VOLCANIC STRATIGRAPHY AND PETROLOGY OF THE MID-CRETACEOUS
SPENCES BRIDGE GROUP NEAR KINGSVALE, SOUTHWESTERN BRITISH COLUMBIA

by
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ABSTRACT

Mid-Cretaceous volcanic rocks called the Spences Bridge and Kingsvale groups by previous authors lie in the Nicoamen Structural Depression which extends from near the town of Princeton for 215 km north-northwestward to the settlement of Pavilion where it is cut by the Fraser Fault System. The lower part of the sequence, comprising various volcaniclastic rocks and lavas, was formally named the Spences Bridge Group after a type locality near the town of Spences Bridge. The rocks subsequently defined as Kingsvale Group are now recognized as being part of the succession originally called Spences Bridge Group; the term Kingsvale Group is abandoned. A distinctive sequence of mostly amygdaloidal andesite, overlying the Spences Bridge rocks between Kingsvale and Spences Bridge, was correlated by previous workers with the Kingsvale Group; those strata are herein formally named Spius Formation. The Spences Bridge Group is expanded to include Spius Formation as its upper part; the composite sequence previously known as the Spences Bridge Group is now called the lower Spences Bridge Group. Recent studies of palynomorphs and plant megafossils indicate an upper Albian age for both the lower Spences Bridge Group and Spius Formation.

In the study area, block faulting, probably related to transtensional tectonics in Eocene time, was the main cause of deformation of the Spences Bridge Group. A north-trending complex graben with vertical displacements of at least 3 km, herein called the Fig Fault Zone, was
apparently filled as it formed by Eocene river sand and gravel. Folding, some of which may have been contemporaneous with volcanism, was mainly restricted to the vicinity of Shovelnose Mountain which displays an overall anticlinal geometry.

The lower Spences Bridge Group in the study area was deposited on a surface of moderate relief underlain by Late Triassic and Early Jurassic volcanic and plutonic rocks. It consists of roughly equal volumes of volcaniclastic rocks and lava which are intercalated throughout the 2.4 km-thick succession. Andesite flows and clastic rocks are ubiquitous; rhyolite is laterally restricted, probably to near-vent areas. Regionally, this group was probably deposited as a set of contiguous terrestrial stratovolcanoes. Fractionation and assimilation can account for petrographic and geochemical observations. Patterns of trace elements and a calcalkaline to weakly tholeiitic trend suggest a subduction-related origin.

Spius Formation in the study area, with a minimum thickness of 600 m, shares a gradational contact with the lower Spences Bridge Group. To the northwest, the stratigraphic relationship is unconformable indicating deformation during a local hiatus in volcanism. Spius flows were probably very fluid, accumulating as a shield volcano atop lower Spences Bridge and adjacent basement rocks. Petrographically, two Spius Formation lava types are recognized. The first, lower Spences Bridge-type, is very similar to andesite of the lower Spences Bridge Group. The second, Spius-type, was apparently hotter and more hydrated. Trace element geochemistry supports
petrography and suggests that Spius Formation lavas are the product of variable magma mixing between melts belonging to the lower Spences Bridge Group and an inferred parental Spius-type magma. The composition of that parental magma suggests that primary Spius-type melts were produced by "within plate" fusion. The change in tectonic affinity may have been caused by disrupted and/or terminated subduction induced by mid-Cretaceous accretion of Terrane II to the North American continental margin.
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1. INTRODUCTION

Cretaceous volcanic rocks in southwestern British Columbia, east of the Fraser Fault System, form a 215 km north-northwest trending belt extending from near the settlement of Pavilion to almost latitude 49° (Figure 1a).

Part of the Cretaceous succession was named Spences Bridge Group by Drysdale (1914) from a type locality near the town of Spences Bridge, at the confluence of the Thompson and Nicola rivers (Figure 1a). Rice (1947) named a second, apparently overlying sequence of Cretaceous rocks the Kingsvale Group, from a type locality along the Coldwater River (Figures 1b, 2) near the settlement of Kingsvale. Subsequently, both terms were used by Duffell and McTaggart (1952) and later authors (Figure 3). Because most studies were concentrated between the Fraser Fault System and the town of Merritt, especially along the Thompson and Nicola river valleys (eg. Duffell and McTaggart, 1952; Jorgensen, 1973; Devlin, 1981; Monger, 1981, 1982; Monger and McMillan, 1984) (Figure 1b), the petrology and field relations of rocks in that area were known in greatest detail. Conversely, rocks in the type area of the Kingsvale Group, despite the use of the term by other authors, were not studied since the work of Rice (1947).

The purpose of this thesis is to re-examine these Cretaceous volcanic rocks in the poorly known type area of the Kingsvale Group, by studying volcanic facies, stratigraphy, depositional relations, age, structure,
petrography and geochemistry. Correlations between the various Cretaceous volcanic units are reviewed and new lithostratigraphic nomenclature is proposed.

All samples used for geochemistry, geochronometry and palynology / paleobotany, plus most of those used for petrography, were taken from exposures in the vicinity of Kingsvale, herein called the study area. The study area is outlined on Figure 1b and shown in detail in Figure 2. UTM grid coordinates (six-digit numbers) define its boundaries and are used throughout this thesis for important locations. All coordinates fall within grid zone 10UFL and should properly be prefixed by that zone designation. Systematics of such coordinates are given on most 1:50,000 scale Canadian Government topographic maps, including 92H/14, 92H/15, 92I/2, and 92I/3 on which the study area is situated. Vehicle access is via the Coquihalla Highway, from Merritt or the town of Hope, the Coldwater Road from Merritt, and many narrower loose surface roads.

The north-flowing Coldwater River passes through Kingsvale and approximately bisects the study area. The other three major streams are north-flowing Spius Creek and its tributaries Prospect Creek and Maka Creek which are located along the northeastern edge of the study area. Except for a few large ponds, the only bodies of still water are Gillis Lake and Fig Lake, near Kingsvale. The two mountains in the area are Shovelnose Mountain (elevation 1700 m) which lies southeast of Kingsvale, and an unnamed, elongate mountain (1620 m) northwest of Kingsvale herein
referred to as "Gillis Ridge" (Figure 2). Forest cover, generally moderate, is heavy on some north-facing slopes. Rock exposure is usually fair, and often excellent at upper elevations.
Reddish brown to green and black, amygdaloidal to dense andesitic flows; minor pyroclastic and epiclastic rocks.

**PREVIOUS NOMENCLATURE**
- Amygdaloidal andesite unit of Thorkelson (1985).
- Upper Kingsvale Group of Duffell and McTaggart (1952).

**REVISED NOMENCLATURE**
- Spius Formation

**lower Albian**
- Varicoloured andesitic to rhyolitic flows; welded and nonwelded ignimbrite, tuff, lahar, conglomerate, sandstone, mudstone and coal.

**PREVIOUS NOMENCLATURE**
- Kingsvale Group (unit 10) of Preto (1979).
- Spences Bridge Group and basal Kingsvale Group of Duffell and McTaggart (1952).
- Spences Bridge Group and Kingsvale Group of Rice (1947).
- Spences Bridge Group of Drysdale (1914).

**REVISED NOMENCLATURE**
- Spences Bridge Group

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**Figure 1**
(a) Distribution of Spences Bridge Group rocks west of the Fraser Fault System (after Monger, 1985).

(b) Inset map showing study area, this thesis.
Figure 3  Schematic stratigraphic section of Spences Bridge Group rocks near Kingsvale, showing revised (this thesis) nomenclature and that of previous authors. Correlations of previous authors' descriptions with this section are based on geological mapping, stratigraphy, and petrology. "Monger '84" refers to Monger and McMillan (1984).
2. PREVIOUS WORK AND REVISED LITHOSTRATIGRAPHIC NOMENCLATURE

2.1 Previous work

Cretaceous volcanic rocks in this region were first investigated by Dawson (1879, 1895, 1896) who assigned them to the Miocene. Drysdale (1914) studied the rocks in greater detail along the Thompson and Nicola rivers, and named the Spences Bridge Group after a type locality near Spences Bridge. Plant fossils collected by Drysdale from the Spences Bridge Group yielded an apparent Jura-Cretaceous age (Knowlton in Drysdale, 1914; Wilson in Drysdale, 1914). An overlying succession of amygdaloidal andesite, called upper Kingsvale Group by Duffell and McTaggart (1952), and Kingsvale Group by Monger (1982, 1985), was correlated by Drysdale with the Tertiary Kamloops Group. Correlation of nomenclature for Drysdale (1914) and later authors is shown in Figure 3.

Rice (1947) studied Cretaceous rocks southwest of Drysdale's (1914) type area. In addition to the Spences Bridge Group, Rice reported the existence of a second, largely clastic, composite volcanic section of rocks apparently unconformably overlying the Spences Bridge Group. The presence of clasts of Spences Bridge Group lava within that section suggested to Rice that the clastic rocks were a younger, deposit derived in part by erosion of the Spences Bridge. Plant fossils collected from these rocks near Kingsvale (Figure 1b) were examined by W. A. Bell who reported an Albian (latest Early Cretaceous) age (Bell in Rice, 1947). Bell also
re-examined Drysdale's (1914) collection of fossils, giving them an Aptian (one stage older) age (Bell in Rice, 1947). These age assignments confirmed Rice's field interpretations and led Rice to separate the apparently younger and overlying rocks from the Spences Bridge Group, and to name them Kingsvale Group (Rice, 1947).

The name Kingsvale Group was subsequently used by several authors to describe a variety of rocks in southwestern British Columbia. Duffell and McTaggart (1952) used the name Kingsvale Group for a succession of sedimentary and volcanic rocks which overlie flows and intercalated clastic rocks of the Spences Bridge Group south and southwest of Spences Bridge. The sedimentary rocks that form the basal part of their Kingsvale Group, comprising well bedded sandstone, siltstone, mudstone, conglomerate and tuff, which represent a dominantly fluvial and lacustrine environment (Devlin, 1981), will be referred to as the Dot beds, named (informally) from the settlement of Dot near which those beds are well exposed (Figure 1b). Plant fossils from the Dot beds were determined by Bell to be of Albian age (Bell in Duffell and McTaggart, 1952). The similarities in floral types and assigned age between these rocks and Rice's Kingsvale locality led Duffell and McTaggart (1952) to apply the name Kingsvale Group to both the Dot beds and the overlying volcanic sequence. These upper volcanic rocks, mostly uniform reddish brown amygdaloidal flows were recognized as resting conformably on either the Dot beds, or where those beds are absent, directly on the Spences Bridge Group or underlying basement rocks.
Maximum thicknesses were estimated by Duffell and McTaggart (1952) to be about 300 m for the Dot beds and 1300 m for the entire Kingsvale Group. From within the underlying Spences Bridge Group, Duffell and McTaggart (1952) also collected fossil leaves from two localities on Gordon Creek, north of Dot, and beside Highway 1 south of the Nicoamen River, to which Bell assigned an Aptian age (Bell in Duffell and McTaggart, 1952).

Jorgensen (1973) studied the Spences Bridge Group and Kingsvale Group of Duffell and McTaggart (1952) northeast of the Nicola River, between Spences Bridge and Merritt. Based on similarity in lithology and attitude he concluded that the Dot beds were simply a continuation of the Spences Bridge Group.

Preto (1979), mapped 2 units between Princeton and Merritt as Kingsvale Group (Figure 1a). Isotopic analyses of flows from one of those units (unit 10) provided a Rb–Sr isochron of 112 ± 10 Ma (Preto, 1979). This unit was intruded by granitoids yielding K–Ar biotite dates of 96.7 ± 2.1 Ma and 96.8 ± 2.6 Ma, and a K–Ar hornblende date of 98.2 ± 2.6 Ma (Preto, 1979). These dates suggest, according to Palmer's (1983) time scale, that Preto's (1979) unit 10 has a probable Aptian or Albian age.

Monger (1981) followed Jorgensen by correlating the Dot beds with the Spences Bridge Group and suggesting that the entire sequence, including the upper amygdaloidal unit, should be considered a single stratigraphic package. However, south of Spences Bridge near Soap Lake, Devlin (1981) described an angular unconformity separating the upper Kingsvale Group of
Duffell and McTaggart (1952) from the underlying Spences Bridge Group, and consequently regarded the amygdaloidal andesites as a separate unit. Devlin followed Monger's (1981) correlation of the Dot beds with the Spences Bridge Group, thereby restricting his usage of Kingsvale Group to the upper lavas. He noted Duffell and McTaggart's (1952) correlation of the Dot beds with Rice's Kingsvale Group, and concluded that Rice's Kingsvale Group must also be part of the Spences Bridge Group. This observation threw the validity of Rice's nomenclature into question, and is a major concern of this thesis.

Monger (1982, 1985) and Monger and McMillan (1984) concurred with Devlin (1981) and reserved the term Kingsvale Group for the upper succession of amygdaloidal lava. Monger (1985) accommodated his observations of post-Spences Bridge Group pre-Kingsvale Group faulting west of the Thompson River, 10 km northeast of Lytton, and the angular unconformity of Devlin (1981) with recent descriptions by the writer (Thorkelson *in* Monger, 1985; Thorkelson, 1985) of conformable relations between the Spences Bridge Group and the amygdaloidal volcanic unit near Kingsvale. Monger (1985) suggested Cretaceous uplift of the Mount Lytton Plutonic Complex to the west was contemporaneous with volcanic deposition, and caused locally angular relationships such as that seen near Spences Bridge.

An additional fossil date from the Spences Bridge Group was obtained by W. S. Hopkins, whose examination of microflora from the
Gordon Creek megafossil locality of Duffell and McTaggart (1952) yielded a mid-Albian to (?) Cenomanian age (Hopkins in Monger and McMillan (1984). Church et al. (1979) reported a 91.6 ± 3 Ma K-Ar whole rock date (upper Cenomanian of Palmer, 1983) from Spences Bridge Group rocks 25 km northwest of Spences Bridge. Monger and McMillan (1984) obtained an 82.0 ± 3.2 Ma whole rock date from a dyke crosscutting flows of the upper amygdaloidal unit.

Drown (1973), Mamu (1974) and Pearson (1974) showed that both the Spences Bridge and Kingsvale groups have undergone zeolite grade metamorphism.

2.2 The need for revised nomenclature

Recent work by the writer has shown that rocks defined as Kingsvale Group by Rice (1947) are inseparable from rocks of the Spences Bridge Group (Thorkelson, 1985). About 5 km southwest of Kingsvale, in the vicinity of Fig Lake, typical Spences Bridge Group andesite and rhyolite (as identified by Rice 1947) stratigraphically overlie the clastic rocks containing the fossils collected by Rice at Kingsvale. The Spences Bridge Group therefore hosts both these fossils and those collected by Drysdale (1914). Furthermore, Rice’s belief that the Kingsvale clastic rocks are composed of erosional detritus shed from Spences Bridge Group rocks after cessation of Spences Bridge Group volcanism appears to have been based on misinterpretation of volcanic facies. A large proportion of the clastic rocks
are deposits of nonwelded ignimbrite (pyroclastic flows) and lahar whose deposition was contemporaneous with adjacent extrusions of rhyolite and andesite. Also present are waterlain epiclastic rocks, mostly arkosic sandstone and wacke, which constitute a common facies of composite volcanic sequences. Pyroclastic and epiclastic rocks are intercalated throughout the volcanic pile, and not restricted to the top of the section, as suggested by Rice (1947).

The upper Kingsvale Group volcanic package of Duffell and McTaggart (1952), that was called the amygdaloidal andesite unit by Thorkelson (1985), is poorly exposed in the area studied by Rice (1947). Consequently, Rice neither recognized it as a distinct unit, nor classified it consistently. For instance, the amygdaloidal andesite unit exposed in the graben 1 km west of Kingsvale (Figure 2) was mapped by Rice as Neogene plateau basalt. The other two exposures in his map area, 6 km east of Kingsvale and at UTM 440400 (Figure 2) were both mapped as Kingsvale Group and therefore included in what is now recognized as part of the Spences Bridge Group.

The two units called Kingsvale Group by Preto (1979) may actually be two different units. Preto's unit 10 is certainly part of the Spences Bridge Group (Monger, 1985; Thorkelson 1985). His unit 11, however, may belong to the Triassic Nicola Group (J. W. H. Monger, personal communication, 1984).

The work of Devlin (1981) and Monger (1982, 1985) indicates that near Spences Bridge deposition of the amygdaloidal andesite unit was
preceeded by a period of faulting and folding. Such relations are local, however, as evidenced by a gradational stratigraphic contact about 4 km southeast of the Spius Creek / Prospect Creek confluence (Figure 2), where the earliest flows of the amygdaloidal andesite unit are intercalated with felsic Spences Bridge Group pyroclastic rocks (Thorkelson in Monger, 1985) (section 5.2.3). The absence of a hiatus between these two units is further indicated by exposures roughly 5 km east of Kingsvale, where the lowest flow of the amygdaloidal andesite unit rests conformably on Spences Bridge Group felsic tuff and sandstone. This evidence of age equivalence, corroborated by recent age determinations (section 3), is a major consideration in the following section on revision of nomenclature. Petrographic and geochemical evidence for regarding these units as products of a single mid-Cretaceous pulse of magma is given in sections 6 and 7.

2.3 Recommendations for lithostratigraphic nomenclature.

The amygdaloidal andesite unit is a distinct lithostratigraphic unit that lacks a formal name and type section as required by the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983). Although Duffell and McTaggart (1952) called this unit upper Kingsvale Group, and later authors (e.g. Monger, 1982) called it Kingsvale Group, the Kingsvale name should not be used because, firstly, this unit is poorly exposed near Kingsvale, and secondly, the rocks Rice (1947) defined as Kingsvale Group are actually part of the Spences Bridge Group, and not correlative with the amygdaloidal andesite unit (Figure 3). To
end the present confusion it is herein proposed that the amygdaloidal andesite unit be named Spius Formation. The name Spius is from Spius Creek along which these rocks are well exposed. The type locality is defined as the area within 2 km of Spius Creek, between Prospect Creek and the Nicola River (Figure 1b).

Locally conformable and gradational relations plus similarities in age, chemistry and some lithologies between Spius Formation and the Spences Bridge Group are convincing reasons to regard these units as a single volcanic package. The writer suggests revision of nomenclature such that the Spences Bridge Group is expanded to include Spius Formation as the upper part of that group. The composite section previously known as the Spences Bridge Group, and is hereby regarded as the lower Spences Bridge Group, remains undivided (Figures 1, 3) and continues to be represented by the type locality of Drysdale (1914). Additional work may result in subdivision and naming of rock units within this lower, lithologically diverse package as formations of the Spences Bridge Group.

2.4 Correlations across the Fraser and Yalakom faults

The abundance of lower Spences Bridge Group rocks immediately east of the Fraser Fault System suggests that correlative rocks are likely to be found across the fault system on the northerly displaced western side. Cretaceous volcanic rocks of rhyolitic to basaltic composition yielding K–Ar dates of 91 to 101 Ma were mapped in the vicinity of Gang Ranch,
British Columbia, and correlated with the Spences Bridge or Kingsvale groups (Mathews and Rouse, 1984). The age and petrology of such rocks suggests that they are equivalent to the lower Spences Bridge Group (W. H. Mathews, personal communication, 1985), and their present geographic position agrees with dextral offset across the Fraser Fault System between the estimates of 70 km and 110 km by Mathews and Rouse (1984) and Kleinspehn (1985), respectively. Some mid-Cretaceous sedimentary rocks between the Fraser and Yalakom faults may also be correlative with the lower Spences Bridge Group but not Spius Formation which has a more restricted areal distribution and a near absence of epiclastic rocks. Cretaceous paleogeographic reconstructions by Kleinspehn (1985) indicate that mid-Cretaceous rocks southwest of the Yalakom Fault were present about 40 km west of the Spences Bridge Group. Volcanic rocks in that region, called Kingsvale Group by Tipper (1978), were apparently separated from the Spences Bridge Group by the partly contemporaneous (Monger, 1981; Kleinspehn, 1985) Jackass Mountain Group, and possibly by rocks of the Mount Lytton Plutonic Complex. Due to their paleogeographic separation and marked stratigraphic dissimilarity (Kleinspehn, 1985), the writer suggests that volcanic rocks and associated sedimentary facies southwest of the Yalakom Fault should not be called Spences Bridge Group. As previously stated for rocks east of the Fraser Fault System, the term Kingsvale Group should also be abandoned for rocks west of that fault system.
3. AGE OF THE SPENCES BRIDGE GROUP

The age of the lower Spences Bridge Group is discussed using the Decade of North American Geology (DNAG) time scale (Palmer, 1983), which gives 113 and 97.5 Ma as the bottom and top of the Albian stage, respectively.

3.1 Age of the lower Spences Bridge Group

3.1.1 Paleobotany of the lower Spences Bridge Group

Before 1976, when the first isotopic date on the lower Spences Bridge Group was published (Church, 1975), the age of that unit was based on a few collections of fossil leaves. The first collection, made by Drysdale and dated by F. H. Knowlton (Knowlton in Drysdale, 1914), gave an apparent Jura-Cretaceous age. That collection, from the Pimainus Hills about 3 km northeast of the Thompson / Nicola river confluence, was later re-examined by Bell along with two other small collections, one from Gordon Creek north of Dot, the other from near the Thompson / Nicoamen river confluence, made by S. Duffell (Bell, 1956; Duffell and McTaggart (1952). Bell assigned all three an Aptian age (Bell in Duffell and McTaggart (1952). He also identified and dated five other collections, three of which were collected by Rice (1947) from outcrops near Kingsvale and Brookmere. Both Rice’s collections and two others made by Duffell from the Dot beds along Shakan Creek, west of Dot, and railway cuts beside the Nicola River,
were assigned an Albian age (Bell *in* Rice, 1947; Bell *in* Duffell and McTaggart (1952).

Largely on the basis of these age assignments, Rice (1947) and Duffell and McTaggart (1952) called the rocks hosting the apparently younger, Albian fossils, Kingsvale Group, and regarded the Spences Bridge Group as strictly Aptian. As discussed in section 2.3, the section previously known as the Spences Bridge Group is herein called the lower Spences Bridge Group, and the fossil-bearing strata called Kingsvale Group by Rice (1947) and basal Kingsvale Group by Duffell and McTaggart (1952) (the Dot beds) are now considered to be equivalent to that unit. Consequently, the lower Spences Bridge Group hosts all of the fossil localities discussed above, and according to Bell's (1956) determinations, is of Aptian to Albian age.

Paleobotany continues to provide estimates of age for the lower Spences Bridge Group, Hopkins (1981) extracted and identified palynomorphs from rock samples he collected from the Gordon Creek fossil locality of Duffell and McTaggart (1952). His estimate of age, mid-Albian to (?) Cenomanian concurs in part with the earlier age assignments of Bell (1956). His suggestion that the lower Spences Bridge Group could be as young as Cenomanian was based on what he termed "the questionable presence of angiosperm pollen". G. E. Rouse re-examined Hopkins' slides in 1986, confirming the presence of early angiosperm pollen. Because of an abundance of tricolpate pollen but absence of tricolporate pollen, Rouse
narrowed the age of Hopkins' samples to late Albian (Thorkelson and Rouse, in preparation).

One collection of palynomorphs and another of fossil leaves made by the writer were identified and dated by Rouse (Thorkelson and Rouse, in preparation). The megaflora were collected from within a new (1985) Coquihalla Highway roadcut through a section of uncertain but probably intermediate stratigraphic position, comprising sandstone, tuff, lahar and coal, about 0.5 km southeast of Kingsvale (UTM 504300). Rouse gave this assemblage, of mostly ferns but also conifers, pteridosperms and early angiosperms, a late Albian age. Palynomorphs, including tricolpate pollen plus a single angiosperm megafossil, recovered from a thin (3–5 m) sandstone bed in felsic tuff about 5 km east of Kingsvale (UTM 548293), also yielded an upper Albian age. Since the strata bearing these fossils are directly and conformably overlain by amygdaloidal andesite flows of Spius Formation, this date represents the age of the youngest lower Spences Bridge Group rocks in that area.

3.1.2 Isotopic dates from the lower Spences Bridge Group

Two isotopic dates from lower Spences Bridge Group rocks in the belt were determined by previous workers. The first, a 91.6 ± 3 (latest Cenomanian) K–Ar whole rock date (Church, 1975; Church et al., 1979) was obtained from lava underlying coal-bearing Tertiary strata, about 24 km northwest of Spences Bridge, near Hat Creek. The second was a 112 ± 10
Ma (2σ) (earliest Albian) Rb-Sr determination from flows about 20 km north of Princeton (Preto, 1979), which has since been recalculated using three additional analyses to 104 ± 22 Ma (2σ) (R. L. Armstrong, personal communication, 1986). From the Summers Creek stocks which intrude those flows, Preto (1979) dated mineral separates yielding 1 hornblende (96.8 ± 2.6 Ma) and 2 biotite (98.2 ± 2.6; 96.7 ± 2.1 Ma) ages. These latest Albian to earliest Cenomanian dates constitute a minimum age for the lower Spences Bridge Group in that area, and fit with an Albian age for the flows. Mathews and Rouse (1984) reported 1 K-Ar hornblende (96.7 ± 3.4 Ma) and 3 K-Ar whole rock (101.0 ± 3; 97.4 ± 3.4; 90.9 ± 3.2 Ma) dates from lavas west of the Fraser Fault System, near the settlement of Gang Ranch, which they correlated with Spences Bridge Group rocks. The oldest date (late Albian) should be regarded as the minimum age of those rocks due to probable and variable Ar loss.

Five K-Ar whole rock dates (58.7 ± 2.3; 80.0 ± 3.0; 83.6 ± 3.0; 90.5 ± 3.3; 94.4 ± 3.4 Ma) were obtained by the writer for lower Spences Bridge Group lava in the study area (Table 1). This large range in age (mid-Cenomanian to late Paleocene) is probably due to variable Ar loss, especially from poorly retentive mesostasis, resulting from zeolite grade metamorphism (eg. Mamu, 1974; P. B. Read, section 6.3) and devitrification. Consequently, even the oldest date is considered to be younger that the actual age of lower Spences Bridge Group rocks in the study area.
TABLE 1: Potassium-Argon Dates

<table>
<thead>
<tr>
<th>Sample #</th>
<th>208B</th>
<th>226C</th>
<th>322B</th>
<th>327B</th>
<th>370C</th>
<th>152I</th>
<th>284B</th>
<th>3768</th>
<th>421B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material dated</td>
<td>Whole rock</td>
<td>Whole rock</td>
<td>Whole rock</td>
<td>Whole rock</td>
<td>Whole rock</td>
<td>Whole rock</td>
<td>Whole rock</td>
<td>Whole rock</td>
<td>Whole rock</td>
</tr>
<tr>
<td>Latitude N.</td>
<td>49° 51' 38&quot;</td>
<td>49° 52' 25&quot;</td>
<td>49° 58' 32&quot;</td>
<td>49° 57' 54&quot;</td>
<td>49° 57' 26&quot;</td>
<td>50° 00' 53&quot;</td>
<td>49° 54' 27&quot;</td>
<td>49° 59' 12&quot;</td>
<td>49° 57' 18&quot;</td>
</tr>
<tr>
<td>Longitude W.</td>
<td>120° 51' 09&quot;</td>
<td>120° 51' 04&quot;</td>
<td>121° 01' 17&quot;</td>
<td>121° 02' 43&quot;</td>
<td>120° 59' 42&quot;</td>
<td>121° 03' 23&quot;</td>
<td>120° 55' 25&quot;</td>
<td>121° 02' 34&quot;</td>
<td>120° 55' 23&quot;</td>
</tr>
<tr>
<td>UTM coordinates</td>
<td>544252</td>
<td>544266</td>
<td>419376</td>
<td>402364</td>
<td>438356</td>
<td>392418</td>
<td>491302</td>
<td>403387</td>
<td>490355</td>
</tr>
<tr>
<td>K (wt. %)</td>
<td>1.18</td>
<td>1.78</td>
<td>0.713</td>
<td>1.14</td>
<td>0.640</td>
<td>1.21</td>
<td>0.540</td>
<td>0.352</td>
<td>2.02</td>
</tr>
<tr>
<td>Radiogenic (^{40} \text{Ar} ) (x 10(^2 ) cm/g)</td>
<td>2.735</td>
<td>5.656</td>
<td>2.687</td>
<td>4.113</td>
<td>2.127</td>
<td>4.426</td>
<td>2.016</td>
<td>1.108</td>
<td>3.918</td>
</tr>
<tr>
<td>Percentage of total (^{40} \text{Ar} )</td>
<td>40.5</td>
<td>60.4</td>
<td>89.6</td>
<td>78.4</td>
<td>62.8</td>
<td>87.1</td>
<td>59.9</td>
<td>40.0</td>
<td>68.7</td>
</tr>
<tr>
<td>Age (Ma)</td>
<td>58.7 ± 2.3</td>
<td>80.0 ± 3.0</td>
<td>94.4 ± 3.4</td>
<td>90.5 ± 3.3</td>
<td>83.6 ± 3.0</td>
<td>91.7 ± 3.3</td>
<td>93.8 ± 3.4</td>
<td>79.2 ± 3.1</td>
<td>49.2 ± 1.8</td>
</tr>
</tbody>
</table>

NOTES: Analyses by K. Scott (K) and J. Harakal (Ar), Department of Geological Sciences, University of British Columbia. K was determined in duplicate by atomic absorption using a Techtron AA4 spectrophotometer and Ar by isotope dilution using an AEI MS-10 mass spectrometer and high-purity \(^{40} \text{Ar} \) spike. Errors reported are for one standard deviation. The constants used were: \( K_a = 0.581 \times 10^{-11} \) year\(^{-1} \), \( K = 4.962 \times 10^{-10} \) year\(^{-1} \), and \( ^{87}K/K = 0.01167 \) at%. 

3.1.3 Interpretation of age determinations

Bell (1956) assigned Albian or Aptian ages to his Lower Cretaceous collections apparently on the basis of angiosperm presence or absence respectively. That practice is generally valid for large assemblages, but is likely to be faulty when applied to small, and therefore probably incomplete collections, such as those made by Drysdale (1914) and Duffell and McTaggart (1952) (G. E. Rouse, personal communication 1985). Although Bell found no angiosperms in those collections and correspondingly applied an Aptian age, the apparent absence of angiosperms may have been the result of a locally fern- and conifer-dominated paleoecology or insufficient sampling. Recent studies of microflora by Rouse (Thorkelson and Rouse, in preparation) show that early angiosperms were, in fact, present in Duffell and McTaggart's (1952) Gordon Creek locality, and that the age of those rocks is late Albian. That finding throws into question Bell's other Aptian calls, on Duffell and McTaggart's (1952) Nicoamen River and Drysdale's (1914) Pimainus Hills collections, and suggests that they may also be of late Albian age. This possibility is supported by the Albian age chosen by Bell for five lower Spences Bridge Group sites in both Rice's (1947) and Duffell and McTaggart (1952) field areas, previously discussed. Recent work by Rouse on (angiosperm-bearing) samples yielding late Albian ages, collected by the writer from the study area, agrees with his findings for the Gordon Creek rocks.
A late Albian age is supported by Preto’s (1979) latest Albian to earliest Cenomanian K–Ar ages of granitoids which intrude lower Spences Bridge Group rocks north of Princeton, his (1979) Albian Rb–Sr isochron, and by Mathews and Rouse’s (1984) late Albian K–Ar dates from correlatives of lower Spences Bridge Group rocks west of the Fraser Fault System, and is therefore regarded as the best estimate of age. Other K–Ar determinations by Mathews and Rouse (1984), Church (1975) and the writer (this thesis) yielding Cenomanian and younger ages are not supported by fossil evidence and are thought to be too young.

3.2 Isotopic ages and paleobotany of Spius Formation.

Until recently, no direct age determination of Spius Formation had been made. Dawson (1896) thought the unit was Miocene in age, and Drysdale (1914) correlated it with the Eocene Kamloops Group. The unit was regarded as Albian by Duffell and McTaggart (1952) who included it in the Kingsvale Group on the basis of apparent conformity with the underlying Dot beds. Monger and McMillan (1984) chose a Late Cretaceous age for Spius Formation, based partly on their 82.0 ± 3.2 Ma K–Ar whole rock date from a dyke cutting Spius Formation, thought to be a feeder to that unit (J. W. H. Monger, personal communication, 1984). Other factors which suggested a Late Cretaceous age were the angular unconformity south of Spences Bridge which separates Spius Formation from the late Early Cretaceous lower Spences Bridge Group (Devlin, 1981), and the Squianny Creek sediments hosting Late Cretaceous fossil fruit (Rouse in Devlin, 1981).
which overlie Spius Formation (Devlin, 1981).

A Cenomanian or earlier age is further supported by two K-Ar whole rock dates obtained by the writer from Spius Formation lava: a 91.7 ± 3.3 Ma date from a flow low in the section, about 1 km northeast of the Spius Creek / Prospect Creek confluence, and a 93.6 ± 3.4 Ma age from rocks of unknown stratigraphic position 0.5 km west of Kingsvale in the Fig Fault Zone. A third K-Ar whole rock date of 79.2 ± 3.1 Ma (Campanian), from probably the lowest Spius Formation flow, about 3 km southeast of the Spius Creek / Prospect Creek confluence, is rejected because the other, stratigraphically higher dates are older.

An upper Albian age for Spius Formation is indicated by palynomorphs, including tricolpate and weakly porate tricolporate pollen, recovered from dark siltstone from an unknown stratigraphic position within Spius Formation in the Fig Fault Zone (Figure 2), and identified by Rouse (Thorkelson and Rouse, in preparation). This fossil age determination equals that made by Rouse for samples from the lower Spences Bridge Group, supporting stratigraphic (section 5.3.2), petrographic (section 6.3), and geochemical (section 7.3) findings which suggest that Spius Formation is, in part, coeval with the lower Spences Bridge Group.
4. STRUCTURE

4.1 Regional structure of the Spences Bridge Group

Cretaceous and Tertiary deformational events affecting the Spences Bridge Group were described by Monger (1985). He envisaged a northeast-southwest compressional or transpressional stress regime in mid-Cretaceous time resulting in faulting, and downfolding of the strata into the Nicoamen Syncline, contemporaneous with deposition. This was followed in the Late Cretaceous to early Tertiary by transtensional strike slip and associated normal faulting giving rise to dextral offset and related minor thrusting on the Yalakom, Hungry Valley and Fraser faults. Such faulting displaced the northern parts of the Spences Bridge Group farther to the north (section 2.4). The precise amounts of offset and the relations between faults is still in question as indicated by differences in details between Monger's (1985) interpretation and those given by such authors as Davis et al. (1978), Mathews and Rouse (1984) and Kleinspehn (1985). Spences Bridge Group rocks east of the Fraser Fault System were greatly affected by transtensional tectonics, and subsequent horst and graben formation. Stress orientation and details of this largely Eocene deformation are given in Ewing (1981a), McMechan (1983) and Monger (1985). Folding of the Spences Bridge Group into the Nicoamen Syncline, as described by Monger (1985) is supported by earlier works describing folding and synclinorium development (Drysdale, 1914; Duffell and McTaggart, 1952;
Jorgensen, 1973), but the time of such deformation was not known until fieldwork by Devlin (1981) and the writer (Thorkelson, 1985). South of Spences Bridge near Soap Lake, Devlin discovered an angular unconformity below which lower Spences Bridge Group rocks are faulted and tilted, and above which lower Spences Bridge flows are relatively flat lying. The writer recorded stratigraphic relations in his study area (section 5.3.2) conflicting with those of Devlin (1981) and indicating that there the lower Spences Bridge Group and Spius Formation share a gradational contact and are, in part, coeval. Monger (1985) noted these differences and accommodated both observations by suggesting that synclinal development was concurrent with eruption of Spences Bridge Group volcanics, and indicated the Nicoamen Syncline extending from the Fraser Fault System to Princeton (Figure 1a). His interpretation conflicts with this work which concludes that present bedding attitudes and outcrop patterns of the Spences Bridge Group in the study area are largely controlled by Tertiary normal faulting, and do not indicate simple synclinal geometry. A lack of simple synclinal form is also evident from bedding attitudes between the Thompson River and the Fraser Fault System (Monger and McMillan, 1984), and north of Princeton, adjacent to Highway 5 (Preto, 1979). Although there is a general consensus of complex folding of rocks in the Nicola River valley and surrounding mountains, the north–northwest trend of fold axes as suggested by Duffell and McTaggart (1952) and Monger (1985) conflicts with the findings of Jorgensen (1973), who mapped synclinal and anticlinal folds in Spences Bridge Group strata north east of the Nicola River, with axes
trending north-northeast. Nevertheless, the Spences Bridge Group is exposed in a linear belt, flanked almost exclusively by the Triassic Nicola Group, the Pennsylvanian to Triassic Cache Creek Group and Mesozoic granitoids (Monger, 1985). This persistent and striking distribution of older and lower-level rock units bounding the Cretaceous volcanic sequence, combined with the irregular bedding attitudes of the Spences Bridge Group leads the writer to prefer the term "elongate structural depression" recommended by W. H. Mathews (personal communication, 1985) over "syncline" used by Monger. The name Nicoamen Structural Depression is therefore used in this thesis.

4.2 Structure in the study area

4.2.1 Faulting

Deformation of the Spences Bridge Group in the study area is mostly the product of transtensional faulting. Consequently, both distribution of rock units and orientation of bedding attitudes are largely controlled by the amount of relative offset between blocks, plus the direction and angle of tilt of those blocks (Figure 2). The faults with greatest offset are those within a complex, north-trending graben which roughly bisects the study area. That graben will be referred to as the Fig Fault Zone, named from Fig Lake which is located within the southern part of that zone (Figure 2). Exposed in the Fig Fault Zone are downthrown blocks of the lower Spences Bridge Group, Spius Formation, and hornblende-needle dacite and
conglomerate of the Eocene Kamloops Group (Figure 4b) (see Ewing, 1981a, 1981b for detailed discussion of the Kamloops Group). Dykes on Mount Thynne, a few km south of Brookmere, correlated on petrologic grounds with the Kamloops Group trend nearly parallel to the Fig Fault Zone. Such parallelism suggests that the Fig Fault Zone was formed in Eocene time. Monger and McMillan (1984) mapped Eocene hornblende–phyric lava flows above Spius Formation on the Nicoamen Plateau, 10 km northwest of the Spius Creek / Prospect Creek confluence, nearly identical in lithology to the Kamloops Group lava in the Fig Fault Zone. Because that lava in the Fig Fault Zone is now juxtaposed against granitoids which form, in part, the basement to the Spences Bridge Group (section 4.2), minimum vertical offset is estimated at 3000 m, the minimum total thickness of Spences Bridge Group strata in the study area (Figure 3). Because such offset, the largest in the study area, occurs across north trending faults, it is concluded that the orientation of maximum crustal extension in the study area during Eocene time was east–west. There are several other important faults in the study area. They were probably also active in the Eocene but may have been, like the Fig Fault Zone, active as early as the mid-Cretaceous. Motion on the McInnes Fault, in the northern region, has downdropped Spius Formation rocks relative to the lower Spences Bridge Group. Along a bend in that fault, a sliver of Kamloops Group lava has been downfaulted relative to both Spences Bridge Group units. The south end of the McInnes Fault meets the Midday Fault which serves as a master for an array of faults to the south. Whereas earlier analysis of the
Fig Fault Zone elucidated the effect of faulting on rock unit distribution, discussion of fault blocks south of the Midday Fault will serve to support the writer's contention that bedding attitudes are largely fault controlled. In the fault block in the northwest corner of the study area, in which the Spius Creek / Prospect Creek confluence is located, bedding dips moderately to the north-northwest. Although not confirmed by bedding measurements, the rock unit distribution in the block immediately to the east suggests that bedding strikes northwest and dips moderately to the northeast. This orientation is shared, as indicated by measurements, with the next fault block (UTM 420400) to the east. Exposed in the small, triangular shaped block still further east (UTM 440400) are flows of Spius Formation which dip to the southeast. The consistency of bedding orientations within each of these four fault blocks, and the abrupt changes in attitude across their bounding faults indicates that rotation by faulting and not folding is responsible for the observed changes in angle and direction of dip. Another noteworthy fault is the east-trending Voght Fault, east of Kingsvale, across which plutonic rocks are juxtaposed against the Spences Bridge Group. A small horst of primarily Nicola Group rocks is also bounded by the Voght Fault, on the northern slope of Shovelnose Mountain.

4.2.2 Folding

Some folding of Spences Bridge Group rocks has certainly occurred but is difficult to quantify. The place where folding is best observed is a roadcut about 2 km west-southwest of Brookmere (UTM 588190), just
outside the study area. There, dark siltstone is synclinally folded about a roughly north trending axis. On the south and west slopes of Shovelnose Mountain, the outcrop pattern suggests north-northwest-trending folding, and the trace of one small syncline is shown (Figures 2, 4a). The presence of vertical bedding striking northwest, 1 km north of Brookmere, is further evidence of deformation; the complexity of folding, and possibly faulting, on the southern slope of Shovelnose Mountain exceeds that which is mapped due to poor exposure and rapid facies changes. Despite the two aforementioned synclines, the gross structure of the Shovelnose Mountain area is likely to be anticlinal as implied by easterly dipping Spius Formation flows conformably overlying the lower Spences Bridge Group on the northeast corner of that mountain. Rocks which underlie "Gillis Ridge" are generally devoid of discernible folds with the exception of the two fault blocks that are adjacent to, and northwest of the Central Horst. Within those blocks, bedding attitudes vary as a result of open folding. Such folding may be part of the penecontemporaneous deformation described by Monger (1985) or due to fault drag in Cretaceous or Tertiary time.

In summary, folds on "Gillis Ridge" are nearly absent, and on Shovelnose Mountain are present in undetermined amounts. The north-northwest axial orientation of the single fold mapped on Shovelnose Mountain supports Monger's (1985) orientation of folding but the overall anticlinal structure in that area conflicts with his preferred synclinal form.
5. STRATIGRAPHY

5.1 Rocks older than the Spences Bridge Group

The Spences Bridge Group rests unconformably on several rock units. North of the study area, rocks of the Pennsylvanian to Triassic Cache Creek Group, Upper Triassic Nicola Group, Lower Jurassic Guichon Batholith and Lower Jurassic to Lower Cretaceous Mount Lytton Plutonic Complex constitute the basement to the Spences Bridge Group (Monger, 1985). South of the study area, the Spences Bridge Group sits on the Nicola Group and Lower Jurassic granitoids (Preto, 1979). Nowhere is the Spences Bridge Group conformable with older rocks.

In the study area, "basement" rocks comprise the Nicola Group and at least two medium-grained plutonic phases. The oldest rocks are andesitic to rhyolitic volcanic facies of the Nicola Group, typically metamorphosed to lower greenschist grade, with incipient foliation. They occur as roof pendants in dominantly plutonic rock. Grey granodiorite to diorite, the first granitoid to intrude the Nicola Group, is commonly agmatitic with dark xenoliths. Intruding both units is pink granite, frequently mylonitized, with fabric that apparently parallels the intrusive contacts of that unit. Such mylonitic foliation is best developed in the Central Horst on "Gillis Ridge" (Figure 2). Preto (1979) obtained a 203 ± 5 Ma K–Ar date from a pink granite clast in lower Spences Bridge Group conglomerate north of Princeton. If that clast and the pink granite are correlated, then all rocks in
the study area on which the lower Spences Bridge Group was deposited are Early Jurassic and older. Other plutonic rocks, which may be as young as Eocene, are also included in this map unit (unit 1, Figure 2).

Three localities in the study area attest to moderate topographic relief of basement rocks at the time of Spences Bridge Group deposition, as suggested by Rice (1947). In the Central Horst, a paleotopographic high is evident where the two lowest strata of the Spences Bridge Group are pinched out against plutonic basement rocks. On the western slopes of Shovelnose Mountain, two windows of granitoid are exposed within lower Spences Bridge Group rhyolite and andesite. Cross section A–A’ (Figure 4a) shows the probable subsurface profile of basement rocks in that area. Folding (section 4.2.2) may have affected the geometry of basement rocks underlying Shovelnose Mountain.

5.2 Stratigraphy of the lower Spences Bridge Group

5.2.1 Introduction

The lower Spences Bridge Group comprises a diverse succession of volcanic and sedimentary rocks that display rapid vertical and lateral facies changes. In the study area the most noticeable lateral variation is observed between the "Gillis Ridge" and Shovelnose Mountain areas. Underlying "Gillis Ridge", as in all places within the study area, pyroclastic and epiclastic rocks are interbedded with lava flows of andesitic composition. On
Shovelnose Mountain, rhyolites as well as andesite are present, and that combination of basic and acid lavas intercalated with clastic rocks is a characteristic feature of the lower Spences Bridge Group throughout its distribution (Duffell and McTaggart, 1952; Jorgensen, 1973; Preto, 1979; Devlin, 1981).

A composite section integrating stratigraphy from throughout the study area is shown in Figure 3. Revised (this thesis) nomenclature is shown on the left hand side of the section, followed to the right by a correlation chart of previous authors' usage. Important aspects of that section are: (1) the unconformity / nonconformity below which sit older rocks that form the basement to the Spences Bridge Group; (2) the presence of an initial andesite flow followed by near-basal basement-clast conglomerate and breccia; (3) the ubiquity of andesite lava and clastic rocks of various types; (4) the predominance of dense over amygdaloidal lava; (5) the laterally restricted presence of rhyolite; and (6) the conformable relationship with the overlying Spius Formation. As seen on both this section and the map of the study area (Figure 2), the volumetric ratio between lava and clastic rocks is approximately 1:1.

5.2.2 Stratigraphy in the Central Horst

The best section for initial description underlies the Central Horst of "Gillis Ridge" (Figure 2) There, the oldest unit is bluish-grey plagioclase + pyroxene andesite lava. It has subtle but consistently oriented flowbanding
and, on weathered surfaces, commonly shows flow brecciation. Overlying that basal flow is conglomerate composed of subrounded to subangular, pebble to cobble size clasts of, almost exclusively, basement lithologies with rare clasts of lower Spences Bridge andesite (Plate 1). Above the conglomerate is a succession of interbedded lavas and volcaniclastic rocks. The most abundant lithologies of the clastic rocks are poorly sorted and weakly- to non-stratified deposits containing clasts of lower Spences Bridge andesite, rhyolite and volcaniclastic rocks and, occasionally, basement lithologies. These rocks are interpreted to be lahar and nonwelded ignimbrite (*ignimbrite* is used here for all pyroclastic flow deposits, as suggested by Fisher and Schmincke, 1984, p. 222). Such deposits are often difficult to distinguish from one another and may physically grade from ignimbrite to lahar with increasing distance from the eruptive vent (Pierson, 1985). Rocks containing primarily monomictic, angular clasts of andesite or rhyolite, in a finer matrix hosting plagioclase crystals, are probably ignimbrite. Lahar can, in places, be confidently identified by the presence of polymictic, rounded boulders in a dark, apparently muddy matrix. Other volcaniclastic rocks in this horst include airfall tuff, generally fine-grained and well-stratified, slightly welded ignimbrite showing partly flattened pumice clasts, and sandstone.

The lavas above the conglomerate are similar to the basal flow: dense, hard, flowbanded, plagioclase + pyroxene phryic andesites. Amygdules are uncommon except in the uppermost flow which has,
especially toward the eastern edge of the horst, abundant vesicles filled with chlorite. Flow banding is quite consistent and generally parallel to bedding measured in adjacent clastic rocks. Columnar jointing is common (Plate 2), and well developed on the top of the ridge.

In the northern part of the horst exposure is poor and lower Spences Bridge rocks are not divided. Exposure becomes progressively worse toward the floor of the Midday Creek valley and the lower Spences Bridge Group there may be overlain by flows of Spius Formation. Although the thickness of known lower Spences Bridge Group stratigraphy in the Central Horst is roughly 2.5 km, the total thickness of that group may exceed 4 km if the lower Spences Bridge Group extends north to the Midday Fault.

*Stratigraphy of the "Gillis Ridge" area*

Although north and northwest trending extensional faults break continuity, lower Spences Bridge Group rocks underlying all of "Gillis Ridge" form a composite sequence which can be regarded as a single section with modest facies changes. East of the Central Horst, in roadcuts above the northeast shore of Gillis Lake, the basal flow of andesite is well exposed. About 1 km west of the lake (UTM 452323) the basement-clast conglomerate unit is present in 60 m-high bluffs. Although in the Central Horst section this unit is mainly composed of moderately rounded pebble to cobble size clasts, here angular to subangular boulders
are common, some exceeding 2 m in diameter. This deposit varies greatly in thickness, ranging from 0 to 100 m within 1 km. The immaturity and large fluctuations in thickness of this unit suggest that it was deposited in fans from nearby fault escarpments or otherwise tectonically disturbed basement rock. The absence of such fanglomerate below the basal lava flow indicates that deformation in that area commenced shortly after initial eruption of lower Spences Bridge Group lava, supporting Monger’s (1985) conception of penecontemporaneous deformation.

Also present near Gillis Lake, in roadcuts above its northern shore, are laharic and tuffaceous rocks hosting beds of dark siltstone. Organic-rich deposits such as these, indicative of ponded water, are found occasionally throughout the volcanic pile. It is from such siltstones, in other places, that palynomorphs were extracted (section 3). From recessive exposures below a powerline, 0.25 km north of Gillis Lake, mud crack casts in sandstone were found, further indicating local shallow water conditions.

The lower half of the section, east of the Central Horst and above the units just discussed, is dominated by coarse and fine grained volcaniclastic rocks comprised, almost exclusively, of lower Spences Bridge Group lithologies. In these rocks, as in all the volcaniclastic rocks in the study area, the occasional clast of basement rock is present. Thin-bedded airfall tuffs underlie two hills on the eastern end of the ridge. North of the ridge crest (UTM 457352) is a small landslide scar in friable lahar, which can be seen from near the Midday Creek / Coldwater River
Stratigraphy northwest of the Central Horst involves more lava than to the east, and the lava/clastite ratio steadily increases toward the northwest where, in the fault block which spans Spius Creek, lavas predominate. Cross section B-B" (Figure 4b) shows the stratigraphy of part of the lower Spences Bridge Group, west of the central horst. Because the rock units directly above the basement unconformity are covered, westward persistence of the basal andesitic flow and fanglomerate is uncertain. As in the Central Horst, the stratigraphy comprises interbedded lavas and volcaniclastic rocks. Near the ridge crest (UTM 425365) bedded airfall tuff overlies plane beds and rare dunal or antidunal bedforms, suggestive of pyroclastic surge deposits. Conformably overlying the lower Spences Bridge Group in this area are flows of Spius Formation. Contact relations with Spius Formation were noted in section 2 and will be further discussed in section 5.3.2.

5.2.4 Stratigraphy of the Shovelnose Mountain area

Compared to the "Gillis Ridge" area, stratigraphy in the Shovelnose Mountain area is poorly known because of insufficient fieldwork complicated by poor exposure and forest cover (Plate 3), uncertain structure (section 4.2.2) and rapid facies changes. Here, in contrast to the "Gillis Ridge" area, rhyolites are present and indeed dominate, although andesite and clastic rocks are also abundant. Two volcanic necks, one on the peak
of Shovelnose Mountain, the other 2 km to the southwest, stand up as resistant knolls (Figure 4a, Plate 3). The first neck is surrounded by related rhyolite flows; the second sits isolated by erosion.

Two types of rhyolite are present: mauve (black when fresh) plagioclase porphyry (Plate 4) and light grey quartz + plagioclase porphyry of higher silica content (section 7.2.1). Both have well-developed, commonly steeply dipping, curviplanar flowbanding indicative of high viscosity. In places, however, such as near the Coldwater River (UTM 505260), mauve rhyolite was fluid enough to pool and subsequently cool by columnar jointing. Because the necks consist of mauve rhyolite only, and are not crosscut by other intrusives, stratigraphically higher andesite on the north side of this mountain must have been extruded from a different (and unknown) centre.

In addition to the typical airfall, lahar, and nonwelded ignimbrite lithologies previously discussed, the Shovelnose Mountain area has at least two deposits of strongly welded ignimbrite containing chloritized fiamme. One is difficult to reach, on the northern slope of the mountain; the other is easily accessed in a railway cut beside the Coldwater River (UTM 504240). A third locality of that rock type is situated on the peak of Mount Thynne, 13 km south of Brookmere.

Cross section A-A* (Figure 4a) shows the stratigraphy and structure of the west and north slopes of Shovelnose Mountain. Conformably overlying lower Spences Bridge Group strata are flows of Spius Formation,
south of Voght Creek.

One spectacular 0.5 km-long outcrop of lower Spences Bridge Group strata is exposed in a Coquihalla Highway roadcut 0.5 km southeast of Kingsvale. There, beds of sandstone, tuff and coal, dipping moderately to the south, are interlayered with lahar (Plate 5). Rocks forming the northern 230 m of roadcut are cut by three nearly vertical faults, probably related to the Voght Fault, which destroy stratigraphic continuity. The southerly 270 m, however, constitutes a single section disturbed only by incipient boudinage, gentle folds (Plate 6) and minor thrust faults (Plate 7). In this section, 49 m (true thickness) of interbedded sandstone, tuff and coal are overlain by 35 m of massive lahar which is overlain by 35 m of sandstone, tuff and coal very similar to the strata beneath the lahar. The uppermost part of the section includes a deposit of accretionary lapilli. Plant megafossils collected from within the strata beneath the lahar are discussed in section 3.1.1. Deformation in this exposure increases northward towards the faults. This observation, a schistose fabric in the coal, plus boudinage, folding and thrusting indicate that deformation is post coalification and lithification and probably related to block faulting associated with Eocene extensional tectonics (section 4.2).

5.2.5 Stratigraphy in the Fig Fault Zone

Stratigraphy of lower Spences Bridge Group rocks in the Fig Fault Zone is simple, and shown on cross section A–A’ (Figure 4a). The lowest
exposed unit comprises tuffaceous rocks and sandstone. Overlying these lithologies are andesite, mauve rhyolite and quartz-eye rhyolite.

Immediately south of the bridge over the Coldwater River at Kingsvale are outcrops of nonwelded ignimbrite containing carbonized and silicified wood fragments. Inspection of these deposits, which continue for a few hundred meters to the south, did not locate the plant fossil site used by Rice (1947) to define the Kingsvale Group. However, the description and photograph of rocks hosting that fossil locality, provided by Rice (1947), closely match the ignimbritic deposits in this area. Consequently, it is assumed that these rocks constitute the type area of the Kingsvale Group, and that the Kingsvale fossil site has been covered by colluvium or removed by erosion. Typical lower Spences Bridge Group andesite and rhyolite which overlie these clastic rocks 3 km to the south near Fig Lake confirm the inclusion of Rice's Kingsvale Group within the lower Spences Bridge Group (section 2.3).

Some plutonic rocks in the study area, included in map unit 1 of figure 2, may be of Cretaceous age and possibly comagmatic with the Spences Bridge Group.
5.3 Stratigraphy of Spius Formation

5.3.1 Introduction

Lithologies of Spius Formation are much less diverse than those of the lower Spences Bridge Group. They consist of dominantly reddish to yellowish brown, green and grey amygdaloidal andesite (Plate 8), with lesser amounts of black to brown dense andesite and dark pyroclastic and epiclastic rocks. Many of the lavas are aphyric except for serpentine-after-olivine pseudomorphs, while others have plagioclase and pyroxene crystals (detailed petrography in section 6.2). Vesicles are filled with chlorite, calcite, quartz, chalcedony, celadonite or zeolites. In contrast to the dense varieties of lava, which are commonly quite fresh, amygdaloidal rocks are usually extremely altered, owing to their high porosity and permeability to groundwater flow. Dense lava commonly constitutes chilled flow bottoms, although some entire flows of this type, especially those bearing plagioclase and pyroxene, are present. Spius Formation lavas are rarely flowbanded and nowhere were columnar joints observed. No vertical or lateral trends have been reported by previous authors or observed by the writer. Because of this uniformity, Spius Formation is mapped almost entirely as a single unit, and a discussion of detailed stratigraphy is not possible. Minimum thicknesses of Spius Formation were estimated at 600 m in the study area (Thorkelson, 1985), and 1000 m near Spences Bridge (Duffell and McTaggart, 1952).
The best exposures of Spius Formation are found in cliffs on the north side of Prospect Creek, 0.5 km west of the Spius Creek / Prospect Creek confluence, where lava flows are interbedded with coarse pyroclastic rocks (Plate 9). These exposures, and the more accessible outcrops along the Spius Creek road east of Spius Creek, form the south end of the type area for Spius Formation (section 2.3).

Flows of Spius Formation conformably overlie felsic tuff and organic-rich sandstone of the lower Spences Bridge Group, on the northeast corner of Shovelnose Mountain (Palynomorphs extracted from that sandstone are discussed in section 3.1.1.). Exposures of Spius Formation in this area are confined to small roadcuts. In the Fig Fault Zone, good exposures are found in the canyon of Gillis Creek, and on a cliff immediately east of a gas pipeline cut, south of the Gillis Lake road (UTM 490302). North of Gillis Creek, Eocene Kamloops Group conglomerate unconformably overlies Spius Formation.

5.3.2 Gradational contact with the lower Spences Bridge Group

The outlier of Spius Formation on the northeast corner of Shovelnose Mountain conformably overlies tuffaceous deposits of the lower Spences Bridge Group. Similarly, Spius Formation flows rest conformably on andesite of the lower Spences Bridge Group in the fault block on the northwest corner of "Gillis Ridge", by the Spius Creek / Prospect Creek confluence. In both those areas, Spius Formation lithologies occupy the
entire section above the contact with Spius Formation. In contrast, 3–4 km southeast of the Spius Creek / Prospect Creek confluence, the lowest flows of Spius Formation are intercalated with welded and crystal tuffs containing quartz and hornblende. Because those minerals are typical of lower Spences Bridge Group rhyolite, but are absent from flows of Spius Formation, the tuffs are correlated with the lower Spences Bridge Group. Therefore, the earliest extrusions of Spius Formation lava were concurrent with the latest emissions of the lower Spences Bridge Group. Close temporal relations between these units are corroborated by age determinations (section 3.1) petrography (section 6.3) and geochemistry (section 7.3).

5.4 Synthesis of mid-Cretaceous physical volcanology

In the study area, deposition of the lower Spences Bridge Group began with extrusion of acid andesite onto a surface of moderate topography underlain by Late Triassic and Early Jurassic volcanic and plutonic rocks. That event was followed by faulting or other tectonic activity which resulted in deposition of basement-clast fanglomerate. Deposition of various lithologies followed, notably andesite, rhyolite, lahar and ignimbrite, indicating both explosive and extrusive styles of eruption. The abundance of volcaniclastic rocks and, in places, rhyolite, suggests that emissions accumulated on paleoslopes of at least moderate steepness. The lack of pillow lavas and marine fossils, and the occasional presence of welded ignimbrite indicates that deposition was subaerial, as noted by Devlin (1981). The composite volcanic stratigraphy of the study area is
similar to that described by previous workers in other parts of the Nicoamen Structural Depression (eg. Duffell and McTaggart, 1952; Preto, 1979). Rhyolite, which was probably extruded in the form of domes and flows of limited extent, is found throughout the depression suggesting that lower Spences Bridge rocks were erupted from several centres and accumulated as a set of contiguous stratovolcanoes. Eruption from multiple vents is corroborated by regional differences in geochemistry (section 7.2.3).

Near Spences Bridge, Spius Formation was deposited on lower Spences Bridge rocks after a period of faulting, folding and erosion (Devlin, 1981; Monger 1982, 1985). In the study area, however, stratigraphic relations are conformable and gradational suggesting that deformation was local. Alternately, deformation could have been widespread, causing angular relations between the units only where deposition was not continuous. The Dot beds, separating a sequence of interbedded lower Spences Bridge Group lavas and volcanioclastics from Spius Formation southeast of Spences Bridge, may represent such a hiatus in local volcanism. Those beds, comprising primarily coarse and fine-grained fluvial and lacustrine rocks (Devlin, 1981) and minor tuff but no lava (Duffell and McTaggart, 1952), suggest that while proximal volcanic activity ceased, followed by erosion and deposition of clastic detritus, distal volcanism yielding the tuffs continued. The source of pyroclastic input to that area could have been located in this writer's study area, where volcanism was uninterrupted and lower Spences Bridge rocks interfinger with flows of Spius Formation.
Spius Formation in the study area was deposited exclusively on the lower Spences Bridge Group. To the north and northwest, however, that formation rests unconformably on rocks of the Nicola Group and Mount Lytton Plutonic Complex respectively (Figure 1a) (Monger and McMillan, 1984). There, the Spius apparently accumulated on lower Spences Bridge rocks and overlapped onto adjacent basement, parts of which may have been stripped of lower Spences Bridge Group strata during the interval of erosion discussed earlier (Monger, 1982). As indicated by highly amygdaloidal textures, most Spius flows were volatile-rich and probably very fluid. The general absence of intercalated clastics suggests that Spius Formation formed a sequence with a low profile and gentle angle of deposition. Reddened (oxidized) flows and a lack of pillows implies subaerial deposition. Lava of this formation probably flowed into in low-lying areas of paleotopography, then accumulated as a shield volcano.

5.5 Eocene Kamloops Group

Kamloops Group hornblende-needle dacite is downdropped in the Fig Fault Zone and a much smaller graben adjacent the McInnes Fault. Its Eocene age is confirmed by a K–Ar whole rock date of 49.2 ± 1.8 Ma (Table 1). The excellent exposure from which that date was obtained is located in a railway cut southwest of the Midday Creek valley (UTM 490355). Mafic hornblende-bearing dykes cut lower Spences Bridge Group strata a few km south of Brookmere on Mount Thynne. Their minerology and geochemistry indicates that they do not belong to the Spences Bridge
Group, but may be feeders to the Kamloops Group.

Also correlated with that group is a thick section of polymictic conglomerate and minor sandstone extending for 6 km north of its unconformable contact with Spius Formation, near Gillis Creek. Although bedding orientations vary, dips are generally moderate to the north, and a thickness of between 2 and 3 km is estimated. Well rounded pebbles and cobbles, supported by a sandy matrix, suggest deposition in a braided stream environment. Clast lithologies are varied, including granitoids plus Nicola, Spences Bridge and Kamloops Group volcanic rocks. Imbrication of pebbles in the northern part of the section (UTM 487357) suggests a northward paleocurrent. Best exposures are along the Coldwater River, 4 km north of Kingsvale (Plate 10).

As discussed in section 4.2.1, the Fig Fault Zone is a complex graben thought to have been active in Eocene time, downdropping Spius Formation and Kamloops Group volcanic rocks by thousands of meters. The thick accumulation of Kamloops Group conglomerate was probably deposited by a north-flowing river, contemporaneous with downfaulting. In this way the graben was filled as it formed.

Some granitoids, included in map unit 1 (Figure 2), may be of Eocene age and coeval with the Kamloops Group.
Plate 1  Fanglomerate comprised of mostly basement (unit 1) clasts, 1 km west of Gillis Lake.

Plate 2  Columnar joints in lower Spences Bridge Group acid andesite near Otter Creek southeast of study area (UTM 634169).
Plate 3  Western slope of Shovelnose Mountain. Resistant knolls are volcanic necks of lower Spences Bridge Group curviplanar flowbanded mauve rhyolite.

Plate 4  Flowbanding in lower Spences Bridge Group mauve rhyolite from Shovelnose Mountain.
Plate 5 Massive lahar overlying interbedded coal and sandstone, lower Spences Bridge Group, 0.5 km southeast of Kingsvale (UTM 504300).

Plate 6 Anticline in lower Spences Bridge Group coal and sandstone beds, UTM 504300, Shovelnose Mountain.
Plate 7  Southerly-directed thrust fault in lower Spences Bridge Group coal and sandstone beds, UTM 504300. Displacement is about 4 m.

Plate 8  Zeolite amygdules in Spius Formation andesite near the confluence of Prospect and Spius creeks.
Plate 9  Intercalated Spius Formation amygdaloidal andesite and coarse pyroclastic rocks 0.5 km west of the confluence of Prospect and Spius creeks.

Plate 10  Kamloops Group conglomerate above the western bank of the Coldwater River 4 km north of Kingsvale.
6. PETROGRAPHY OF THE SPENCES BRIDGE GROUP

6.1 Introduction

This chapter is based on field observations, roughly 300 hand specimens and over 50 thin sections. Because the emphasis of petrography in this thesis is on primary mineralogy and textures, visibly altered and highly amygdaloidal samples were intentionally avoided. Consequently, the metamorphic history of the Spences Bridge Group is only briefly discussed and the reader is directed to earlier work by Drown (1973), Mamu (1974) and Pearson (1974) for descriptions of (zeolite grade) metamorphism northwest of the study area. Plagioclase and orthopyroxene compositions were determined by optical techniques described in Deer, Howie and Zussman (1966). Petrographic terminology follows definitions given by Hughes (1982). Visually estimated modes for whole rock, groundmass and phenocrysts are given in Table 2 for six Spences Bridge Group lava classifications.

6.2 Petrography of the lower Spences Bridge Group

Three distinct lava types are recognized in the study area and mapped as separate units in Figure 2. Andesite is the most abundant type, followed by quartz-free ("mauve") rhyolite and quartz-phyric rhyolite. Distribution of these lithologies is discussed in section 5.2.
### TABLE 2: Visually Estimated Modes Of Primary Minerology

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Notes: tr = trace amount, equilibrium phase; xc = trace amount, xenocryst phase; S.B. = Spences Bridge.
Andesites are characterized in hand specimen by their dark bluish to purplish grey color, abundant plagioclase and pyroxene phenocrysts and subtly flowbanded or massive texture. In thin section, phenocrysts constitute about 20% of the rock, fine grained groundmass from 30–40% and largely devitrified glassy mesostasis from 40–50% (Table 2). Acid andesites have a slightly higher mesostasis/groundmass ratio than basaltic andesites, but are decisively distinguished only by chemistry (section 7.2). Groundmass grains of phenocrysts are sometimes slightly aligned but usually have only felt texture.

Plagioclase phenocrysts, typically 2 mm long and commonly showing oscillatory zoning from intratelluric crystallization, account for about two thirds, by volume, of the phenocryst population. Compositions vary both within individual grains and throughout the andesite suite but are usually from An\(_{45}\) to An\(_{55}\). In the freshest samples, plagioclase is nearly free from alteration; more commonly, grains are variably saussuritized and may be completely albitized.

Both orthopyroxene and augite are also ubiquitous in andesites. Orthopyroxene varies in composition from En\(_{80}\) (bronzite) to En\(_{65}\) (hypersthen). It is the least stable phenocryst, commonly altered to chlorite. It is normally acicular and usually untwinned, but is occasionally twinned by interpenetration (Plate 11). Augite, more stable than either plagioclase or orthopyroxene, forms stubby, nearly equant grains almost invariably contact twinned on (100) (Plate 12). Orthopyroxene and augite
each comprise about 16% of the phenocryst volume, with augite being less abundant in acid andesite than basaltic andesite. Magnetite phenocrysts, not visible in hand specimen, constitute only 3% of the phenocrysts. Rarely, the former presence of olivine is inferred from pseudomorphs composed of serpentine (or some other mafic phyllosilicate) and opaque oxides. Because of its rare occurrence, olivine is regarded as xenocrystic and not part of the equilibrium phenocryst assemblage. Apatite exists in trace amounts in some andesites as inclusions in plagioclase or pyroxene.

In all the andesites, some plagioclase and pyroxene grains sit isolated while others form glomerocrysts (Plates 13–15). Because orthopyroxene contributes only minimally to such glomeroporphyritic texture, phenocryst clusters are mainly composed of augite and plagioclase. The occasional incorporation of orthopyroxene and magnetite into glomerocrysts, however, attests to the concurrent precipitation of all four major phases under intratelluric conditions. Although magnetite phenocrysts are relatively low in abundance, smaller grains comprise nearly a third of the groundmass in andesites. Pyroxene (30%) and plagioclase (40%) completes the groundmass mode.

Rhyolite lacking quartz phenocrysts, listed as mauve rhyolite in Table 2, is similar in general appearance to andesite in thin section. Differences include higher mesostasis and lower phenocryst proportions, much higher plagioclase/pyroxene groundmass and phenocryst ratios, an increase in phenocryst magnetite, and higher apatite contents. In hand specimen and
outcrop scales mauve rhyolite is identified by a near absence of mafic phenocrysts. Conspicuous flowbanding has facilitated fracturing and subsequent groundwater flow, causing greater alteration to rhyolite than to contiguous andesite.

Quartz rhyolite differs from mauve rhyolite in several ways. In addition to light grey color, quartz phenocrysts, reduced magnetite and increased apatite contents, plus trace amounts of pyrite, some quartz rhyolite contains hornblende in place of pyroxene. Such hornblende, identified in hand specimen by its acicular shape, black color and low lustre, is largely altered to opaque oxides. Quartz grains, which form resistant bumps on weathered outcrop surfaces, are extremely embayed in thin section (Plate 16). Because the stability of quartz in magma is reduced with decreasing pressure (Gill, 1981), such corrosion may be the result of precipitation at depth followed by partial resorption upon magmatic uprise. Alternately, the quartz grains may be xenocrysts rendered unstable and corroded by the host melt, but the resorption explanation is preferred because of abundant quartz in the groundmass (Table 2) and high silica content of the rocks (section 7.2.1).

Tuffaceous rocks of the lower Spences Bridge Group comprise a wide variety of lithologies, from airfall tuff to agglomerate. Lithologic descriptions and distributions are discussed in section 5.2. One visually striking rock type is welded ignimbrite containing collapsed pumice fragments (fiamme) and shards. More commonly, tuffs are nonwelded and
contain undeformed or gently compressed devitrified shards (Plate 17). Fragmental volcanic rocks contain grains of the various minerals found in lower Spences Bridge Group lavas, namely plagioclase, pyroxene, magnetite, apatite and quartz. They tend to be more felsic than andesites with which they are frequently interbedded, suggesting that magmas of higher silica content were more explosive.

6.3 Petrography of Spius Formation

Lava of Spius Formation comprises two distinct end-member lithologies defining a spectrum of rock types. The first lithology to be discussed is herein called Spius-type, the second is lower Spences Bridge-type for reasons which will be given in this section and developed in section 7.3.2. Spius-type lava is found exclusively in Spius Formation. It is amygdaloidal, except for some flow bottoms, with vesicles filled by chlorite, zeolites, chalcedony and other low metamorphic grade minerals. From amygdules, P. B. Read (personal communication, 1986) identified laumontite by X-ray diffraction and prehnite by optical means and concluded that Spences Bridge Group rocks in the study area were altered to zeolite grade. The mesostasis (devitrified glass) constitutes only about 20% of the rock, whereas the groundmass makes up 70% (Table 2). The remaining 10% is occupied almost entirely by pseudomorphs of serpentine (or other mafic phyllosilicates) and opaque oxides after olivine (Plate 18). No relict olivine remains, but characteristic six sided outlines, consistently mafic pseudomorphs, and the lack of another silicate phenocryst phase
argue strongly for the former presence of olivine. Trace amounts of anhedral, apparently partially decomposed crystals of plagioclase, orthopyroxene and augite are present in most samples (Plates 19–23). Such grains, because of their consistently ragged appearance and probable state of disequilibrium with the host melt, are interpreted as being corroded xenocrysts. Magnetite grains are found within and adjacent to many of the anhedral augite crystals, their growth apparently facilitated by liberation of iron during corrosion (Plates 19, 2). The groundmass is dominated by strongly aligned, unzoned microlites of plagioclase (An₅₀–An₆₅), creating a striking hyalopilitic texture, with lesser amounts of olivine, pyroxene and magnetite. An excellent example of Spius-type lava with almost no xenocrysts can be found immediately above the uppermost lower Spences Bridge Group strata, about 5.5 km east of Kingsvale (UTM 553295). Thorkelson (1985) noted the occasional presence of outwardly similar amygdaloidal rocks within the lower Spences Bridge Group (Figure 3). Those flows, however, do not contain olivine or its pseudomorphs.

The other end member of the lava spectrum in Spius Formation is lower Spences Bridge-type. That lithology is identical in most ways to andesite lava of the lower Spences Bridge Group, with plagioclase dominating the phenocryst assemblage followed by equal amounts of augite and bronzitic to hypersthenic orthopyroxene. Like lower Spences Bridge Group andesites, this type also has trace amounts of serpentine after olivine, felty groundmass and orthopyphric phenocryst textures, plus a high
percentage of mesostasis. Unlike lower Spences Bridge Group andesites, this lava type has minor amounts of corroded augite. Spius-type magmas were probably hotter and richer in volatiles that lower Spences Bridge-type magmas as indicated by the (former) presence of only olivine phenocrysts, and the abundance of amygdules. A good example of this lava type is located at UTM 393417, about 20 m east of the Spius Creek road.

Lavas which are intermediate between Spius-type and lower Spences Bridge-type show variable amounts of pseudomorphed olivine plus highly corroded crystals and glomerocrysts of plagioclase, contact-twinned augite and scattered orthopyroxene within a variably hyalopilitic groundmass. The presence of such corroded minerals, which, if undamaged would typify the main phenocryst assemblage in lower Spences Bridge Group andesites, suggests that hotter, Spius-type magma mixed in variable proportions with cooler, more fractionated and less hydrated lower Spences Bridge-type melts and rendered phenocrysts of the latter type unstable. Where Spius-type magma dominated the mixture, the resultant lava was rich in olivine and poor in corroded lower Spences Bridge-type phenocrysts. Where lower Spences Bridge-type magma dominated, olivine ceased to be precipitated, and instead plagioclase and pyroxene were formed.

In the study area, most Spius Formation flows consist of hyalopilitic, amygdaloidal lava bearing pseudomorphs of olivine, suggesting that Spius-type magmas dominated the majority of mixtures. The former presence of olivine suggests that after mixing only minimal fractionation
occurred. These hypotheses are supported by patterns of trace elements, discussed in section 7.3.2.
Plate 11  Interpenetration-twinned bronzite in lower Spences Bridge Group basaltic andesite. Crossed polarizers.

Plate 12  Euhedral augite twinned on (100) in lower Spences Bridge Group acid andesite. Crossed polarizers.
Plate 13  Plagioclase glomerocryst in lower Spences Bridge Group acid andesite. Crossed polarizers.

Plate 14  Augite (with minor hypersthene) glomerocryst in lower Spences Bridge Group andesite. Crossed polarizers.
Plate 15  Plagioclase (grey), augite (blue) and hypersthene (brown) glomerocryst in lower Spences Bridge Group acid andesite. Crossed polarizers.

Plate 16  Deeply embayed (corroded) quartz crystal in high-silica lower Spences Bridge Group rhyolite. Crossed polarizers.
Plate 17  Undeformed shards (centre and lower left), hornblende (upper right) and plagioclase (upper left) in nonwelded lower Spences Bridge Group airfall tuff. Plane light.

Plate 18  Pseudomorph of serpentine (or another mafic phyllosilicate) after olivine in Spius Formation basaltic andesite. Crossed polarizers.
Plate 19  Embayed augite crystal, twinned on (100), containing large magnetite grain in blue sector, in Spius Formation andesite. Crossed polarizers.

Plate 20  Anhedral augite containing two magnetite grains in Spius Formation andesite. Crossed polarizers.
Plate 21  Inclusion-rich, partly decomposed plagioclase in Spius Formation andesite. Crossed polarizers.

Plate 22  Anhedral augite + plagioclase glomerocryst in Spius Formation andesite. Crossed polarizers.
7. GEOCHEMISTRY OF THE SPENCES BRIDGE GROUP

7.1 Introduction

Thirteen lower Spences Bridge Group and 10 Spius Formation specimens, all lavas, were analyzed for major elements by X-ray fluorescence by the Geological Survey of Canada in Ottawa. All samples, except for 2 from the lower Spences Bridge Group, were additionally analyzed, also by XRF, for trace elements at the Department of Oceanography, University of British Columbia. Field locations and complete chemical data sets of specimens are listed in Table 3. A key to chemical plots is given in Figure 5.

7.2 Geochemistry of the lower Spences Bridge Group

7.2.1 Major element chemistry

Analysis of the geochemistry of the lower Spences Bridge Group begins with a classification plot of $K_2O$ and $SiO_2$ contents (Figure 6)(after Taylor, 1969). Most samples are classified as low to medium $K$ andesite, evenly split between basaltic and acid types. No basalts or dacites are present in the suite, but three samples, with $SiO_2 > 68\%$, are classed as rhyolite. The relative scarcity of rhyolite is due to bias in sampling toward mafic rocks; the presence of dacite in the study area is therefore considered probable, but the presence of basalt unlikely. Although not
TABLE 3: Major And Trace Element Chemistry

lower Spences Bridge Group

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<th>74B</th>
<th>114</th>
<th>117</th>
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| Longitude W. | 120° 57' 10" | 120° 58' 45" | 121° 01' 54" | 121° 00' 37" | 121° 03' 36" | 120° 51' 02"
| UTM coordinates | 470320 | 451339 | 412360 | 427345 | 390407 | 544266 |
| Rock type | pl+px and. | pl+px and. | pl+px and. | pl+px and. | pl+px and. | pl+px and. |
| SiO₂ | 58.8 | 60.9 | 61.5 | 54.3 | 55.8 | 60.3 |
| TiO₂ | 0.76 | 0.81 | 0.88 | 1.25 | 0.81 | 0.79 |
| Al₂O₃ | 18.5 | 15.7 | 16.5 | 17.2 | 17.0 | 16.7 |
| MnO | 0.13 | 0.13 | 0.13 | 0.16 | 0.18 | 0.14 |
| MgO | 2.98 | 3.62 | 2.42 | 4.22 | 4.65 | 1.86 |
| FeO* | 6.1 | 5.9 | 5.7 | 8.4 | 7.5 | 6.2 |
| CaO | 6.11 | 5.88 | 5.89 | 8.96 | 8.72 | 5.34 |
| Na₂O | 2.9 | 2.7 | 2.4 | 2.9 | 2.4 | 3.0 |
| K₂O | 0.34 | 2.07 | 2.09 | 0.91 | 0.87 | 2.25 |
| H₂O | 2.3 | 1.9 | 1.7 | 1.3 | 1.1 | 1.2 |
| CO₂ | 0.2 | 0.2 | 0.1 | 0.1 | 0.5 | 0.5 |
| P₂O₅ | 0.18 | 0.20 | 0.24 | 0.30 | 0.19 | 0.19 |
| Ba | 582.6 | 643.8 | 676.9 | 325.3 | 261.8 | 799.2 |
| Cr | 9 | 61 | -6 | 39 | 41 | 24 |
| Nb | 5.4 | 6.0 | 5.7 | 4.8 | 4.7 | 6.6 |
| Ni | 8.9 | 18.3 | 9.0 | 18.1 | 11.9 | 13.4 |
| Rb | 3.2 | 35.5 | 39.5 | 9.2 | 10.6 | 54.9 |
| Sr | 516.4 | 519.4 | 630.8 | 659.4 | 596.3 | 436.2 |
| V | 141.8 | 172.7 | 412.7 | 283.6 | 261.7 | 156.4 |
| Y | 32.7 | 21.5 | 26.1 | 28.4 | 22.5 | 28.5 |
| Zr | 166.1 | 135.9 | 161.6 | 127.7 | 78.0 | 184.2 |

Notes: SiO₂ to P₂O₅ in weight%; Ba to Zr in ppm; FeO* = total Fe as FeO;
pl+px and. = plagioclase + pyroxene andesite.
### TABLE 3, continued

#### lower Spences Bridge Group

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Notes: SiO₂ to P₂O₅ in weight%; Ba to Zr in ppm; FeO* = total Fe as FeO;
m. rhyolite = mauve rhyolite; q. rhyolite = quartz rhyolite; pl+px and. = plagioclase + pyroxene andesite.
TABLE 3, continued

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Notes: SiO₂ to P₂O₅ in weight%; Ba to Zr in ppm; FeO* = total Fe as FeO; pl+px and. = plagioclase + pyroxene andesite; serp. and. = serpentine-after-olivine andesite.
### TABLE 3, continued

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<tr>
<td><strong>P₂O₅</strong></td>
<td>0.30</td>
<td>0.31</td>
<td>0.52</td>
<td>0.39</td>
<td>0.35</td>
<td>0.36</td>
</tr>
<tr>
<td><strong>Ba</strong></td>
<td>348.1</td>
<td>535.1</td>
<td>549.4</td>
<td>576.7</td>
<td>594.0</td>
<td>593.4</td>
</tr>
<tr>
<td><strong>Cr</strong></td>
<td>104</td>
<td>101</td>
<td>119</td>
<td>142</td>
<td>107</td>
<td>103</td>
</tr>
<tr>
<td><strong>Nb</strong></td>
<td>5.9</td>
<td>7.0</td>
<td>10.9</td>
<td>15.3</td>
<td>10.8</td>
<td>10.1</td>
</tr>
<tr>
<td><strong>Ni</strong></td>
<td>63.1</td>
<td>63.5</td>
<td>69.4</td>
<td>73.4</td>
<td>72.3</td>
<td>68.5</td>
</tr>
<tr>
<td><strong>Rb</strong></td>
<td>19.8</td>
<td>25.2</td>
<td>6.5</td>
<td>9.2</td>
<td>30.4</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>Sr</strong></td>
<td>779.8</td>
<td>569.1</td>
<td>803.0</td>
<td>772.3</td>
<td>548.3</td>
<td>953.5</td>
</tr>
<tr>
<td><strong>V</strong></td>
<td>159.1</td>
<td>163.6</td>
<td>182.8</td>
<td>142.3</td>
<td>141.1</td>
<td>142.0</td>
</tr>
<tr>
<td><strong>Y</strong></td>
<td>23.9</td>
<td>24.3</td>
<td>32.9</td>
<td>24.9</td>
<td>28.7</td>
<td>24.4</td>
</tr>
<tr>
<td><strong>Zr</strong></td>
<td>134.5</td>
<td>157.0</td>
<td>200.4</td>
<td>177.8</td>
<td>200.4</td>
<td>180.0</td>
</tr>
</tbody>
</table>

**Notes:** SiO₂ to P₂O₅ in weight%; Ba to Zr in ppm; FeO* = total Fe as FeO; pl+px and. = plagioclase + pyroxene andesite; serp. and. = serpentine-after-olivine andesite.
classed separately on this diagram, two types of rhyolite are represented:
the two specimens with 68%<SiO₂<70% are plagioclase + pyroxene phyric
and usually mauve in color; the sample with SiO₂=73.5% has quartz
phenocrysts in addition to plagioclase + pyroxene/hornblende. The former
type will be referred to as mauve rhyolite, the latter as quartz rhyolite.
Petrographic details are given in section 6.2.

The lower Spences Bridge Group is further classified on several
chemical diagrams. Figure 7, plotting K₂O+Na₂O vs. SiO₂, shows that the
suite is entirely subalkaline (Irvine and Baragar, 1971). Figure 8, based on
MgO to FeO* (total iron as FeO) ratios, indicates a calcalkaline to
transitional trend because andesites are generally calcalkaline but rhyolites
are transitional to tholeiitic (Miyashiro, 1974). Unlike K₂O vs. SiO₂, most
oxide vs. SiO₂ patterns on (Harker) variation diagrams show little scatter
from smooth curvilinear trends (Figures 9–15). Where lower Spences Bridge
Group trends differ significantly from those of Spius Formation, on P₂O₅
and TiO₂ vs. SiO₂ plots, envelopes are drawn around the andesites of each
unit. CaO, FeO*, MgO, Al₂O₃, TiO₂, and P₂O₅ all decrease in concentration,
from basic to acid compositions, due to fractionation of plagioclase, augite,
orthopyroxene, magnetite and apatite. Na₂O concentrations rise because of
its low concentration in fractionating phases.

7.2.2 Minor and trace element chemistry

Most of the analyzed minor and trace elements are plotted on a spider diagram (Figure 16), discussed by Thompson et al. (1984), where element concentrations are normalized to chondritic values except Rb, K and P which are normalized to those of "primitive mantle." Normalizing factors, in ppm, are given above each element on the diagram. Shown in addition to plots of basaltic andesites of the lower Spences Bridge Group is the pattern of a basalt, regarded as a representative arc lava by Thompson et al. (1984), from the New Hebrides. Because such patterns are best interpreted for the most primitive rocks in a suite, acid andesites and rhyolites of the lower Spences Bridge Group are not plotted here.

As described earlier for K (in Figure 6), Ba, Rb and K show considerable variation in normalized concentrations, but are notably higher than Nb, plotted to their immediate right. The nearly flat pattern of Nb, P, Zr, Ti and Y is interrupted by high Sr values. That Sr peak is characteristic of arc lavas, as evidenced by a similar peak in the New Hebrides pattern. Overall, the lower Spences Bridge Group pattern follows that of the New Hebrides sample, having a Nb dip and high values of low field strength (large ion lithophile) elements (Ba, Rb, K, Sr) relative to high field strength elements (Nb, P, Zr, Ti, Y). The larger spread in values of Ba, Rb and K
relative to other elements may be the result of their greater mobility in aqueous solutions (Shervais, 1982).

The arc character of the lower Spences Bridge unit is further manifested by Zr, Ti, and V patterns. In Figure 17, Zr vs. Ti (from Pearce, 1982), all lower Spences Bridge Group specimens plot within the field of arc lavas. In Figure 18, V vs. Ti (from Shervais, 1982), a calcalkaline trend is observed where basaltic andesite has Ti/V ratios between 15 and 30, and acid andesite, mauve rhyolite and quartz rhyolite have, except in one specimen, reduced V contents and increased Ti/V ratios. This pattern, consistent with petrography, is indicative of magnetite fractionation and subsequent rapid loss of V from the melt.

Except for one specimen with a magnesium number (Mg#) of 62.2, all lower Spences Bridge Group rocks have numbers less than 60 (Figure 19) (Mg# = 100[Mg/Mg+Fe²⁺] \text{atomic}, based on 0.3 = [Fe₂O₃/FeO] \text{weight}). Ni contents vary from 33 ppm in the sample with highest Mg# to 3 ppm in quartz rhyolite. Cr contents, shown in Figure 20, range from 78 to 0 ppm. Because all samples plot well below Mg# 67, 100 ppm Ni and 300 ppm Cr, they must be fractionated and not primary, mantle-equilibrated melts (Gill, 1981). In particular, the low Ni concentrations are probably due to considerable olivine fractionation. A similar plot to Figure 19 is shown in Figure 21; Ni vs. MgO. The dashed arrow through the lower Spences Bridge Group field represents 50% (by weight) fractionation, based on average phenocryst weight proportions in lower Spences Bridge Group andesites and
Rayleigh (immediate, disequilibrium) fractionation (Cox, Bell and Pankhurst, 1979). Pyroxene compositions were assumed to be En$_{75}$ (37 weight % MgO) for orthopyroxene and Di$_{75}$ (18 weight % MgO) for augite. Partition coefficients used for Ni are listed in Table 4. The vector in Figure 21 indicates that 50% fractionation can account for the observed range of MgO contents and nearly that of Ni in lower Spences Bridge Group andesites.

Vectors for 50% fractionation, based on the same phase and fractionation parameters as those used for Ni, and the partition coefficients given in Table 4, are shown in Figures 20–26 where they are compared to the range in element concentrations for andesites, shown enveloped. Figures 20, 22 and 23 show that the range in Cr, Nb and Y contents is compatible with 50% fractional crystallization. However, maximum Zr contents exceed predicted (vector) values, and require 63% fractionation (Figures 24, 25). Even if Zr behaved completely incompatibly, with a partition coefficient of 0, 61% fractionation would have had to occur. These high degrees of fractionation are not possible, however, as MgO concentrations would drop to 0 at 59% crystallization. Divergence of Zr trends from expected behavior is further illustrated in Figure 26 where the andesite field shows a doubling of Zr/Nb ratios, from about 15 to 30, in contrast to nearly constant vector values. Assimilation of (probably acid) material with high levels of Zr but about the same Y, Nb, Cr and Ni as lower Spences Bridge Group andesites can account for the anomalous Zr concentrations.
TABLE 4: Partition Coefficients

<table>
<thead>
<tr>
<th></th>
<th>Nb</th>
<th>Y</th>
<th>Zr</th>
<th>Ni</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plagioclase</strong></td>
<td>0.025</td>
<td>0.06</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Orthopyroxene</strong></td>
<td>0.35</td>
<td>0.45</td>
<td>0.08</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td><strong>Augite</strong></td>
<td>0.3</td>
<td>1.5</td>
<td>0.25</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td><strong>Magnetite</strong></td>
<td>1.0</td>
<td>0.5</td>
<td>0.2</td>
<td>10</td>
<td>32</td>
</tr>
<tr>
<td><strong>Olivine</strong></td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>58</td>
<td>34</td>
</tr>
</tbody>
</table>

Notes: (1) Coefficients for Nb, Y, Zr from Pearce and Norry (1979).
(2) Coefficients for Ni, Cr from Gill (1981).

TABLE 5: Selected Component Contents For Inferred Parental Spius-Type Magma

<table>
<thead>
<tr>
<th>Component</th>
<th>Range in composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>170 – 190 ppm</td>
</tr>
<tr>
<td>Ni</td>
<td>120 – 130 ppm</td>
</tr>
<tr>
<td>Nb</td>
<td>17 – 18 ppm</td>
</tr>
<tr>
<td>Zr</td>
<td>230 – 250 ppm</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.635 – 0.660%</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.4 – 1.5%</td>
</tr>
<tr>
<td>MgO</td>
<td>6.0 – 6.5%</td>
</tr>
</tbody>
</table>
Higher silica (Figure 6) and lower Ni and MgO (Figure 21) show that mauve rhyolite is more evolved than andesite and that quartz rhyolite is more evolved than both. Mauve rhyolite appears to be a product of continued fractionation of andesite, with lower Ni and higher Nb, Y and Zr. Concentrations of Zr and Nb in mauve rhyolite increase by about 1.8 times over maximum contents in andesite, showing continued incompatibility whereas Y increases only slightly due to greater compatibility, especially with apatite and augite (Pearce and Norry, 1979). In quartz rhyolite, concentrations of Nb, Y and Zr are sharply reduced from their levels in mauve rhyolite, with Zr decreasing to a level below that of most acid andesites, and Y dropping to concentrations less than those of even basaltic andesite. These changes, from incompatibility to compatibility are due to the onset of zircon and, in some cases, hornblende precipitation (Pearce and Norry, 1979), as indicated by petrography (Table 2).

7.2.3 Regional variations and conclusions

Chemistry of lower Spences Bridge Group samples collected from outside the study area indicate regional variation in both major and trace elements. Preto (1979) reported major element chemistry for 5 samples of lava (his unit 10) roughly 20 km north of Princeton (Figure 1). As with lower Spences Bridge Group rocks in the study area, they follow a calcalkaline trend (Preto, 1979). However, when plotted on a P_2O_5 vs. TiO_2 diagram (Figure 27), which confines lower Spences Bridge Group and Spius Formation suites from the study area to individual fields, Preto's rocks
define a third and separate field. Smith (1986) collected specimens from the Nicola River valley between Merritt and Spences Bridge (Figure 1b). His rocks also show a calcalkaline trend but differ from those in the study area by including basalts, some with Mg# > 67, and Ni > 80 ppm.

The calcalkaline to transitional nature of the Spences Bridge Group, in accord with Ti/V and Ti/Zr ratios and spider diagram patterns from rocks in the study area, clearly indicates a subduction-related origin. Regional chemical variations suggest that the lower Spences Bridge Group was erupted from numerous centres with individual chemical characteristics, supporting stratigraphic conclusions given in section 5.4.
Key to chemical plots

Spius Formation

- basaltic andesite
- acid andesite

lower Spences Bridge Group

- basaltic andesite
- acid andesite
- mauve rhyolite
- quartz rhyolite

Field of Spius Formation andesites

Field of lower Spences Bridge Group andesites

Inferred Parental Spius-type Magma

Field of magma mixing

50% fractionation, lower Spences Bridge Group

2% fractionation, Spius Formation

Figure 5 Key to chemical plots (Figures 6 - 28).
Figure 6  K$_2$O vs. SiO$_2$ classification diagram (after Taylor, 1969). Symbols identified in Figure 5.
Figure 7  $K_2O+Na_2O$ vs. $SiO_2$ classification diagram (after Irvine and Baragar, 1971). Symbols identified in Figure 5.
Figure 8  FeO*/MgO vs. SiO₂ classification diagram (after Miyashiro, 1974). Symbols identified in Figure 5.

FeO* = total Fe as FeO
Figure 9  CaO vs. SiO$_2$ diagram. Symbols identified in Figure 5.
Figure 10  FeO* vs. SiO₂ diagram. FeO* = total Fe as FeO.
Symbols identified in Figure 5.
Figure 11  MgO vs. SiO$_2$ diagram. Symbols identified in Figure 5.
Figure 12  $\text{Al}_2\text{O}_3$ vs. $\text{SiO}_2$ diagram. Symbols identified in Figure 5.
Figure 13  TiO₂ vs. SiO₂ diagram. Symbols identified in Figure 5.
Figure 14  $P_2O_5$ vs. $SiO_2$ diagram. Symbols identified in Figure 5.
Figure 15  Na$_2$O vs. SiO$_2$ diagram. Symbols identified in Figure 5.
Figure 16. Chondrite-normalized spider diagram for lower Spences Bridge Group basaltic andesites (after Thompson et al., 1984).
Figure 17  Ti/1000 vs. Zr classification diagram (after Pearce, 1982). Symbols identified in Figure 5.
Figure 18  V vs. Ti/1000 diagram (after Shervais, 1982). Symbols identified in Figure 5.
Figure 19  Mg# vs. Ni diagram. Mg# = 100(Mg/Mg+Fe*)\textsuperscript{atomic} based on 0.3=(FeO/FeO)\textsuperscript{weight}. Symbols identified in Figure 5.
Figure 20  Cr vs. Nb diagram. Symbols identified in Figure 5.
Figure 21 Ni vs. MgO diagram. Symbols identified in Figure 5.
Figure 22  Ni vs. Nb diagram. Symbols identified in Figure 5.
Figure 23  Ni vs. Y diagram. Symbols identified in Figure 5.
Figure 24  Ni vs. Zr diagram. Symbols identified in Figure 5.
Figure 25. Cr vs. Zr diagram. Symbols identified in Figure 5.
Figure 26  Nb vs. Zr diagram. Symbols identified in Figure 5.
Figure 27  TiO₂ vs. P₂O₅ diagram. Symbols identified in Figure 5.

lower Spences Bridge Group flows, north of Princeton (Preto, 1979)
Basaltic andesites, Spius Formation
New Hebrides arc, sample FMA2 (Thompson et al., 1984)
* Average parental Spius-type magma
Field of lower Spences Bridge Group basaltic andesites

Figure 28 Chondrite-normalized spider diagram for Spius Formation basaltic andesites (after Thompson et al., 1984).
7.3 Geochemistry of Spius Formation

7.3.1 Major element chemistry

Major element chemistry of Spius Formation is very similar to that of the lower Spences Bridge Group. Consequently, the 10 Spius Formation specimens are classified as subalkaline (Figure 7), calcalkaline (Figure 8), low to medium potassium, acid and basaltic andesites (Figure 5). Trends on oxide vs. SiO$_2$ diagrams are nearly identical to those of the Spences Bridge Group for sodium, calcium, aluminum and iron (Figures 9, 10, 12, 15), but show slightly higher average magnesium contents (Figure 11). However, Spius Formation has significantly higher P$_2$O$_5$ and TiO$_2$ concentrations, forming nearly separate fields on Harker diagrams (Figures 13, 14).

7.3.2 Trace element chemistry

P, Ti and several trace elements are plotted on a (mostly) chondrite normalized diagram (spider diagram) used by Thompson et al. (1984) (Figure 28). Details of spider diagrams are given in section 7.2.2. Shown in addition to individual plots of Spius Formation basaltic andesites are the field of basaltic andesites for the lower Spences Bridge Group (from Figure 16), and a pattern for a basalt specimen from the New Hebrides arc, regarded by Thompson et al. (1984) as a typical arc rock.
The Spius Formation suite shows a wide variation of Ba, Rb and K values with an average Ba value exceeding that for K. Although 2 specimens show a slight drop to Nb from K, the other two show a rise, and average Nb values are about equal to average Rb and K. Sr forms a peak between Nb and elements plotted to the right. P, Zr, Ti and Y cause the pattern to generally slope downward to the right, with local high values at Zr and Y. Except for the lack of a Nb dip relative to K the shape of the Spius Formation pattern is the same as that for the lower Spences Bridge Group, with Ba>Rb, K; Nb<Sr>P; Sr>P<Zr; P<Zr>Ti; and Zr>Ti<Y. Spius Formation has about the same low field strength element (Ba, Rb, K, Sr) values as the lower Spences Bridge Group, but generally higher high field strength elements (Nb, P, Zr, Ti, Y), especially Nb, P and Zr. Compared to the New Hebrides sample, Spius Formation shows a reverse Ba to K trend, and elevated Nb, P and Zr, but has a similar peak at Sr. "Parental Spius-type magma" values, also shown on the spider diagram, are discussed later.

Figure 17 (from Pearce, 1982) shows the classification of Spius Formation lavas on a Ti vs. Zr plot. Five specimens plot within the field of arc lavas, three lie on or near the edge of that field and two are classified as within plate lavas. This contrasts with the lower Spences Bridge Group which falls entirely within the arc lavas field. The different tectonic affinity of Spius Formation is further demonstrated on a V vs Ti plot (after Shervais, 1982) (Figure 18), where samples plot between Ti/V
ratios of 32 and 60. Such ratios, which exceed the normal range for arc lavas but are found in back-arc, ocean island and alkalic basalts, are indicative of low oxygen fugacity during fusion (Shervais, 1982), probably caused by low water contents in the source material (Miyashiro, 1974). This finding is opposite to that expected from the typically massive vesiculation and presumably high water contents of erupting Spius Formation lavas, but may be explained by post-fusion assimilation of hydrous minerals and crustal fluids. Another odd aspect is the general decrease in Ti/V ratios from basaltic to acid andesites. Because bulk partition coefficients for V are always greater than or equal to those for Ti, Ti/V ratios never decrease by fractional crystallization (Shervais, 1982). Consequently, fractionation cannot be the dominant process connecting the basic and more acid members of this Spius Formation suite.

Fractionation is also rejected because of positive correlations between Ni and Nb, Ni and Y, Ni and Zr, Cr and Nb, and Cr and Zr (Figures 20, 22–25). For fractional crystallization to account for these trends, Nb, Y and Zr would have had to behave compatibly, being preferentially incorporated into the fractionating mineral assemblage. The phenocryst modes for both Spius-type and lower Spences Bridge-type rocks (Table 2), and the expected partition coefficients given in Table 4, indicate that Nb, Y and Zr would behave incompatibly, increasing in the residual liquid, whereas Ni and Cr with bulk coefficients $>1$ would behave compatibly and drop in concentration. These trends are especially true of Spius-type magma whose
phenocryst mode is dominated by olivine having partition coefficients that are very low (0.01) for Nb, Y and Zr (Pearce and Norry, 1979) but very high for Ni(58) and Cr(34) (Gill, 1981).

As suggested by petrography in section 6.3, Spius Formation lava may be the product of magma mixing between lower Spences Bridge Group and Spius-type melts. Spius-type magma, bearing primarily olivine, was probably hotter than lower Spences Bridge-type magma, resulting in a mixture that destabilized and resorbed existing pyroxene and plagioclase phenocrysts. This less evolved nature of Spius-type magma is evident on Mg# vs. Ni and MgO vs. Ni plots (Figure 19), where Spius Formation is shown to have higher Mg# and MgO values, and much higher Ni contents. Furthermore, probable higher water contents in Spius-type magma, as inferred by greater vesicularity, may have lowered liquidus temperatures of the magma mixtures and contributed to pyroxene and plagioclase corrosion (Kushiro, 1975).

Magma mixing is graphically illustrated in Figures 20–22, and 24–27. There, fields of mixing are shown between lower Spences Bridge Group andesitic compositions and an inferred parental Spius-type magma. Since these diagrams are rectilinear, the fields of mixing follow straight lines (Gill, 1981). Concentrations of elements in the inferred parental melt (Table 5) were determined by linear extrapolation from the field of lower Spences Bridge andesites, through the field of Spius Formation andesites, to an arbitrary position. That position was selected by assuming that Spius
andesites with greatest Spius-type character are the product of about 80:20 parental Spius-type to lower Spences Bridge-type mixing. Although it is impossible to determine the exact mixing ratios, a maximum proportion of 80% parental Spius-type magma seems reasonable because of nearly ubiquitous xenocrysts in Spius-type andesites (section 6.3) and the lack of an obviously parental composition within the suite. A considerably lower maximum proportion is improbable because Spius-type andesites volumetrically dominate the Spius Formation succession, and therefore parental Spius-type melts were likely to dominate the magma mixtures. Consistency in the inferred composition was achieved by using some elements in more than one diagram; Ni, Zr and Nb, for instance, are each used three times on plots showing mixing relations. Using the above parameters, the parental melt was determined to have higher concentrations of Ni, Cr, Nb, Zr, Ti, P, and Mg than those in Spius Formation andesites. The range in concentration of each element is limited, on average, to about 7.5% of its concentration in the inferred parental melt (Table 5). Although no specific range in concentration for Y was determined, because of a lack of close agreement between diagrams, it is probable that Y, like the other high field strength elements, had a higher concentration in the parental melt than in Spius Formation andesites.

The observed fields of Spius Formation andesites on Ni vs. Zr and Ni vs. MgO plots lie entirely within the indicated fields of mixing and thereby support the mixing model. On Ni vs. Nb, Cr vs. Nb, Cr vs. Zr, Nb
vs. Zr and TiO₂ vs. P₂O₅ plots, Spius Formation fields have the same
general direction of elongation as the fields of mixing, although some
specimens fall outside those specific ranges in composition. Spius
Formation specimens on some other plots, however, notably those with Y
or Ba, do not form linear patterns which trend toward the field of lower
Spences Bridge andesites, and therefore suggest mixing of Spius-type
magma with either more basic (eg. Figure 23, Ni vs. Y) or strictly acid
andesitic (eg. Figure 18, V vs. Ti; Figure 14, P₂O₅ vs. SiO₂) lower Spences
Bridge-type melts. Because similar concentrations of most major element
oxides, such as CaO, FeO*, MnO, Al₂O₃, Na₂O and K₂O, are shared by both
units, magma mixing does not produce distinct major element patterns.
Mixing proportions between Spius and lower Spences Bridge magma types,
according to the selected parental Spius-type compositions, vary between
about 15% and 95% Spius-type magma. High proportions of lower Spences
Bridge-type melts in some rocks account for the observed petrographic
similarity of some flows in Spius Formation to typical andesite of the
lower Spences Bridge Group (section 5.2).

This single-stage mixing model generally accounts for the observed
patterns of trace elements in Spius Formation. In reality, such mixing was
certainly more complex, with multi-stage mixing, concurrent fractionation
and assimilation of country rock, plus a wider range in both parental
Spius-type and lower Spences Bridge-type compositions. These variables,
plus alteration, are probably responsible for the scatter of data beyond the
suggested fields of mixing.

The effects of 2% post-mixing fractionation, for a 75:25 Spius to lower Spences Bridge Group mix, based on petrography of Spius-type specimens and partition coefficients listed in Table 4, are shown by arrows in Figures 20-22; 24-27. Those vectors, indicating rapid drops in Ni and Cr concentrations show that post-mixing fractionation must have been slight; such low degrees of fractionation cannot account for the observed ranges of incompatible elements such as Zr and Nb (Figure 26), again indicating that fractionation cannot be the main process linking the compositions of Spius Formation lavas. Consequently, the calcalkaline trend of Spius Formation as observed in Figure 8 is not a product of fractionation but one of mixing, and does not reflect the tectonic affinity of primary Spius-type magma.

The compositions selected for parental Spius-type magma are shown on both the spider diagram (Figure 28) and Ti vs. Zr plot (Figure 17). On the spider diagram, parental Zr and Nb values are much higher than those of typical arc lava (for instance, the New Hebrides sample). Correspondingly, that parental melt is classified as within-plate lava by Ti and Zr. The change in trace element character, from low concentrations of high field strength elements in the lower Spences Bridge Group to high concentrations in Spius Formation, is likely due to lower oxygen fugacity, caused by less hydrous conditions (Miyashiro, 1974), during production of Spius-type melts. Such reduced oxygen fugacity, in agreement with high Ti/V ratios, would
have decreased the stability of oxide minerals such as rutile, sphene, zircon, magnetite and apatite in the source region, thereby releasing greater amounts of Nb, Y, Zr, Ti and P into primary Spius-type magma (Pearce, 1982).

7.4 Tectonic interpretation of geochemistry

Major and trace element geochemistry suggests that primary lower Spences Bridge melts were products of subduction-related hydrous fusion (section 7.2.3). If Spius-type magmas were subsequently produced by continued subduction, then the downgoing oceanic lithosphere, which presumably supplied the water for lower Spences Bridge fusion, must have been largely stripped of its hydrous upper section. Since water is a significant constituent of both the sedimentary (layer 1) and basaltic (layer 2) portions of oceanic crust (Basaltic Volcanism Study Project, 1981; Gill, 1981) it seems probable that these fractions were removed from the descending slab. However, water released during dehydration of downgoing oceanic lithosphere, and resultant decrease of liquidus temperatures is thought to be a major cause of partial fusion of slab and mantle material, and subsequent generation of arc magmas (Gill, 1981). Consequently, if the hydrous portions of the descending slab were removed, lower degrees of partial melting would be expected, resulting in elevated alkali and alkali earth contents (Basaltic Volcanism Study Project, 1981). Because Spius Formation basaltic andesites show no overall increase in K, Rb and Sr, and only a slight increase in Ba over comparable rocks in the lower Spences
Bridge Group (figure 27), it appears that primary Spius-type melts were produced by equivalent amounts of partial fusion.

Stripping of the upper oceanic crust from descending lithosphere and the maintenance of consistent percentages of partial melting may be explained by a change in the style of subduction. Incipient jamming of the downgoing slab against the overriding plate could have resulted in lithospheric delamination and subsequent obduction or underplating of the hydrous upper oceanic crust onto the upper plate. Such jamming may also have caused the descending slab to buckle downwards more steeply, thereby increasing the angle of subduction. Assuming constant rates of plate motion, steeper subduction is likely to have increased the rate of heating of the slab. Rapid heating may have facilitated partial melting equal in degree to that of the lower Spences Bridge Group, and subsequent production of primary Spius-type magma. Those melts must have then fractionated olivine, assimilated water and mixed with lower Spences Bridge-type magma, produced earlier under "normal" arc conditions, prior to eruption. Such disturbed subduction, possibly the precursor to cessation of arc volcanism, is consistent with the upper stratigraphic position held by Spius Formation.

According to Monger (1984), the Spences Bridge Group was built on the western edge of the North American continental margin above an easterly-dipping subduction zone, Terrane II, resting on the (descending) oceanic plate to the west of North America, collided with and became
accreted to the easterly-moving continent in mid-Cretaceous time (Monger et al., 1982; Monger, 1984; Souther, in preparation). Perhaps jamming and delamination of the oceanic slab occurred as the continent approached Terrane II, followed by cessation of arc volcanism upon collision.

An alternate and preferred model of magmatic evolution is that primary Spius-type melts were produced by localized, incipient rifting below a waning lower Spences Bridge arc. There, anhydrous melting of upwelling asthenosphere could have occurred, resulting in liquids with non-arc geochemical character. Such a change in tectonic regime was ascribed to volcanic rocks in the vicinity of the Rio Grande rift in Colorado and New Mexico (Basaltic Volcanism Study Project, 1981). There, diminishing calcalkaline arc volcanism in the late Oligocene was replaced by eruption of tholeiitic and minor alkaline rift-related lavas. The cause of rifting was interpreted to be a result of reduced rates of plate convergence and subduction, yielding back-flow and localized upwelling of asthenosphere. Upward convection and partial melting of the asthenosphere is regarded by Thompson et al. (1984) as a typical and final magmatic development in volcanic arcs affected by collisional tectonics. Accordingly, the collision of North America with Terrane II, as discussed earlier, may have terminated the production of lower Spences Bridge-type melts and facilitated generation of rift-related parental Spius-type magmas. Fractionation, assimilation and mixing, as described in the delamination model, must have occurred prior to effusion of Spius Formation lava.
8. CONCLUSIONS

1. The Kingsvale Group, as originally described by Rice (1947), is recognized as being part of the Spences Bridge Group as defined by Drysdale (1914); the term Kingsvale Group is therefore abandoned.

2. The sequence of mostly amygdaloidal andesite overlying the Spences Bridge Group of Drysdale (1914), and called Kingsvale Group by Duffell and McTaggart (1952), is formally named Spius Formation.

3. The Spences Bridge Group is expanded to include Spius Formation as its upper part; the section previously known as the Spences Bridge Group is called lower Spences Bridge Group.

4. Cretaceous volcanic rocks west of the Fraser Fault System in the vicinity of Gang Ranch are probably the northerly displaced correlatives of the lower Spences Bridge Group (Mathews and Rouse, 1984). Because of paleogeographic separation (Kleinspehn, 1985) it is recommended that Cretaceous rocks southwest of the Yalakom Fault should be called neither Kingsvale Group nor Spences Bridge Group.

5. Isotopic age determinations are compatible with recent studies of palynomorphs and fossil leaves suggesting an upper Albian age for both Spius Formation and the lower Spences Bridge Group.

6. The Spences Bridge Group is exposed in a 215 km
north-northwesterly trending block-faulted synclinorium herein called Nicoamen Structural Depression (after Monger, 1985).

7. Block faults in the study area are recognized as a manifestation of early Tertiary transtensional tectonics as described by Ewing (1981a). A north-trending complex graben displaying minimum vertical displacements of 3000 m, herein named the Fig Fault Zone, was apparently filled as it formed by Eocene river sand and gravel.

8. Folds are nearly absent from the "Gillis Ridge" part of the study area, but are present in undetermined amounts on Shovelnose Mountain. The overall geometry of that mountain is inferred to be anticlinal.

9. In the study area, the lower Spences Bridge Group was deposited on a surface of moderate topography underlain by rocks of the Upper Triassic Nicola Group and granitoids of probably Late Triassic to Early Jurassic age.

10. The lower Spences Bridge Group comprises a sequence, at least 2400 m thick, of interbedded volcaniclastic rocks, dominated by lahar and nonwelded ignimbrite, and lava. Lava types include basaltic and acid andesite, quartz-free (mauve) rhyolite and quartz-phyric rhyolite. Andesites and volcaniclastic rocks are ubiquitous whereas rhyolites have a restricted lateral distribution.

11. Basement-clast fanglomerate near the base of the succession
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supports Monger’s (1985) suggestion of penecontemporaneous deformation.

12. In the study area, the overlying Spius Formation is at least 600 m thick and interfingers with the lower Spences Bridge Group indicating overlapping time of deposition.

13. Regionally, deposition of the lower Spences Bridge succession as a set of contiguous terrestrial stratovolcanoes was followed by extrusion of very fluid, gas-rich Spius Formation flows which accumulated as a shield volcano.

14. Lower Spences Bridge Group lavas in the study area can be related by plagioclase, orthopyroxene, augite, magnetite, quartz and hornblende fractionation, and (minor ?) assimilation of probably acid country rock. A calcalkaline to transitionally tholeiitic trend, plus typical arc patterns of trace elements indicate a subduction-related origin.

15. Two end-members of Spius Formation lavas are recognized:
Spius-type which is volumetrically dominant and generally amygdaloidal, contains abundant grains of serpentine-after-olivine and trace amounts of corroded plagioclase, orthopyroxene and augite xenocrysts; lower Spences Bridge-type which is nearly identical to andesites of the lower Spences Bridge Group.

16. Petrography and patterns of trace elements suggest that Spius Formation lavas are the product of variable mixing between magmas
of the lower Spences Bridge Group, and an inferred parental Spius-type melt having within-plate geochemical character. That parental melt was the product of relatively anhydrous fusion, followed by olivine fractionation and assimilation of volatiles.

17. Generation of primary Spius-type may have been accomplished by delamination and removal of the basaltic and sedimentary (hydrous) portions of the downgoing oceanic slab. Alternately and preferrably, those melts could be the product of incipient rifting and partial fusion of upwelling asthenosphere. Either situation could have been realized by the accretion of Terrane II to the North American continental margin in mid-Cretaceous time (eg, Monger et al., 1982), causing disruption and/or termination of subduction.
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