite (Fig. 15). Medium to dark grey limestone is rare, and forms layers or lenses, <1-2 m thick, intercalated with siltstone.

Green to grey, fine- to coarse-grained sandstone occurs locally in the northeastern part of assemblage one, and becomes more common at higher stratigraphic levels to the southwest. It occurs as thin- to thick-bedded intervals that are commonly intercalated with dark grey to green siltstone (Fig. 16). The sandstones are notably similar to those of assemblage two. They are feldspathic, but also include grey to green volcanic lithic grains and altered mafic minerals or lithic grains. Volcanic quartz forms a minor but conspicuous component of some sandstone beds on the low ridge east of Likely (Fig. 3).

Basalt forms two lenses within assemblage one, on Spanish Mountain and on the low slopes south of the east end of Spanish Lake (Fig. 3). The basalt is grey to green, massive to pillowed (Fig. 17), locally variolitic, and composed mainly of a low-grade metamorphic mineral assemblage that includes

Fig. 14. Thin-bedded siltstone, assemblage one of the Nicola Group, 2 km east-southeast of Spanish Mountain.

Fig. 16. Coarse-grained sandstone interbedded with siltstone, assemblage one of the Nicola Group, 1.5 km east of Spanish Mountain.

Fig. 15. Slaty argillite, assemblage one of the Nicola Group, 3 km northwest of Spanish Mountain.

Fig. 17. Pillowed basalt, assemblage one of the Nicola Group, Spanish Mountain.

calcite, plagioclase, epidote, chlorite, and actinolite. A sample analyzed by Logan and Bath (2006) from the lens south of eastern Spanish Lake (their Spanish Mountain sample) displays geochemical characteristics of normal mid-ocean ridge basalt, a result confirmed by a sample collected from the same unit in 2015. Additional samples from both lenses were collected in 2017; results are pending.

Assemblage one is mainly Middle Triassic, based on conodonts extracted from thin limestone lenses. Struik (1988) reported that a conodont collection from the northeast side of the assemblage on the shore of Quesnel Lake is early-middle Anisian (early Middle Triassic), and that another collection, also from the north shore of the lake but near the southwest contact of the assemblage, is late Ladinian to Carnian (Middle to Late Triassic). A third collection, from the central part of the assemblage, 2 km south of the east end of Spanish Lake, is early Anisian (Panteleyev et al., 1996; sample 87MB-16-02).

3.5.2. Assemblage two

Assemblage two forms a northwest-trending belt of sandstones, with local siltstone and conglomerate, southwest of assemblage one. Where best exposed, north of Quesnel Lake, the rocks in this belt young to the southwest, and appear to be conformable with adjacent siltstones and sandstones of assemblage one. However, the beds are commonly overturned, dipping steeply to the northeast (Fig. 3).

Assemblage two consists almost entirely of grey to green, fine- to coarse-grained, locally gritty, volcanogenic sandstone. Grains of feldspar are the predominant constituent, and are accompanied by feldspathic and mafic lithic grains, and variably altered mafic minerals (mainly pyroxene). The sandstone commonly forms distinct thin to thick beds that locally display normal grading. Thin beds of green to grey siltstone, or dark grey argillite, may be interbedded with the sandstones (Fig. 18), or form the tops of graded sandstone beds. Pebble conglomerate (Fig. 19) locally forms thin to very thick beds intercalated with sandstone. The subangular to subrounded clasts are mainly pyroxene±plagioclase-phyric and aphyric mafic volcanic rocks, but locally include feldspar porphyry, microdiorite, and siltstone.

Fig. 18. Thin- to medium-bedded volcanic sandstone, with thin layers of siltstone and argillite, assemblage two of the Nicola Group, 5 km east of Mount Warren.

Fig. 19. Pebble conglomerate, assemblage two of the Nicola Group, 4.7 km southeast of Mount Warren.

Assemblage two has not been dated in the Spanish Lake map area, but assemblage one, directly beneath the contact on the north shore of Quesnel Lake, has yielded late Ladinian to Carnian (Middle to Late Triassic) conodonts (Struik, 1988). Rocks in the upper part of assemblage two, 20 km south of Spanish Lake, have yielded Late Carnian conodonts (Panteleyev et al., 1996; sample 88AP-10/3-C2), and correlative rocks elsewhere in the region are mainly Carnian to lower Norian (Schiarizza, 2016).

3.5.3. Assemblage three

Assemblage three is exposed in the southwest corner of the Spanish Lake map area, on and adjacent to the ridge system that includes Mount Warren (Fig. 3). It consists mainly of medium to dark green, brown-weathered, amygdaloidal pyroxene-phyric basalt that is typically massive, but locally pillowed (Fig. 20). Euhedral to subhedral pyroxene phenocrysts (commonly 1-10 mm) form 5-25% of the rock. Ovoid to amoeboid amygdules, filled with various combinations of quartz, epidote, calcite and chlorite, are typically <1-2 mm, but locally are as large as 2 cm. Small (1-2 mm) plagioclase phenocrysts are present in some exposures, and plagioclase laths may also be evident in the epidote-calcite-altered groundmass.

Basalt breccia, consisting of pyroxene porphyry fragments in a matrix of plagioclase, pyroxene and small lithic grains (Fig. 21), is associated with basalt flows near the Mount Warren summit. The breccias contain coarse (<1-20 cm) angular to subrounded fragments and vary from matrix to clast supported. The fragments are exclusively pyroxene porphyry, but show considerable textural variation (size and proportion of pyroxene phenocrysts, presence or absence of plagioclase phenocrysts and amygdules). Although some could be flow

Fig. 20. Pillowed pyroxene-phyric basalt, assemblage three of the Nicola Group, Mount Warren.

Fig. 21. Pyroxene porphyry breccia, assemblage three of the Nicola Group, 500 m northwest of Mount Warren.

breccias, it is suspected that they are mainly locally derived epiclastic deposits.

The contact between assemblage three and assemblage two is not exposed, nor particularly well constrained. It is inferred to be a steeply dipping, possibly overturned, stratigraphic contact (Fig. 4), based on regional relationships showing that assemblage three rests stratigraphically above assemblage two, and the structure in the westernmost exposures of assemblage two, where overturned beds dip steeply northeast (Fig. 3). Assemblage three is not well dated, but is inferred to be Norian based on its regional stratigraphic position (Schiarizza, 2016), between assemblage two (Carnian-Norian) and assemblage four (upper Norian-Rhaetian).

4. Dikes and sills

A suite of dioritic dikes and sills intrudes assemblage one of the Nicola Group on and around the Spanish Mountain ridge system. Most of these intrusions are fine-grained, equigranular hornblende diorite, but porphyritic varieties, with phenocryst of plagioclase, are common. More felsic dikes are also present, but rare, and contain phenocrysts of plagioclase, hornblende, biotite and quartz. A characteristic feature of these intrusions is the presence of sparse to abundant mafic to ultramafic xenoliths, <1-3 cm acoss, including biotite hornblendite and pyroxenite. Rhys et al. (2009) reported that, at the Spanish Mountain gold prospect, just west of Spanish Lake (Fig. 3), sills and dikes of this suite are affected by all phases of deformation, alteration and quartz veining that affect the host rocks of assemblage one. Four separate intrusive bodies yielded U-Pb zircon ages ranging from 185.6 ±1.5 Ma to 187.3 ±0.8 Ma (Rhys et al., 2009). These ages, the predominant dioritic composition, and the characteristic ultramafic xenoliths, suggest that the Spanish Mountain dikes and sills are related to a suite of ultramafic-mafic intrusions that cut Nicola and Slocan rocks in the Canim Lake area, 90 km SE of Spanish Lake. Diorite from one of these intrusions (Iron Lake complex) yielded a zircon U-Pb age of 190.4 ±0.5 Ma, and diorite from another (Aqua Creek complex) yielded a zircon U-Pb age of 184.0 ±0.4 Ma (Schiarizza et al., 2013).

Most other dikes and small intrusive bodies in the Spanish Lake area are suspected to be Triassic. These include pyroxene porphyry dikes, similar to the basalts of assemblage three, that locally cut siltstone and sandstone of assemblages one and two of the Nicola Group, and fine-grained, weakly foliated and chlorite-altered hornblende diorite that cuts the Slocan Group near the metabasalt lens north of the west end of Spanish Lake.

5. Structural geology

The Spanish Lake map area comprises two contrasting structural domains, separated by an inferred fault under Spanish Lake and adjacent low-lying areas. The eastern domain includes the Slocan Group and underlying Paleozoic rocks, and preserves northeast-verging folds cut by younger southwest-verging structures. The western domain encompasses the three Nicola Group assemblages, which define a southwest-younging, commonly overturned panel that forms part of the forelimb of a major southwest-verging fold. Mesoscopic structural fabrics are unevenly developed across the area, with a distinct break at the domain boundary. All units of the Slocan Group display a strong penetrative cleavage or schistosity, commonly cut by a younger well-developed crenulation cleavage. A penetrative cleavage is locally developed in fine-grained rocks of assemblage one, but is unevenly developed and generally not evident in the volcanic rocks or sandstones, and is absent from all Nicola rocks of assemblages two and three. The break in cleavage intensity coincides with a slight difference in metamorphic grade, as schists and phyllites of the Slocan Group commonly contain biotite, whereas slates of the Nicola Group (assemblage one) do not.

The structure of the Slocan Group is characterized by bedding that dips at moderate angles to the southwest, a penetrative phyllitic cleavage or schistosity (S1) that also dips to the southwest, more or less parallel to, or steeper than, the associated bedding, and a well-developed crenulation cleavage (S2) that dips at moderate to steep angles to the northeast. Mesoscopic folds (F1) associated with S1 schistosity are rare, but those observed plunge steeply to the northwest, southeast, or east. At least one medium-scale, northeast-verging F1 fold is documented by a panel of rocks, several hundred metres wide, that is subvertical and youngs to the east. Other variations in bedding and S1 orientations are due to folds related to the northeast-dipping S2 crenulation cleavage, with axes that plunge gently to the northwest or southeast (Fig. 22). Locally, fold axes of similar orientation are related to a crenulation cleavage that dips gently to the southwest. Relationships are unclear, but it is suspected that this crenulation cleavage is younger than the predominant northeast-dipping crenulation cleavage (S2).

Beds of assemblage one dip at moderate to steep angles and young to the southwest and contain a locally developed slaty cleavage that dips mainly to the northeast, at shallower angles than bedding (Fig. 23). The beds most commonly dip to the southwest, and are right-way-up, but locally dip northeast and are overturned. Local panels of gently dipping, right-way-up beds are inferred to form the short limbs of asymmetric folds (Fig. 4). Actual observations of mesoscopic folds that might be related to the slaty cleavage were rare, and these showed highly variable shapes and orientations, with axes plunging northwest, north, northeast, east and southeast. Younger folds, which deform the slaty cleavage, plunge gently northwest or southeast, and may display a weakly-developed axial planar crenulation cleavage that dips steeply, mainly to the southwest.

Fig. 22. Phyllite and siltstone of the Slocan Group, deformed by northwest plunging folds with axial planar crenulation cleavage (parallel to pencil), 400 m north of the east end of Spanish Lake. View is northwest; crenulation cleavage dips northeast, bedding and slaty cleavage dip mainly southwest.

Fig. 23. Platy argillite, assemblage one of the Nicola Group, 3.5 km northwest of Spanish Mountain. View is to the north; beds dip about 45º northeast and are presumed to be overturned, weak slaty cleavage is refracted, but dips about 20º northeast.

Steeply dipping, southwest-facing rocks in the western part of assemblage one pass southwestward, apparently conformably, into well-bedded rocks of assemblage two that dip mainly to the northeast, but are overturned. The transition, farther southwest, into assemblage three is also inferred to be a steeply dipping, southwest-younging stratigraphic contact (Fig. 4), although bedding was not observed in this unit.

The structure of the Nicola Group in the Spanish Lake area, comprising steeply dipping, in part overturned, west-younging beds cut by more gently northeast-dipping cleavage (seen only in assemblage one), indicates that it occupies the forelimb of a major southwest-verging fold. This structure was recognized by Rees (1987), who referred to the fold as the Spanish Lake anticline. It is suspected that the slaty cleavage related to this fold correlates with the well-developed, northeast-dipping S2 crenulation cleavage in the Slocan Group. Structures related to the older northeast-verging folds that are prevalent in the Slocan Group were not recognized in the Nicola Group, although vestiges of such structures might be present in poorly-understood mesoscopic folds rarely observed in assemblage one.

The contact between the Nicola Group (assemblage one) and Slocan Group is inferred to be a fault, because it juxtaposes two units of the same age, and also juxtaposes two contrasting structural domains. Rees (1987) thought that the contact was stratigraphic, and folded by the southwest-verging Spanish Lake anticline, whereas Struik (1988), recognizing that the two units were in part the same age, inferred that it was an east-directed thrust fault (Spanish thrust) that carried the Nicola Group above the Slocan Group. The Spanish thrust is apparently an important structure regionally (Struik, 1988; Bloodgood, 1990), but it is suspected, mainly due to the contrasting structural domains, that the contact in the Spanish Lake area is a younger structure. This fault records northeast-side-up displacement, such that the older Spanish thrust was eroded on the northeast side of the fault, and is in the subsurface on the southwest side. It might be a northeast-dipping thrust or reverse fault that is younger than, but perhaps broadly related to, the southwest-verging folds in the area.

6. Discussion

6.1. Paleogeographic setting of assemblage one

Assemblage one of the Nicola Group consists, in large part, of siltstone and argillite, with local accumulations of pillowed basalt that has geochemical characteristics of mid-ocean ridge basalt. The main link to the Nicola Group is provided by fine- to coarse-grained volcanic sandstones that are intercalated with the finer-grained rocks and become more abundant at higher stratigraphic levels. These sandstones are lithologically similar to volcanic sandstones of assemblage two, a major component of the Nicola Group regionally, that conformably overlies western exposures of assemblage one. These characteristics, and its location on the east side of the Nicola arc, which was generated by eastward subduction, suggest that assemblage one preserves the remnant of a back-arc basin. The Middle Triassic age for most rocks of assemblage one indicates that the Nicola arc, although represented mainly by Late Triassic rocks, was initiated during, or before, the Middle Triassic.

The Slocan Group represents a siliciclastic basin, in part the same age as assemblage one, east of the Nicola Group. The relationship and proximity of this basin to the back-arc basin of assemblage one is uncertain. However, the presence of arc volcanic rocks in the Slocan Group suggests a possible link. Arc volcanism may have been initiated in the Slocan basin in the Middle Triassic, then migrated westward, with formation of the assemblage one back-arc basin, to its current position and main axis of Late Triassic arc magmatism. Evaluating this scenario will require more precise ages for specific sedimentary and volcanic units in the Nicola and Slocan groups.

6.2. Structural correlations

The Nicola Group in the Spanish Lake area occurs on the partially-preserved, southwest-younging forelimb of a large southwest-verging fold. The Slocan Group, to the northeast, includes northeast-verging folds that are deformed by a younger set of structures related to a northeast-dipping crenulation cleavage. It is suspected that this crenulation cleavage, and related folds, are the same age as the southwest-verging fold in the Nicola Group, and therefore that the southwest-verging structures postdate the northeast-verging structures. This pattern was recognized by Rees (1987), who interpreted the Slocan and Nicola groups as an intact, west-younging stratigraphic succession that had been carried eastward, on an Early Jurassic thrust fault at the base of the Crooked amphibolite, and then deformed by southwest verging folds in the Middle Jurassic.

The structural pattern recognized by Rees (1987) in the Spanish Lake area, comprising east-directed thrusting of Slide Mountain and Quesnel terranes above pericratonic rocks, followed by west-directed folding and thrusting of this previously assembled thrust stack, has also been recognized elsewhere in the region (Ross et al., 1985; Brown et al., 1986; Schiarizza and Preto, 1987; Murphy et al., 1995). Commonly, most of the early stage east-directed convergence was inferred to have occurred along an Early Jurassic thrust fault at the base of the Crooked amphibolite (Ross et al., 1985; Brown et al., 1986). However, Struik (1988) noted that the Slocan Group and assemblage one of the Nicola Group are the same age, and he postulated that they were juxtaposed across an east-directed thrust fault (the Spanish thrust) that probably had significant displacement and regional extent. This interpretation suggested that a significant component of the convergence between Quesnel terrane and adjacent pericratonic rocks occurred along the Spanish thrust. Furthermore, McMullin et al. (1990) proposed that the thrust fault at the base of the Crooked amphibolite is a Permo-Triassic structure, suggesting that the thrust-stacking of Slide Mountain and Quesnel terranes above pericratonic rocks was a protracted event, with the Spanish thrust as the main post-Triassic structure.

The Spanish thrust is not exposed in the Spanish Lake map area, where it is inferred to have been offset by a younger structure that forms the contact between the Slocan Group and assemblage one of the Nicola Group. Nevertheless, the contrast in sandstone composition and basalt geochemistry between these two age-equivalent units suggests significant lateral displacement, and it is inferred, following Struik (1988), that this displacement occurred on the east-directed Spanish thrust. The east-verging folds within the Slocan Group formed in the footwall of this thrust fault and are probably related. They probably formed in the late Early Jurassic, based on age constraints for easterly-verging structures along and near the eastern margin of Quesnel terrane elsewhere in southern (Murphy et al., 1995) and central (Nixon et al., 1997) British Columbia.

The partially preserved southwest-verging fold in the Nicola Group is correlated with a set of prominent southwest-verging structures documented throughout the region, which deform pericratonic rocks and structurally overlying rocks of Slide Mountain and Quesnel terranes (Ross et al., 1985; Schiarizza and Preto, 1987; Ferri and Schiarizza, 2006). The fold in the Spanish Lake area is markedly similar to a large west-verging anticline that deforms the Fennell Formation (Slide Mountain terrane) and underlying pericratonic rocks in the Clearwater-Barriere area, 150 km southeast of Spanish Lake (Schiarizza and Preto, 1987). This fold postdates structural emplacement of the Fennell Formation above pericratonic rocks, and has a steeply-dipping, west-facing forelimb more than 10 km wide. At deeper structural levels, in pericratonic rocks, these folds are represented by large southwest-verging nappes with amplitudes of several tens of kilometres (Ferri and Schiarizza, 2006). The southwest-verging folds formed mainly in the early Middle Jurassic, based in part on a 174 ±4 Ma U-Pb age for metamorphic titanite from near Quesnel Lake (Mortensen et al., 1987).

7. Conclusions

Assemblage one of the Nicola Group forms a northwest-trending belt of Middle Triassic rocks that dips steeply, youngs southwest, and is stratigraphically overlain to the southwest by younger, Late Triassic assemblages of the Nicola Group. It, and adjacent Nicola assemblages are on the partially preserved forelimb of a major southwest-verging fold that probably formed in the Middle Jurassic. Assemblage one is juxtaposed against Middle Triassic rocks of the Slocan Group to the northeast, across a fault that postdates the southwest-verging fold, and probably accommodated northeast-side-up displacement.

Assemblage one consists mainly of siltstone and argillite, but also includes pillowed basalt that has geochemical characteristics of mid-ocean ridge basalt, and volcanic sandstones, similar to sandstones elsewhere in the Nicola Group, that become more abundant at higher stratigraphic levels. It is inferred to comprise the remnants of a back-arc basin that formed on the east margin of the Nicola arc. The Middle Triassic age of the basin implies that the Nicola arc, represented mainly by Late Triassic rocks, was initiated during, or before, the Middle Triassic.

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