University of Alberta

Geological and geochemical links between Quesnel "terrane" strata and ancestral North America, southern Canadian Cordillera

by

Jennifer Lee Esther Unterschutz ©

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Geological and geochemical links between Quesnel "terrane" strata and ancestral North America, southern Canadian Cordillera** by Jennifer Unterschutz, in partial fulfillment of the requirements for the degree of Master of Science.

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Abstract

The contact between North American strata and the Quesnel "terrane" in southeastern B.C. has been interpreted as a fault, yet mapped as an unconformity. This study shows that the contact is unexposed in the Silver Star area (near Vernon, B.C.). New geochemical and Nd isotopic provenance studies of Triassic clastic metasedimentary rocks assigned to the Quesnel "terrane" in southeastern B.C. show that detritus was derived from both primitive and evolved sources, which were proximal and are geochemically indistinguishable from the Quesnel volcanic arc and Canadian miogeocline, respectively. Twenty-four samples yield εNd_{220} values between –9.1 and +5.6, Eu anomalies between 0.6 and 1.0, and La_N/Yb_N ratios between 3.8 and 11.4. Detrital zircons (~192 Ma) from the Quesnel "terrane" show evidence of Proterozoic inheritance. This inferred Triassic to early Jurassic depositional link between North America and the Quesnel "terrane" suggests a pericratonic, non-exotic, origin for the Quesnel terrane in southeastern B.C.

To my parents:
Collin and Doreen

Opportunity is nothing
without belief in oneself.

You gave me that.

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There were several points during my program at which I wondered why the heck I decided to do this. But as I look back at what I've written here, it becomes clear. Not only were the rocks cool, but the experience and people along the way were cooler.

Table of Contents

Chapter Page

Discussion

3. North American margin origin of Quesnel terrane strata in the southern Canadian Cordillera: Inferences from geochemical and Nd isotopic characteristics of Triassic metasedimentary rocks

Results

Discussion and Implications

Implications

List of Tables

Table Page

Chapter 2

Chapter 3

List of Figures

Figure Page

Chapter 1

Chapter 2

Chapter 3

List of Plates

Chapter 2

Chapter 1

Introduction

The North American Cordillera is a mountain belt that runs along the entire western margin of North America. The Canadian component is over 2000 km in length and 750 km in width (Fig. 1-1). This mountain belt has been studied for over a century, but it was not until the paradigm of plate tectonics became accepted in the 1970's that a real understanding of the processes responsible for this mountain belt became known. Interactions between the Pacific, Juan de Fuca, Gorda, and Explorer plates, and the now extinct Kula and Farallon plates with the North American plate were responsible for orogenesis. The west coast of North America was a dominantly passive continental margin until the opening of the present day Atlantic ocean in the late Early Jurassic, which catalyzed its transition into a compressive orogen (Coney 1972; Bond and Komintz 1984; Engebretson et al. 1985; Thompson et al. 1987; Monger 1989, 1997; and references therein).

The North American Cordillera is characterized by a large variety of rock types that are often localized in occurrence, including abundant oceanic rocks, and rare blueschist rocks, in the middle of what is now a major land mass. Plate tectonics provides a means for transporting and accreting these different rock assemblages to the margin of North America. In the Klamath Mountains of California, Irwin (1972) recognized these discontinuous rock assemblages, and designated them "terranes". This provided for the first time a method of dividing and classifying these disparate rock assemblages. The value of this methodology for mapping in the Cordillera was quickly recognized, and the definition of a terrane evolved into a "fault bounded slice of crust that possesses an internally consistent geologic record, but one that is distinct with respect to those of neighboring terranes". When an uncertain relationship between many of these terranes and North America was recognized, the term "suspect terrane" was conceived (Coney 1980). Previous geologic mapping was then revisited, and "terrane" assemblages were defined throughout the North American Cordillera. Coney (1980) estimated that > 70% of the North American Cordillera is composed of rocks of a suspect nature.

Terrane classification was applied to all rocks outboard of the North American margin, often before an allochthonous, or fault-bounded, character was demonstrated (Fig. 1-1). In support of the terrane system of classification is abundant paleomagnetic data from plutons throughout the Cordillera. Paleomagnetic investigations in many of these terranes identified igneous rocks with very different paleo-poles, at the time of their crystallization, when compared to contemporaneous rocks along the North American margin. In many cases paleontological investigations have also been used to support a distant origin for many of these terranes. However, the great transport distances interpreted based on these paleontologic and paleomagnetic data are often not supported by geologic evidence, and many discrepancies remain today. Research presented in Chapter 2 on the Quesnel terrane outlines such an example.

Subsequent to their earlier designation, some "terranes" have come to be recognized as not befitting the definition of a terrane. In some cases, such as the Kootenay terrane, a depositional relationship with North American margin rocks has been demonstrated, and these rocks can no longer correctly be referred to as "suspect", nor as a "terrane" (Coulpron and Price 1995). The work presented in this thesis focuses on another such discrepancy, in southeastern British Columbia, on the relationship between the easternmost of these purported accreted elements, the Quesnel terrane, and rocks now demonstrated to be tied to, or derived from North America (Fig. 1-1). The Quesnel terrane is defined as an intra-oceanic arc that formed, in places, on top of crust of oceanic character (Monger 1977, 1985; Mortimer 1986, 1987; Gabrielse et al. 1991; Monger et al. 1982, 1991; Souther 1991; Dostal et al. 2001). Over 200 km of west-to-east overlap between the Quesnel terrane and North America is estimated (e.g., Ghosh 1995, and references therein), although this fault has never been documented in the field. Paleomagnetic and paleontologic evidence suggests that this terrane formed significantly to the south of its present location, and remained there until the Cretaceous. In contrast, unconformable relationships have been reported between rocks of this terrane, and rocks tied to, or derived from, North America (Jones 1959; Read and Okulitch 1977; Klepacki 1983; Klepacki and Wheeler 1985; Höy and Andrew 1991; Roback and Walker 1995; Thompson and Daughtry 1996, 1997, 1998).

This thesis focuses on the geologic relationship between the Quesnel "terrane" and ancestral North America in southeastern British Columbia, Canada. Research is presented in two-parts, in paper format. Chapters 2 and 3 are independently complete studies, related to one another by their similar focus.

Chapter 2 presents a geologic study of the Silver Star area, where rocks of the Quesnel terrane are in contact with rocks of the pericratonic Kootenay "terrane". Six months of field work were undertaken to investigate this contact and determine its nature, in addition to determining the geologic history of the area. An interpretation of this history is presented, and the outcome suggests that an unconformable contact is possible, but, because the contact is unexposed in the Silver Star area, this study was not conclusive. Augmenting the geologic study, U-Pb geochronology revealed Jura-Cretaceous plutonism in the area, and suggested an easterly provenance for sedimentary rocks of the Quesnel terrane, from volcanic rocks with inheritance from Proterozoic crust. Nd isotope studies revealed an *in-situ* origin for granites on Silver Star Mountain, contamination of Eocene mantle melts by continental crust, and a continental origin for Paleozoic sedimentary rocks in the study area.

Logistical support for work in Chapter 2 was provided by NSERC grants to P. Erdmer, the Ancient Pacific Margin NATMAP project of the Geological Survey of Canada through R.I. Thompson, and K.L. Daughtry, at that time with Discovery Consultants in Vernon, B.C. I conducted the field work, data analysis, and wrote this chapter, with the intention of submitting for publication to the *Canadian Journal of Earth Sciences*. Co-authors on this paper will include P. Erdmer, R.I. Thompson, K.L. Daughtry, L.M. Heaman, and R.A. Creaser. Editorial comments for this chapter were received from P. Erdmer. I prepared the original geological maps and cross-sections in AUTOCAD format, which were given to R. Macleod of the Geological Survey of Canada for geo-referencing and integration into the NATMAP database, and for final digital cartographic preparation of the map. I prepared samples for U-Pb geochronology and Nd isotope analysis, which were then chemically processed and analyzed in the laboratories of L.M. Heaman and R.A. Creaser, respectively, at the Radiogenic Isotope Facility at the University of Alberta.

Chapter 3 presents a provenance study of Upper Triassic metasedimentary rocks of the Quesnel terrane, using Nd isotopes and trace element geochemistry. This study developed in response to the inconclusive mapping in the Silver Star area, and was designed as a test of the hypothesis that the Quesnel terrane could have developed unconformably on top of North American rocks. The test involved searching for detrital input from North American sources in these now metamorphosed sedimentary rocks. It also sought to test the validity of the classification of all Upper Triassic metasedimentary assemblages of oceanic character into the Quesnel terrane, by sampling rocks throughout this terrane in southeastern British Columbia, and examining their compositions in relation to their geographic position. This study suggests that these rocks are correctly designated as part of the same Upper Triassic succession, and that they consistently show derivation from two proximal sources, one with the primitive character of volcanic facies in the Quesnel terrane to the west, the other with a signature identical to more inboard deposits of the Cordilleran miogeocline to the east. This information, when combined with existing geologic data, strongly supports a pericratonic interpretation for the Quesnel strata, and suggests its status as being "suspect" or a "terrane" is incorrect.

The research presented in Chapter 3 was funded by NSERC grants to P. Erdmer and R.A. Creaser, and the Ancient Pacific Margin NATMAP project through R.I. Thompson at the Geological Survey of Canada. K.L. Daughtry contributed to scientific discussion. I completed the data analysis, and wrote this chapter. A version of this chapter has been accepted for publication in the Geological Society of America *Bulletin*, April 2002 issue, with co-authors R.A. Creaser, P. Erdmer, R.I. Thompson and K.L. Daughtry. Editorial comments were received from all co-authors, in addition to reviewers through the Geological Society of America *Bulletin*, including P.J. Patchett, L. Farmer, and an anonymous reviewer. Samples were crushed at the University of Alberta, three of which I completed myself, with the remaining prepared under the direction of R.A. Creaser. Samples were chemically processed and analyzed for Sm and Nd isotopic compositions in the lab of R.A. Creaser at the Radiogenic Isotope Facility at the University of Alberta. Major and trace element composition measurements were completed at Washington State University.

In conclusion, this study confirms what geologic mapping has been suggesting since the mid-1980's, that the "terrane" designation for Quesnel strata is inappropriate. This may be viewed by some as a simple problem of semantics, solved by redefinition of the term "terrane", or Quesnel itself, but it makes the point that certain assumptions made in regards to the origin of these disparate rock assemblages need revisiting, and that perhaps these rocks should be considered "innocent" of an allochthonous designation until proven "guilty".

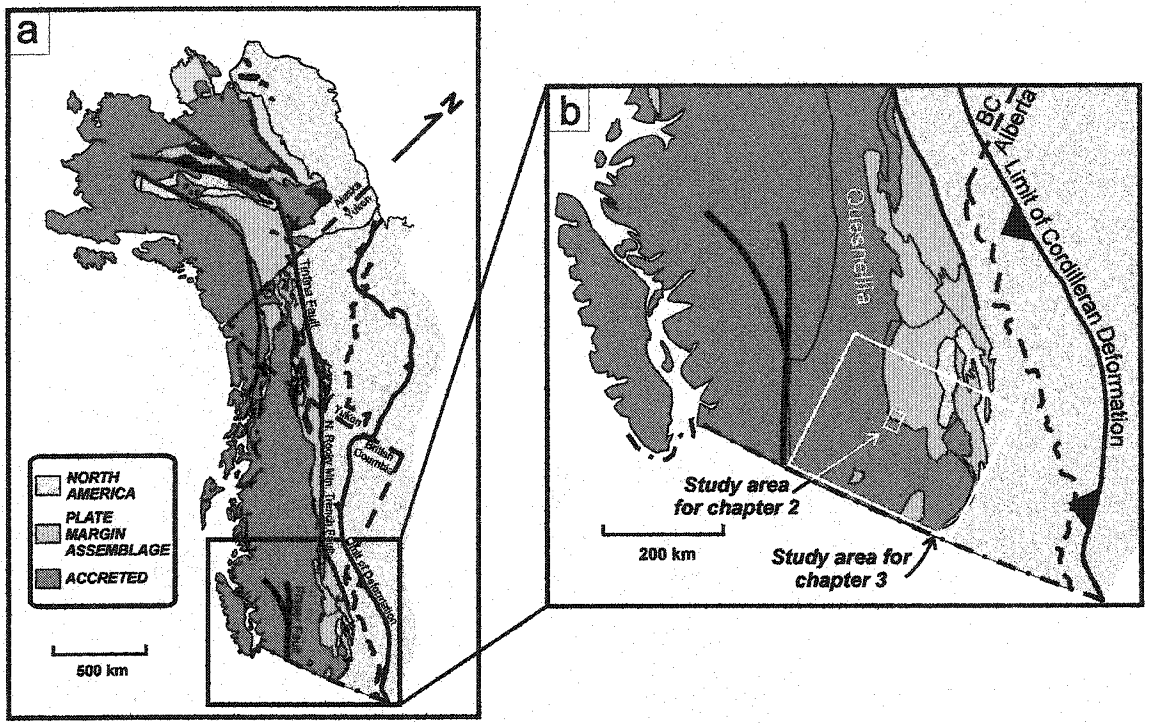

Figure 1-1. Simplified tectonic assemblage maps differentiating rocks interpreted to be of North American, plate margin assemblage, and accreted origin, showing (a) Canadian and Alaskan Cordillera, and (b) southeastern British Columbia. Figure (b) denotes the boundary of the Quesnel terrane and the study areas for chapters 2 and 3. The eastern extent of this mountain belt is indicated by solid lines marking the limit of deformation (modified from Wheeler and McFeeley 1991).

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Chapter 2

Geology of the Silver Star area, southeastern British Columbia: Implications for an early Jurassic link between the Quesnel "terrane" and ancestral North America

A version of this chapter is being prepared separately for submission to the Canadian Journal of Earth Sciences. A version of Figure 2-1 will be submitted to the Geological Survey of Canada, to be published as an Open File report.

Introduction

The contact between garnet- and higher-grade metamorphic rocks of mid- to late Paleozoic - early Mesozoic(?) age and lower-grade metamorphic rocks of late Paleozoic to Upper Triassic-early Jurassic(?) age is located in the Silver Star (Aberdeen) Mountain area, British Columbia (B.C.), Canada (Fig. 2-1). It is the proposed contact between accreted terranes and North American derived rocks in southeast B.C. (e.g. Coney 1980; Monger et al. 1982; Wheeler et al. 1991), i.e. the suture zone of the Cordilleran orogen, interpreted to have formed during the Jurassic by thrusting of allochthonous Quesnel terrane rocks over North American strata, with approximately 200 km of overlap (e.g. Ghosh 1995). This proposed fault has yet to be observed in the field. The contact has also been described as a discrete zone of extension that developed as a result of orogenic collapse during the Eocene, and juxtaposed low-grade and high-grade metamorphic rocks. It has been variably estimated to record between 30 and 90 km of displacement (Templeman-Kluit and Parkinson 1986; Bardoux 1993; Johnson 1994; Johnson and Brown 1996). A third interpretation describes the contact as an unconformity, requiring a North American origin for the low-grade strata, and negating the presence of a fault between the 'basement' and 'cover' rocks (Jones 1959; Read and Okulitch 1977; Klepacki 1983; Klepacki and Wheeler 1985; Höy and Andrew 1991; Roback and Walker 1995; Thompson and Daughtry 1996, 1997, 1998).

The main purpose of this investigation was to test the hypothesis that rocks in the Silver Star area, assigned to the Quesnel terrane (Quesnellia), stratigraphically overlie pericratonic North American rocks. This work formed part of the Geological Survey of

Canada's Ancient Pacific Margin NATMAP project. Six months of geological mapping at 1:20 000 scale were completed during the summers of 1998 and 1999, encompassing parts of BCGS TRIM maps 82L.025, 026, 035, 036, 045, and 046. The results are presented in Figure 2-1 (in pocket). Despite efforts to discover an area where this contact was exposed, the paucity of natural outcroppings, exhaustive drift cover, and vegetation made this impossible. The location of the contact was narrowed down to within several tens of meters on Silver Star Mountain and along Alderson Creek (Fig. 2-1). This study establishes a detailed stratigraphy for the area, provides interpretations of the structural, metamorphic, and plutonic history of the area, and provides further evidence suggesting a stratigraphic tie between rocks of the Quesnel terrane, and rocks of the ancestral North American margin.

Geologic Setting

Regional framework

The Canadian Cordillera is over 2000 km in length and 700 km in width (Fig. 2-2a), part of an orogenic belt that runs along the entire west coast of North America. The eastern limit is defined at the front of the Rocky Mountain fold and thrust belt, and the western limit by the edge of the North American plate. The orogen can be divided into five morphogeological belts, which are, from west to east, the Insular, Coast, Intermontane, Omineca, and Foreland belts (Fig. 2-2c, Gabrielse et al. 1991). This study is located in the southern portion of the Omineca belt, which, similar to the Coast belt, is characterized by igneous and metamorphic assemblages (Fig. 2-2c). The Omineca and Coast belts were originally interpreted to be the result of subduction producing an Andean-type magmatic arc, (Armstrong 1988, and references therein), but they have subsequently been reinterpreted as a continent-continent style collision zone, formed when the North American craton collided with the Intermontane and Insular superterranes (Terrane I and II of Monger et al. 1982) during the Jurassic and Cretaceous times, respectively (Fig. 2-2c; Monger et al. 1982; Gabrielse et al. 1991; Monger 1997).

The Cordillera has been divided into terranes, defined as fault bounded slices of crust preserving an internally consistent geologic record, and distinct from neighboring terranes (Irwin 1972). It was subsequently recognized that some of these terranes may have originated far from their present locations, and the term "suspect terrane" was applied (Coney 1980). In the southern Omineca Belt, the easternmost of these is the Quesnel terrane, described as a Late Triassic to Early Jurassic intra-oceanic arc that developed, in places, above Ordovician to Triassic rocks of arc and oceanic affinity (Monger 1977, 1985; Mortimer 1986, 1987; Gabrielse et al. 1991; Monger et al. 1982, 1991; Souther 1991; Dostal et al. 2001). This arc system includes the Nicola, Slocan, Ymir, and Rossland groups in southern B.C. The "basement" to the Quesnel terrane is divided into the Harper Ranch and Okanagan subterranes (Monger 1977, 1985; Monger et al. 1982, 1991; Mortimer 1987; Gabrielse et al. 1991; Souther 1991; Dostal et al. 2001).

The suspect nature of the Quesnel terrane was based on the presence of Tethyan and mixed Tethyan-Boreal fauna, which led to the inference that the Quesnel arc developed off shore, a minimum of 500 km south of its current latitude (e.g. Taylor et al. 1984; Carter et al. 1991). Paleomagnetic data have been used to interpret latitudinal displacements in excess of 2400 km (e.g. Symons 1983; Irving et al. 1985; Rees et al. 1985; Symons 1985). Radio-isotope studies of the Upper Triassic Nicola Group volcanic rocks of the Quesnel terrane, which show no evidence for contamination from underlying continental crust, have been used to propose an allochthonous, intra-oceanic, origin for the Quesnel terrane (Smith et al. 1995; Armstrong 1988). In contrast, U-Pb zircon geochronology from igneous units of the Quesnel terrane in the Kootenay Arc region (Fig. 2-2b), including volcanic tuffs from the upper Elise Formation (late Sinemurian to early Toarcian) and the 200 Ma Lexington porphyry, show evidence of inheritance from Proterozoic crust (Höy and Dunne 1997; Dostal et al. 2001). Interaction with continental crust in eastern parts of the Quesnel terrane, within the Omineca belt, is also suggested by $^{87}Sr/^{86}Sr_i$ ratios > 0.704 for Mesozoic igneous rocks, increasing eastward to values between 0.705 and 0.707 in the Kootenay Arc region (Fig. 2-2b; Armstrong 1988). Nd isotope and trace element geochemistry of metasedimentary rocks flanking the east side of the Upper Triassic Quesnel arc give εNd_T values between –9.1 and +5.6, La/Sc ratios between 0.38 and 4.76, and Eu anomalies between 0.6 and 1.0

(Unterschutz et al. 2002), suggesting derivation, in part, from a proximal source with the geochemical characteristics of evolved continental crust. The most compelling evidence in favour of an allochthonous interpretation for the Quesnel terrane was a geochemical study of igneous rocks in southeast British Columbia by Ghosh (1995), which showed an apparent increase in crustal contamination in igneous rocks in mid-Jurassic time, and was used to propose the onset of obduction at that time. However, Unterschutz et al. (2002) demonstrated that the data do not necessarily indicate a change of basement character, but, alternatively may show increasing degrees of crustal contamination toward the craton since the late Paleozoic. The Quesnel terrane may have developed on easterly thickening crust of the North American margin.

Unconformable relationships between Quesnel terrane strata and rocks of ancestral North America have been described throughout southeast B.C. (Jones 1959; Read and Okulitch 1977; Klepacki 1983; Klepacki and Wheeler 1985; Höy and Andrew 1991; and Thompson and Daughtry 1998). The most compelling evidence comes from approximately 75 km northwest of Nelson, in the Kootenay Arc region (Fig. 2-2b, d), where Upper Triassic rocks of the Slocan Group, of the Quesnel terrane, lie unconformably on rocks that are tied to the North American miogeocline (Klepacki 1983; Klepacki and Wheeler 1985).

The present study is of an area near Vernon B.C. (Figs. 2-1, 2-2), approximately 150 km west of the Kootenay Arc. As in the Kootenay Arc, on Silver Star Mountain, pericratonic North American rocks (Kootenay terrane, Fig. 2-2d) are in contact with rocks of the Quesnel terrane (Fig. 2-2d). These pericratonic rocks are part of the Mount Ida Group (Jones 1959), and include the Silver Creek Formation, and possible equivalents of the Tsalkom, Sicamous, Eagle Bay and Chapperon successions. Regionally, rocks of the Mount Ida Group have been interpreted to sit in the hanging wall of the Eagle River-Okanagan Valley fault, the local expression of low-angle extensional faults that would juxtapose low-grade rocks with high-grade rocks (Fig. 2-2d; e.g. Templeman-Kluit and Parkinson 1986; Johnson 1994; Johnson and Brown 1996). Although Paleozoic units are correlated with the Mount Ida Group in this study, their high-grade nature has led to previous correlations with possible equivalents in the footwall of the Eagle River-

Okanagan Valley fault, the Hunters Range Assemblage of the Shuswap Complex (Johnson 1994; Thompson and Daughtry 1996). Overlying the Mount Ida Group in the study area are rocks currently interpreted to be allochthonous, assigned to the Quesnel terrane, including possible equivalents of the Harper Ranch and Okanagan subterranes, as well as the Slocan, Nicola, Ymir, and Rossland groups, and the Ashcroft Formation.

Previous Mapping

The first geological map including the study area was published by Dawson (1898). Dawson recognized four units in the Vernon area; an Archean Shuswap series, the Cambrian Nisconolith series, the Carboniferous Cache Creek formation, and Miocene basalts. He noticed that the Nisconolith series, now a part of the Upper Triassic succession of the Quesnel terrane, appeared to be deposited upon an irregular surface and thus varied greatly in thickness across the mapped area. This was followed by a geological map and report by Daly in 1915. In 1959, Jones published a geological map and report on Vernon map area (82L, Fig. 2-2d), at a scale of four miles to one inch (1:253 440). Jones recognized several unconformities within the study area, at least one of which is pre-Triassic (Read and Okulitch 1977). Read and Okulitch (1977) recognized a highly irregular surface upon which Triassic rocks were deposited, in some places overlying rocks of the Harper Ranch or Okanagan subterranes, and in others rocks of North American affinity. The study area was later included in a regional compilation at 1:250 000 scale by Okulitch (1979). Most recently, Thompson and Daughtry (1996, 1997, 1998) reported on studies within the Vernon map area (Fig. 2-2c) that describe the possibility of an unconformable relationship between Quesnel terrane strata and North America.

Geology

Layered Units

The following represents descriptions of units mapped within the study area (Fig. 2-1). Nowhere within the field area was a complete section for any unit observable. Showing a constant thickness for units across the field area on the map is likely an oversimplification, considering that these rocks are heterogeneously strained (see Structural Geology section below).

Pgn

Pgn outcrops in one area along the eastern boundary of the map area, in the Trinity Valley (Fig. 2-1). This unit is a pelitic paragneiss of uncertain age and affinity, and is interpreted to be the oldest unit within the study area. The contact between Pgn and overlying units was not observed in the field, nor was the basal contact, thus leaving the thickness of Pgn unknown. Possible correlatives include similar gneissic rocks to the north and east within the Shuswap Complex, and lacking any better constraints, a Proterozoic age is assigned.

Dcq (Chase Formation)

Dcq outcrops in three areas of the map, along Fortune and South Fortune Creek, northeast of Vernon along B.X. Creek, and north of Lumby near Gallon Creek (Fig. 2-1). Dcq is a calcareous quartzite to siliceous marble, with lesser amounts of carbonaceous argillite and metasiltstone. Grain size varies within layers from fine to coarse. Rarely, metamorphic minerals including diopside and tremolite are present, variable from mm to several cm in length. Fresh surfaces vary in colour from white to blue-grey. The most striking feature of this unit is the differential weathering pattern visible on weathered surfaces, due to the preferential weathering out of calcite, leaving quartz crystals and quartz-rich layers protruding and creating a distinctly pitted surface (Plate 2-1b). This unit commonly contains greater than 50% intrusive granitic and pegmatitic material, in the form of sills and dykes. These intrusions were named the Silver Star Intrusions by Jones (1959), and are described in more detail under the section on Igneous Units below. In the Fortune Creek area, Dcq preserves a high degree of strain and is, in places, augen gneiss. Intrusive material from this locality, when viewed in thin section, shows protomylonitic fabric, with feldspar porphyroclasts that are relatively rigid and form augen in a finer grained foliated matrix. The basal contact of Dcq was not observed in the study area, leaving its thickness unknown.

Dcq is correlative with unit Pc of Glombick et al. (2000), of inferred Late Proterozoic – (?) Early Paleozoic age, that outcrops just south of the study area along

Kalamalka lake, the Devonian Cqm in Vernon and Lardeau map areas (R.I. Thompson, personal communication, 2001), and the Chase Quartzite (Chase Formation, Jones 1959; Campbell and Okulitch 1973). A Devonian age was established for the Chase Formation based on the analysis of two concordant detrital zircons with $^{207}Pb/^{206}Pb$ ages of 405 ± 13 and 424 ± 13 Ma (Thompson et al. 2002), and the age of the cross-cutting 365.9 ± 2.7 Ma granodiorite unit Dg (U-Pb zircon, Slemko 2000). The Chase Formation outcrops along strike, across the Okanagan Valley, 11 km northwest of the Dcq locality in Fortune Creek (Jones 1959). Campbell and Okulitch (1973) mapped the Chase Formation as a member of Pba (Silver Creek Formation, see below).

Pgr

Pgr is a greenstone unit that outcrops in three places in the northeastern portion of the study area (Fig. 2-1), where it has been completely altered to fine-grained chlorite and sericite. Pgr may be a distinct lithologic unit, a facies change within unit Pba (see below, Fig. 2-1), or simply be a more altered layer of mafic rock within Pba (see below). If these rocks are not part of unit Pba (see below), possible correlative rocks in the region include the Tsalkom and Sicamous Formations or the Eagle Bay Group. Only three outcrops of this unit were observed, leaving the geologic significance of this unit unresolved by present work.

Pba (Silver Creek Formation)

Pba outcrops throughout the study area; in the northernmost portion of the map, at the base of Fortune Creek, on Silver Star Mountain, along the Trinity Valley, and just north of Lavington (Fig. 2-1). This unit consists of medium- to coarse-grained biotite- and/or amphibole-rich quartzofeldspathic schist and amphibolite, with lesser amounts of marble, micaceous quartzite, and calc-silicate schist. Metamorphic minerals in pelitic layers variably include K-feldspar, sillimanite, kyanite, staurolite, garnet, biotite and muscovite, while amphibole is characteristic of amphibolite units, and diopside, garnet, and tremolite of calc-silicate units. Rusty alteration often coats weathered surfaces. Similar to Dcq, Pba also commonly contains over 50% intrusive material in the form of granitic and pegmatitic dykes and sills. This material was designated the Silver Star

Intrusions by Jones (1959), and is described below under the Igneous Units section. Pba is estimated to be 600 m thick above unit Dcq, from projected map relations (Fig. 2-1).

Pba overlies Dcq, and although the contact was not observed, it can be defined within tens of meters along Fortune Creek, and South Fortune Creek (Fig. 2-1). There is no change in fabric orientation or metamorphic grade across this boundary, and the contact is inferred to be stratigraphic and conformable. This is similar to relationships described by Jones (1959) and Campbell and Okulitch (1973) between the Chase Formation and the Silver Creek Formation, to which Dcq and Pba are correlated, respectively, based on lithologic similarities and relative stratigraphic position.

The age of Pba is inferred to be Devonian, based on correlation with the Silver Creek Formation. The age of underlying Dcq (see Dcq above) places a maximum age on Pba to be Devonian. To the north near Sicamous, Slemko (2000) mapped Dg (365.9 ± 2.7 Ma granodiorite) to cut early (?) Paleozoic Eagle Bay Formation rocks, and described the Silver Creek Formation (Pba) to be stratigraphically overlain by the early (?) Paleozoic Sicamous Formation, in turn overlain by the Eagle Bay Formation. To the northwest, the Devonian Little Shuswap Gneiss cuts the Silver Creek Formation (Pba; personal communication from R. Friedman and A.V. Okulitch to N. Slemko, Slemko 2000).

Pcs

Pcs outcrops in three locations within the study area; in the north along Joyce Creek, on Silver Star Mountain, and on Vernon Hill (Fig. 2-1). Pcs consists of carbonaceous pelitic to semi-pelitic phyllite and schist, with lesser amounts of calcareous slate, micaceous and/or pyritic quartzite, and calc-silicate schist. Units vary in grain size from fine to coarse, and in colour from black to grey to blue-grey. Locally, compositional layering, and more rarely transposed bedding features including grading, cross-bedding, truncation, and flame structures, are preserved within layers that vary from mm to cm in thickness. In the northern portion of the study area, unit Pcsl, a distinctive black calcareous slate within unit Pcs, was mapped over a strike distance > 3 km. Pcs is characterized by the presence of some or all of the following metamorphic porphyroblasts: staurolite, kyanite, garnet, plagioclase, biotite and muscovite (Plates 2-1c, 2-6a), which give a characteristic knotted appearance to the rock. On weathered surfaces, Fe-rich porphyroblasts and pyrite are often rusty in colour, or can be completely weathered out leaving a rusty residue. This weathering out may be facilitated by retrograde metamorphism of metamorphic minerals to chlorite and sericite, visible in thin sections of unweathered samples. Granitic and pegmatitic material of the same character that pervades unit Pba is present within Pcs, but in diminished quantity, comprising 10 to 20% of the succession near the base, decreasing upward to 0%.

The contact between Pcs and Pba appears to be conformable, and in fact may be a transitional depositional contact, as suggested by Unterschutz et al. (1999) near Sovereign Lake on Silver Star Mountain. There, an approximately 100 m thick zone in which interlayered rocks could be assigned to either the overlying or underlying successions is well exposed. This could be consistent with a transitional depositional contact, or with tectonic juxtaposition, but a stratigraphic contact is favoured based on the continuity of fabric and metamorphic grade across this zone, and a lack of systematic repetition of units such as might be expected in isoclinal folding. The Pcs-Pba contact is drawn at the base of this transitional zone, which marks the last occurrence of sillimanite-bearing schist within unit Pba. Although a continuous section of Pcs is not observable within the field area, down plunge projection suggests a maximum thickness of 1 km (Fig. 2-1).

Psc (Spa Creek Assemblage)

Psc outcrops in the northern portion of the map area, east of Kendry Creek (Fig. 2-1). Psc consists of marble, stretched quartzite cobble metaconglomerate, biotite- and/or amphibole-rich schist, chloritic schist, and intermediate to felsic tuffaceous, ignimbritic, and porphyritic metavolcanic rocks. This succession contains two lithologically distinct mappable units that have proved to be good marker horizons for defining structures within the area (Fig. 2-1). The lowermost of these is unit Psccgl, a stretched and flattened quartzite cobble metaconglomerate, interpreted to form the base of Psc, and in which cobbles are stretched and flattened to current length:width:height ratios between 5:2:1 and 10:2:1 (Plate 2-1d). These stretched cobbles define an east-northeast plunging shape lineation (Fig. 2-1), and indicate strain within these rocks. Metamorphic porphyroblasts of garnet statically overgrow foliation in this unit, on average between

0.25 and 1 cm in diameter, and are more resistant to weathering than the host rock (Plate 2-1d). The second marker horizon is PScmb, a foliated, white to grey and white banded, coarsely crystalline marble unit. This coloured banding is visible at thicknesses varying from 1 cm to greater than 10 m. This unit forms resistant ridges in an area that is topographically flat (Fig. 2-1), which makes it an excellent marker horizon for mapping purposes (Plate 2-2a). PScmb varies in thickness between approximately 50 and 100 m.

Within PSC are intermediate to felsic tuffaceous, ignimbritic, and porphyritic metavolcanic units that vary in colour from dark to light grey, and which can be massive or foliated depending on the absence or presence of orientable minerals. The ignimbrite units often contain fine-grained clasts that are difficult to identify, but one of the more felsic layers with a biotite- and amphibole-rich matrix contains larger flattened clasts of quartzite and fine-grained volcanic rocks, approximately 1-3 cm long and 0.5 cm thick, aligned in the foliation. A distinctive intermediate biotite-rich porphyry unit with aggregates of chlorite and interbedded layers of amphibole-rich schist is also present. Another distinctive volcanic unit is characterized by the presence of metamorphic bow-tie amphiboles that can reach several cm in length. These volcanic units vary in thickness from > 50m to a scale of tens of cm where they are interlayered with sedimentary units, which include pelitic to semi-pelitic schist and phyllite. On weathered surfaces, these rocks can have a distinctive brown to rusty coloured coating.

Retrograde metamorphism affects PSC, in some places resulting in complete replacement of original minerals by chlorite, biotite, and sericite. The top of unit PSC is not seen, but plunge projection suggests a minimum thickness of 400 m.

PSC is interpreted to unconformably overlie unit Pcs, forming the uppermost unit in what appears to be an upright section northward from Fortune Creek (Fig. 2-1). Based on lithological similarities and relative stratigraphic positions, this unit is correlated with the Spa Creek Assemblage of Erdmer et al. (2001). East of Kendry Creek is the only area where unit PSC is present, suggesting that these rocks may represent a localized volcanic environment or, more likely, based on the correlation of these rocks westward across the Okanagan Valley to localities near Glenemma and Spa Creek (see Fig. 2 of Erdmer et al. 2001), they were eroded or tectonically removed from their position in the stratigraphic sequence (possibilities are discussed below). To the south, on Vernon Hill, units Pmv and Pccs (below) may represent distal equivalents to unit Psc. An unconformable basal contact between Psc and Pcs is suggested by the presence of the stretched quartzite cobble metaconglomerate, Psccgl. Read and Okulitch (1977) interpreted this conglomerate to be the basal Triassic conglomerate of their regional sub-Triassic unconformity, and correlated this succession with the Glenemma and Spa Creek localities. Age constraints for this unit remain poor, but U-Pb geochronology from Erdmer et al. (2001) reveals a maximum age for the conglomerate to be 555.6 ± 2.5 Ma. Further constraints are provided by the age of the underlying unit Dcq, indicating a Devonian or younger age for these rocks. Psc is overlain by late Triassic – early Jurassic (?) rocks of unit Ms (see below), providing a minimum age for Psc.

Pmv

Pmv outcrops in the southern portion of the map area, on Vernon Hill (Fig. 2-1). This unit consists of intermediate to mafic metavolcanic rocks including biotite and/or actinolite schist, amphibolite, carbonaceous argillite, metasiltstone, metasandstone, and calc-silicate schist. Sedimentary units vary in colour from blue-grey to grey to brown. Static metamorphic porphyroblasts overprint regional fabric and include garnet, amphibole and biotite, some of which are now retrograded to biotite and chlorite. Sills and dykes of Jgtd (see below) are common within Pmv. The thickness of this unit remains unknown, but is > 500 m on Vernon Hill.

Pmv overlies unit Pcs on Vernon Hill (Fig. 2-1), and along with unit Pccs may represent distal equivalents of the Psc. Based on lithologic similarities, these units may also correlate with the Chapperon Group (Daughtry et al. 2000). The basal contact of Pmv was not observed, but is interpreted to be conformable, based largely on the continuity of fabric across this contact. However, some evidence exists that may support a fault contact between these units, and this possibility is discussed in the Structure section.

Pccs

Pccs outcrops in the southern portion of the map area, on Vernon Hill (Fig. 2-1). This unit consists of carbonaceous and calcareous metasiltstone and metasandstone, varying in colour from blue-grey, to grey, to white. Layer parallel sills of granitic material, with thicknesses of a few mm to cm are folded along with compositional layering. These rocks are cut by patchy occurrences of granitic pegmatite, and dykes of unit Esp (see below). The thickness of this unit is unknown, but is approximately 200 m on Vernon Hill.

Unit Pccs overlies unit Pmv. This contact is not observed, but is inferred to be unconformable, marked by the occurrence of a sedimentary breccia, with a very fine-grained carbonaceous matrix and randomly oriented clasts, at the base of this contact. This contact was first suggested as unconformable by Jones (1959), which he termed the Lavington unconformity, although his interpretation regarding surrounding geology differed greatly from that presented here. Jones' interpretation would correlate unit Pccs with Carboniferous (?) and Permian Cache Creek Group rocks, and unit Pmv with Monashee Group rocks, which he inferred to be Precambrian. More age constraints are now available, and unit Pccs is inferred to be Paleozoic, with a maximum Devonian age indicated by the underlying unit Pba, and, like unit Pmv, may be a distal equivalent to unit PSC in the northern portion of the map area (Fig. 2-1).

Pccs is characterized by tight to isoclinally folded strata (Plate 2-1e). Compositional layering is distinct in these units, defined by colour and grain size, and appears unfolded when viewed from two-dimensional outcrops on the hilltops, due to the upright nature of these folds. Only in cliff exposures is the high degree of shortening apparent.

PHRmv (Harper Ranch Group)

PHRmv outcrops in the southern portion of the map area, northeast of Lavington (Fig. 2-1). PHRmv is a succession of intermediate metatuffaceous rocks, usually a characteristic mint-green colour, white marble, black to grey layered marble, dark grey carbonaceous argillite and blue-grey, to grey, to white metasiltstone. The distinctive white marble beds are interlayered with other units, but become the dominant lithology at the top of this succession where they are greater than 10 m in thickness. This suggests a transition from an active volcanic regime to a quiescent one that would permit reef growth. The basal contact of this unit is not seen. PHRmv underlies rocks of the Ms (see below) succession.

Based on lithologic similarities, these rocks are correlated with the Harper Ranch Group, currently considered the basement, in places, to the Quesnel terrane (Monger 1977, 1985; Monger et al. 1982, 1991; Mortimer 1987; Gabrielse et al. 1991; Souther 1991). Wheeler and McFeely (1991) made this correlation in the study area (Fig. 2-2d). Fossils, including Crinoid fragments, a Productid fragment, and fragments of corals within comparable marbles approximately 2 km to the south across the Coldstream Valley (Fig. 2-1) suggest a Permian age for these rocks (F-8 locality of Jones 1959, identified by P. Harker, 1951).

PHRmb (Harper Ranch Group)

PHRmb outcrops on the north side of the Coldstream Valley (Fig. 2-1) and consists of massive white to blue-grey marble that forms resistant cliffs. These rocks are indistinguishable from the upper marbles in unit PHRmv, but are not interlayered with volcanic rocks at this location. These units are assigned a Permian age based on the presence of disarticulated Crinoid stems (location 98 JU 323, Appendix 2-1), fragments also observed in the F-8 locality of Jones (1959, see details above).

Ms (Quesnel "terrane")

Ms outcrops throughout the study area (Fig. 2-1). This unit consists of black, to blue-grey, to white carbonaceous and calcareous argillite, slate, metasiltstone, and metasandstone, with lesser metaconglomerate, grey to white marble, and green augite porphyry. The sedimentary rocks preserve fine laminations in some areas, but layers are usually cm to tens of cm thick, and primary features such as cross-bedding, grading, flame structures, microfossils, and trace fossil borings are often preserved (Plate 2-2c). R.I. Thompson (unpublished data, personal communication 2001) identified two localities of Upper Triassic fossils north of Lavington, identifying time-equivalent deposits to the Slocan, Nicola, and Ymir groups in this region. Upper Triassic conodonts were also discovered in lithologically identical rocks, 15 km east of Lavington (Okulitch and Cameron 1976). Unit Ms varies in metamorphic grade from rare occurrences of garnet-grade rocks near the base, upward to biotite- and then chlorite-grade rocks.

Two marker units occur within unit Ms. These include Maug and Mcgl. Maug is a green augite porphyry. In the Silver Star area this unit is conformable with regional schistosity (Fig. 2-1). Small dykes of Maug cut stratigraphy locally near the large area of Maug in the Trinity Valley, and isolated outcrops occur lower in the succession within Ms, Pccs, and Pcs. These could be feeder dykes to the flow, or they may indicate a cross-cutting relationship between Maug and Ms. Although some outcroppings of Maug are massive, others are foliated, and in places folded (Plate 2-2b) with surrounding sedimentary units of Ms, which lends support to the interpretation of Maug as a primary element within the Ms succession, as it is inferred to be in this study. Augite porphyry is found both in Upper Triassic rocks of the Nicola Group to the west, and in Early Jurassic Rossland Group rocks to the east (Preto 1977; Preto et al. 1979; Monger 1985; Höy and Dunne 1997).

Mcgl is a metaconglomerate on Silver Star Mountain that varies from matrix- to clast-supported, with flattened sub-angular to sub-rounded clasts of dominantly limestone and marble, with lesser amounts of quartzite, schist, plagioclase porphyry and granite(?) clasts, of pebble to cobble size (4 mm to 256 mm; Plate 2-3a, b). At least four interbeds of Mcgl occur on Silver Star Mountain, two of which were mappable over distances between 0.5 and 1 km (Fig 2-1). These are interpreted as separate beds and not as folds of the same layer because each layer differs slightly from one another in overall clast size, shape and matrix character. Similar conglomerate units occur at other locations within the mapped area (Table 2-1), and may be correlative, but these could not be tracked over any distance and thus do not appear on the map. These conglomerates vary from matrix to clast-supported, with a variation in clast size at different locations from a few mm to 15 cm in length, but on average were between 1 and 4 cm in length (see Table 2-1 for descriptions, Plate 2-3d, e, f).

A maximum age of 182.6 ± 4.2 Ma or 192 ± 3 Ma for Mcgl on Silver Star Mountain is interpreted from U-Pb detrital zircon geochronology from a whole-rock sample (Fig. 2-4b, c, see Geochronology section). Although it remains possible that this age may be metamorphic in nature, an igneous origin for these zircons appears most likely based on the low metamorphic grade of the strata, and the fact that several of the zircons are concordant (see below). If these zircons are metamorphic, then the maximum age of these rocks is known from a poorly preserved fusulinid within a limestone clast in this unit, determined by L. Rui (personal communication, 1999) to be most likely Permian in age, but possibly Pennsylvanian (Plate 2-3c). A Pennsylvanian(?)-Permian age for limestone clasts would be consistent with derivation from nearby PHR strata.

Interpreting the zircons within this unit to be detrital suggests that the uppermost strata on Silver Star Mountain are of early Jurassic age or younger. This interpretation suggests that Quesnel arc deposition may have continued from late Triassic time into early Jurassic in the Silver Star area, and that strata of early Jurassic age may be more widespread throughout the southern Cordillera than previously thought. Potential source rocks for these zircons are not known within the local area, nor are they common within the Cordillera, but possibilities exist in the Kootenay Arc region to the east, and to the west in the Quesnel volcanic arc (see Geochronology section for details).

The total thickness of Ms remains unknown, but it reaches approximately 500 m on Silver Star Mountain (Fig. 2-1). If Mcgl on Silver Star Mountain represents the base of an early Jurassic succession, then the underlying Triassic sequence would be no thicker than 300 m.

The most striking feature of unit Ms is that it sits atop every older unit in the area except Pgn, Pmv, and Pccs (Fig. 2-1). On Silver Star Mountain, Ms truncates underlying unit Pcs, which outcrops beneath it to the west, but is missing from the stratigraphic section to the north, south, and east where Ms overlies Pba. Along Fortune Creek, Ms overlies unit Dcq, indicating Pba is missing from the stratigraphic sequence there. Based on the fact that unit Ms overlies several older units in the area, and appears to cut down through stratigraphy to the north, south, and east, an unconformable basal contact is inferred. Alternative interpretations include a structural contact, with truncation of several underlying units a factor of the pre-faulting structure of units in the footwall. Unconformable relationships in the study area were first suggested by Jones (1959). Read and Okulitch (1977) also interpreted a sub-Triassic unconformity in the study area, and throughout southeast B.C.

Evvs

Evvs outcrops just north of Lavington in the Coldstream Valley (Fig. 2-1). This unit consists of andesite, dacite, and rhyolite with lesser pyroclastic and epiclastic flows, volcanic breccia, and volcaniclastic and clastic sediments including breccia and conglomerate (see below: Esbr, Ecgl). Eocene rocks cut and sit atop nearly every other lithology where they outcrop on the north side of the Coldstream Valley (Fig. 2-1). A cross-cutting relationship between a pyroclastic volcanic breccia and Ms can be observed on a road cut between Lavington and Becker Lake, and is interpreted as a volcanic vent (location 99 JU 15, Appendix 2-1; Fig. 2-1). Bedding in the volcaniclastic successions north of Lavington is graded in places. Interbedded volcanic rocks are a characteristic grey-green colour, fine-grained, and commonly have calcite and/or quartz veins. Alteration to chlorite and epidote makes primary mineralogy difficult to discern, but vestiges of primary plagioclase are common, visible in thin section. Pyroclastic flows occur in succession from the base of the valley 4 km north of Lavington, upward in succession to the northeast, and to the east where they are capped by Miocene basalts (Mab, see below; Fig. 2-1). Some of these units have a distinct epidote green colour to matrix or clast, likely a result of alteration by hydrothermal or deuteric fluids, with phenocrysts of amphibole and pyrite in both. Matrix mineralogy is often almost completely altered to chlorite, epidote and/or sericite, and in some samples a devitrified matrix is epidotized, but relict hornblende and plagioclase can be identified in thin sections of less altered rocks. Successive flows contain angular fragments from underlying flows. The flows dip steeply, which may reflect a steep original topography, and/or structural rotation that occurred subsequent to deposition. Based on lithologic similarities, these rocks are correlated with the Eocene Kamloops Group, similar to interpretations of Jones (1959) and Okulitch (1974).

Esbr and Ecgl

These two units outcrop in the south-central portion of the map area along the Coldstream Valley (Fig. 2-1). They occur in greatest abundance in a graben, northeast of Lavington, which is approximately 1 km in width and nearly 3 km in length (Fig. 2-1). Esbr is a heterolithic sedimentary breccia unit that contains angular fragments of dark grey carbonaceous metasedimentary rock, volcanic rocks, coal, granite, marble and slate (Plate 2-2d). Ecgl contains rounded clasts of black argillite, slate, marble and volcanic rocks. The variety of clasts increases upward in the graben succession. Clasts in both vary in diameter from mm to 30 cm, but have a bimodal size distribution, with estimated means around 1.5 and 5 cm. Potential sources of these clasts can be found in surrounding rock units, including the pyroclastic volcanic units of Evvs. Similar units occur directly south of the mapped area on Bluenose Mountain (Ekc of Glombick 2000).

Mab

Mab outcrops approximately 4 km northeast of Lavington in the Coldstream Valley. Mab are amygdaloidal and vesicular basalt flows, with olivine and plagioclase phenocrysts. Some flows may be intermediate in composition, based on their slightly lighter colour. One vesicular flow contained entrained clasts of non-vessicular, fine-grained rock that were small and difficult to identify. A possible feeder dyke was found in the northern most outcrops of Mab (99 JU 428 and 429, Appendix 2-1; Fig. 2-1), which was a massive, black-grey, non-vesicular rock with clasts of vesicular rock within. Alternatively, this could be the base of an overlying basalt flow that incorporated clasts from the top of an underlying flow. These basalts are correlated with the Miocene basalts mapped directly south of the Coldstream Valley (Fig. 2-1) by Church and Suesser (1983).

Igneous Units

Silver Star Intrusions

Jones (1959) termed the abundant granite and pegmatite that pervades units Dcq and Pba (> 50% of rock unit), and is less abundant in Pcs (< 20%), the Silver Star Intrusions. These intrusions could not be mapped separately from the lithologic units they intrude because of their near ubiquitous presence within them throughout the field area. The intrusions vary from granite to tonalite in composition, and from aplite to pegmatite in grain size. The majority of these are sills and lenses, concordant with planes of foliation and compositional layering, and with thicknesses between mm and tens of cm. However, dykes and larger masses >10 m in thickness also occur. It is likely that several intrusive phases are present. A single outcrop in the northern portion of the map area (98 JU 77, Appendix 2-1) reveals relationships between some phases that contain relict magmatic epidote. At this outcrop, the host rock of amphibole schist is cut by granodiorite, which is in turn cut by a biotite-bearing aplite, cut by pegmatite. Quartz veins in this outcrop are cut by both pegmatite phases. This is the only outcrop at which epidote was observed. The presence of magmatic epidote in granitic magmas has been interpreted to indicate an origin deep in the crust, with a rapid ascent rate to prevent complete resorption of the mineral (Brandon et al. 1996).

In other areas, granodiorite cuts pegmatite, indicating that multiple phases of magmatism may have occurred, or that all phases are broadly contemporaneous. Although some outcrops of these intrusions are massive, others are foliated, which suggests emplacement was pre-, syn- and post-tectonic, as was first suggested by Jones (1959). Accessory minerals within granitic units are variable, but include biotite, muscovite, garnet, tourmaline, and zircon. Pegmatite phases can consist solely of feldspar and quartz, or contain accessory minerals including muscovite, biotite, tourmaline, diopside, garnet, and amphibole. No direct age constraints for these units exist. Attempts to date a muscovite tonalite unit that cuts unit Pcs on Silver Star Mountain were unsuccessful.

Nd analysis of a sample from near Sovereign Lake (Fig. 2-1, 00 JU 02) is consistent with an *in-situ* origin for these melts, which is consistent with the high metamorphic grade of rocks near the base of Pba on Silver Star Mountain (see below).

Ptum

Ptum intrudes unit Pba in the northeastern portion of the map area (Fig. 2-1). This unit is a talc-rich chromite-bearing serpentinite. In places it is almost entirely altered to serpentine, but in some outcrops original mineralogy is discernable, and thin section examination shows the presence of talc, tremolite, and calcite, with possible epidote, olivine and anthophyllite. Prior to alteration, this rock was likely peridotite, and is interpreted to be intrusive and to correlate with the Old Dave intrusions described by Jones (1959). Contact relationships were not observed.

Jgtd

Jgtd outcrops in two locations along the Coldstream Valley in the southern portion of the map area (Fig. 2-1). Jgtd is a medium- to coarse-grained granite to granodiorite that contains variable amounts of biotite (0 to 20%), muscovite (0 to 10%), garnet (0 to 5%), and zircon (accessory). In places, quartz and feldspar define a rodding lineation. Jgtd cuts Pmv and Pcs on Vernon Hill. U-Pb zircon dating yielded a date of 145 ± 4 Ma for a sample from the southwest side of Vernon Hill (Fig. 2-1, Fig. 2-3, see Geochronology section).

Jgtd on Vernon Hill is correlated with a lithologically similar pluton outcropping 10 km to the east along the Coldstream Valley (Fig. 2-1). In this eastern area, Jgtd is cut off by an Eocene normal fault, and is interpreted to cut units Ms and Pba.

?peg

?peg outcrops as a mappable unit for over 4 km in the northern portion of the map area, and is a biotite and/or muscovite ± garnet granitic pegmatite body (Fig. 2-1). It cuts unit Pba. Pegmatite is present throughout unit Pba, but there is likely more than one phase (see section Pba above).

Esp

Esp outcrops over mappable extents along the Coldstream Valley on Vernon Hill, north of Lavington, and east of Lumby (Fig. 2-1). Esp consists of porphyry dykes that are variably dominated by K-feldspar, plagioclase, or biotite, and which cut nearly every other unit in the field area. A "salt and pepper", or specked black and white, appearance is characteristic of these dykes. They are massive, except locally where brittle faulting has taken place and they show slickenside fabric. On Vernon Hill, entrained clasts of foliated granite are found within (Plate 2-2e). An Eocene age is assumed based on the lack of penetrative foliation and entrainment of foliated granite clasts, indicating emplacement after the latest phase of deformation, as well as on cross-cutting relationships observed with all older units except Pgn, Dcq and Psc.

Structural Geology

Rocks in the study area have undergone multiple phases of deformation, evident at scales from the microscopic to map scale. Mesozoic and older layered lithological units are penetratively deformed, and have been subjected to at least four phases of deformation (D_1 - D_4). Strain is heterogeneously distributed.

Folding (see Fig. 2-1)

Shallow northwest plunging box-like folds, with amplitudes of ~150 m and wavelengths > 1 km, are defined within PSC by the white and grey striped marble marker member (PSCmb) and quartzite cobble conglomerate (PSCclg) member (Fig. 2-1). These folds are also outlined in the surface trace of unit Pcsl, a distinctive black calcareous slate within the carbonaceous phyllite and schist succession (Pcs)(Fig. 2-1). On the basis of stratigraphic continuity upward from Fortune Creek, these folds are interpreted to be plunging gently northwest and verging southwest. A reversal of schistosity is also apparent in unit Pba, directly north of where PSC outcrops, and may indicate the continuation of this fold northward (Fig. 2-1). Pre- Upper Triassic deformation (pre-D_1) was interpreted from Spa Creek Assemblage (PSC) rocks directly west of the study area (Erdmer et al. 2001), however the present study could not substantiate or disprove this. These folds are inferred to result from D_2 deformation, and to extend into the Upper Triassic succession (Fig. 2-1). PSC rocks show evidence of at least two phases of folding. D_2 deformation led to the development of a steep penetrative foliation within the rocks, inferred to be axial planar to these folds, that was folded during subsequent deformation (D_3, Fig. 2-5). Compositional layering is not well preserved in most units of PSC on the outcrop scale.

Late Triassic - early Jurassic rocks show evidence of three phases of shortening (D_1-D_3). The earliest (D_1) resulted in a layer parallel, or near-parallel, cleavage (S_1) that shows evidence of having been subsequently folded twice, in north-south and east-west directions, approximately orthogonal to one another (D_2 and D_3) (Plate 2-4a; Figs. 2-6, 2-7). D_2 shortening was directed east-west, and resulted in the development of a spaced axial planar cleavage (S_2), in places a crenulation of S_1 cleavage, and is associated with upright west verging folds in some units, which vary in tightness from gentle to isoclinal (Plate 2-4a). S_2 is also a plane of flattening, defined by the shape of clasts in unit Mcgl on Silver Star Mountain.

Compositional layering (S_0), S_1, and S_2 surfaces were folded about an east-west axis (Figs. 2-5, 2-6, 2-7) during north-south oriented shortening (D_3). This deformation resulted in broad map scale folds that plunge east and verge north, with amplitudes >2 km and wavelengths > 9 km. Mesoscale open to isoclinal folds, with amplitudes between 5 and 30 cm, and wavelengths of cm to several m are heterogeneously distributed throughout all Mesozoic and older rock units in the area (Figs. 2-1, 2-8). Mesoscale folding appears most intense in areas near the axis of this fold, and orientations of penetrative fabrics show the greatest variability in this area (Fig. 2-1).

Similar deformation structures are visible within rocks throughout the field area. In suitable lithologies, layer parallel to near-parallel foliation (S_1) is consistently observed, and interpreted as resulting from D_1 deformation (Figs. 2-6, 2-7). On Vernon Hill, where three-dimensional exposures of outcrops are common, D_2 folding is also evident within Pmv, Pccs, and Pcs units, defined by bedding (S_0) and a near bedding-parallel cleavage (S_1) (Figs. 2-6, 2-7; Plates 2-1e, 2-4c). Unit Pccs is characterized by tight to isoclinal folds that are co-axial with D_2 structures (Plates 2-1e, 2-4c). D_2 resulted in spaced cleavage (S_2) development in these units, which is axial planar to mesoscale folds where observed. S_2 foliations were subsequently folded about a northeast trending fold axis in this area during D_3 (Fig. 2-5).

The 145 Ma Jgtd on Vernon Hill places constraints on the timing of latest deformation. The foliated nature of this intrusion indicates that D_3 deformation must be syn- or post-145 Ma. Foliation of rafts within the pluton are folded about a shallowly east plunging fold axis (91/8, Fig. 2-7), suggesting that plutonism post-dates D_3 folding, but occurs before the end of D_3 (Fig. 2-7).

The most recent folding episode is related to an episode of extension (D_4) in the Eocene that affected the entire southern Canadian Cordillera. There are various models proposed that describe the mechanisms and speculate on the causes of this extension (e.g. Brown and Read 1983; Templeman-Kluit and Parkinson 1986; Bardoux and Mareschal

1994; Johnson and Brown 1996) that will not be outlined here. Normal faulting associated with this extension resulted in localized outcrop scale drag folds.

Faulting

At least three episodes of faulting occurred within the mapped area. The earliest was a well-developed mylonite zone, at least 1.5 to 2 km thick, which occurs on Silver Star Mountain within units Dcq, Pba, and Pcs. In units Dcq and Pba, where rocks are coarse-grained, mylonitic fabric is most apparent in the granitic and pegmatitic sills and dykes intruding the rocks. In unit Pcs, where compositional layering is preserved, mylonitic foliation is apparent through preservation of rootless isoclines parallel to layering, indicating transposition of original bedding. In thin section, asymmetric shear sense indicators including c-s fabric, c' structures, and winged porphyroblasts (Plate 2-5) attest to the non-coaxial strain. Quartz grains show textures indicative of ductile deformation, including undulose extinction, ribbons, and serrated grain boundaries. Plagioclase, on the other hand, behaves variably in both ductile and brittle manners, suggesting formation of this zone between temperatures of 300°C and 450°C (Scholz 1988). Three oriented samples from layered rocks in this zone indicated the sense of shear to be consistently top to the east along these north-striking mylonitic shear planes (Plate 2-5). This mylonite zone extends to the eastern portion of the map area to unit Pba, outcropping along the west side of Trinity Valley, where it is best developed within intrusive granitic rocks of assumed Jurassic age. A stretching lineation associated with this zone is oriented east-west (Fig. 2-8). In unit Pcs, a biotite aggregate lineation parallels this stretching lineation (Fig. 2-8). One sample of foliated granite near Sovereign Lake, however, shows well-developed c-s fabric with a top to the west sense of shear, but attitude that is concordant with surrounding rocks (Plate 2-5g). A more detailed examination of this zone may determine is these data are related, and age determinations on this granite would place a maximum age on its deformation.

Constraints on the timing of mylonitic deformation are provided by cross-cutting relationships with granitoid rocks, including multiple phases of pegmatite. As recognized by Jones (1959), there are pre-, syn- and post-tectonic granites in the Silver Star area.

This mylonite zone post-dates peak metamorphism (see below), indicated by offset kyanite and staurolite grains by c' structures within the mylonite zone (Plate 2-5), an interpretation supported by fractured and broken up garnet grains within this zone, and pressure shadows surrounding garnets (Plate 2-5). Peak metamorphism was a static event that overprinted regional D_1 fabric, and this mylonite zone is folded during D_2 deformation, indicating that mylonitic deformation occurred between peak metamorphism and D_2 folding.

An east-west striking fault in the northern portion of the map area places unit Pba over PSC and Pcs rocks, and is inferred to be associated with the second phase of folding (D_3). This fault contact was not observed in the field. Evidence for this fault includes the truncation of unit PSCmb, and the steep orientation of the contact between units Pba and Pcs near Kendry Creek (Fig. 2-1), inferred from the surface trace across topography. This fault is interpreted to be a steep contraction fault, dipping between approximately 60 and 75°, with a minimum dip-slip displacement of 1 to 1.5 km (cross section A-A', Fig. 2-1).

Local evidence of shearing (99 JU 130, 134, 411, and 457, Appendix 2-1) near the contact of Pmv and Pccs with Pcs on Vernon Hill indicates that a fault contact between these units may be possible, although it is not inferred here due to the limited number of localities at which such deformation was observed. Deformation at 99 JU 130 was brittle, while 99 JU 134, 411, and 457 show semi-brittle to ductile deformation. In thin sections of the latter, quartz grains show undulose extinction and serrated grain boundaries. It is inferred that this deformation is related to localized Eocene extension, discussed below.

The most recent faults are related to regional extension in the Eocene, a phenomenon well documented throughout the Canadian Cordillera (e.g. Brown and Read 1983; Templeman-Kluit and Parkinson 1986; Bardoux and Mareschal 1994; Johnson and Brown 1996). Along the Coldstream Valley in the southern portion of the map area, four normal faults are inferred that post-date deposition and intrusion of units in Evvs, interpreted to be Eocene in age, and juxtapose younger rocks on older rocks in some areas (Fig. 2-1). These faults were not observed, but are inferred to dip steeply (> 60°) based on surface traces of these faults along topography. These faults are likely temporally associated with, and may have acted as conduits for, hydrothermal alteration, which is enhanced along the two faults northeast of Lavington. Along the normal fault northeast of Becker Lake on Vernon Hill, rocks have been bleached and leached, and this alteration is noted as the Lavington Zone on BCGS MINFILE report no. 082LSW120. At the outcrop scale, normal faults with displacements of millimeters to meters, parallel to compositional layering or schistosity where observed, also document this extension (Plate 2-4d). These late faults can make the interpretation of structural data more difficult by rotating earlier fabrics.

Discussion of Cross-Sections

On cross-section constructions (Fig. 2-1), lines separating units represent enveloping surfaces, within which rocks are heterogeneously deformed, varying from homoclinal to isoclinal at the outcrop scale. These enveloping surfaces are intended to define the gross lithological layering throughout the area, and dip shallower than schistosity, and often bedding, measured at the outcrop scale.

Metamorphism

Metamorphic grade in the study area varies from partial melting (above second sillimanite isograd) in lower horizons of Pba, to chlorite-muscovite-grade in upper horizons of unit Ms, to epidote alteration in unit Evvs. A transition from sillimanite-K-feldspar-grade to chlorite-muscovite-grade occurs over a vertical thickness of approximately 1.5 km on Silver Star Mountain, a progression that should occur over a depth of approximately 12 to 15 km under normal geothermal gradient conditions. This transition appears to be progressive, with all intermediate metamorphic zones present, but attenuated. The reason for the attenuation is beyond the scope of this study, but may be related to stretching and flattening attested to in unit Psccgl, where quartzite cobbles show length:width:height ratios of between 5:2:1 and 10:2:1 (Plate 2-1d). However, the timing of this ductile deformation in Psc remains uncertain, and may be pre-Triassic (e.g. Erdmer et al. 2001).

At least three phases of metamorphism occurred within the mapped area. Metamorphism accompanied regional cleavage development (S_1/D_1), along surfaces parallel or near parallel to compositional layering. S_1 surfaces are defined by platy mineral growth, including chlorite and muscovite in upper horizons, and biotite and amphibole in lower horizons, recording greenschist to amphibolite-grade conditions. These surfaces are overprinted by a random growth of metamorphic minerals (Plate 2-6). For example, in unit Ms, this event is indicated by the presence of randomly oriented biotite, muscovite, and chlorite. Unit Pcs has randomly oriented porphyroblasts of staurolite, kyanite, garnet, plagioclase, biotite, and muscovite (Plate 2-6a). Unit Pmv is characterized by randomly oriented biotite and/or amphibole. Sillimanite-bearing Pba is somewhat more difficult to interpret due to intense overprinting by subsequent shear fabrics. However, static porphyroblasts of the same mineral assemblages as in unit Pcs are present, including rare relic kyanite and staurolite that has a "moth-eaten" appearance (Plate 2-6b, c), suggesting they are not in equilibrium with the present assemblage.

Mylonite development on Silver Star Mountain was accompanied by sillimanite growth in unit Pba, roughly parallel to the stretching lineation. In unit Pcs, biotite-grade metamorphism is indicated by the presence of biotite aggregates parallel to the stretching lineation in the underlying Pba (Fig. 2-8). These aggregates are inferred to be prograde based on their well-defined crystal habit and the lack of any relic minerals preserved within them.

Metamorphic biotite, muscovite and chlorite define a steep spaced cleavage (S_2), with a spacing of 0.2 to 1 mm, that is associated with first phase folding (D_2).

Retrogradation of metamorphic minerals occurs in all metamorphosed rock units, indicated by partial reactions to amphibole, biotite, chlorite and sericite, and is likely related to an Eocene thermal event accompanied by volcanism in the area. These events are also likely responsible for epidote alteration of some Eocene units.

Geochronology

Methodology and Analytical Technique

U-Pb geochronology was applied to zircons from three samples, in attempt to determine the timing of crystallization of two granitic units (00 JU 01, 00 JU 02), and to examine the provenance of Mcgl (JU SS CGL, Plate 2-3a,b). All processing and analyses were completed at the University of Alberta. Following mechanical breakdown of samples using a sledgehammer and rock press, heavy mineral separates were obtained using a jaw crusher, disk mill and Wilfley table. Further isolations were made using a 70-mesh sieve and Franz isodynamic magnetic separator, followed by density separation using methylene iodide. If zircon samples were large, further separation using the Franz separator was undertaken. Zircons were then hand picked and separated into fractions based on similarities of shape, size, colour and inclusions. No fractions were abraded prior to analysis. Following separation into fractions, zircons were processed in an ultra-clean laboratory to extract U and Pb, and then analyzed by thermal ionization mass spectrometry on a VG 354 mass spectrometer in the Radiogenic Isotope Facility. Mineral fractions and analytical results were processed according to procedures outlined in Heaman et al. (2002), and results are shown in Table 2-2. All analytical data were standardized against the NBS981 Pb and U500 U standards, with errors reported to 1σ. Age determination calculations were completed using the program Isoplot (Ludwig 1992) and denote discordia line upper and lower intercept ages based on two-error linear regression treatment of the data, with uncertainties reported to 2σ. The ages were calculated using the decay constants and present day $^{238}U/^{235}U$ ratio of Jaffey et al. (1971).

Sample Descriptions

Sample 00 JU 01 is a foliated granite from Vernon Hill (Fig. 2-1), considered representative of unit Jgtd, which varies from granite to granodiorite in composition. 00 JU 01 contains accessory amounts of biotite and garnet, and trace amounts of muscovite. The sample shows evidence of shearing, with strain apparent in quartz grains and in K-feldspar. Plagioclase grains are visibly zoned in thin section. Cross-cutting relationships between this pluton and foliation in surrounding host rocks place timing constraints on earliest deformation, but the internal fabric of this rock places a maximum age on the latest deformation.

Sample 00 JU 02 is a foliated muscovite-tonalite sill from near Sovereign Lake on Silver Star Mountain, where it cuts foliation in unit Pcs (Fig. 2-1). This sample contains accessory amounts of biotite and rutile. 00 JU 02 is considered part of the Silver Star Intrusions (see above) that are pervasive within Pba and Dcq, and become diminished in quantity upward in the section through unit Pcs. This rock places a minimum age on unit Pcs, and may record pre-Triassic deformation within the area.

Sample JU SS CGL is a conglomerate sample of unit Mcgl (Ms) where it outcrops along the road to Silver Star Mountain (Fig. 2-1, Plate 2-3, Appendix 2-1). This unit is described under the Stratigraphy section, as part of unit Ms. Analyses on this sample aimed at testing for detrital contribution from sources of North American affinity, and to provide a possible maximum age for Mcgl.

Zircon Descriptions and Results

Three fractions of zircon were analyzed from sample 00 JU 01, chosen from the 1° magnetic fraction, separated during the final Franz procedure run at 1.8 A. These zircons had moderate to high U levels (366 to 643 ppm) and Th/U ratios (0.26-0.34; Table 2-2). Fraction 1 consisted of 48 clear, slender, euhedral zircons (Plate 2-7a) that gave a ^{207}Pb/^{206}Pb date of 156.3 ± 0.9 Ma and was the least discordant at 5.8%, (Table 2-2). Fraction 2 consisted of 9 of the larger euhedral or nearly euhedral grains, which contained mineral inclusions (Plate 2-7b). These zircons gave a ^{207}Pb/^{206}Pb date of 167.0 ± 1.7 Ma and were 10.9% discordant (Table 2-2). Fraction 3 was an exceptionally large euhedral grain (~5 mm in length, Plate 2-7c) with mineral inclusions, and yielded a ^{207}Pb/^{206}Pb date of 167.3 ± 2.5 Ma, and was 10.5% discordant (Table 2-2). Combined, these three fractions define a discordia line with a lower intercept of 145 ± 4 Ma, and an upper intercept of 587 ± 240 Ma (Fig 2-3).

Two fractions were run from sample 00 JU 02, chosen from the 1° magnetic fraction separated during the final Franz procedure run at 1.8 A. For this sample, the 1° magnetic fraction was considered the best. Fraction 1 consisted of 16 large, colourless, subhedral zircons that lacked any visibly apparent cores or inclusions, and was 20.8% discordant (Plate 2-8a; Table 2-2). This fraction had moderate U levels (389 ppm) and low Th/U ratios (0.14), which can be characteristic of metamorphic zircons (Table 2-2). Fraction 1 gave a ^{207}Pb/^{206}Pb date of 302.5 ± 1.4 Ma (Table 2-2). Fraction 2 was 66.0% discordant, had similar chemical characteristics to Fraction 1 (307 ppm U, Th/U = 0.13), and yielded a ^{207}Pb/^{206}Pb date of 765.2 ± 1.3 Ma (Table 2-2).

Little zircon was recovered from a > 20 kg sample of Mcgl (JU SS CGL), leaving the final Franz step, which further separates zircons isolated during methylene iodide density separations, unnecessary. Five single-grain analyses were completed on zircons retrieved from this sample (Plate 2-9). Discordance among the zircons ranged from –12.3 to 69.4 % (Table 2-2). U levels were low, varying between 126 and 198 ppm amongst all fractions. Th/U ratios were quite variable, between 0.05 and 0.23 (Table 2-2). $^{207}Pb/^{206}Pb$ dates from the fractions varied between 166.1 ± 27.7 and 771.9 ± 21.2 Ma (Table 2-2). Fractions 1, 2, 3, and 5 plot, within error, on the Concordia curve, between approximately 184 and 209 Ma (Fig. 2-4). Measurements from Fraction 3 are not used in any age calculations due to poor precision during analyses, and the high concentration of common Pb in the sample (114 pg, Table 2-2). Unusual for data from detrital zircon studies are that two combinations of three zircon analyses lie on a discordia line. Fractions 2, 4 and 5 define a discordia line with a lower intercept of 182.6 ± 4.2 Ma, and an upper intercept of 1646 ±110Ma, with an MSWD of 1.8 (Fig 2-4b). Fractions 1, 2, and 4 also define a discordia line with a lower intercept of 192 ± 3 Ma and an upper intercept of 1799 ± 110 Ma, with an MSWD of 1.9 (Fig. 2-4c).

Interpretations and Implications

The 145 ± 4 Ma lower intercept of the discordia line from sample 00 JU 01 (Fig 2-3), is interpreted to be the igneous crystallization age of unit Jgtd, with the upper intercept suggestive of inheritance from a possible Proterozoic source. However, the lack of precision of the upper intercept, 587 ± 240 Ma (Fig.2-3), makes speculation difficult. It is possible that the lower intercept represents a metamorphic age, but this seems unlikely based on the near concordant analyses, and the chemical characteristics of the zircons. A crystallization age at the Jurassic-Cretaceous boundary provides a minimum age for units Pmv and Pcs and foliation surfaces cut by this pluton, and a maximum age of latest deformation. These results are indicative of magmatic activity in the Silver Star area during the late Jurassic - early Cretaceous time, which is interpreted as a period of magmatic quiescence in this region and the Cordillera in general (Woodsworth et al. 1991; Yorath 1991).

Possible interpretations of data from sample 00 JU 02 are offered with little confidence at this time. If these fractions lie on the same discordia curve, two interpretations are possible. The lower intercept of 237.5 ± 1.1 Ma may represent the age of the intrusion, with an inherited component from crust with an age of 2388 ± 49 Ma (Fig. 2-9). If the zircons are metamorphic, then the lower intercept may represent a metamorphic event, and the upper a possible crystallization age. However, that implies that units Pcs and Pba are older than 2388 Ma, which is impossible if the underlying unit Dcq is Devonian. It is possible that the highly discordant data is indicative of the complex geologic processes that occurred on Silver Star Mountain, including multiple episodes of deformation and metamorphism (see above).

The limited number of zircons retrieved from JU SS CGL (Mcgl), and the unusual fact that fractions 2 and 4 can be fit onto a discordia line with either fraction 1 or 5, suggests two possibilities in which three zircon fractions were sourced from the same rock. Fraction 3 also falls on these lines, but is not considered because of high amounts of common Pb (114 pg) and poor precision during measurement of isotopic ratios (Table 2-2). Lower intercepts of these discordia lines are interpreted to represent possible crystallization ages of this source, between 182.6 ± 4.2 Ma (fractions 2, 4, and 5) and 192 ± 3 Ma (fractions 1, 2, and 4), and upper intercepts to represent inheritance from zircons with an average age between 1632 (fractions 2, 4, and 5) and 1799 ± 110 Ma (fractions 1, 2, and 4) (Fig. 2-4). This interpretation provides a maximum age of early Jurassic for unit Mcgl, making correlations with the Ymir and/or Rossland groups in the Kootenay Arc region, approximately 160 km to the east, or the early to middle Jurassic Ashcroft Formation, approximately 120 km to the west, possibilities. Of the two possible maximum age interpretations, 192 ± 3 Ma may be more likely, as sources of this age are abundant, and an upper intercept of 1800 Ma matches the 1800-2100 Ma ages of exposed basement rocks throughout this region (Armstrong et al.1991; McDonough and Parrish 1991; Murphy et al. 1991; Parkinson 1991). The penetrative deformation and presence of comparable fabric within these rocks to underlying rocks of inferred upper Triassic age suggests that they have undergone the same episodes of deformation and metamorphism, which further requires an early Jurassic age for these rocks if this basin was closed by

185-187 Ma (Murphy et al. 1995), and also suggests the maximum age interpretation of 192 ± 3 Ma is more likely. The age determinations were not available during mapping of these rocks, and future research should focus on determining the extent of rocks of this age in the area, and examining the possibility that they were deposited after initial deformation of underlying strata.

Possible sources of these zircons are abundant in the Kootenay Arc region (Fig. 2.2b), and include the Elise volcanics of the Rossland Group, estimated to be between 197.1 ± 0.5 Ma (U-Pb zircon, Höy and Dunne 1997) and early Toarcian (Frebold and Little 1962, <183.6 +1.6/-1.1 from Okulitch 1999), although in places they may be as young as 173.1 +6/-0.2 Ma (U-Pb zircon, Höy and Dunne 1997). Other potential sources in the Kootenay Arc region (Fig. 2-2b) that correspond to the lower intercept age of 182.6 ± 4.2 Ma include the Cooper Creek stock (180.6 +6.5/-7.1 Ma, U-Pb zircon) and Alwyn Creek porphyry (185 +24/-29 Ma, U-Pb zircon), (Murphy et al. 1995). Rossland Group rocks are interpreted to have formed in a continental arc setting, and zircons show evidence of inheritance from crust with an average age of 2.28 Ga (Höy and Dunne 1997). This is also the case for the Cooper Creek Stock (2105 +264/-281 Ma) and the Alwyn Creek porphyry (2220 ± 120 Ma; Murphy et al. 1995). Potential sources also exist to the west, in the area of Quesnel arc volcanism. These include the Wild Horse Batholith (196 ± 1 Ma, U-Pb zircon, Parrish and Monger 1992), Bromley Pluton (193 ± 1 Ma, U-Pb zircon, Parrish and Monger 1992), Pennask Batholith (194 ± 1 Ma, U-Pb zircon, Parrish and Monger 1992), and Nicola Batholith (190 ± 10 Ma, Rb-Sr, unpublished data of R.L. Armstrong in Ghosh 1995). Within the eastern volcanic facies of the Nicola Group, potential sources include the Copper Mountain intrusions (Voigt Stock, 194 ± 7 Ma, K-Ar biotite; Lost Horse Gulch, 195 ± 8 Ma, K-Ar biotite; Smelter Lake Stock, 197 ± 8, K-Ar biotite; Preto 1972). Of these possibilities, an eastern origin is favoured because zircons from the Kootenay Arc region show evidence of inheritance from Proterozoic sources, a characteristic also seen in the Mcgl detrital zircons. Although it remains possible that the lower intercept age for zircons from JU SS CGL may be metamorphic, with an inherited detrital component, this is unlikely based on the low metamorphic grade of the strata, and the fact that several zircons plot near the Concordia curve.

Isotope Geochemistry

Sampling Methodology

Seven samples were selected for Sm-Nd isotopic analysis (Table 2-3). Sample 98 JU 162 (Pcs) was originally mapped as part of unit Ms, and analyzed as part of the provenance study on Upper Triassic metasedimentary rocks presented in Chapter 3 (Unterschutz et al. 2002). The remaining six samples are of igneous rocks, analyzed to assist in interpretation of the tectonic setting of the Silver Star area. Sample 98 JU 532 (Maug) provides a test of whether this augite porphyry may be a flow within the Ms succession, through comparison with available data from Nicola Group volcanic units west of the study area. Samples 98 JU 606, 513, and 568 are from layers parallel to bedding in Ms strata. They were originally thought to be flows in the Ms succession, but, subsequent mapping in 1999 revealed a cross-cutting relationship with unit Ms, and they are thought to be Eocene in age (Esp). Nd isotope analyses of samples 00 JU 01 (Jgtd) and 02 (Silver Star Intrusions), granite and tonalite respectively, were completed with the intent of integrating the results with U-Pb zircon geochronology results from the same samples, in attempt to determine the tectonic setting at the time of their emplacement.

Analytical Technique

Sm-Nd isotopic analyses were conducted at the Radiogenic Isotope Facility at the University of Alberta using isotope dilution mass spectrometry (see Creaser et al. 1997 for methods). Results are presented in Table 2-3. Samples 98 JU 606, 513, 568, 532, and 162 were run on a VG 354 mass spectrometer, on which the $^{143}Nd/^{144}Nd$ value determined for the Shin Etsu Nd standard was 0.512097 ± 12 (1 SD, n = 40). Samples 00 JU 01, and 02 were run on a Sector 54 mass spectrometer, on which the $^{143}Nd/^{144}Nd$ value determined for the Shin Etsu Nd standard was 0.512106 ± 16 (1 SD, n = 12). These standard values are in agreement with previous determinations for the standard by Tanaka et al. (2000). Data were corrected to a $^{143}Nd/^{144}Nd$ value of 0.512107 for Shin Etsu, which is equivalent to 0.511850 for the La Jolla standard (Tanaka et al., 2000). Chemical processing blanks were < 400 pg for Nd and Sm.

Results and Interpretations

The composition of clastic sedimentary rocks tends to reflect their source areas, and, as the Sm-Nd isotopic system has been shown to be relatively unaffected by erosion, transportation, deposition, and low-grade metamorphic processes (Taylor and McLennan 1985), it can be used to provide information on the source areas of clastic rocks (e.g. Goldstein et al. 1984; Creaser et al. 1997). Sample 98 JU 162 from unit Pcs yields an εNd_{300} value of –5.5 and a T_{DM} model age of 1.59 Ga, suggesting derivation from an evolved continental crustal source (Table 2-3). An age of 300 Ma was used in calculations; the age of the rock is limited by underlying units Pba and Dcq of Devonian age, and overlying Upper Triassic rocks. A 50 m.y. difference in age would only change the εNd value by half an epsilon unit. This evolved composition is consistent with a pericratonic affinity, and with compositions of more inboard Pennsylvanian to Triassic clastic deposits of the Cordilleran miogeocline (Boghossian et al. 1996; Garzione et al. 1997).

Eocene biotite porphyry units give εNd_{50} values of –5.6 and –3.6, while the plagioclase porphyry unit gives an εNd_{50} of +2.8 (Table 2-.3). For the purposes of calculations in this study, a 50 Ma age is used for these samples (Table 2-3). In a comprehensive geochemical study of Paleozoic to Early Tertiary igneous rocks, Ghosh (1995) interpreted Paleocene to Eocene igneous rocks with intermediate εNd_T values (–2.4 to –7.6) to be sourced largely from mantle melting, with variable input from crustal material. This is consistent with observations of entrained rocks within Eocene dykes on Vernon Hill (Plate 2-2e), and T_{DM} model ages between 0.85 and 1.49 Ga. The positive εNd_T value from the plagioclase porphyry unit probably reflects a mantle origin for the melt, with a lesser degree of input from crustal materials. Further geochemical analyses, including Sr-isotope analysis, in addition to a geochronological study on these samples, may reveal the reason for the difference in Nd isotope compositions between these rocks.

The sample of Maug, 98 JU 532, yields an εNd_{220} value of +4.1 (Table 2-3), which is slightly less positive than values from contemporaneous Nicola Group volcanic rocks to the west (εNd_T +5.0 to +7.9, Smith et al. 1995). The positive εNd value of Maug lends support to interpretation of Maug as a flow within the Ms succession, correlative with volcanic rocks in the Nicola Group.

Jgtd (00 JU 01) from Vernon Hill yields an εNd_{145} value of –2.2, and a T_{DM} model age of 1.03 Ga (Fig. 2-1; Table 2-3). The negative value implies some interaction with continental crust, which is consistent with Proterozoic inheritance shown by zircons from this same sample. This value also is consistent with εNd_T values of +8 to -13 from intrusive Middle Jurassic through Cretaceous igneous rocks presented by Ghosh (1995).

The muscovite tonalite sample (00 JU 02) from the Sovereign Lake area on Silver Star Mountain yields an εNd_{300} value of –13.6, and a T_{DM} model age of 2.34 Ga (Table 2-3). The result is less precise than for other samples due to low concentrations of Sm and Nd (0.13 and 0.62 ppm, respectively), but a difference of 0.000020 in the measured $^{143}Nd/^{144}Nd$ ratio (the 2 SD uncertainty on this measurement) would only change the εNd_{300} value by 0.4 of an epsilon unit. This change would not alter the highly evolved character of this sample that could only originate from melting of continental crust. This suggests an *in-situ* melting origin for the Silver Star Intrusions in units Pba and Dcq. For the purposes of calculation, an age of 300 Ma was used, derived from the $^{207}Pb/^{206}Pb$ date from zircon fraction 1, the least discordant for this sample.

Discussion

Geologic History

The oldest rocks of known age in the study area, Dcq and Pba, represent a transition from shallow water, continental margin, dominantly quartzofeldspathic deposits in Devonian time, to deeper water, carbonaceous deposits of Pcs in the late Paleozoic. Lithologic similarities with the Silver Creek Formation (Pba) have led previous authors to variably correlate Pba and Dcq with North American rocks including the Paleozoic Lardeau Group and the Neoproterozoic Windermere Supergroup and Hunters Range Assemblage (Okulitch 1979; Johnson 1990, 1994; Thompson and Daughtry 1996).

Consistent with derivation from a continental source, but distinct from contemporaneous deposits of the Cordilleran miogeocline ($\varepsilon \mathrm{Nd}_T$ between –14.6 and –6.6, Boghossian et al. 1996; Garzione et al. 1997), are the $\varepsilon \mathrm{Nd}_{400}$ values for the Silver Creek Formation, between –20.2 and –22.2 (Erdmer et al. 2001). The abundant presence of mafic material (Pgr and equivalents?) intruding and possibly interlayered within unit Pba, may be indicative of a period of extension in or after Devonian time, and possibly rifting along the margin, similar to a 370 Ma episode of rifting in the northern Cordillera (e.g. Thompson et al. 1987). The presence of pyritic stringers, black slate, and abundant carbon in unit Pcs suggests deposition in a restricted basin environment. This basin may be part of a distal passive margin environment, or could be part of a back-arc basin environment, located between the more outboard late Paleozoic volcanic arc of the Harper Ranch Group and ancestral North America.

Unit Pcs is unconformably overlain by the Spa Creek Assemblage (PSC) in the northern portion of the map area (Fig. 2-1), indicating a transition from quiet basin sedimentation to that of an active volcanic regime. This may reflect migration of a late Paleozoic arc craton-ward into back-arc basin sedimentary rocks, or signify the end of passive margin deposition. The presence of the quartzite cobble conglomerate (PSCcgl) at the base of this succession suggests derivation from a nearby source of continental affinity. This is consistent with correlative conglomerate units of the Spa Creek Assemblage west of the study area, in which clasts of quartzite, schist, and Eocambrian granite are found (Erdmer et al. 2001). Potential sources may have been uplifted during tectonic processes associated with volcanism in the area. The timing of deposition of PSC remains to be established, but an Upper Paleozoic age is inferred. Unit Pmv, which overlies Pcs in the southern portion of the map area, may represent a more distal equivalent to PSC, and unit Pccs eroded components from PSCmb. The contact between Pcs and Pmv was not observed, leaving the nature of it uncertain, but the concordance of structures and metamorphic grade across this contact, and within both units, suggests that it may be conformable. Late Paleozoic volcanism is also indicated by the presence of unit PHRmv, which is interlayered and overlain by unit PHRmb, suggesting that the newly formed volcanic edifice may have provided a suitable environment for reef growth.

Provenance studies of the Harper Ranch Group (Quesnel subterrane) that span the U.S. - Canada border in the southern Kootenay Arc region (Fig. 2-2b) suggest that sediment was derived from source areas ranging in age from 0.37 to 2.7 Ga, which may have been proximal as suggested by the presence of quartzite clasts in conglomerate of the Upper Paleozoic Mount Roberts Formation (Roback and Walker 1995).

The contact between Late Triassic – early Jurassic rocks (Ms) and older units within the study area could be interpreted as either structural or unconformable, but based on the fact that unit Ms overlies every older unit in the area except Pgn, Pmv and Pccs, and that this basal surface cuts down through stratigraphy to the north, south and east of Silver Star Mountain, an unconformable basal contact is inferred. The mylonite zone in rocks underlying unit Ms on Silver Star Mountain and to the east along the Trinity Valley may represent a tectonic contact, however, mylonite is not observed elsewhere beneath rocks of the Quesnel "terrane", further suggesting that a tectonic contact is not the case. A sub-Triassic unconformity has been previously suggested for the Silver Star area (Jones 1959; Read and Okulitch 1977) and is documented in other areas of southeast British Columbia (Read and Okulitch 1977; Klepacki 1983; Klepacki and Wheeler 1985; Roback and Walker 1995).

An unconformable contact between unit Ms and older rocks in the area would imply a shift from a volcanic environment in the late Paleozoic, to one of a more distal, back-arc basin between the Quesnel volcanic arc to the west, and ancestral North America to the east, by the Upper Triassic. The presence of up to 40% carbon dust in Upper Triassic metasedimentary rocks implies a restricted basin environment. In this scenario, both North America and the Quesnel volcanic arc would have been potential sources for detritus in the interlayered sands, silts and muds of unit Ms. This possibility is supported by geochemical and isotopic characteristics of sediments spanning this proposed back-arc basin that are interlayered with volcanic units to the west and unconformable with North American derived sediments to the east, and which indicate a mixed provenance between rocks of a primitive arc nature, and evolved continental crust (Unterschutz et al. 2002). Maug may represent a period of enhanced volcanic activity, or migration of the volcanic arc eastward. An eastward migration of the arc is attested to by the occurrence of early

Jurassic volcanic rocks of the Rossland Group in the Kootenay Arc region, 250 km east of volcanic rocks of the Late Triassic Quesnel arc. Deposition continued into the early Jurassic, when schistose rocks of continental affinity and early Jurassic igneous rocks were exposed, eroded, and deposited in this basin (Mcgl).

The basin between the Quesnel "terrane" and North America is estimated to have closed by the late Early Jurassic (185-187 Ma, Murphy at al. 1995), suggesting initial deformation of these rocks prior to this time. Rocks were buried and a bedding parallel cleavage developed under greenschist to lower amphibolite metamorphic conditions. Lowermost units were buried to depths greater than 20 km, if normal geothermal gradient conditions are assumed, creating conditions under which peak metamorphic mineral assemblages formed, statically overprinting earlier foliation. Continued deformation led to mylonitization of units Dcq, Pba, and Pcs near Silver Star Mountain, in a top-to-the-east direction, under sillimanite-grade metamorphic conditions. Continued east-west shortening led to the development of map- and outcrop-scale west-verging folds, under greenschist to lower amphibolite grade metamorphic conditions. These structures were subsequently folded during north-south shortening that created broad, south-verging, map-scale folds. Unit Jgtd intruded and crystallized around 145 Ma, possibly after north-south shortening began, but prior to the end of deformation.

Extension and volcanism during the Eocene are attested to by the presence of breccia and conglomerate graben fill along the Coldstream Valley, porphyry dykes (Esp) cutting older rock units in the area, volcanic rocks (Evvs), and normal faulting. Eocene units are capped by Miocene basalts (Mab) near Lavington that are the most recent evidence of volcanic activity in the study area. Mab is interpreted to have erupted in a back-arc setting, related to subduction of the Farallon plate (now Juan de Fuca plate) beneath the North American plate (Souther 1991).

North American Ties

The Quesnel "terrane" has been interpreted as an intra-oceanic arc that developed off the coast of North America, over an east-dipping subduction zone, and in places on top of Ordovician to early Triassic basement of oceanic and island arc affinity (Mortimer

1987). This is supported by geochemical and Nd isotope studies on Nicola Group volcanic rocks from this arc (Mortimer 1987; Smith et al. 1995). Paleomagnetic and biostratigraphic data from rocks of the Quesnel "terrane" have been used to suggest great distances separated this arc from the margin at this latitude as late as in mid-Cretaceous time (e.g. Carter et al. 1991; Taylor et al. 1984; Symons 1983; Irving et al. 1985; Rees et al. 1985; Symons 1985). Some of these studies suggest northward translation of up to 2400 km occurred between Cretaceous and Paleogene time. However, it should be noted that while these data can be used to suggest a more southerly origin, the paleontologic data do not require it, and the paleomagnetic data within the Quesnel "terrane" are sparse and highly variable. Most germane to this argument is that no such fault has been found in the southern Canadian Cordillera (Gabrielse 1991; Wheeler and McFeely 1991). Also in conflict with a southerly origin are geologic relationships in the Kootenay Arc region, where Upper Triassic rocks of the Quesnel "terrane" unconformably overlie rocks tied to, or derived from, North America (Klepacki 1983; Klepacki and Wheeler 1985), and where later shortening within these rocks occurred in the early Jurassic (Murphy et al. 1995). These interpretations also contradict geochemical evidence from the 200 Ma Lexington pluton in the same area, which intrudes strata of the Quesnel "terrane" and shows evidence of inheritance from Proterozoic basement (Dostal et al. 2001).

Early Jurassic detrital zircons from unit Ms of the Quesnel "terrane" in the Silver Star area show evidence of inheritance from Proterozoic crust, and are similar in age and inheritance to zircons from igneous rocks in the Kootenay Arc region, suggesting a depositional link between the two areas. Detailed studies within the Silver Star area show rocks of the Quesnel "terrane" to overlie all older rock units in the field area, except Pgn, Pmv and Pccs, which is consistent with a structural or unconformable basal contact. A mylonite zone was located beneath this contact on Silver Star Mountain and to the east in the Trinity Valley, but was not observed elsewhere in the field area. This suggests that Quesnel "terrane" strata in the Silver Star area may also sit unconformably on top of North American derived rocks. Geologic relationships describing unconformable contacts between the Quesnel "terrane" and rocks of North American origin, provenance studies on sediments within this "terrane" showing derivation from nearby old continental crust, and igneous rocks intruding this "terrane" with Proterozoic inheritance prior to the proposed obduction onto the North American margin, can be interpreted to suggest that the Quesnel "terrane" developed as a distal continental margin arc, overlapping North American strata in the east, and arc and oceanic rocks in the west.

Table 2-1: Outcrop locations and descriptions of conglomerate units possibly correlating with Mcgl

Sample	Latitude	Longitude	Description
98 JU 605	50 18 39.2	118 59 57.6	clasts vary from several cm to >20 cm diameter; in general, smaller clasts are metasandstone, larger clasts are argillite; matrix varies from silt to sand sized particles; folded
99 JU 480	50 17 14.4	119 10 30.4	silty-sand matrix; clasts are mm to cm in diameter, angular, and flattened
99 LH 20	50 19 21.8	118 58 25.4	silty matrix; matrix-supported, with sub-rounded metasandstone clasts
99 LH 26	50 19 57.1	118 58 54.5	clast-supported; slate and metasandstone clasts, few mm to 15 cm in length; slate clasts contain sand clasts
99 LH 50	50 20 26.8	118 57 53.3	matrix-supported; interlayerd with metasandstone units; clasts include metasiltstone, metasandstone, slate and argillite; most clasts < 5cm in diameter

Table 2-2: U-Pb zircon results for samples from Silver Star area, southeastern British Columbia

											Model Ages (Ma)			
Description*	Weight (µg)	U (ppm)	Th (ppm)	Pb (ppm)	Th/U	TCPb (pg)	^{206}Pb/ ^{204}Pb	^{206}Pb/ ^{238}U	^{207}Pb/ ^{235}U	^{207}Pb/ ^{206}Pb	^{206}Pb/ ^{238}U	^{207}Pb/ ^{235}U	^{207}Pb/ ^{206}Pb	%Disc
JUSSCGL														
1 z, (1) yel, br	5	195	30	6	0.15	5	344	0.03017±6	0.2057±252	0.04943±59	191.6±0.3	189.9±2.1	168.4±27.4	-14.0
2 z, (1) sub, sor, br	5	126	29	5	0.23	7	180	0.03057±9	0.2191±457	0.05197±10	194.1±0.6	201.1±3.8	284.0±45.3	32.1
3 z, (1) sr, br, os	5	136	13	27	0.09	114	31	0.03186±9	0.2735±2930	0.06226±69	202.4±5.9	238.1±23.1	607.4±100.	71.5
4 z, (1) cl, ang, bd	4	156	8	7	0.05	8	209	0.03909±9	0.3501±362	0.06496±65	247.2±0.5	304.8±2.7	772.9±21.1	69.3
5 z, (1) cl, bd, os, fe	4	198	43	6	0.22	3	411	0.02896±5	0.2021±289	0.05063±70	184.0±0.3	186.9±2.4	224.1±31.6	18.1
00JU-01														
1 z, (48) sl, eu, cl, sm	167	643	190	15	0.30	11	14371	0.02311±6	0.1567±39	0.04918±2	147.3±0.4	147.8±0.3	156.3±0.9	5.8
2 z, (9) lg, min incl, eu to ceu, sp	172	663	171	15	0.26	63	2672	0.02339±1	0.1593±78	0.04940±4	149.1±0.7	150.1±0.7	167.0±1.7	10.9
3 z, (1) lg, min incl, br, eu	69	367	123	9	0.34	20	1844	0.02348±3	0.1599±27	0.04939±5	149.6±0.2	151.6±0.2	166.2±2.5	10.1
00JU-02														
1 z, (16) lg, sub	71	392	48	14	0.12	17	3854	0.03793±5	0.2739±42	0.05237±3	240.0±0.3	245.8±0.3	301.6±1.4	20.8
2 z, (96) sm, eu, most nc, some f	76	307	38	14	0.13	26	2388	0.04279±7	0.3818±68	0.06472±4	270.1±0.4	328.4±0.5	765.2±1.3	66.0

Notes: *(number of zircons in fraction), sl=slender, eu=euhedral, cl=clear, spg=some partial grains, ceu=close to euhedral, br=broken, lg=large, sub=subhedral, sm=small, nc=colorless, fi=fluid inclusions, bd=black dust, sr=sub-rounded, br=brown, os= orange stains, yel=yellow, so=slightly orange, ang=angular, pg=partial grain, fe=fractured edges; see Plate U-Pb for photos. All errors reported to 1 sigma. TCPb = total common lead in the analysis. Th concentration is estimated from the amount of ^{208}Pb and ^{207}Pb/^{206}Pb age, with correction for Pb-loss in discordant fractions. All atomic ratios were corrected for fractionation and initial common Pb (Stacey and Kramers 1975).

Table 2-3. Sm-Nd results for samples from the Silver Star area, British Columbia

Sample	Rock Type	Age (Ma)	Latitude (N)	Longitude	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$*	εNd_0	εNd_T	T_{DM} (Ga)
98JU-162	C-rich metasiltstone	300	50 32 34.0	119 25 15.5	4.05	19.98	0.1225	0.51221 ± 11	-8.4	-5.5	1.59
98JU-532	Augite porhphyry	220	50 21 40.2	119 04 50.7	2.97	13.31	0.1351	0.512760 ± 7	2.4	4.1	0.78
98JU-606	Biotite porphyry	50	50 19 17.5	119 00 49.8	7.79	36.99	0.1274	0.512431 ± 7	-4.0	-3.6	1.29
98JU-513	Biotite porphyry	50	50 22 15.0	119 03 38.2	5.54	26.12	0.1282	0.512327 ± 6	-6.1	-5.6	1.49
98JU-568	Plagioclase porphyry	50	50 21 40.5	119 04 33.8	4.29	18.27	0.1420	0.512762 ± 7	2.4	2.8	0.85
00-JU-01	Granite	145	50 15 07.4	119 12 34.5	4.72	26.91	0.1060	0.512438 ± 7	-3.9	-2.2	1.03
00-JU-02	Muscovite tonalite	300	50 21 26.3	119 06 26.8	0.13	0.62	0.1255	0.511803 ± 20	-16.3	-13.6	2.34

Notes: Upper Triassic sedimentary strata, from the Silver Star area and located on Figure 2-1, are detailed in Chapter 3. * ± 2 SD.

$\varepsilon Nd = [(^{143}Nd/^{144}Nd)_{Sample(}{}^{143}Nd/^{144}Nd_{CHUR})-1]*10^4$(DePaolo and Wasserburg, 1976), values used were $^{143}Nd/^{144}Nd_{CHUR,today}$ = 0.512638 (Goldstein 1984) and $^{147}Sm/^{144}Nd_{CHUR,today}$ = 0.1966 (Jacobson and Wasserburg 1980). T_{DM} based on model of Goldstein (1984)

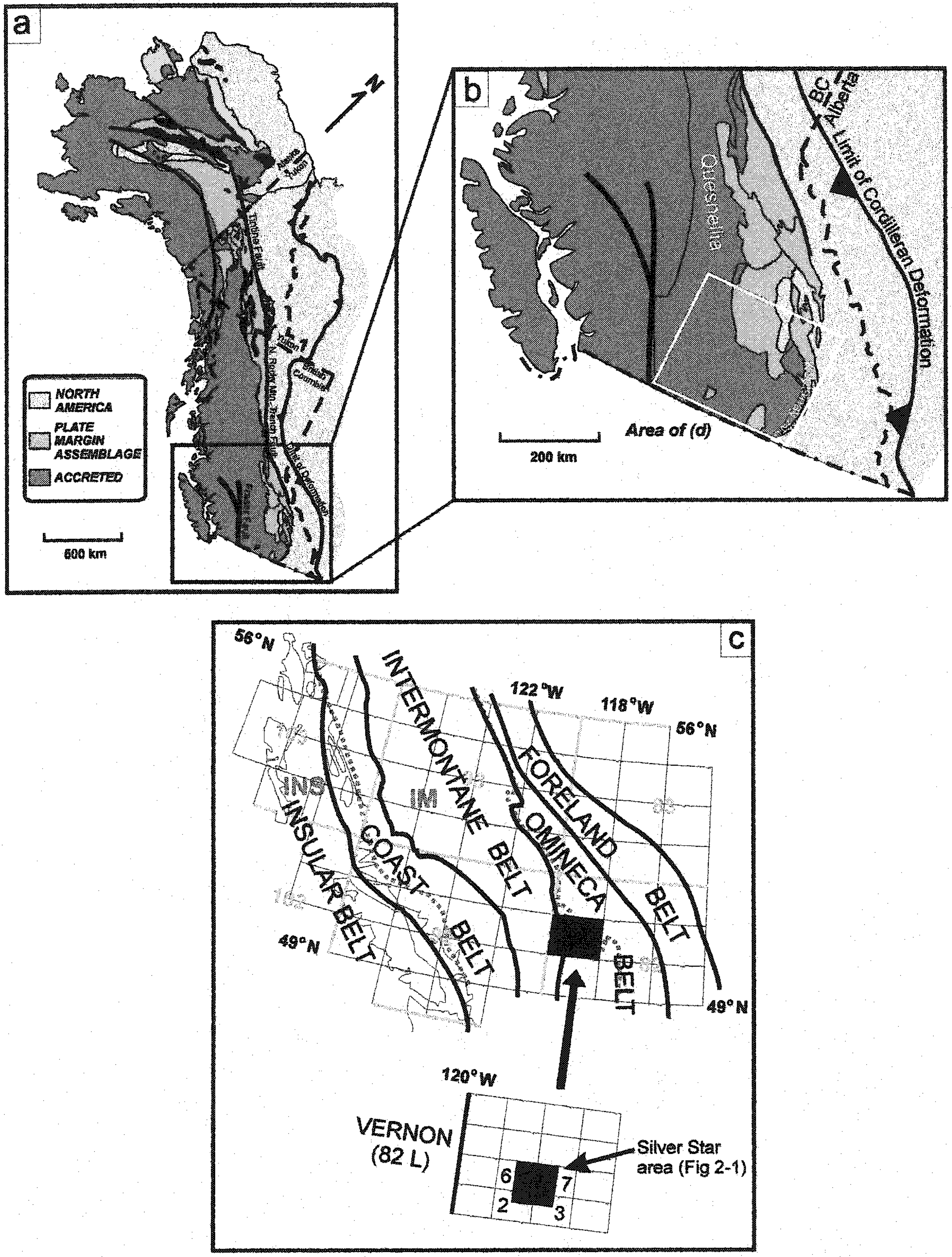
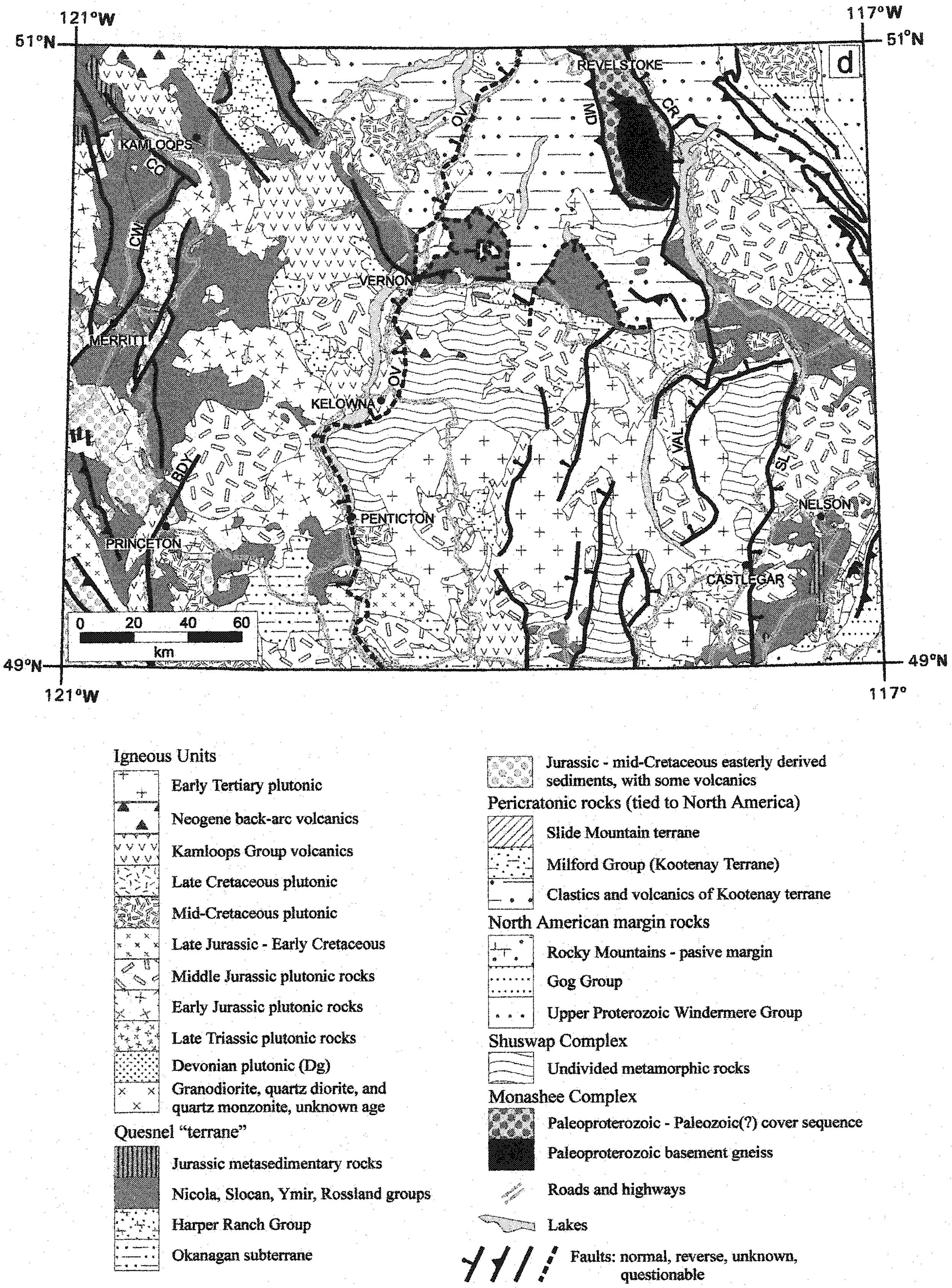


Figure 2-2: Regional geology of British Columbia. Maps showing (a) Canadian and Alaskan Cordillera, differentiating rocks presently interpreted to be of North American, plate margin assemblage, and accreted origin; (b) outline of Quesnel terrane, location of the Kootenay Arc, and outline of area in figure d; (c) geomorphological belts in black, superterrane boundaries in dotted grey: Intermontane (IM), Insular (INS), Vernon map area (82L), and the Silver Star area (Fig. 2-1), modified after Gabrielse et al 1991; (d) simplified tectonic assemblage assemblage map. Faults denoted are Cherry Creek (CC),Coldwater (CW),Boundary (BDY), Eagle River-Okanagan Valley (OV), Monashee Decollement (MD), Columbia River (CR), Valkyr (VAL),and Slocan Lake (SL). a, b and c simplified from Wheeler and McFeely (1991).


121°W
117°W
51°N
51°N
d
REVELSTOKE
MD
CR
OV
KAMLOOPS
CC
CW
VERNON
MERRITT
KELOWNA
OV
BDY
VAL
SL
NELSON
PENTICTON
PRINCETON
CASTLEGAR
0
20
40
60
km
49°N
49°N
121°W
117°
Igneous Units
Early Tertiary plutonic
Neogene back-arc volcanics
Kamloops Group volcanics
Late Cretaceous plutonic
Mid-Cretaceous plutonic
Late Jurassic - Early Cretaceous
Middle Jurassic plutonic rocks
Early Jurassic plutonic rocks
Late Triassic plutonic rocks
Devonian plutonic (Dg)
Granodiorite, quartz diorite, and quartz monzonite, unknown age
Quesnel "terrane"
Jurassic metasedimentary rocks
Nicola, Slocan, Ymir, Rossland groups
Harper Ranch Group
Okanagan subterrane
Jurassic - mid-Cretaceous easterly derived sediments, with some volcanics
Pericratonic rocks (tied to North America)
Slide Mountain terrane
Milford Group (Kootenay Terrane)
Clastics and volcanics of Kootenay terrane
North American margin rocks
Rocky Mountains - pasive margin
Gog Group
Upper Proterozoic Windermere Group
Shuswap Complex
Undivided metamorphic rocks
Monashee Complex
Paleoproterozoic - Paleozoic(?) cover sequence
Paleoproterozoic basement gneiss
Roads and highways
Lakes
Faults: normal, reverse, unknown, questionable

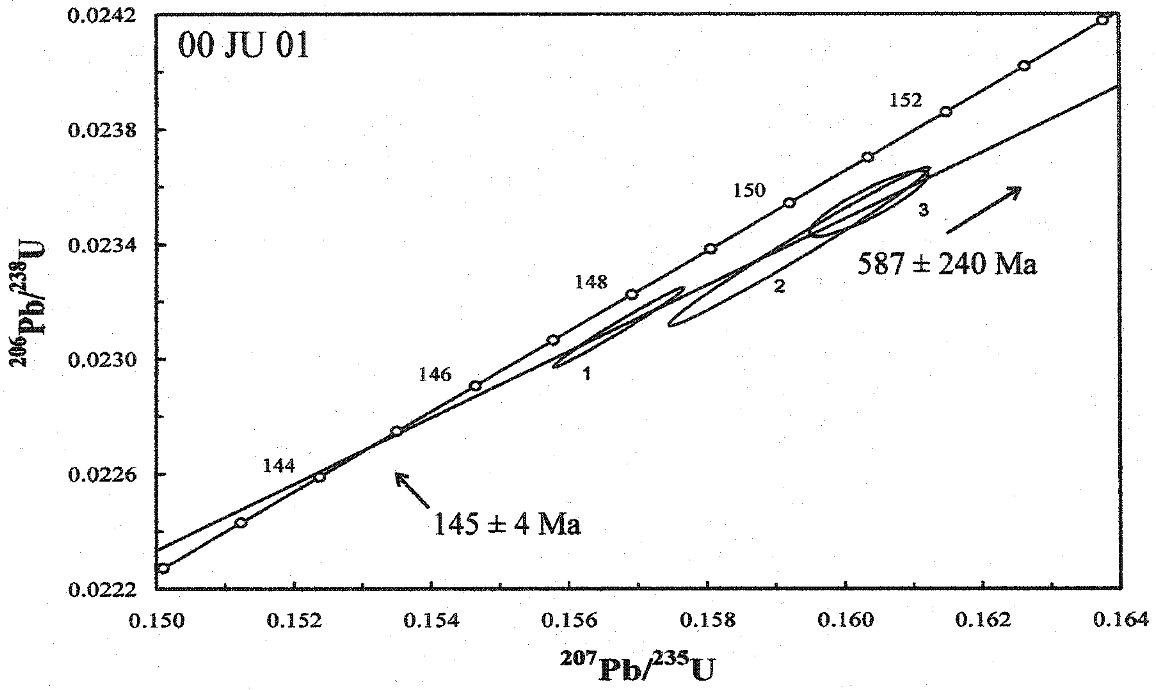
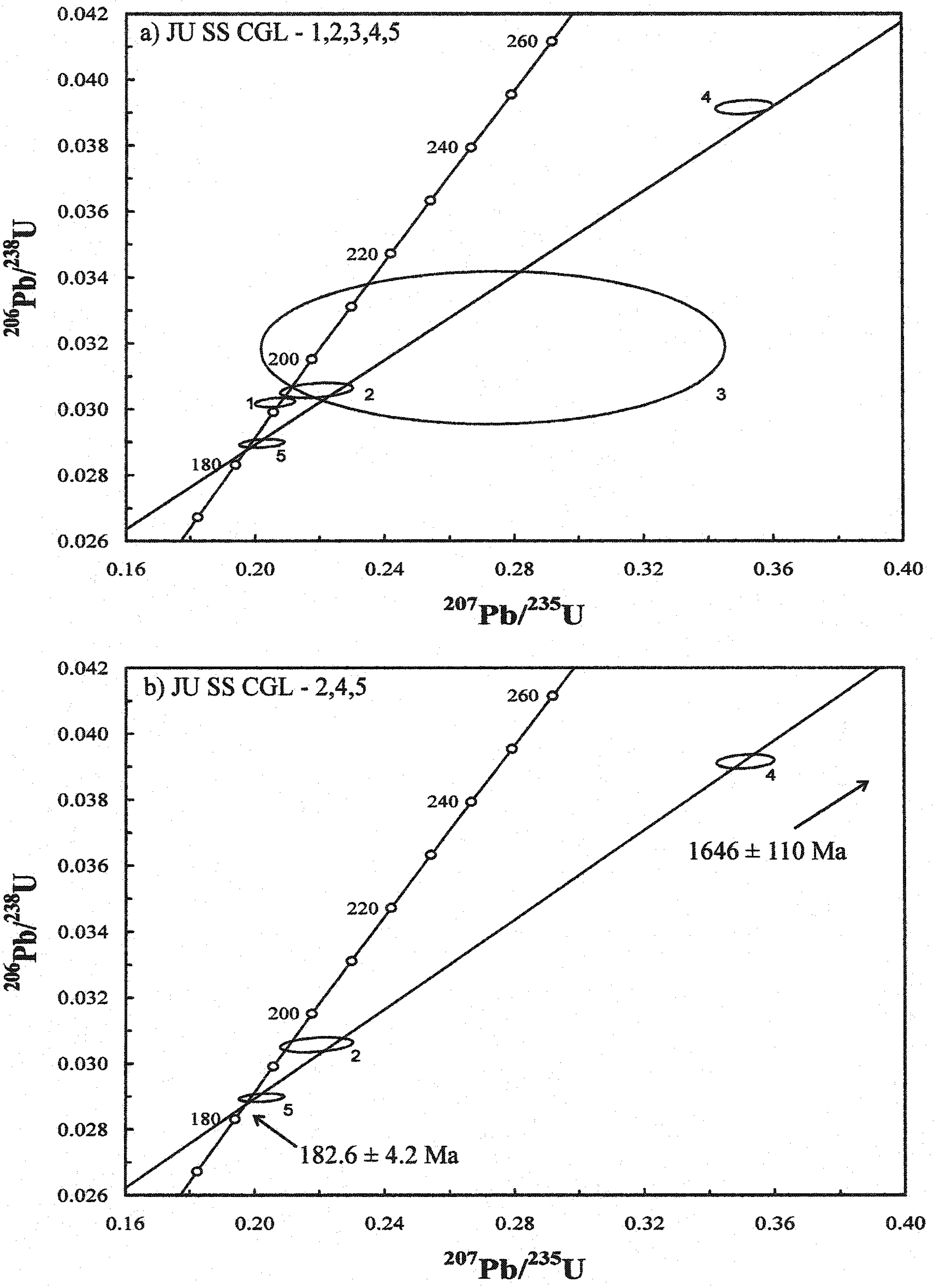


Figure 2-3: U-Pb concordia plot of zircons from 00 JU 01, the Vernon Hill granite. Error ellipses represent 2σ uncertainty. MSWD is 0.89.


a) JU SS CGL - 1,2,3,4,5
0.042
0.040
0.038
0.036
0.034
0.032
0.030
0.028
0.026
$^{206}Pb/^{238}U$
0.16
0.20
0.24
0.28
0.32
0.36
0.40
$^{207}Pb/^{235}U$
260
240
220
200
180
1
2
3
4
5
b) JU SS CGL - 2,4,5
0.042
0.040
0.038
0.036
0.034
0.032
0.030
0.028
0.026
$^{206}Pb/^{238}U$
0.16
0.20
0.24
0.28
0.32
0.36
0.40
$^{207}Pb/^{235}U$
260
240
220
200
180
2
4
5
1646 ± 110 Ma
182.6 ± 4.2 Ma

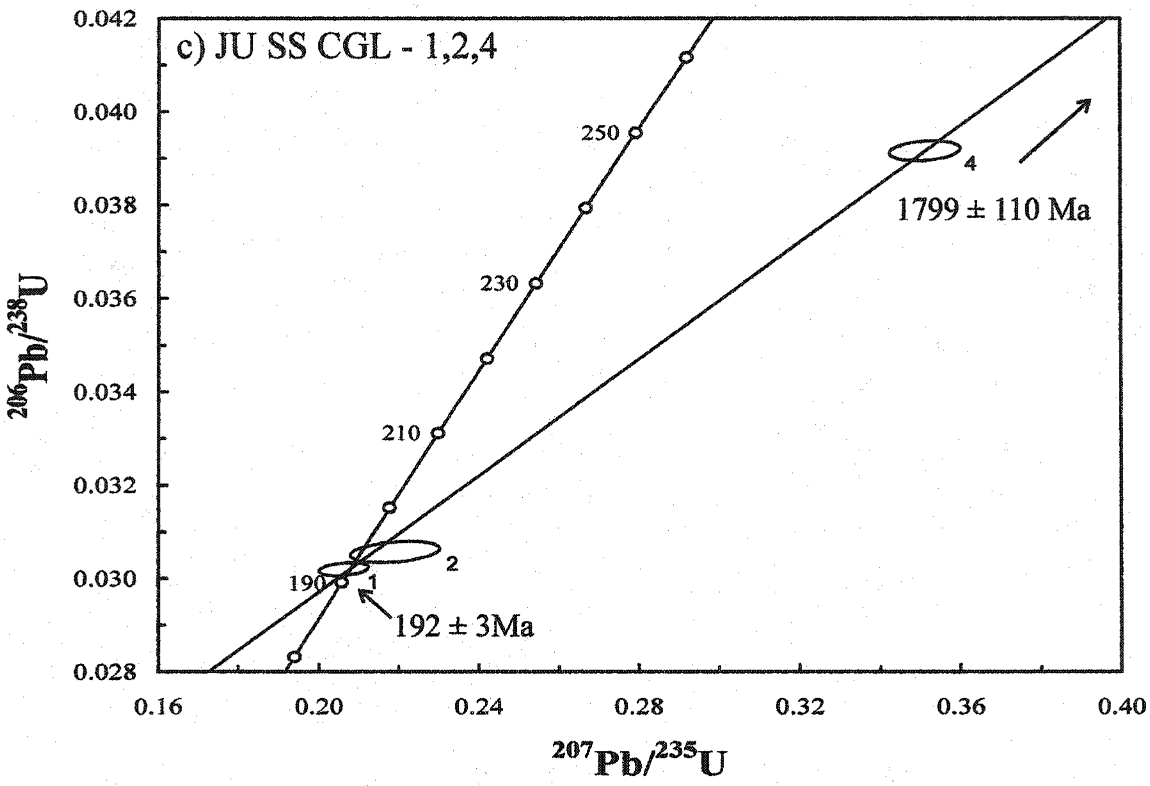


Figure 2-4: U-Pb concordia plots of zircons from JU SS CGL, conglomerate unit Mcgl (see Fig. 2-1). Plots show (a) all fractions, MSWD = 6.0 (b) fractions 2, 4, and 5, MSWD = 1.8, and (c)1, 2, and 4, MSWD = 1.9. Error ellipses represent 2σ uncertainty.

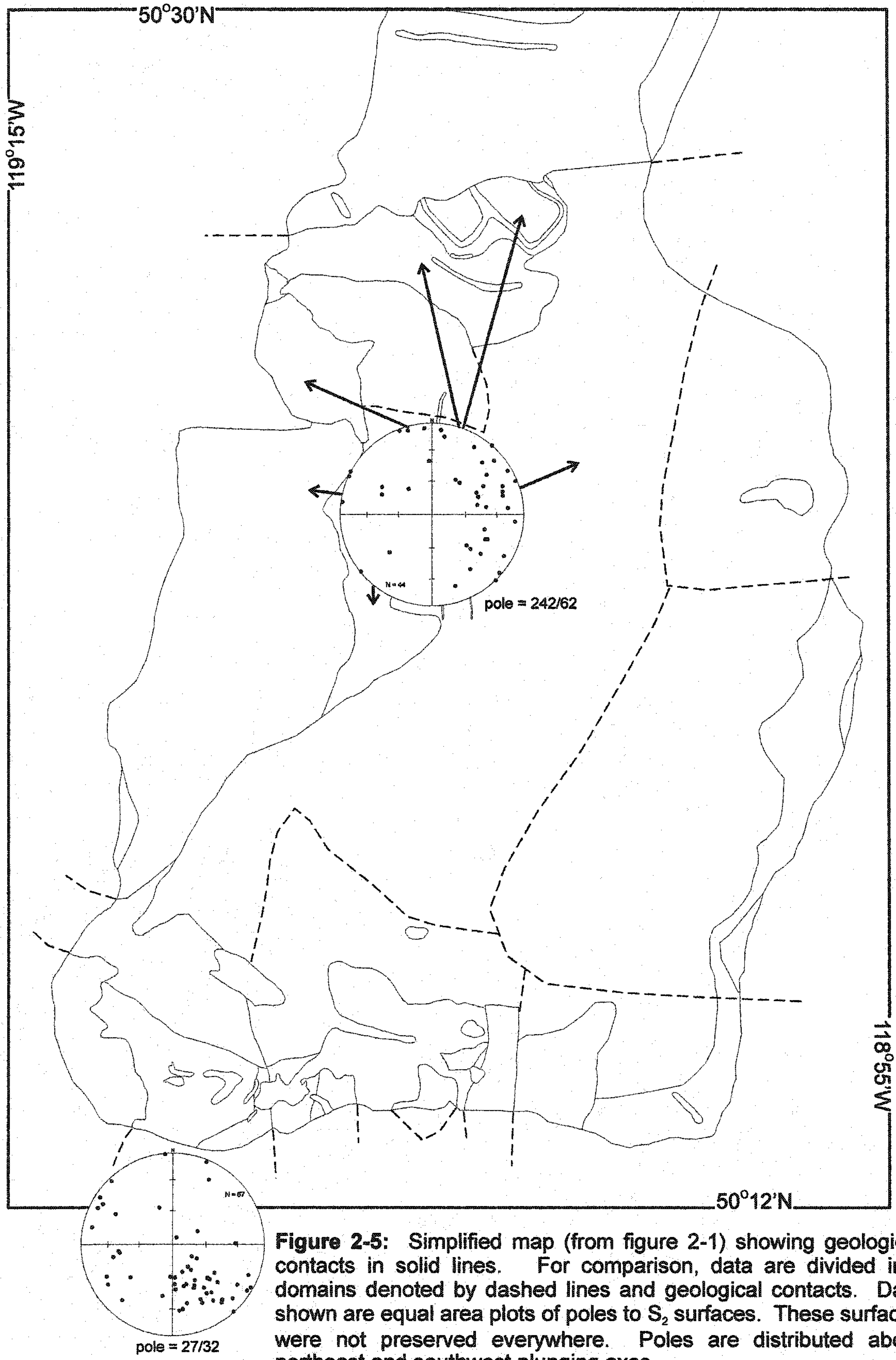


Figure 2-5: Simplified map (from figure 2-1) showing geological contacts in solid lines. For comparison, data are divided into domains denoted by dashed lines and geological contacts. Data shown are equal area plots of poles to S_2 surfaces. These surfaces were not preserved everywhere. Poles are distributed about northeast and southwest plunging axes.

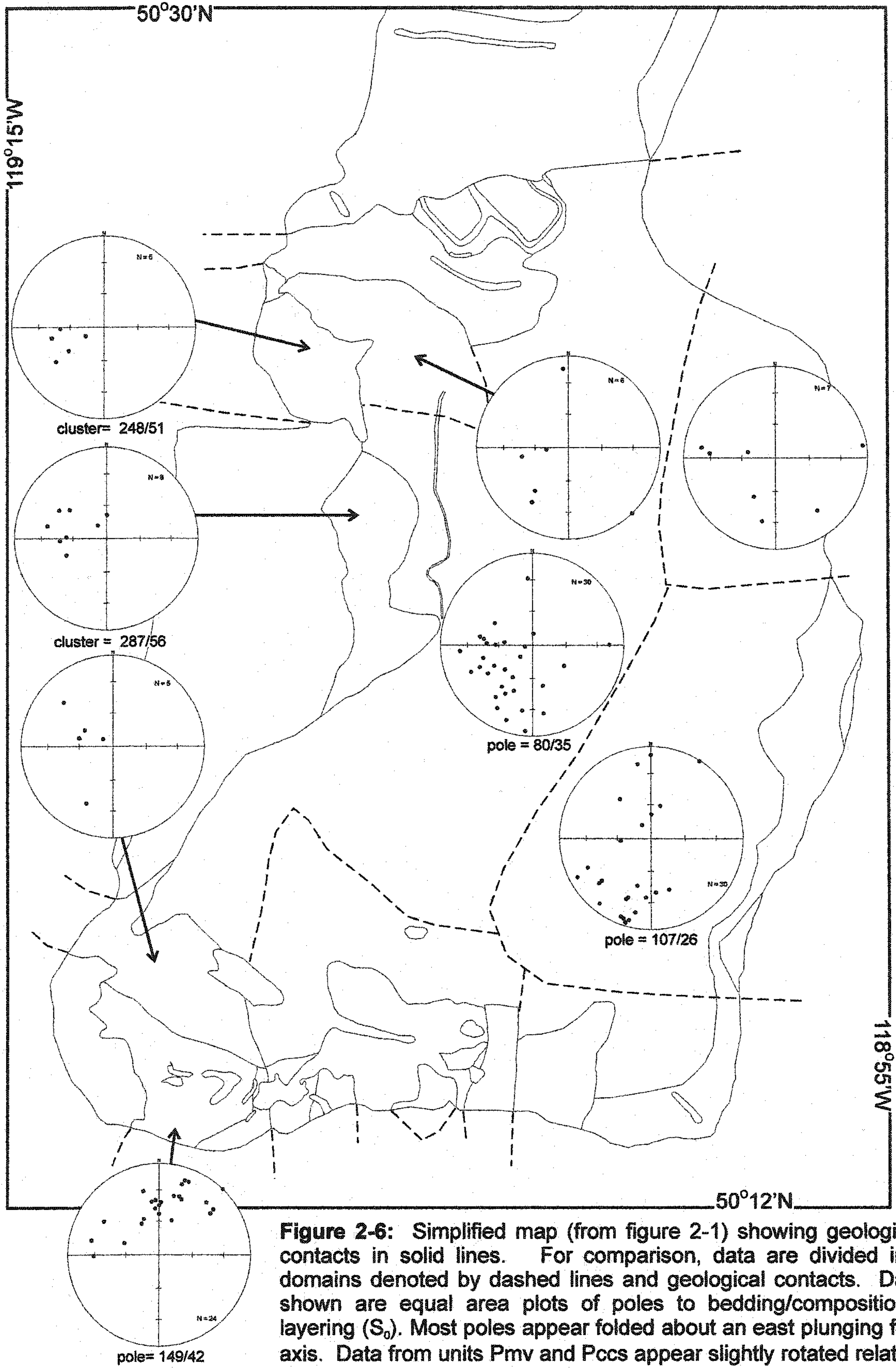


Figure 2-6: Simplified map (from figure 2-1) showing geological contacts in solid lines. For comparison, data are divided into domains denoted by dashed lines and geological contacts. Data shown are equal area plots of poles to bedding/compositional layering (S_0). Most poles appear folded about an east plunging fold axis. Data from units Pmv and Pccs appear slightly rotated relative to this, and are folded about a southeast plunging axis.

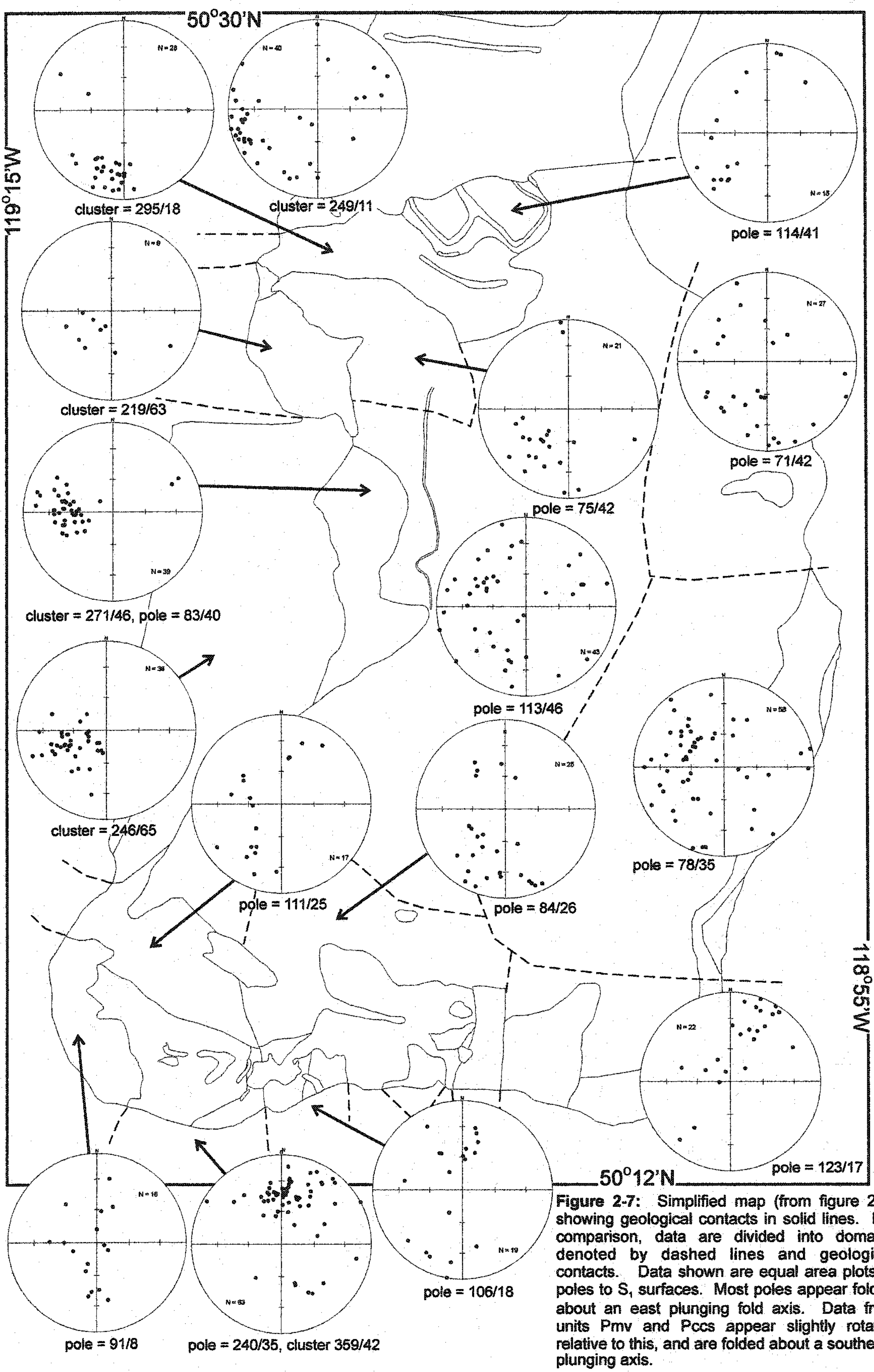


Figure 2-7: Simplified map (from figure 2-1) showing geological contacts in solid lines. For comparison, data are divided into domains denoted by dashed lines and geological contacts. Data shown are equal area plots of poles to S_1 surfaces. Most poles appear folded about an east plunging fold axis. Data from units Pmv and Pccs appear slightly rotated relative to this, and are folded about a southeast plunging axis.

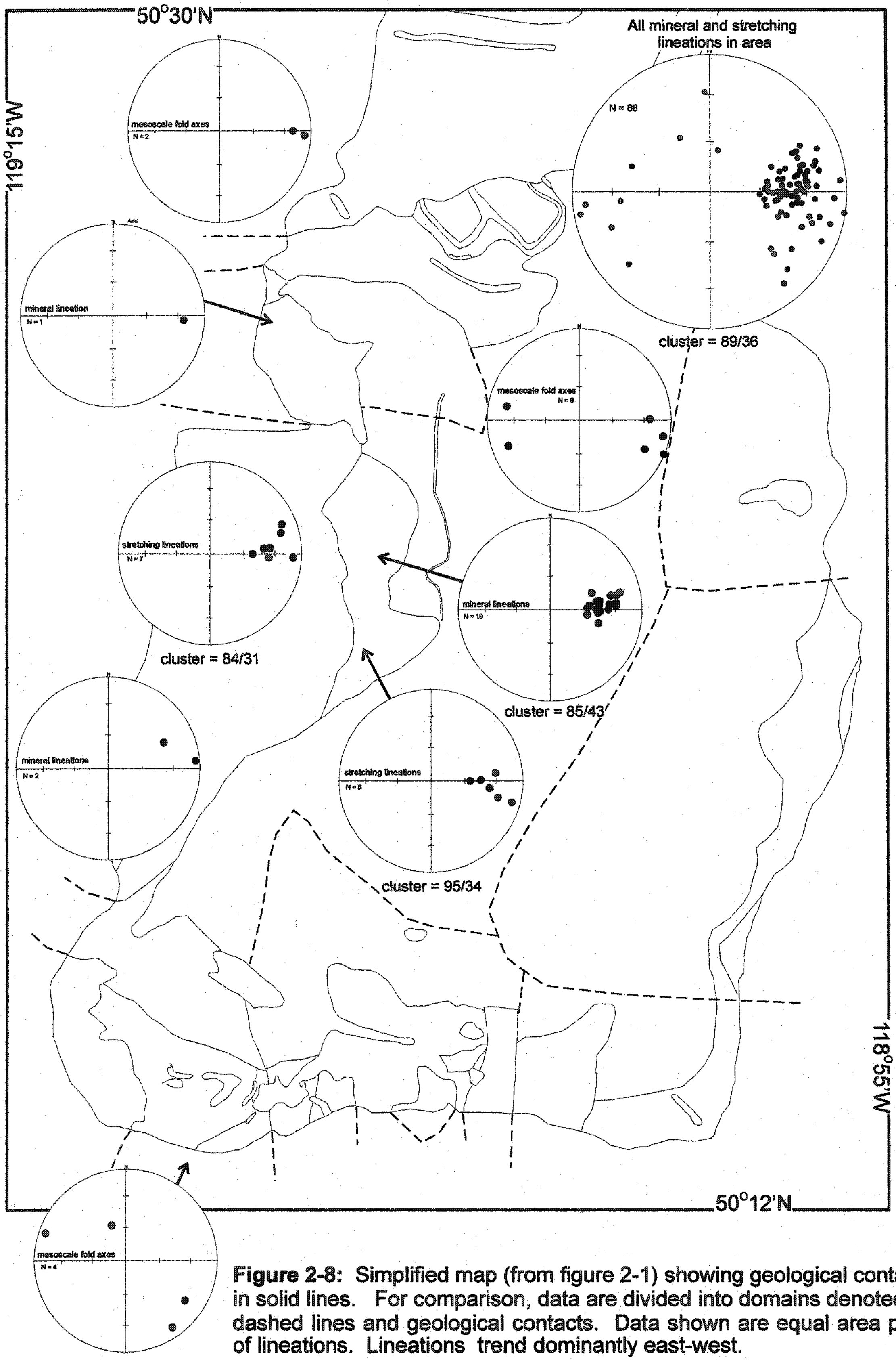


Figure 2-8: Simplified map (from figure 2-1) showing geological contacts in solid lines. For comparison, data are divided into domains denoted by dashed lines and geological contacts. Data shown are equal area plots of lineations. Lineations trend dominantly east-west.

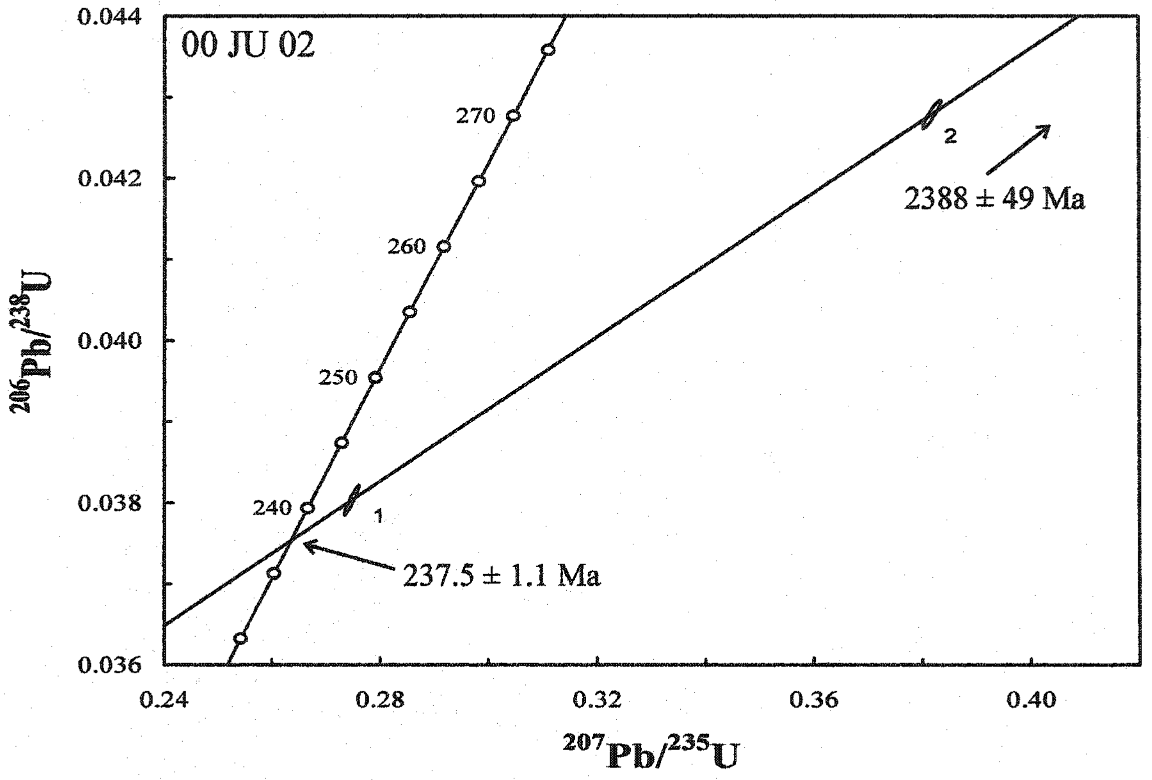


Figure 2-9: U-Pb concordia plot of zircons from 00 JU 02, the Silver Star tonalite. Error ellipses represent 2σ uncertainty.

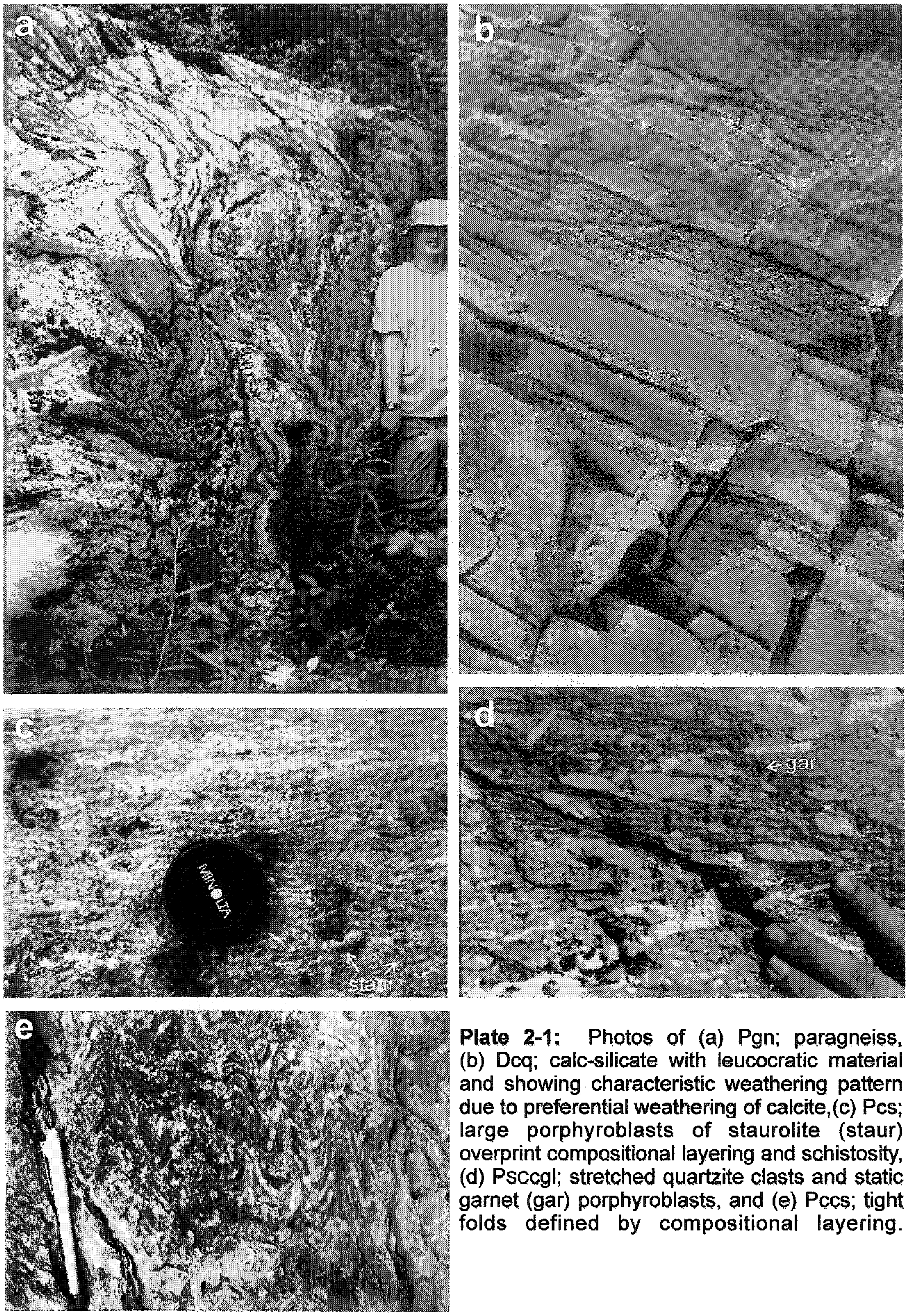


Plate 2-1: Photos of (a) Pgn; paragneiss, (b) Dcq; calc-silicate with leucocratic material and showing characteristic weathering pattern due to preferential weathering of calcite,(c) Pcs; large porphyroblasts of staurolite (staur) overprint compositional layering and schistosity, (d) Psccgl; stretched quartzite clasts and static garnet (gar) porphyroblasts, and (e) Pccs; tight folds defined by compositional layering.

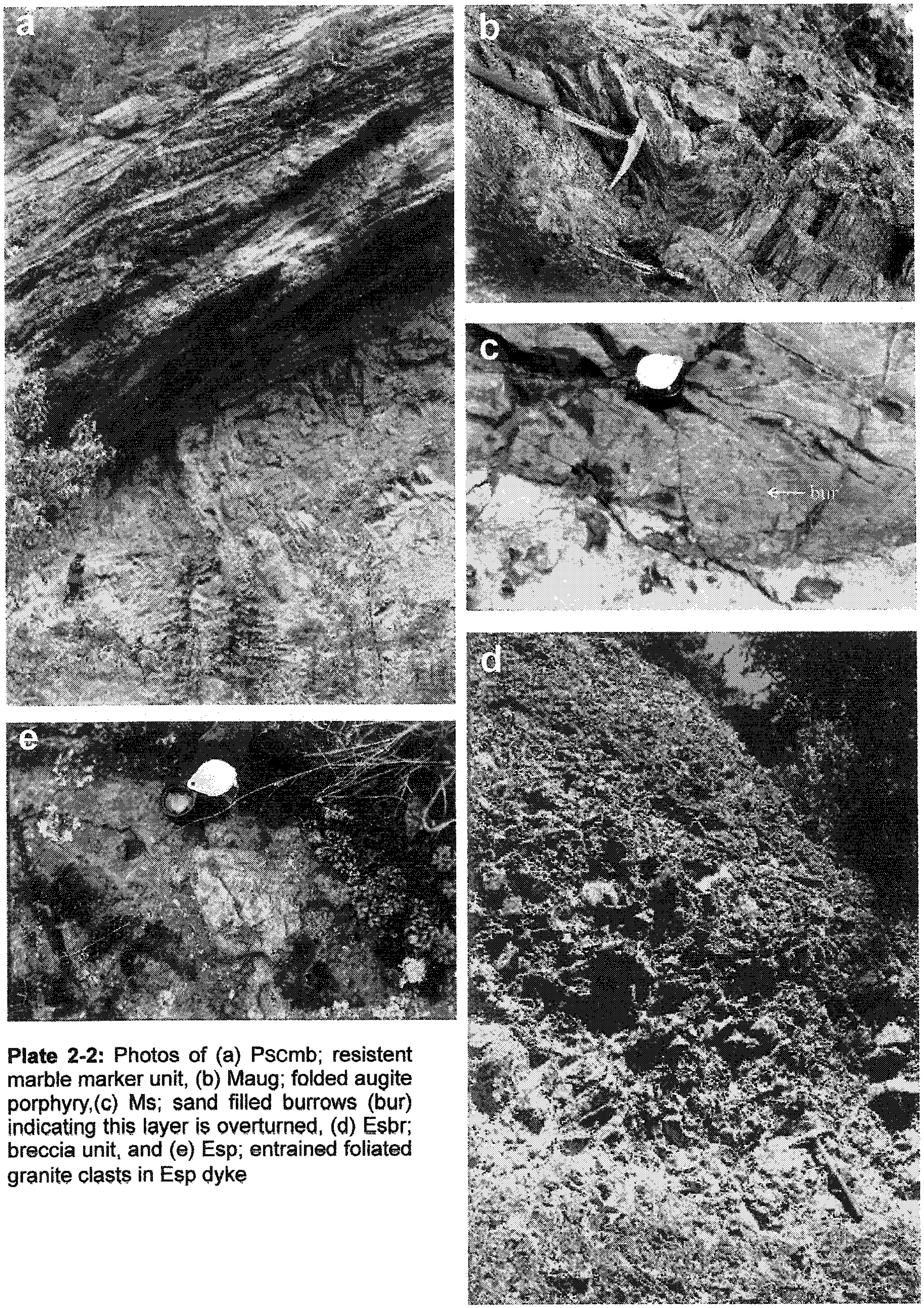


Plate 2-2: Photos of (a) Pscmb; resistent marble marker unit, (b) Maug; folded augite porphyry,(c) Ms; sand filled burrows (bur) indicating this layer is overturned, (d) Esbr; breccia unit, and (e) Esp; entrained foliated granite clasts in Esp dyke

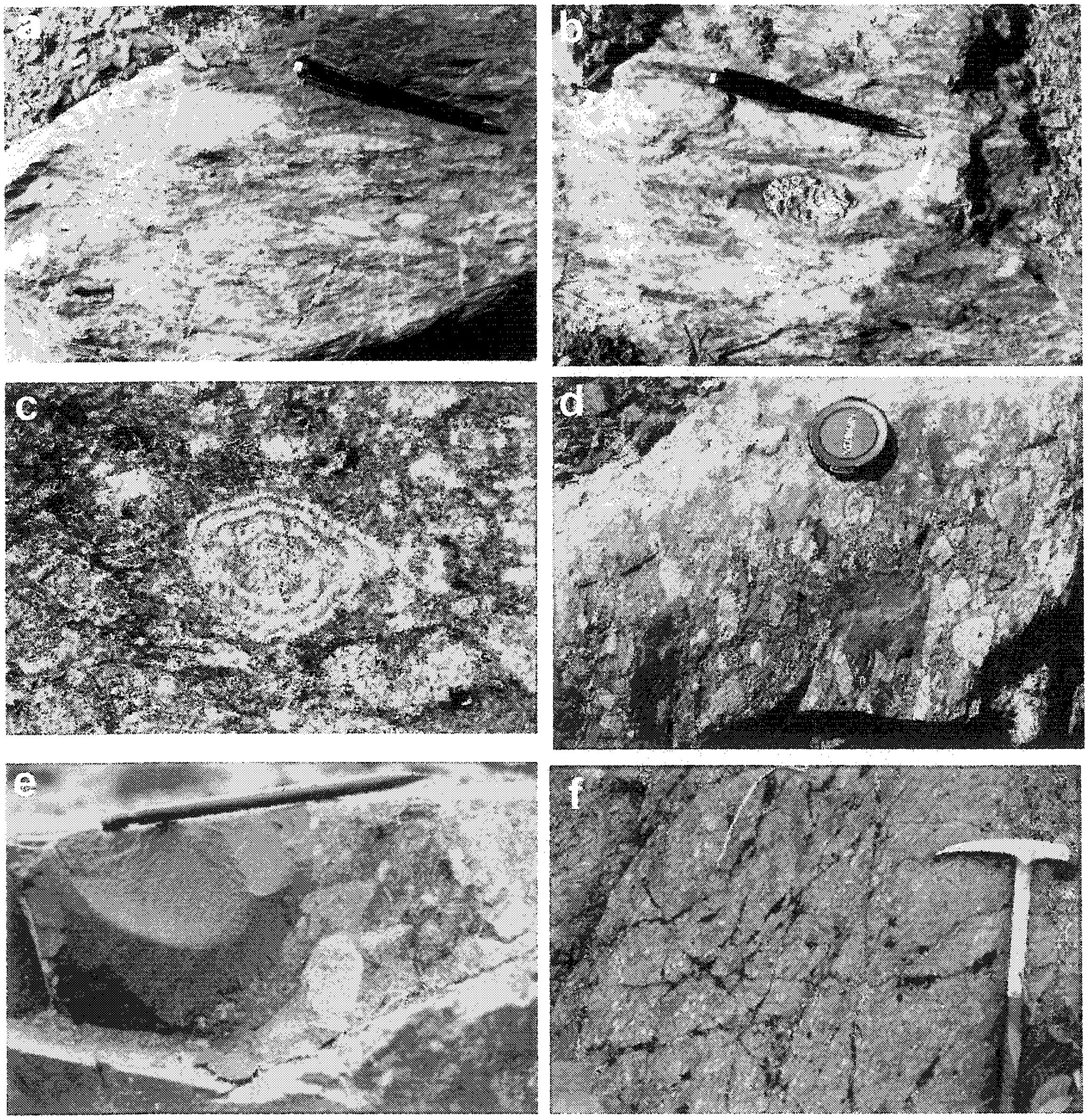


Plate 2-3: Photos of (a) Mcgl: JU SS CGL; clasts define a plane of flattening, (b) Mcgl: JU SS CGL; one granitoid cobble was observed at this locality, (c) Mcgl: JU SS CGL; photomicrograph of fusulinid within limestone clast (field of view = 3.2 mm), (d) Mcgl?: 99 LH 26; slate to metasandstone clasts, some slate clasts contain sandstone clasts, (e) Mcgl?: 99 LH 26; close-up photo showing contact with argillite, (f) Mcgl?: 99 LH 50; matrix supported conglomerate

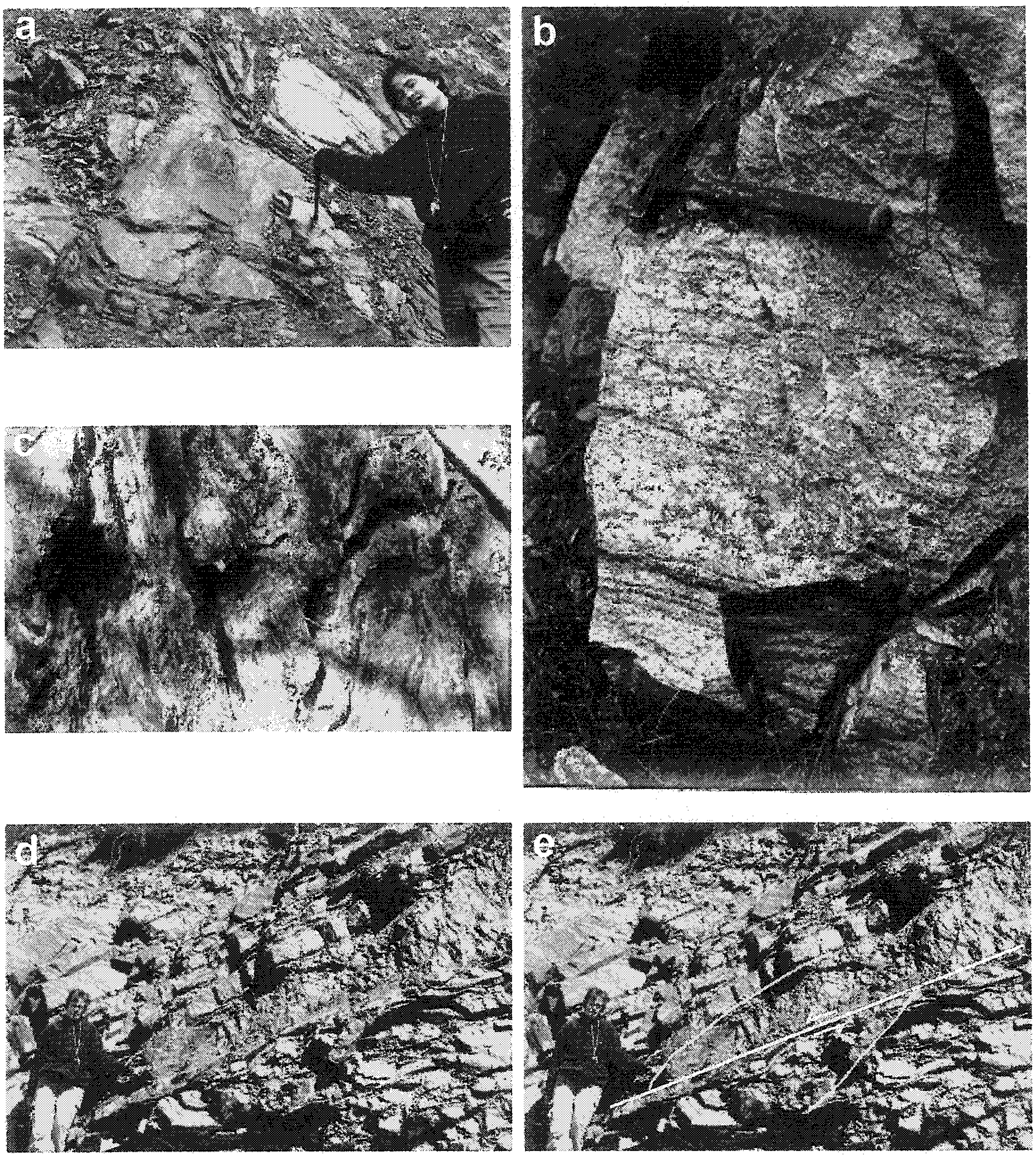


Plate 2-4: Photos of (a) Ms; two phases of folding, (b) Pba; mylonite, largely granitic and pegmatitic material with some schist, (c) Pccs; folding of layering, and near layer parallel cleavage,(d and e) Pmv; offset quartz vein along a normal fault, the base of the quartz vein is traced in yellow and the fault is traced in white

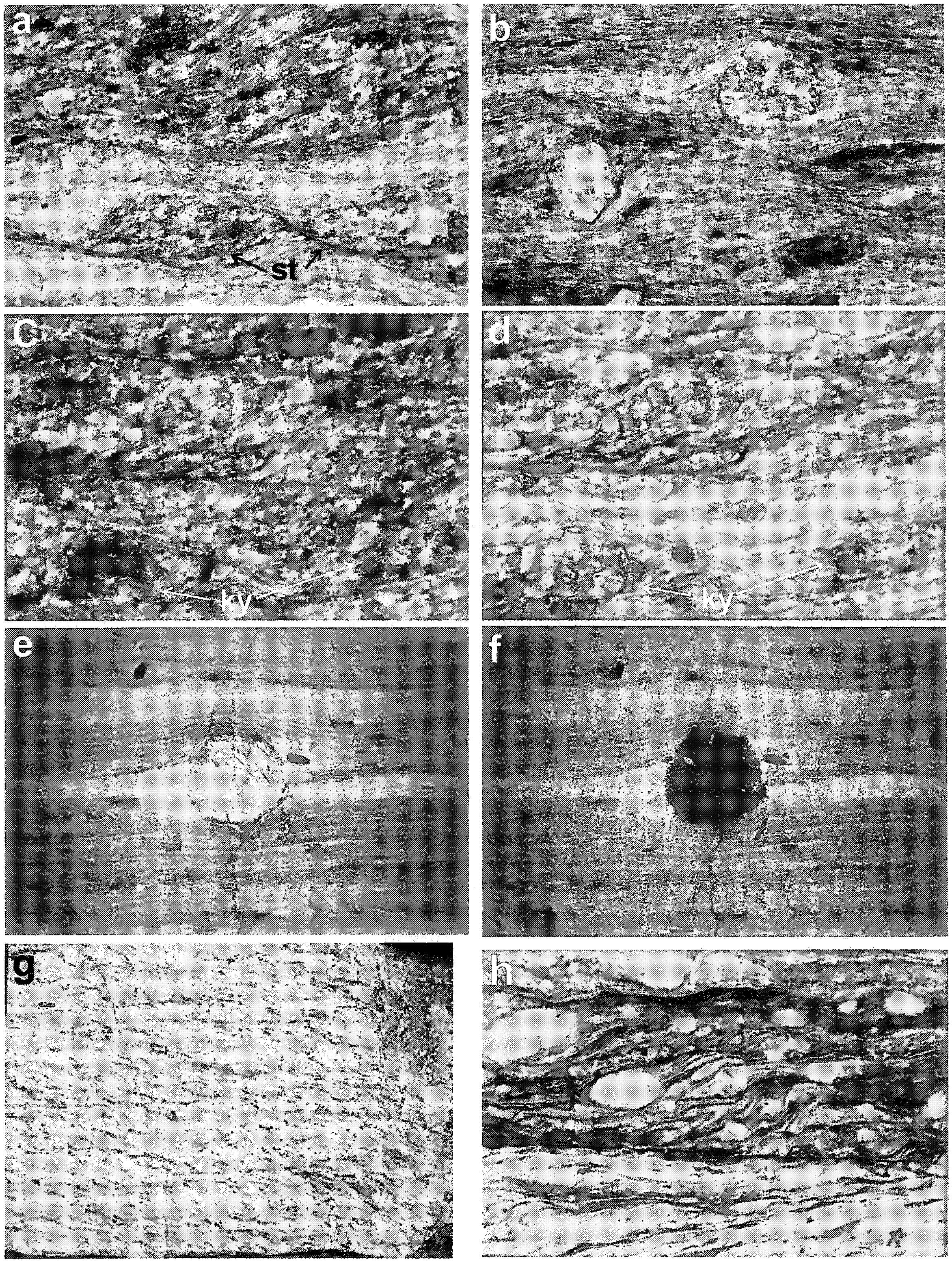


Plate 2-5: (a-f) Photomicrographs of oriented samples, looking north; (a) S. Lake; C, S, and C` surfaces indicating a top to the east sense of shear. Staurolite (st) porphyroblast is offset along C' surface. (b) 98 JU 290; δ-morphology garnet, indicating a top to the east sense of shear, (c) S. Lake; looking north, cross-polarized light, C, S, and C`surfaces indicating a top to the east sense of shear. Kyanite (ky) porphyroblast is offset along C` surface. (d) view of (c) under plane-polarized light, (e and f) 99 JU196A; looking north, plane- and cross-polarized light views of garnet porphyroblast, with quartz-rich layer suggesting top to the east sense of shear. (g) 98 JU 309: looking north well developed c-s fabric in a granite indicating top to the west sense of shear, (h) photomicrograph of Pba (unoriented) showing well developed ductile shear fabric. Fields of view are 3.2mm for a, b, c, d and f, 12.8 mm for e and f, and true scale for g.

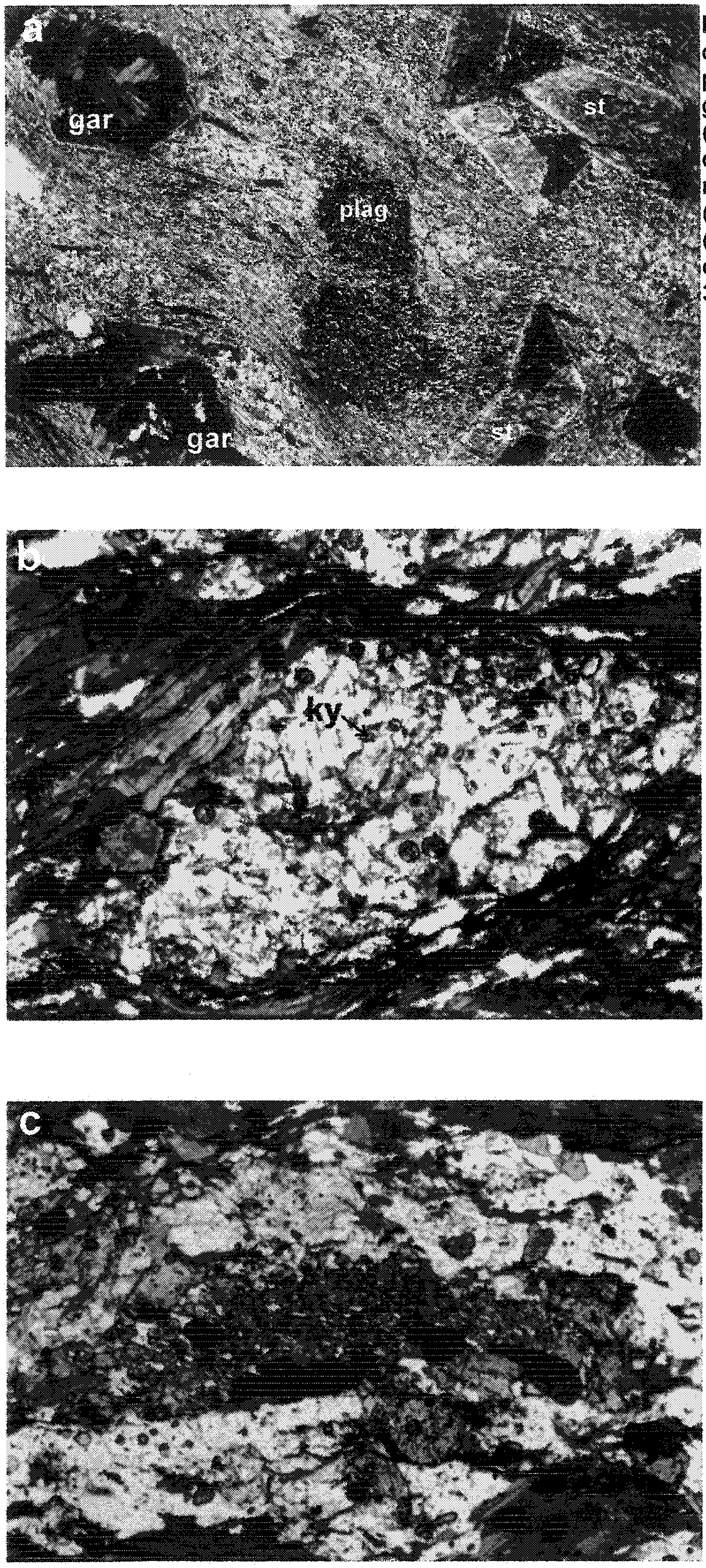


Plate 2-6: Photomicrographs of (a) Pcs; metamorphic porphyroblasts of staurolite (st) garnet (gar), and plagioclase (plag) overprint regional fabric defined by biotite and muscovite, cross-polarized view (b) Pba; relict kyanite (ky), and (c) Pba; relict staurolite. Fields of view are 12.8 mm for a and 3.2 mm for b and c.

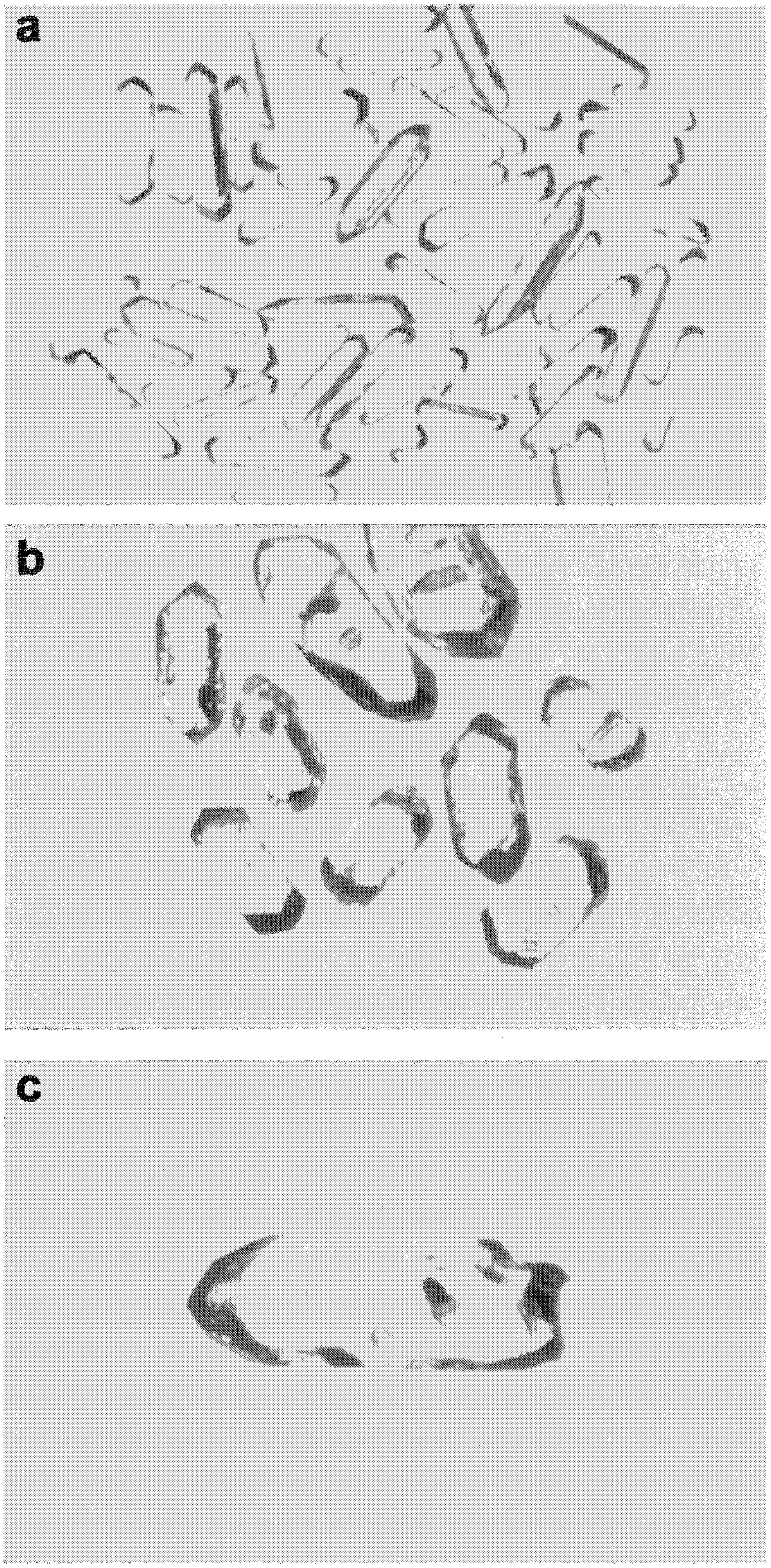


Plate 2-7: Photos of zircons from sample 00 JU 01. (a) fraction 1, n = 48, (b) fraction 2, n = 9, (c) fraction 3, single grain. Fields of view are 1.8 mm, 1.38 mm, and 1.1 mm respectively.

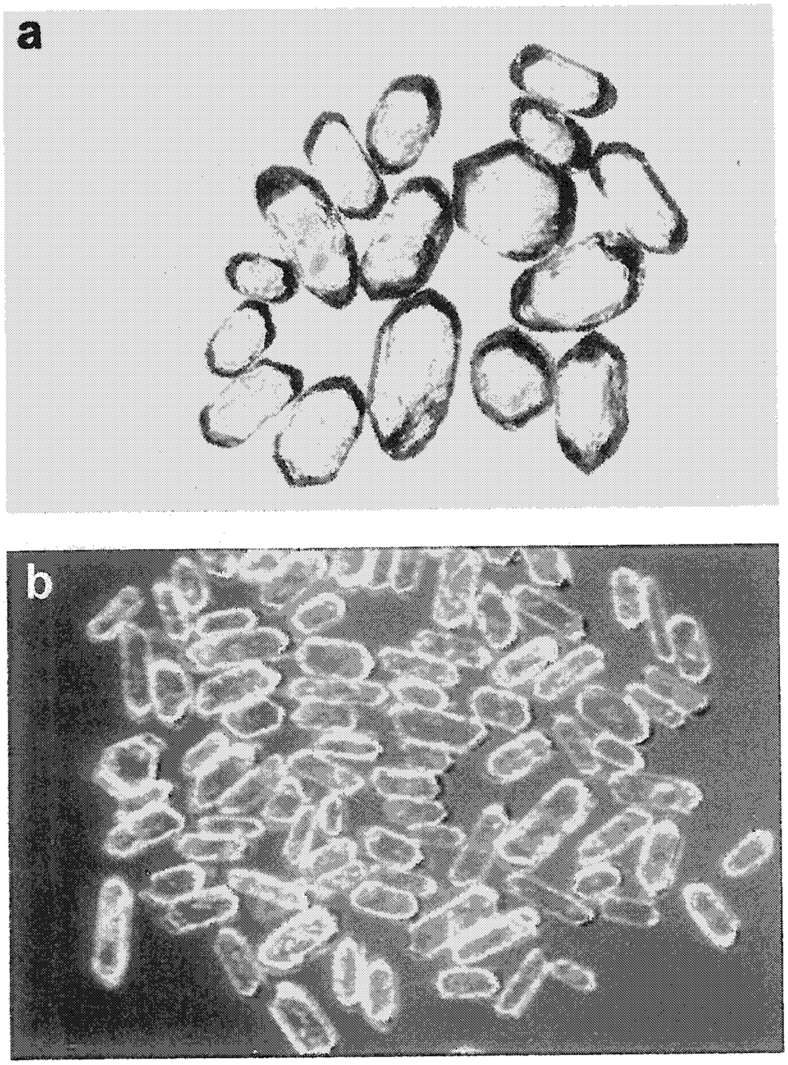


Plate 2-8: Photos of zircons from sample 00 JU 02. (a) fraction 1, n = 16, (b) fraction 2, n = 96. Field of view is 1.1 mm for (a) and (b).

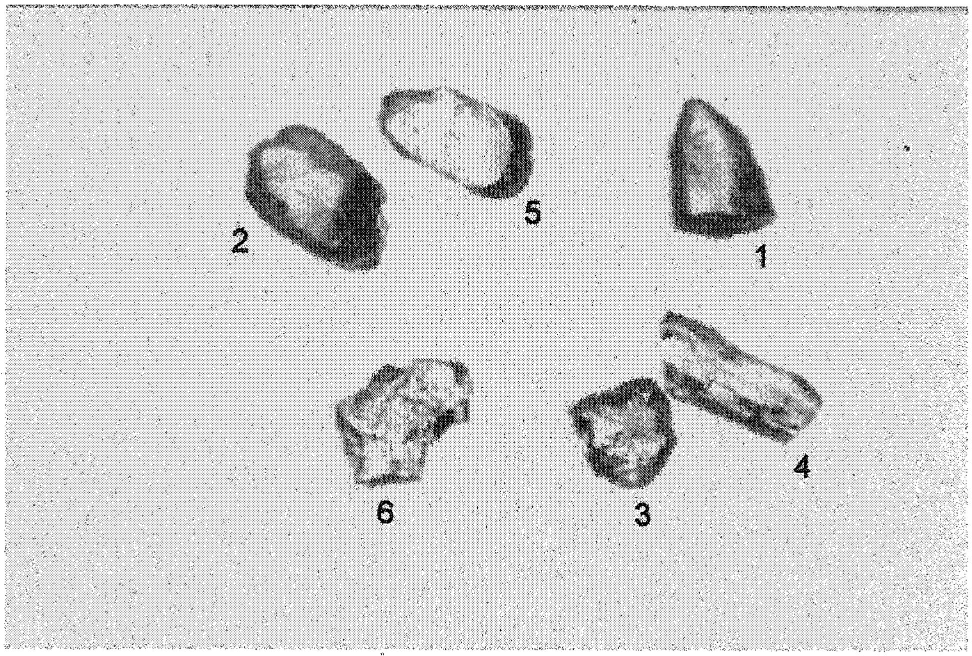


Plate 2-9: Photo of detrital zircons from unit Mcgl (JU SS CGL). Field of view is 1.1 mm. Fractions are as labelled. Zircon 6 was not analyzed.

Appendix 2-1: Station Locations

Station	**UTM**		**Station**	**UTM**	
	Easting	Northing		Easting	Northing
98JU0001	356791	5596456	98JU0049	349863	5589440
98JU0002	356107	5595508	98JU0050	349948	5589332
98JU0006b	352733	5589804	98JU0051	349824	5589363
98JU0012	348859	5588284	98JU0052	349530	5589545
98JU0014	349115	5587921	98JU0053	349479	5589035
98JU0015	351136	5596017	98JU0054	349548	5588875
98JU0016	351197	5596117	98JU0055	349681	5588352
98JU0017	351267	5596110	98JU0056	349738	5588408
98JU0018	351184	5595821	98JU0057	349910	5588463
98JU0019	351154	5595581	98JU0058	349926	5589006
98JU0020	351207	5595285	98JU0059	350010	5589015
98JU0021	351294	5594840	98JU0060	349991	5589103
98JU0022	351185	5594796	98JU0061	349921	5589223
98JU0023	351026	5594058	98JU0062	349936	5589081
98JU0024	350993	5593954	98JU0063	349581	5589236
98JU0025	351075	5593841	98JU0064	349550	5589121
98JU0025b	351297	5594116	98JU0065	348467	5590776
98JU0026	351167	5593503	98JU0066	348965	5590571
98JU0027	351071	5593203	98JU0067	348972	5590519
98JU0028	349986	5592764	98JU0068	349075	5590537
98JU0028b	349978	5592652	98JU0069	349141	5590583
98JU0029	349983	5592605	98JU0070	349285	5590608
98JU0030	349968	5592497	98JU0071	349684	5590483
98JU0031	350016	5592452	98JU0072	349810	5590444
98JU0032	350034	5592497	98JU0073	349864	5590594
98JU0032b	350155	5592563	98JU0074	349951	5590457
98JU0033	350195	5592520	98JU0075	357916	5597951
98JU0034	350251	5592482	98JU0076	357581	5597882
98JU0034b	350307	5592460	98JU0076b	356700	5596707
98JU0035	350352	5592495	98JU0077	354242	5595730
98JU0036	350389	5592522	98JU0078	354074	5593195
98JU0037	350459	5592542	98JU0079	353949	5593038
98JU0037b	350449	5592568	98JU0080	353783	5592833
98JU0037c	350585	5592545	98JU0081	354040	5592746
98JU0037d	350699	5592563	98JU0082	354184	5592659
98JU0038	350977	5595904	98JU0083	348974	5591277
98JU0039	350859	5592664	98JU0084	349200	5591389
98JU0040	350836	5592617	98JU0085	349491	5591219
98JU0041	351893	5592800	98JU0086	349885	5591052
98JU0042	351872	5592634	98JU0087	349913	5591110
98JU0043	353284	5592509	98JU0088	349975	5591022
98JU0044	353313	5592364	98JU0089	349956	5590951
98JU0045	351667	5592576	98JU0090	349961	5590907
98JU0048	348989	5589570	98JU0091	349993	5590817
98JU0092	350022	5590660	98JU0141	352687	5590317

98JU0093	350084	5590725
98JU0094	350114	5590759
98JU0095	350061	5590828
98JU0096	350073	5590937
98JU0097	350110	5590931
98JU0098	351337	5595601
98JU0099	351437	5595775
98JU0100	351464	5595682
98JU0101	351526	5595730
98JU0102	351607	5595615
98JU0103	351850	5595581
98JU0104	352067	5595584
98JU0105	352216	5595612
98JU0106	352297	5595548
98JU0107	352569	5595656
98JU0108	352675	5595604
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98JU0111	351295	5592444
98JU0112	351320	5592345
98JU0113	351451	5592364
98JU0114	351476	5592246
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98JU0116	351755	5592080
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98JU0118	352150	5592174
98JU0119	351995	5592150
98JU0120	352071	5592222
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98JU0124	349930	5591287
98JU0125	350087	5591230
98JU0126	350164	5591231
98JU0127	350353	5591171
98JU0128	350459	5591071
98JU0129	350730	5591153
98JU0130	350919	5591077
98JU0131	350974	5591027
98JU0132	351232	5591002
98JU0133	351569	5591038
98JU0134	351582	5591031
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98JU0137	350707	5591688
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98JU0193	354381	5589026

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98JU0143	351448	5589242
98JU0144	351377	5589051
98JU0145	351571	5589337
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98JU0154	353018	5593381
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98JU0157	354279	5589152
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98JU0160	347806	5589614
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98JU0170	348961	5588306
98JU0171	348998	5588297
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98JU0198	355157	5590660
98JU0199	355487	5591051
98JU0200	355379	5590876
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98JU0202	355015	5590335
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98JU0207	354849	5589286
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98JU0210	354721	5588858
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98JU0222b	352933	5590213
98JU0222c	352931	5590199
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98JU0223	353525	5591287
98JU0224	353333	5591466
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98JU0233	354687	5592033
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98JU0237	355088	5591833
98JU0238	355246	5592005
98JU0239	355283	5592154
98JU0293	350646	5582781

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98JU0242	355420	5593101
98JU0243	355255	5593252
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98JU0248	352260	5587849
98JU0249	351918	5587607
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98JU0251	351468	5587346
98JU0252	352552	5587396
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98JU0265	353310	5579645
98JU0266	353439	5580105
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98JU0268	350977	5580136
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98JU0285	352720	5582093
98JU0286	350203	5581047
98JU0287	350233	5581509
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98JU0291	350616	5582540
98JU0292	350724	5582533
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98JU0296	350390	5582433
98JU0297	350425	5582231
98JU0298	350447	5581901
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98JU0300	350124	5581476
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98JU0302	350056	5581422
98JU0303	350035	5581347
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99JU0717	347857	5587322
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99JU2tri	357186	5591552
99JU3tri	357314	5591662
99JU4tri	357211	5590593
00JU0001	342483	5568991
00JU0002	350094	5580482
S. Lake	350231	5580534

Appendix 2-2: Structural Measurements

Legend

Foliations

s-bed: bedding/compositional layering; sufol: cleavage/schistosity;
s-fol1: secondary cleavage/schistosity/crenulation cleavage, ju: joints;
s-fol2: third cleavage/shistosity; suplw: slickenside surface; fu: mylonitic foliation
buax: axial plane

Lineations

l-1: mineral lineation; lu: streching lineation, l-fold1:fold axis; l-int1: intersection lineation;
l-ss: slickenline lineation;

Station	Structure	Azimuth	Dip
98JU0005	sufol	359	56
98JU0005	s-bed	56	50
98JU0005	s-fol1	321	89
98JU0005	s-bed	359	56
98JU0023	sufol	346	81
98JU0023	sufol	318	80
98JU0025	sufol	355	86
98JU0028	sufol	155	75
98JU0028	sufol	140	76
98JU0028b	sufol	315	66
98JU0031	sufol	0	73
98JU0031	sufol	0	80
98JU0032	sufol	6	81
98JU0032b	sufol	347	89
98JU0033	sufol	329	85
98JU0034b	ju	194	21
98JU0034b	sufol	336	79
98JU0035	sufol	330	60
98JU0037c	sufol	13	86
98JU0040	sufol	335	72
98JU0048	l-1	331	53
98JU0048	sufol	264	51
98JU0049	sufol	274	62
98JU0050	sufol	275	51
98JU0051	sufol	266	62
98JU0054	sufol	310	58
98JU0054	sufol	321	74
98JU0055b	sufol	297	84
98JU0055b	sufol	304	80
98JU0056	sufol	305	74
98JU0060	sufol	304	55
98JU0067	s-bed	282	59
98JU0067	sufol	282	59
98JU0070	sufol	276	61
98JU0074	sufol	278	80
98JU0077	ju	187	41
98JU0083	sufol	278	52
98JU0085	l-1	11	65
98JU0085	sufol	270	66
98JU0086	l-ss	255	60
98JU0086	suplw	212	60
98JU0098	sufol	339	84
98JU0110	sufol	333	73
98JU0110b	sufol	350	74
98JU0111	sufol	343	80
98JU0112	sufol	338	78
98JU0114	sufol	336	73
98JU0115	sufol	321	59
98JU0117	sufol	342	86
98JU0117	sufol	356	68
98JU0118	sufol	8	56
98JU0119	sufol	352	71
98JU0120	sufol	352	75
98JU0121	sufol	346	81
98JU0125	sufol	90	84
98JU0125	ju	180	82
98JU0128	sufol	287	69
98JU0129	sufol	300	53
98JU0129	ju	22	85
98JU0131	sufol	274	78
98JU0132	sufol	298	69
98JU0137	sufol	292	73
98JU0140	sufol	71	61
98JU0140	s-bed	358	58
98JU0141	sufol	310	59
98JU0142	sufol	280	67
98JU0143	s-fol1	219	58
98JU0143	sufol	319	65
98JU0143	s-bed	319	65
98JU0143	sufol	312	69
98JU0143	sufol	310	67
98JU0143	s-fol2	52	65

98JU0144	s-bed	308	50
98JU0144	sufol	205	70
98JU0144	ju	65	45
98JU0151	sufol	168	62
98JU0157	sufol	255	67
98JU0159	sufol	25	36
98JU0160	sufol	262	51
98JU0162	sufol	272	70
98JU0162	l-1	103	19
98JU0163	sufol	290	62
98JU0164	sufol	328	50
98JU0166	sufol	310	30
98JU0167	sufol	308	34
98JU0167	l-1	94	24
98JU0167	sufol	305	42
98JU0168	sufol	308	38
98JU0168	sufol	287	40
98JU0169	sufol	312	38
98JU0169	sufol	312	30
98JU0169	lu	85	30
98JU0171	sufol	312	27
98JU0172	sufol	310	31
98JU0174	sufol	290	36
98JU0176	sufol	308	28
98JU0176	l-ss	77	29
98JU0178	s-bed	304	61
98JU0178	sufol	304	61
98JU0178	suplw	175	80
98JU0178	l-ss	153	74
98JU0181	sufol	265	39
98JU0181	sufol	270	31
98JU0181b	sufol	301	32
98JU0181b	sufol	296	35
98JU0186	sufol	263	78
98JU0187	sufol	292	85
98JU0190	sufol	279	50
98JU0190	sufol	288	56
98JU0191	sufol	270	60
98JU0194	ju	200	55
98JU0194	ju	341	50
98JU0197	sufol	30	70
98JU0197	l-1	80	55
98JU0198	sufol	314	76
98JU0199	ju	186	68
98JU0199	sufol	97	79
98JU0201	sufol	315	40
98JU0202	sufol	331	47
98JU0202	sufol	320	49
98JU0203	ju	124	84
98JU0203	sufol	14	49
98JU0204	sufol	52	48
98JU0204	ju	175	72
98JU0205	sufol	53	48
98JU0207	sufol	300	53
98JU0208	sufol	300	53
98JU0208	l-1	141	15
98JU0213	sufol	180	61
98JU0213	sufol	295	49
98JU0214	sufol	75	68
98JU0215	sufol	299	51
98JU0216	sufol	295	61
98JU0218	sufol	290	57
98JU0218	sufol	290	57
98JU0221	sufol	293	71
98JU0227	sufol	315	63
98JU0237	sufol	100	78
98JU0237	sufol	103	76
98JU0238	sufol	102	47
98JU0240	sufol	220	43
98JU0241	sufol	165	37
98JU0247	sufol	273	83
98JU0250	l-fold1	90	21
98JU0250	sufol	297	39
98JU0250	l-fold1	90	21
98JU0251	sufol	263	80
98JU0251	sufol	85	87
98JU0251	sufol	263	80
98JU0254	sufol	284	78
98JU0259a	sufol	166	45
98JU0259a	l-int1	217	45
98JU0259b	l-int1	219	72
98JU0259b	sufol	144	67
98JU0260	suplw	12	20
98JU0260	lu	105	10
98JU0260	sufol	17	53
98JU0260	sufol	41	25
98JU0260	sufol	40	15
98JU0260	l-ss	88	18
98JU0261	sufol	0	48
98JU0261	sufol	10	49
98JU0263	sufol	136	73
98JU0263	s-bed	280	46
98JU0265	sufol	72	48
98JU0265	ju	322	80
98JU0267	sufol	8	34
98JU0269	sufol	10	44
98JU0271	sufol	320	46
98JU0274	sufol	339	51

98JU0274b	sufol	4	46
98JU0280	sufol	348	49
98JU0280	sufol	355	38
98JU0282	sufol	324	41
98JU0288	sufol	357	44
98JU0288	lu	97	49
98JU0289	sufol	12	48
98JU0290	sufol	358	55
98JU0290	l-1	84	55
98JU0292	sufol	0	48
98JU0292	sufol	13	46
98JU0292	l-1	90	46
98JU0293	sufol	5	53
98JU0294	sufol	10	44
98JU0300	sufol	325	31
98JU0308	sufol	345	49
98JU0309	l-1	78	28
98JU0309	sufol	1	33
98JU0309	sufol	355	34
98JU0309	l-1	80	30
98JU0310	l-1	74	30
98JU0310	sufol	335	30
98JU0311	sufol	328	52
98JU0312	sufol	320	45
98JU0313	sufol	331	55
98JU0314	sufol	328	38
98JU0316	sufol	352	41
98JU0318	sufol	56	14
98JU0318	s-bed	56	14
98JU0319	sufol	32	62
98JU0319	l-1	98	57
98JU0320	sufol	32	44
98JU0320	l-ss	284	6
98JU0320	suplw	152	14
98JU0320	sufol	42	9
98JU0320	s-bed	91	21
98JU0322	sufol	345	36
98JU0322	l-1	77	33
98JU0323	sufol	346	53
98JU0324	sufol	340	46
98JU0331	sufol	339	66
98JU0333	sufol	350	41
98JU0334	sufol	354	38
98JU0335	sufol	337	51
98JU0340	sufol	301	70
98JU0345	sufol	279	21
98JU0346	sufol	341	40
98JU0347	sufol	284	19
98JU0347	l-1	85	5
98JU0354	sufol	329	19
98JU0356	sufol	292	20
98JU0357	sufol	357	16
98JU0359	sufol	292	46
98JU0365	sufol	306	44
98JU0366	sufol	354	35
98JU0366	lu	85	35
98JU0367	sufol	340	45
98JU0373	sufol	320	37
98JU0373	l-1	65	34
98JU0375	s-bed	180	73
98JU0376	sufol	330	38
98JU0377	sufol	17	53
98JU0392	sufol	283	63
98JU0398b	sufol	326	29
98JU0402	sufol	293	39
98JU0404	lu	74	21
98JU0404	sufol	19	25
98JU0405	lu	68	17
98JU0405	sufol	340	17
98JU0407	sufol	342	29
98JU0407	lu	83	30
98JU0409	sufol	333	52
98JU0413	sufol	2	38
98JU0413	lu	97	36
98JU0413	ju	205	64
98JU0417	sufol	339	54
98JU0417	lu	91	52
98JU0420	sufol	342	51
98JU0422	sufol	2	40
98JU0423	l-1	87	57
98JU0423	sufol	4	55
98JU0426	sufol	40	23
98JU0430	sufol	355	53
98JU0431	sufol	270	63
98JU0435	sufol	127	60
98JU0438	sufol	15	37
98JU0440	lu	80	37
98JU0440	sufol	328	36
98JU0441	sufol	355	55
98JU0441	lu	90	55
98JU0442	l-1	90	49
98JU0442	sufol	337	51
98JU0443b	sufol	4	45
98JU0443b	lu	89	45
98JU0445	sufol	12	44
98JU0446	sufol	358	37
98JU0446	l-1	90	37
98JU0447	sufol	340	23

98JU0447	l-1	76	23		98JU0491	sufol	335	54
98JU0448	sufol	350	48		98JU0492	sufol	354	36
98JU0448	l-1	74	46		98JU0494	s-bed	7	44
98JU0449	sufol	333	48		98JU0494	s-bed	306	47
98JU0451	sufol	355	29		98JU0500	s-bed	323	57
98JU0451	l-1	87	29		98JU0501	s-bed	337	52
98JU0452	sufol	350	36		98JU0504	s-bed	315	15
98JU0453	sufol	350	45		98JU0505	s-bed	318	33
98JU0453	l-1	80	45		98JU0506	sufol	45	64
98JU0454	sufol	359	38		98JU0506	s-fol1	222	42
98JU0455	l-1	85	36		98JU0508a	sufol	288	41
98JU0455	sufol	356	36		98JU0508b	ju	110	50
98JU0456	sufol	25	44		98JU0508b	sufol	245	74
98JU0456	l-1	90	44		98JU0509	sufol	288	53
98JU0457	sufol	15	31		98JU0509	s-bed	95	10
98JU0457	l-1	85	30		98JU0510	sufol	42	35
98JU0458	sufol	345	48		98JU0511	sufol	285	8
98JU0458	l-1	80	48		98JU0512	sufol	288	64
98JU0459	l-1	85	46		98JU0513	ju	43	20
98JU0459	sufol	345	46		98JU0513b	ju	348	60
98JU0460	sufol	350	55		98JU0513b	ju	144	43
98JU0462	sufol	344	34		98JU0513d	sufol	3	45
98JU0463	lu	104	26		98JU0513e	s-bed	345	46
98JU0464	sufol	310	50		98JU0513f	sufol	2	31
98JU0464	sufol	340	41		98JU0513g	s-bed	30	39
98JU0465	sufol	344	35		98JU0514	sufol	43	41
98JU0468	sufol	359	64		98JU0514	l-1	79	35
98JU0470	sufol	340	30		98JU0515	s-bed	2	41
98JU0470	lu	107	23		98JU0516	sufol	2	55
98JU0470	sufol	333	41		98JU0517	sufol	4	42
98JU0471	sufol	338	53		98JU0518	sufol	5	31
98JU0473	sufol	341	42		98JU0518	l-1	84	29
98JU0474	sufol	345	35		98JU0519	sufol	20	39
98JU0474	sufol	334	40		98JU0520	sufol	15	76
98JU0475	sufol	340	33		98JU0531	sufol	264	77
98JU0476	sufol	341	76		98JU0531	sufol	53	48
98JU0476	sufol	333	40		98JU0538	sufol	86	75
98JU0477	sufol	356	34		98JU0538	s-bed	86	75
98JU0479	sufol	357	41		98JU0539	sufol	261	31
98JU0479	lu	94	36		98JU0560	sufol	10	71
98JU0480	sufol	335	53		98JU0560	sufol	8	73
98JU0481	sufol	329	54		98JU0560	sufol	5	75
98JU0483	sufol	338	35		98JU0561	sufol	21	59
98JU0486	sufol	351	18		98JU0562	sufol	356	45
98JU0487	sufol	336	51		98JU0562	l-1	106	45
98JU0488	sufol	338	45		98JU0562	ju	158	85
98JU0489	sufol	333	56		98JU0563	sufol	4	34
98JU0490	sufol	343	48		98JU0563	sufol	354	32
98JU0490	lu	85	41		98JU0605	s-bed	291	81

98JU0564	sufol	6	45		98JU0605	s-bed	122	89
98JU0565	sufol	359	50		98JU0605	sufol	6	70
98JU0565	l-1	68	50		98JU0607	sufol	15	36
98JU0566	sufol	354	34		98JU0607	sufol	34	34
98JU0566	l-1	88	34		98JU0607	sufol	10	38
98JU0566	l-1	92	45		98JU0610	sufol	49	51
98JU0566	s-fol1	131	38		98JU0611	fu	34	33
98JU0566	s-fol1	150	85		98JU0612	sufol	49	73
98JU0566	l-int1	75	30		98JU0615	s-bed	355	27
98JU0566	sufol	354	45		98JU0617	l-1	63	27
98JU0569	l-1	90	32		98JU0617	sufol	20	49
98JU0569	sufol	22	39		98JU0617b	sufol	30	47
98JU0571	sufol	1	55		98JU0617b	l-1	65	31
98JU0571	l-1	98	50		98JU0622	s-bed	4	61
98JU0573	sufol	13	54		98JU0623	sufol	108	18
98JU0575	s-bed	305	59		98JU0625	sufol	285	74
98JU0576	s-bed	327	48		98JU0625	sufol	265	75
98JU0577	sufol	25	40		98JU0626	s-bed	232	62
98JU0577	sufol	40	45		98JU0626	sufol	269	83
98JU0578	sufol	18	34		98JU0626	sufol	251	84
98JU0578	l-1	97	33		98JU0628	sufol	234	76
98JU0579	sufol	36	45		99LH0001	fu	55	62
98JU0580	sufol	13	72		99LH0004	sufol	69	28
98JU0581	sufol	70	49		99LH0004	sufol	75	32
98JU0581	lu	90	37		99LH0006	sufol	40	35
98JU0584	sufol	356	81		99LH0011	sufol	314	41
98JU0585	sufol	270	47		99LH0016	s-bed	335	65
98JU0586	l-1	357	28		99LH0016	sufol	291	87
98JU0586	sufol	357	28		99LH0016	s-bed	319	60
98JU0587	s-bed	355	68		99LH0016	sufol	283	81
98JU0587	sufol	345	90		99LH0016	ju	9	41
98JU0588	sufol	293	44		99LH0016	j	48	78
98JU0588	sufol	302	43		99LH0023	sufol	246	65
98JU0590	l-int1	92	49		99LH0023	sufol	246	65
98JU0590	sufol	342	55		99LH0025	s-bed	332	80
98JU0590	s-bed	14	62		99LH0025	s-bed	332	80
98JU0592	sufol	30	45		99LH0026	sufol	189	13
98JU0593	l-1	69	32		99LH0027	sufol	101	45
98JU0593	sufol	25	37		99LH0027	sufol	101	45
98JU0593	lu	69	32		99LH0029	sufol	40	52
98JU0593	sufol	25	37		99LH0029	sufol	27	45
98JU0594	sufol	312	32		99LH0029	sufol	47	45
98JU0595	sufol	285	90		99LH0030	ju	131	66
98JU0596	sufol	297	81		99LH0030	sufol	35	32
98JU0597	sufol	103	39		99LH0030	l-1	114	12
98JU0598	sufol	16	37		99LH0031	sufol	52	34
98JU0599	sufol	73	25		99LH0033	sufol	12	35
98JU0602	sufol	276	14		99LH0035	sufol	43	70
98JU0604	s-bed	282	72		99JU0046	subed	90	39

99LH0041	sufol	340	40		99JU0047	ju	80	89
99LH0044	sufol	340	35		99JU0047	ju	238	37
99LH0045	sufol	330	68		99JU0051	s-fol1	204	13
99LH0045	l-1	93	60		99JU0051	sufol	204	23
99LH0049	sufol	12	55		99JU0052	s-bed	85	52
99LH0052	sufol	190	42		99JU0054	ju	111	49
99LH0061	sufol	47	35		99JU0055	ju	323	60
99LH0061	sufol	25	34		99JU0055	ju	282	55
99LH0061	sufol	36	49		99JU0055	subed	205	55
99LH0061	l-1	134	35		99JU0060	subed	215	59
99JU0001	sufol	95	46		99JU0061	sufol	248	58
99JU0001	l-1	135	21		99JU0063	sufol	275	61
99JU0001	s-fol1	236	24		99JU0078	sufol	340	23
99JU0001	s-bed	90	37		99JU0079	s-bed	34	39
99JU0001	sufol	79	50		99JU0079	sufol	0	30
99JU0001	s-fol1	266	30		99JU0080	s-bed	14	31
99JU0001	suplw	67	39		99JU0081	sufol	37	44
99JU0001	l-1	125	28		99JU0081	ju	226	45
99JU0001	s-bed	100	49		99JU0082	sufol	51	46
99JU0004	s-fol1	119	70		99JU0085	ju	53	51
99JU0004	s-bed	109	75		99JU0087	s-bed	42	61
99JU0004	s-fol2	1	73		99JU0089	ju	320	87
99JU0004	s-bed	116	76		99JU0090	l-1	73	42
99JU0004	lu	288	40		99JU0090	sufol	1	44
99JU0004	lu	264	35		99JU0092	s-fol1	352	75
99JU0004	sufol	109	75		99JU0092	s-bed	114	36
99JU0004b	s-bed	38	70		99JU0092	l-1	250	25
99JU0005	s-bed	37	11		99JU0092	s-fol1	58	70
99JU0007	sufol	311	31		99JU0092	sufol	114	36
99JU0007	sufol	335	37		99JU0093	s-bed	52	30
99JU0007	sufol	330	36		99JU0093	s-fol1	18	87
99JU0007	sufol	301	41		99JU0093	s-fol1	33	28
99JU0007	sufol	281	40		99JU0093	sufol	98	29
99JU0008	sufol	257	65		99JU0093	l-1	228	22
99JU0009	s-bed	280	74		99JU0093	ju	52	30
99JU0015	s-bed	104	89		99JU0094	s-bed	90	45
99JU0015	s-bed	116	76		99JU0099	s-bed	286	87
99JU0017	s-bed	10	76		99JU0100	s-bed	297	82
99JU0018	sufol	13	56		99JU0103	sufol	303	60
99JU0024	s-bed	251	50		99JU0104	sufol	300	46
99JU0034	sufol	49	41		99JU0104	sufol	305	49
99JU0035	subed	116	10		99JU0104	lu	87	29
99JU0035	ju	130	68		99JU0106	l-1	87	29
99JU0035	ju	201	74		99JU0106	sufol	357	26
99JU0035	ju	86	51		99JU0107	l-1	111	29
99JU0037	subed	185	40		99JU0107	sufol	11	29
99JU0039	subed	172	23		99JU0108	s-bed	295	58
99JU0042	subed	189	81		99JU0110	sufol	291	73
99JU0045	subed	220	62		99JU0178	s-bed	30	29

99JU0117	sufol	316	32		99JU0191	s-fol1	123	79
99JU0117	l-1	74	32		99JU0203	ju	4	61
99JU0120	sufol	32	41		99JU0203	sufol	124	70
99JU0121	sufol	298	52		99JU0204	s-bed	86	50
99JU0122	sufol	326	75		99JU0205	sufol	191	74
99JU0124	ju	214	72		99JU0205	s-bed	108	70
99JU0124	sufol	101	62		99JU0207	s-bed	141	61
99JU0125	sufol	259	55		99JU0207	sufol	241	52
99JU0126	sufol	267	44		99JU0207	ju	46	68
99JU0129	sufol	116	79		99JU0209	s-bed	92	48
99JU0130	sufol	114	62		99JU0209	s-fol2	283	46
99JU0132	ju	49	79		99JU0209	s-fol1	179	58
99JU0132	ju	256	68		99JU0209	sufol	92	48
99JU0134	s-fol1	267	36		99JU0211	sufol	116	39
99JU0135	ju	21	79		99JU0212	s-fol1	348	56
99JU0135	ju	40	78		99JU0212	sufol	238	55
99JU0137	sufol	102	50		99JU0212	s-bed	112	55
99JU0138	s-fol1	334	69		99JU0213	s-bed	109	57
99JU0140	ju	224	40		99JU0213	sufol	223	54
99JU0141	ju	229	65		99JU0215	sufol	91	52
99JU0142	ju	254	65		99JU0215	s-fol1	235	55
99JU0144	ju	216	70		99JU0215	s-bed	91	52
99JU0144	ju	247	38		99JU0216	sufol	226	90
99JU0146	sufol	30	85		99JU0216	s-bed	110	33
99JU0152	ju	176	64		99JU0217	sufol	102	30
99JU0152	sufol	291	28		99JU0217	s-fol1	228	70
99JU0153	sufol	199	7		99JU0218	sufol	42	60
99JU0153	ju	210	74		99JU0218	s-bed	85	42
99JU0153	lu	80	5		99JU0218	s-fol1	266	41
99JU0154	sufol	293	21		99JU0219	s-fol1	8	84
99JU0154	ju	206	75		99JU0219	sufol	252	74
99JU0155	ju	217	79		99JU0219	s-bed	212	71
99JU0157	ju	122	84		99JU0220	sufol	85	42
99JU0157	sufol	279	51		99JU0220	s-fol1	311	70
99JU0157	sufol	280	56		99JU0220	sufol	305	53
99JU0158	sufol	276	46		99JU0220	s-bed	85	42
99JU0163	lu	99	1		99JU0220	s-fol1	37	82
99JU0163	ju	208	87		99JU0220	s-bed	305	53
99JU0163	sufol	90	12		99JU0225	s-bed	282	55
99JU0165	ju	187	80		99JU0229	ju	242	44
99JU0165	ju	245	59		99JU0229	sufol	95	52
99JU0166	ju	234	70		99JU0231	s-fol1	243	57
99JU0167	sufol	214	12		99JU0231	sufol	104	49
99JU0167	lu	264	10		99JU0231	ju	351	82
99JU0171	sufol	125	69		99JU0232	sufol	75	50
99JU0174	s-bed	104	56		99JU0232	s-fol1	251	38
99JU0177	s-fol1	209	87		99JU0233	s-fol1	26	80
99JU0177	sufol	96	49		99JU0233	sufol	251	38
99JU0233	sufol	84	46		99JU0262	sufol	67	48

99JU0234	s-fol1	243	61		99JU0262	s-bed	67	48
99JU0234	sufol	85	47		99JU0264	sufol	82	49
99JU0237	l-fold1	338	56		99JU0264	s-bed	82	49
99JU0237	sufol	100	39		99JU0264	s-fol1	328	72
99JU0238	sufol	92	44		99JU0265	s-bed	76	61
99JU0238	s-fol1	242	42		99JU0265	sufol	76	61
99JU0239	s-fol1	234	65		99JU0266	sufol	73	42
99JU0239	ju	350	68		99JU0267	s-bed	31	60
99JU0239	sufol	92	36		99JU0269	sufol	109	44
99JU0244	sufol	68	43		99JU0269	s-fol1	211	64
99JU0245	sufol	78	54		99JU0269	s-fol1	322	49
99JU0245	s-fol1	256	56		99JU0270	sufol	121	52
99JU0246	sufol	80	59		99JU0270	s-fol1	222	77
99JU0246	s-fol1	274	29		99JU0271	sufol	125	44
99JU0246	s-fol2	23	45		99JU0271	s-fol1	85	89
99JU0247	l-ss	133	11		99JU0272	sufol	155	44
99JU0247	suplw	83	24		99JU0272	s-fol1	222	77
99JU0248	sufol	86	48		99JU0273	sufol	143	64
99JU0248	s-fol1	281	48		99JU0273	s-fol1	46	86
99JU0249	s-fol1	152	25		99JU0273	s-fol1	120	7
99JU0249	sufol	84	48		99JU0274	sufol	99	64
99JU0250	s-fol1	12	79		99JU0274	s-fol1	353	50
99JU0250	s-fol1	30	77		99JU0274	s-fol1	226	41
99JU0250	s-fol1	15	75		99JU0275	sufol	97	54
99JU0250	sufol	84	30		99JU0275	s-fol1	223	46
99JU0250	sufol	86	47		99JU0276	s-fol1	212	72
99JU0252	s-fol1	210	25		99JU0276	sufol	95	76
99JU0252	s-bed	140	66		99JU0276	s-fol1	234	28
99JU0253	s-fol1	43	19		99JU0277	s-fol1	220	54
99JU0253	s-fol1	112	87		99JU0277	s-fol1	351	49
99JU0253	sufol	131	80		99JU0277	sufol	97	63
99JU0255	s-fol1	214	46		99JU0278	sufol	97	61
99JU0255	sufol	152	90		99JU0282	sufol	79	26
99JU0255	s-fol1	55	42		99JU0283	sufol	44	38
99JU0256	s-fol1	255	39		99JU0287	s-fol1	212	20
99JU0256	sufol	123	71		99JU0287	sufol	97	57
99JU0257	s-fol1	28	60		99JU0287	sufol	84	47
99JU0257	sufol	116	56		99JU0287	s-fol1	234	49
99JU0257	s-fol1	244	44		99JU0289	s-fol1	228	89
99JU0258	s-fol1	312	71		99JU0292	s-fol1	212	85
99JU0258	s-fol1	264	62		99JU0292	sufol	111	46
99JU0258	sufol	110	44		99JU0295	sufol	115	79
99JU0259	sufol	112	75		99JU0297	ju	1	90
99JU0259	sufol	128	82		99JU0297	sufol	294	74
99JU0260	sufol	99	60		99JU0297	ju	291	82
99JU0261	s-fol1	261	61		99JU0302	ju	129	45
99JU0262	s-fol1	202	78		99JU0302	ju	240	75
99JU0262	s-fol1	251	26		99JU0302	ju	188	29
99JU0304	ju	9	67		99JU0361	l-fold1	145	12

99JU0304	ju	192	34		99JU0361	l-fold1	289	8
99JU0312	sufol	246	65		99JU0361	l-fold1	124	23
99JU0313	sufol	246	65		99JU0361	buax	106	39
99JU0317	s-bed	332	80		99JU0362	sufol	119	57
99JU0317	sufol	332	80		99JU0362	s-fol1	230	72
99JU0319	s-bed	56	14		99JU0362	s-fol2	59	32
99JU0319	sufol	52	85		99JU0363	s-bed	134	90
99JU0319	s-bed	56	14		99JU0365	sufol	251	40
99JU0321	suplw	152	14		99JU0365	s-bed	112	75
99JU0321	s-bed	91	21		99JU0365	s-bed	12	65
99JU0321	l-ss	284	6		99JU0365	s-fol1	70	35
99JU0321	sufol	42	9		99JU0366	s-bed	132	66
99JU0331	ju	207	81		99JU0367	s-fol1	231	57
99JU0336	subed	0	24		99JU0367	l-fold1	216	15
99JU0340	s-fol1	238	38		99JU0367	sufol	53	58
99JU0340	sufol	76	48		99JU0368	sufol	58	31
99JU0341	s-fol1	33	84		99JU0369	s-bed	19	33
99JU0341	sufol	124	21		99JU0370	sufol	167	34
99JU0345	ju	64	31		99JU0370	s-bed	61	32
99JU0345	ju	264	57		99JU0383	sufol	25	25
99JU0348	sufol	349	31		99JU0386	sufol	308	55
99JU0349	s-bed	308	80		99JU0387	ju	187	81
99JU0349	ju	37	85		99JU0387	sufol	64	10
99JU0349	s-fol1	198	56		99JU0393	ju	125	80
99JU0349	sufol	312	70		99JU0393	ju	68	78
99JU0351	ju	9	82		99JU0393	ju	323	68
99JU0351	s-fol1	82	45		99JU0394	sufol	92	47
99JU0351	sufol	319	64		99JU0397	s-bed	359	61
99JU0351	s-bed	319	64		99JU0397	s-bed	67	35
99JU0351	s-bed	319	64		99JU0408	s-bed	297	65
99JU0351	s-fol1	82	45		99JU0410	sufol	61	70
99JU0352	sufol	338	62		99JU0410	sufol	317	72
99JU0352	sufol	235	49		99JU0412	l-fold1	87	61
99JU0352	s-bed	52	45		99JU0412	sufol	9	55
99JU0352	s-fol1	338	62		99JU0414	s-bed	165	59
99JU0352	sufol	235	49		99JU0416	s-bed	264	50
99JU0352	s-bed	52	45		99JU0417	ju	139	46
99JU0353	sufol	356	53		99JU0419	sufol	307	39
99JU0353	sufol	344	63		99JU0429	suflow	359	63
99JU0353	sufol	344	63		99JU0439	s-bed	193	84
99JU0354	s-bed	80	71		99JU0446	subed	295	86
99JU0354	sufol	80	71		99JU0447	s-bed	322	57
99JU0354	s-bed	80	71		99JU0456	sufol	251	34
99JU03547	s-bed	200	24		99JU0456	s-fol1	69	54
99JU0359	sufol	80	42		99JU0456	s-fol1	67	61
99JU0359	sufol	107	46		99JU0456	s-fol1	344	74
99JU0359	s-fol1	224	44		99JU0457	s-fol1	322	45
99JU0361	buax	118	56		99JU0457	sufol	249	81
99JU0457	sufol	244	82		99JU0495	sufol	116	49

99JU0458	sufol	57	52		99JU0496	sufol	170	76
99JU0458	s-fol1	303	48		99JU0496	s-fol1	0	50
99JU0459	s-fol1	291	46		99JU0496	ju	110	73
99JU0459	sufol	54	44		99JU0496	s-bed	265	50
99JU0460	sufol	251	77		99JU0500	sufol	0	77
99JU0462	sufol	274	65		99JU0500	s-bed	291	59
99JU0463	sufol	316	64		99JU0501	sufol	279	45
99JU0464	sufol	291	82		99JU0501	ju	166	57
99JU0465	sufol	299	82		99JU0501	ju	60	75
99JU0472	sufol	99	43		99JU0501	s-fol1	180	86
99JU0472	s-fol2	130	63		99JU0502	s-bed	90	80
99JU0472	s-fol1	219	73		99JU0506	sufol	309	38
99JU0475	sufol	11	47		99JU0506	s-fol1	254	41
99JU0475	sufol	109	61		99JU0509	ju	79	90
99JU0476	sufol	100	44		99JU0509	ju	115	68
99JU0480	sufol	320	79		99JU0509	ju	95	53
99JU0480	s-bed	72	55		99JU0510	s-fol1	100	46
99JU0484	s-fol1	301	54		99JU0510	sufol	280	45
99JU0484	s-bed	23	37		99JU0512	ju	106	47
99JU0484	sufol	180	73		99JU0512	ju	113	64
99JU0485	sufol	16	47		99JU0512	ju	216	74
99JU0485	ju	198	32		99JU0514	s-bed	282	60
99JU0485	l-1	110	46		99JU0514	s-bed	299	40
99JU0486	sufol	92	53		99JU0514	sufol	41	61
99JU0486	l-1	133	39		99JU0514	sufol	189	77
99JU0487	sufol	356	10		99JU0514	sufol	172	85
99JU0488	sufol	106	30		99JU0514	s-bed	172	85
99JU0488	s-fol1	226	72		99JU0515	s-fol1	236	43
99JU0488	s-bed	106	30		99JU0515	sufol	65	59
99JU0489	s-bed	289	82		99JU0515	s-fol1	325	72
99JU0490	s-fol1	209	80		99JU0515	s-bed	65	59
99JU0490	ju	233	35		99JU0516	s-fol1	146	28
99JU0490	s-bed	285	82		99JU0516	s-fol1	58	45
99JU0490	sufol	285	82		99JU0516	s-fol1	220	73
99JU0491	s-bed	287	86		99JU0516	sufol	311	63
99JU0492	s-fol1	7	87		99JU0517	sufol	315	62
99JU0492	s-bed	286	45		99JU0517	s-fol1	228	56
99JU0492	sufol	286	45		99JU0517	sufol	127	31
99JU0492	s-fol1	67	64		99JU0517	s-bed	315	62
99JU0493	sufol	168	88		99JU0518	sufol	288	28
99JU0493	sufol	54	56		99JU0518	s-fol1	211	89
99JU0493	s-bed	292	61		99JU0519	s-fol1	97	43
99JU0494	sufol	181	83		99JU0519	s-fol1	158	87
99JU0494	s-bed	275	55		99JU0519	sufol	297	45
99JU0494	ju	142	38		99JU0521	s-fol1	79	71
99JU0494	sufol	234	82		99JU0521	sufol	280	33
99JU0495	ju	203	23		99JU0523	sufol	314	45
99JU0495	ju	184	77		99JU0523	sufol	204	86
99JU0523	ju	114	59		99JU0560	sufol	100	80

99JU0526	ju	184	87		99JU0560	ju	171	81
99JU0526	ju	104	55		99JU0561	sufol	122	62
99JU0526	ju	278	44		99JU0561	s-foll	138	70
99JU0527	s-foll	165	60		99JU0562	sufol	118	65
99JU0527	s-foll	50	68		99JU0562	s-foll	47	69
99JU0527	sufol	88	38		99JU0562	s-foll	11	44
99JU0528	s-foll	232	70		99JU0562	sufol	122	78
99JU0528	s-bed	12	25		99JU0567	sufol	118	54
99JU0528	sufol	333	64		99JU0567	s-foll	31	64
99JU0530	s-foll	130	70		99JU0567	s-foll	21	17
99JU0530	s-foll	219	84		99JU0570	sufol	109	71
99JU0530	s-bed	274	33		99JU0577	sufol	144	20
99JU0530	sufol	274	33		99JU0577	s-foll	5	62
99JU0530	s-foll	122	59		99JU0577	sufol	138	18
99JU0532	s-bed	8	70		99JU0577	s-foll	25	82
99JU0532	s-bed	279	62		99JU0577	s-foll	344	89
99JU0532	sufol	279	62		99JU0578	s-foll	6	71
99JU0532	s-foll	113	85		99JU0581	sufol	108	30
99JU0532	s-foll	183	83		99JU0585	ju	305	49
99JU0532	sufol	8	70		99JU0592	s-foll	216	70
99JU0533	s-foll	48	56		99JU0592	sufol	108	47
99JU0533	s-foll	211	84		99JU0592	s-bed	108	47
99JU0533	sufol	311	75		99JU0592	s-foll	5	79
99JU0533	s-bed	311	75		99JU0594	s-foll	16	71
99JU0536	sufol	262	81		99JU0594	sufol	104	55
99JU0540	s-foll	357	70		99JU0600	sufol	95	38
99JU0540	sufol	69	83		99JU0602	s-foll	181	74
99JU0540	s-bed	69	83		99JU0602	s-foll	215	59
99JU0540	s-fol2	105	90		99JU0602	sufol	95	28
99JU0541	sufol	1	65		99JU0602	sufol	95	28
99JU0541	sufol	268	78		99JU0602	s-foll	215	59
99JU0545	sufol	60	23		99JU0602	s-foll	181	74
99JU0549	s-foll	111	17		99JU0603	sufol	60	39
99JU0549	sufol	121	88		99JU0605	sufol	91	31
99JU0549	s-foll	210	90		99JU0605	s-foll	239	39
99JU0550	sufol	110	88		99JU0605	sufol	109	36
99JU0551	sufol	151	68		99JU0605	s-foll	131	71
99JU0552	sufol	125	84		99JU0608	sufol	54	20
99JU0553	sufol	109	77		99JU0608	s-foll	241	56
99JU0554	sufol	110	52		99JU0609	sufol	58	40
99JU0554	s-foll	356	58		99JU0630	s-foll	19	31
99JU0554	ju	24	84		99JU0630	sufol	300	24
99JU0555	sufol	119	45		99JU0631	sufol	277	82
99JU0556	s-foll	9	84		99JU0632	sufol	296	72
99JU0556	sufol	113	75		99JU0632	s-foll	152	30
99JU0558	sufol	102	45		99JU0633	sufol	279	71
99JU0558	s-foll	338	57		99JU0633	s-foll	169	43
99JU0558	s-foll	359	86		99JU0635	sufol	300	70
99JU0635	s-foll	184	35		99JU0659	sufol	145	22

99JU0636	sufol	280	90		99JU0660	sufol	158	56
99JU0636	s-fol1	191	30		99JU0660	s-bed	279	62
99JU0637	sufol	256	55		99JU0661	s-bed	292	45
99JU0639	sufol	102	60		99JU0661	sufol	221	79
99JU0639	s-fol1	241	63		99JU0661	sufol	136	56
99JU0641	sufol	315	36		99JU0662	sufol	86	62
99JU0641	s-fol1	214	84		99JU0662	sufol	285	54
99JU0642	sufol	285	69		99JU0663	s-bed	86	62
99JU0642	s-fol1	148	58		99JU0663	sufol	86	62
99JU0645	s-bed	347	7		99JU0663	s-fol1	22	49
99JU0646	sufol	77	59		99JU0664	sufol	56	65
99JU0646	s-bed	301	34		99JU0664	s-bed	299	51
99JU0646	sufol	164	83		99JU0664	sufol	159	58
99JU0647	s-bed	5	25		99JU0666	sufol	292	82
99JU0647	sufol	322	89		99JU0666	s-fol2	161	33
99JU0647	sufol	74	85		99JU0666	s-fol1	29	52
99JU0648	sufol	29	54		99JU0669	sufol	334	77
99JU0648	sufol	335	86		99JU0670	sufol	319	69
99JU0648	s-bed	256	38		99JU0671	sufol	206	61
99JU0648	l-fold1	112	1		99JU0675	s-fol1	305	71
99JU0648	l-fold1	281	21		99JU0675	sufol	31	88
99JU0648	l-fold1	250	19		99JU0675	s-fol1	155	88
99JU0648	l-fold1	101	8		99JU0678	l-1	79	20
99JU0649	s-bed	261	65		99JU0678	s-fol1	57	64
99JU0650	s-fol1	235	62		99JU0678	s-fol1	139	79
99JU0650	s-fol1	131	90		99JU0678	sufol	59	37
99JU0650	sufol	336	52		99JU0678	l-1	87	23
99JU0650	s-fol1	69	88		99JU0678	s-fol1	159	88
99JU0650	s-bed	336	62		99JU0678	s-fol1	72	72
99JU0650	s-bed	9	48		99JU0678	s-bed	214	34
99JU0651	l-fold1	105	25		99JU0678	s-bed	38	45
99JU0651	l-fold1	114	23		99JU0678	sufol	23	49
99JU0651	l-fold1	104	22		99JU0678	s-fol1	158	72
99JU0651	l-fold1	89	24		99JU0678	s-fol1	252	71
99JU0652	sufol	280	80		99JU0678	sufol	48	40
99JU0653	s-fol1	28	90		99JU0679	s-bed	0	33
99JU0653	sufol	300	15		99JU0679	s-fol1	96	82
99JU0655	s-fol1	25	89		99JU0680	sufol	14	49
99JU0655	sufol	309	48		99JU0680	s-fol1	151	54
99JU0655	s-fol1	48	31		99JU0680	s-fol1	99	75
99JU0656	s-bed	331	39		99JU0681	sufol	13	44
99JU0656	sufol	223	75		99JU0681	s-fol1	165	69
99JU0657	s-bed	299	68		99JU0681	s-fol1	122	76
99JU0658	sufol	12	79		99JU0682	sufol	153	71
99JU0658	sufol	165	45		99JU0682	l-fold1	78	35
99JU0658	s-bed	275	84		99JU0682	l-fold1	87	28
99JU0659	s-bed	289	76		99JU0682	l-fold1	84	34
99JU0659	sufol	21	74		99JU0682	l-fold1	90	34
99JU0682	l-fold1	91	33		99JU0693	sufol	322	46

99JU0682	s-bed	38	42
99JU0683	s-bed	47	48
99JU0683	sufol	47	48
99JU0683	l-1	97	49
99JU0683	s-fol1	124	38
99JU0683	s-fol1	318	52
99JU0683	s-bed	23	45
99JU0683	sufol	23	45
99JU0683	l-1	92	45
99JU0683	s-fol1	168	42
99JU0684	s-bed	12	55
99JU0684	sufol	12	55
99JU0684	l-1	104	55
99JU0684	s-fol1	159	45
99JU0684	ju	105	74
99JU0685	sufol	31	50
99JU0685	s-fol1	172	50
99JU0685	s-fol2	85	67
99JU0685	ju	94	88
99JU0685	s-bed	46	45
99JU0685	l-1	107	41
99JU0685	s-bed	31	50
99JU0686	s-bed	2	36
99JU0686	sufol	14	41
99JU0686	l-1	93	40
99JU0686	sufol	155	62
99JU0687	s-bed	357	42
99JU0687	l-1	92	43
99JU0687	sufol	1	47
99JU0687	s-fol1	134	68
99JU0687	l-1	94	47
99JU0687	ju	209	67
99JU0688	s-bed	337	39
99JU0688	sufol	10	40
99JU0688	l-1	99	39
99JU0688	s-fol1	144	63
99JU0688	sufol	17	46
99JU0689	sufol	5	52
99JU0689	s-fol1	221	66
99JU0689	ju	201	73
99JU0689	ju	200	59
99JU0690	s-fol1	226	90
99JU0690	sufol	318	63
99JU0691	s-fol1	162	70
99JU0691	sufol	293	59
99JU0692	sufol	279	51
99JU0692	s-fol1	158	88
99JU0693	s-bed	226	90

99JU0694	s-fol1	87	49
99JU0694	sufol	344	51
99JU0694	s-bed	344	51
99JU0694	s-fol1	204	56
99JU0695	sufol	349	43
99JU0695	s-fol1	74	85
99JU0695	s-bed	349	43
99JU0695	s-fol1	154	45
99JU0696	s-bed	355	20
99JU0696	l-fold1	93	8
99JU0697	s-fol1	222	47
99JU0697	sufol	341	44
99JU0698	s-fol2	119	74
99JU0698	s-fol1	196	50
99JU0698	sufol	318	40
99JU0700	s-bed	324	54
99JU0700	s-bed	358	39
99JU0704	lu	93	10
99JU0704	sufol	299	13
99JU0704	sufol	211	66
99JU0705	sufol	305	14
99JU0706	sufol	333	33
99JU0706	s-fol1	205	54
99JU0707	sufol	356	26
99JU0707	s-fol1	175	72
99JU0709	s-bed	348	48
99JU0710	sufol	337	37
99JU0711	s-bed	326	38
99JU0711	s-fol1	210	80
99JU0711	s-fol2	150	63
99JU0712	sufol	334	18
99JU0712	s-bed	334	18
99JU0714	s-fol1	85	84
99JU0714	s-fol1	8	88
99JU0714	sufol	299	20
99JU0715	sufol	291	15
99JU0715	s-fol1	221	87
99JU0715	s-fol1	185	80

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Chapter 3

North American margin origin of Quesnel terrane strata in the southern Canadian Cordillera: Inferences from geochemical and Nd isotopic characteristics of Triassic metasedimentary rocks

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Introduction

The most inboard of the proposed accreted tectonic elements of the southeastern Canadian Cordillera, the Quesnel terrane (Quesnellia), has been described as a Triassic to early Jurassic intra-oceanic arc, formed in places atop Ordovician to Permian rocks of arc- and oceanic-affinity (Monger, 1977, 1985; Mortimer, 1986, 1987; Gabrielse et al., 1991; Monger et al., 1982, 1991, Souther, 1991; Dostal et al., 2001). Petrologic, geochemical and isotopic characteristics of metavolcanic rocks of the Upper Triassic Nicola Group, included as part of the Quesnel terrane, have been interpreted to reflect an arc setting with limited crustal contamination (Mortimer, 1986, 1987; Smith et al., 1995). Neodymium and Sr isotopic data from Late Triassic to Early Jurassic plutons intruding, and part of, the Quesnel terrane also show no clear evidence for extensive crustal contamination and have thus been interpreted to indicate that there was no continental crust beneath the Quesnel terrane at that time (Ghosh, 1995).

Current uncertainty regarding the basal contact of the Quesnel terrane exists because of conflicting interpretations regarding its relationship with underlying rocks. The Quesnel terrane is hypothesized to have been obducted onto rocks of the ancient North American margin between mid-Jurassic and Paleocene time, along a thrust fault with approximately 200 km of west-to-east displacement (e.g., Ghosh, 1995, and references therein). In southeast British Columbia, the Upper Triassic Nicola Group of the Quesnel terrane includes low-grade clastic metasedimentary strata that interfinger with volcanic rocks. These metasedimentary strata have been correlated with units to the east, also part of the Quesnel terrane, that are interpreted to unconformably overlie Paleozoic pericratonic rocks of the ancient margin (Jones, 1959; Read and Okulitch, 1977; Klepacki, 1983; Klepacki and Wheeler, 1985; Höy and Andrew, 1991; Roback and

Walker, 1995; Thompson and Daughtry, 1996, 1997, 1998; and Unterschutz et al., 1999a). Observation of this contact west of Lower Arrow Lake (Fig. 3-1) is complicated by the paucity of outcrop. In addition, there are metamorphic clasts, including Proterozoic granite (555.6 ± 2.5 Ma, U-Pb zircon), in metaconglomerate of undetermined age beneath what appears to be a thin veneer of Quesnel terrane strata, 30 km northwest of Vernon (see Fig. 3-1) (Erdmer et al., 2001a). This metaconglomerate has been interpreted to represent a continuation of pericratonic rocks across the Okanagan Valley (Erdmer et al., 2001a) into an area where the Quesnel terrane was thought to be 24 to 30 km thick (e.g. Cook et al., 1992; Varsek and Cook, 1994). Approximately 100 km west of Vernon in the Nicola horst, an area of high-grade metamorphic rocks surrounded by low-grade strata of the Quesnel terrane, an igneous clast in metaconglomerate is ~1.04 Ga (U-Pb zircon, Erdmer et al., 2001b). This has been interpreted to indicate that Proterozoic crust was at the surface at the time of deposition of these rocks, and further supports the hypothesis that the lithosphere in this area is not simply a thick crustal slice of the Quesnel terrane (Erdmer et al., 2001b).

An unconformable contact between rocks of the Quesnel terrane in southeastern British Columbia and rocks tied to the North American craton would preclude any significant displacement of the Quesnel arc with respect to the margin since the late Triassic. This would also preclude its status as an allochthon or, alternatively, suggests that some rocks in southeastern British Columbia are incorrectly assigned to the Quesnel terrane. This study examines the possibility that the Quesnel terrane is pericratonic by examining the provenance characteristics of sedimentary rocks deposited contemporaneously with Quesnel arc development, and prior to the proposed obduction onto the continental margin.

Clastic sedimentary rocks are widely used as indicators of sedimentary provenance because sedimentary basins reflect the nature of their source areas (e.g., Bhatia and Crook, 1986; Nelson and DePaolo, 1988; Frost and Coombs, 1989; McLennan and Taylor, 1991; McLennan and Hemming, 1992; McLennan et al., 1993, 1995; and references therein). Elements such as Th, Sc, Cr, Co and the rare earth elements (REE, including Sm and Nd) are effective provenance tracers because of their low concentrations in river- and sea-water, their low oceanic residence times, and because they have been shown to be immobile during geological processes such as weathering, diagenesis and low-grade metamorphism (Taylor and McLennan, 1985, and references therein). These elements "see through" the effects of low-grade metamorphism (e.g. Feng et al., 1992; Creaser et al., 1997). This study is seeded in previous work, in which three samples of clastic sedimentary rocks from Triassic strata in the Quesnel terrane were analyzed for Nd isotopic compositions, and which revealed the presence of continental detritus in the sedimentary record (Ghosh and Lambert, 1989; Patchett and Gehrels, 1998). This paper presents Nd isotopic and geochemical data from 24 clastic metasedimentary rocks along a ~ 300 km transect of the Quesnel terrane in southeastern British Columbia, in attempt to track the abundance, distribution, and lithological controls of this continental signature, to assess whether the source of evolved continental material was proximal to the depositional basin, and to determine the likelihood that this source was North American.

The term 'evolved' is used to refer to rocks with geochemical and Nd isotopic characteristics compatible with the old upper continental crust (OUC) provenance type defined by McLennan et al. (1993), which describes rocks that have undergone intracrustal melting processes and have εNd_0 values ≤ -10 and Eu/Eu* values ~0.60-0.70. The term 'primitive' is used to refer to rocks with geochemical characteristics compatible with the young undifferentiated arc (YUA) provenance type of McLennan et al. (1993), which represents young, mantle derived volcanic and plutonic rocks from arcs that have not undergone intracrustal differentiation processes and have εNd_0 values +5 and Eu/Eu* values ~ 1.0. The geochemical and Nd isotopic data reported here confirm that the volcanic component of the Quesnel arc, represented by Nicola Group volcanic rocks, was not the only source of detritus for intercalated clastic strata, and indicate that detritus was also derived from an evolved continental source. The similarity of the evolved Nd isotope and geochemical data to rocks from the North American miogeocline suggests that North America and the Quesnel arc are the most likely sources of detritus within the Triassic clastic succession of the Quesnel terrane in southeastern British Columbia. This interpretation implies a parautochthonous or distal continental margin origin for the Quesnel arc, which, in turn, implies that the Quesnel terrane in the southeastern Canadian Cordillera is not exotic.

Geologic Framework

The Paleozoic basement of the Quesnel terrane is poorly known, but has been divided into the Harper Ranch subterrane, a sequence of arc-related clastic, volcaniclastic, and volcanic rocks and podiform carbonates, and the Okanagan subterrane, which includes limestone, chert, argillite, basalt and ultramafic rocks (Read and Okulitch, 1977; Monger, 1977; Monger et al. 1991). The Quesnel arc assemblage within the study area (Fig. 3-1) sits, in places, upon this Paleozoic basement and consists of low-grade metamorphosed sedimentary, volcaniclastic, and volcanic rocks of the Slocan, Ymir, and Nicola groups (Fig. 3-2) (Jones, 1959; Little, 1960; Schau, 1968, 1970; Preto, 1977; Read and Okulitch, 1977; Souther, 1977; Klepacki, 1983; Klepacki and Wheeler, 1985; Höy and Andrew, 1988; Monger et al., 1991; and references therein). In south-central British Columbia, the Nicola Group has been divided into three belts (Preto, 1977; Preto et al., 1979; Monger, 1985; Monger et al., 1982, 1991). The western belt consists of Upper Carnian to Lower Norian felsic, intermediate and more rarely mafic volcaniclastic rocks, and includes local ignimbrite, minor carbonate, and pelite. These rocks interfinger structurally and depositionally with the more outboard Cache Creek terrane (Travers, 1977). The central belt is characterized by a transition to intermediate volcanic and volcaniclastic rocks - mainly feldspar and feldspar-augite porphyry - with local carbonate and volcanic sandstone of early Norian age, overlain by pillow basalt, augite porphyry, volcaniclastic rocks, and alkaline flows of late Norian age. The eastern belt is broadly similar to the central belt, but includes a greater proportion of volcaniclastic rocks (Preto, 1977; Preto et al., 1979). The three belts are structurally juxtaposed in some areas (Preto et al., 1979; Monger, 1985), while grading depositionally into one another in other areas (Schau, 1968; Mortimer, 1987; and references therein). A lateral facies transition has been recorded eastward into a sedimentary facies, the temporal and lithological correlative of the Slocan and Ymir groups (Fig. 3-2) (Mortimer, 1987; Monger et al., 1991; Thompson and Daughtry, 1998), which consists of argillite, slate and metasiltstone with local lenses of volcaniclastic rocks, limestone and breccia.

On the basis of macro- and microfossils in sedimentary rocks of the Nicola and Slocan groups, the time span of deposition of the studied Triassic strata ranges from 227 to 210 Ma (Okulitch and Cameron, 1976; Travers, 1977; Preto, 1979; Orchard, 1985;

Read, 1996; Thompson and Daughtry, 1996). This time span is supported by absolute age determinations. An Rb-Sr isochron of 222 ± 15 Ma was obtained from a high- to low-potassium basalt to rhyolite suite of the Nicola Group (Smith et al. 1995). A tuff in the western belt of the Nicola Group has been dated at 222.5 ± 1.4 Ma (U-Pb zircon, Moore et al., 2000). A minimum age of the Nicola Group is provided by the crosscutting Guichon batholith (210 ± 3 Ma , U-Pb zircon, Mortimer et al. 1989).

Previous Nd Isotope and Geochemical Studies

Mortimer (1987) used major and trace element data from volcanic rocks of the Nicola Group, together with the presence of reefoid limestones and extrusive rocks of silicic to intermediate composition and the absence of pillow basalt and ophiolite, to refute early interpretations that the Nicola Group formed at a mid-oceanic ridge in a rift setting (Hollister, 1976; Preto, 1977; Souther, 1977). Mortimer (1987) further inferred that the magmas represented by the volcanic rocks had geochemical characteristics of island-arc and intraplate tectonic settings (Mortimer, 1987). This proposal is supported by εNd_T values ranging from +5.0 to +7.9, consistent with values expected in early Mesozoic island arcs (Smith et al., 1995). Geochemical and Nd isotope studies on the Paleozoic Harper Ranch and Okanagan subterranes within the Quesnel terrane reveal positive εNd_T values (+2.9 to +11.6), and La_N/Yb_N ratios between 0.4 and 4 (Ghosh, 1995; Patchett and Gehrels, 1998; Dostal et al., 2001). In the Greenwood area, middle Triassic rocks of the Brooklyn Group also have geochemical (La_N/Yb_N ratios between 2.5 and 4.5) and Nd isotope values (εNd_{230} values between +5.5 and +8.4) consistent with an island-arc setting (Dostal et al., 2001).

Previous isotopic analysis of sedimentary strata from the Nicola, Slocan and Ymir groups revealed εNd_T values ranging from –5 to –12 (Ghosh and Lambert, 1989; Patchett and Gehrels, 1998; Unterschutz et al., 1999b). These values contrast strongly with the positive εNd_T values of contemporaneous volcanic facies in the Nicola Group (Smith et al., 1995). Negative εNd_T values are not typical of intra-oceanic arcs, rather, they reflect a contribution from evolved continental crust to the arc setting.

Patchett and Gehrels (1998) suggested that negative εNd_T values of sedimentary rocks from the Quesnel and Cache Creek terranes, which are consistent with results from the North American miogeocline (Jackson, 1992; Boghossian et al., 1996; Garzione et al., 1997), could indicate proximity to ancestral North America. They placed constraints on this proximity by suggesting that if North America was the source of this continental detritus via water-borne transport, the oceanic Cache Creek terrane, tied to the western margin of the Quesnel terrane, was at a maximum distance of between 1,500 and 3,000 km from the continent during its development (Patchett and Gehrels, 1998). Further constraints on the location of these terranes are provided by Nd isotopic compositions of Triassic miogeoclinal strata in northern British Columbia and southwestern Alberta (Jackson, 1992; Boghossian et al., 1996), which are consistently evolved ($\varepsilon Nd_{220} = -6.8$ to -10.7). This failure to demonstrate a contribution to the miogeocline from the Quesnel arc may provide a limit to the eastern extent of significant sediment influx from the arc, and thus help define its position relative to the North American margin in Triassic time.

Sampling Method and Analytical Technique

Twenty-four samples of metasedimentary rocks from the Slocan, Ymir, and Nicola groups of southeastern British Columbia, ranging in grain size from clay- to sand- and in metamorphic grade from greenschist to amphibolite, were analyzed for their major, trace element, and Sm-Nd isotopic composition and concentrations (Tables 3-1, 3-2, 3-3; Fig. 3-1). Although these three groups are considered correlative (e.g. Monger et al., 1991, and references therein), a definitive link between Nicola Group rocks and those of the Slocan and Ymir groups has yet to be documented. The present study attempts to address this concern by examining sedimentary strata from all three groups. Sample RC 99-14 comes from the eastern belt and samples RC 99-15, RC 99-16, and RC 99-17 come from the sedimentary facies belt of the Nicola Group as defined by Monger (1985, and references therein). The remaining samples come from the sedimentary-dominated successions of the Slocan and Ymir groups, or rocks correlated to these groups or the sedimentary facies of the Nicola Group. Samples analyzed showed minor or no surface alteration and were not collected near crosscutting veins or intrusions that may have altered the bulk chemistry. The sampling of a range in sediment grain size from clay to sand allowed an assessment of whether grain size controls the Nd isotopic composition (Table 3-2). All samples were examined in thin section to determine primary grain size and mineralogy.

Samples were ground to < 30 μm powder, and major and trace element concentrations determined at Washington State University using XRF (x-ray fluorescence) and ICP-MS (inductively coupled plasma mass spectrometry) techniques outlined by Johnson et al. (1999) and Knaack et al. (1994), respectively. Sm-Nd isotopic analyses were conducted at the Radiogenic Isotope Facility at the University of Alberta using isotope dilution mass spectrometry (e.g., Creaser et al., 1997). Over the period of analyses presented here, the ^{143}Nd/^{144}Nd value determined for the Shin Etsu Nd standard was 0.512097 ± 13 (1SD, n = 34), in agreement with previous determinations for the standard by Tanaka et al. (2000). Data were corrected to a ^{143}Nd/^{144}Nd value of 0.512107 for Shin Etsu, which is equivalent to 0.511850 for the La Jolla standard (Tanaka et al. 2000). Chemical processing blanks were < 400 pg for Nd and Sm.

Results

Petrography

Clastic metasedimentary rocks used in this study are composed of particles varying between clay- and sand-size. These rocks vary in metamorphic grade from chlorite- to biotite-grade with the exception of two samples, which are garnet-grade (PE 99-40 and PE 99-24; Table 3-2). Samples were examined in thin section to evaluate detrital grain size and mineralogy. Determining primary mineralogy is complicated by the presence of up to 40% fine-grained opaque material in many samples, most likely graphite, and by the subsequent growth of metamorphic minerals, particularly biotite and chlorite. Most samples contain some percentage of very fine-grained material that cannot be identified in thin section; samples PE 99-40, PG 99-691, RC 99-2, RC 99-9, RC 99-14, and RC 99-17 are too fine-grained to discern the primary mineralogy. Some general observations can be made from the samples in which the primary mineralogy could be observed. Samples are divided into two groups, based on clearly differing quartz and plagioclase contents (Table 3-2). The quartz-rich group includes rocks with modal compositions of greater than 40% quartz and between 0 to 10% plagioclase; the quartz-poor group samples have modal compositions of less than 30% quartz and up to 40% plagioclase. These two groups cannot be differentiated in hand sample.

Major Element Chemistry

Major element abundances are used to provide a general lithological classification of the studied rocks (Table 3-1). SiO_2 contents vary between 48 and 89 wt. % and Al_2O_3 contents between 5 and 21 wt. %. Chemical classification of the sediments using log(SiO_2/Al_2O_3) vs. log(Na_2O/K_2O) (Pettijohn et al., 1987) defines the analyzed samples as greywacke (n = 14), lithic arenite (n = 9), and arkose (n = 1) (Fig. 3-3). Because of the known mobility of major elements during processes such as weathering and metamorphism (cf: Taylor and McLennan, 1985, and references therein), further analysis of these elements was not pursued.

Trace Element Chemistry

The analyzed samples show a broad range of trace element compositions (Table 3-1). They are enriched in the light rare earth elements (LREE) (Fig. 3-4), with La_N/Yb_N ratios between 3.85 and 11.40; La/Sc ratios range between 0.38 and 4.76, and Th/Sc ratios vary between 0.09 and 1.62 (Table 3-1; Fig. 3-5a,b,c). When compared with Nicola Group volcanic rocks and clastic sedimentary rocks of the North American miogeocline, the values for the Triassic metasedimentary rocks overlap both and form a roughly linear trend between the two (Fig. 3-5a,b,c). This variation in enrichment is also reflected in Eu/Eu* values that range between 0.6 and 1.0 (Table 3-1; Fig. 3-4); the lack of an Eu anomaly generally indicates the presence of first-cycle volcanogenic sediments (Taylor and McLennan, 1985). Using the elements La, Th, Sc, and Zr, tectonic discrimination diagrams for graywacke (Bhatia and Crook, 1986) allow distinction between oceanic island arc, continental island arc, active continental margin and passive margin environments of deposition. Samples in this study form an array between fields of high Sc – low Th, Zr, La and low Sc – high Th, Zr, La (Fig. 6). Volcanic rocks of the Nicola Group plot within the high Sc – low Th, Zr, La areas of the diagrams (Fig. 3-6). No geochemical data from Triassic sedimentary rocks of the North American miogeocline are available; Devonian miogeoclinal strata, the closest in age for which data are available, plot within the low Sc – high Th, Zr, La fields (Fig. 3-6).

Nd Isotopic Data

Sm-Nd isotopic abundances provide information on the source of detritus in clastic sedimentary rocks (e.g. Goldstein et al., 1984). Nd isotopic data are reported in epsilon units (εNd) and using depleted mantle model ages (T_{CR}; Goldstein et al., 1984). For the purpose of calculation, a depositional age of 220 Ma is assumed.

The Triassic metasedimentary rocks show a large range in εNd_{220} values, from –10 to +5.5 (Table 3-1). The relationship between εNd_{220} values and trace element abundance in the metasedimentary rocks is illustrated in Figure 5 (d,e), where εNd_{220} values are plotted against La/Sc and Th/Sc ratios. In general, samples with more positive εNd_T values show lower Th/Sc and La/Sc ratios. The data define a broadly linear trend between contrasting values for Nicola Group volcanic rocks and clastic sedimentary rocks of the North American miogeocline (Fig 5d,e, Fig. 3-7). Calculated Nd model ages for the samples show a large variation from 0.63 to 2.27 Ga, indicating contributions of clastic influx from rocks having at least two different average crustal residence ages (Table 3-2).

To investigate the extent of influence of nearby volcanic rocks on the composition of sedimentary rocks, rocks both adjacent to and remote from interlayered volcanic units were sampled. Samples RC99-10 and RC99-11 were collected from the lowest exposed part of the Ymir Group, where no volcanic rocks are known locally, and yielded εNd_{220} values of -6.9 and –8.5, respectively. Samples RC99-9 and RC99-12 were collected from the upper part of the Ymir Group, near the contact with overlying volcanic rocks of the Elise Formation, and yielded εNd_{220} values of +3.5 and +4.0. The clear influence of local volcanic sources on sediment composition is also shown by the correlation of data from petrographic analysis with εNd_{220} values. Quartz-poor samples are characterized by positive εNd_{220} values (Table 3-2) and contain a high proportion of plagioclase, indicating that they are less mature sediments. This is further supported by the lack of a Eu anomaly in quartz-poor samples RC 99-12, RC 99-16, and PE 99-44 (Table 3-1), a geochemical characteristic considered indicative of first cycle volcanogenic detritus

(Taylor and McLennan, 1985). Quartz-rich samples show negative εNd_{220} values (Table 3-2) and contain very little plagioclase, suggesting they are more mature sediments. Quartz-rich samples each possess a negative Eu anomaly (Table 3-1), a geochemical characteristic considered indicative of rocks having undergone intracrustal differentiation processes, in this case indicating that characteristic in the source rocks for the Triassic metasedimentary rocks (Taylor and McLennan, 1985).

Geochemical characteristics can be related to the grain size of rocks analyzed. For example, Jackson (1992) found that within the Cache Creek terrane of northern British Columbia and the Yukon, fine-grained clastic rocks yield generally more negative εNd_T values and older model ages than coarser grained samples. While the relationship was not without exception (for example, one sample of argillite yielded an εNd_{200} value of +6, more positive than the corresponding sandstone), the results imply that evolved continentally derived detritus may travel long distances in fine-grained sediment fractions and influence the isotopic composition of rocks quite distant from the source. However, in this study, no correlation between grain size and εNd_{220} value was found, with rocks of all grain sizes showing variable εNd_{220} values (Table 3-2, Fig. 3-8). There also is no east-west or north-south trend in the data, i.e., rocks did not display a clear evolution or break from evolved to primitive characteristics in relation to geographic position (Fig. 3-9).

Discussion and Implications

Sediment Source

The large variations in εNd_{220} values and Nd model ages of the Triassic metasedimentary rocks of the Quesnel terrane in southeastern British Columbia show that the Quesnel volcanic rocks could not have been the only source of detritus for the intercalated sedimentary strata (Fig. 3-7). A similar spread is seen in trace element abundances that vary between high Sc – low Th, Zr, La sources such as mafic volcanic rocks, and low Sc – high Th, Zr, La sources such as felsic continental crust (Fig. 3-6) (cf: Creaser et al., 1997). The Bhatia and Crook (1986) plot (Fig. 3-6) was not used to infer a tectonic setting of deposition, rather, it was used to differentiate between geochemically variable source rocks. All geochemical and isotopic data are consistent with a mixed provenance from sources with distinctly different chemical characteristics, which include a primitive source and an evolved continental source.

A North American Source?

Volcanic rocks of the Nicola Group possess Nd isotopic and geochemical characteristics consistent with a primitive arc origin (Mortimer, 1987; Smith et al., 1995), and are the most obvious proximal source with a primitive composition for the Triassic metasedimentary rocks examined here. The nature of the evolved source is more speculative, but comparison of our data with values from the North American miogeocline shows that the compositions of the more evolved samples are similar to those of the miogeoclinal strata (Figs. 3-5, 3-7). The geochemical and Nd isotopic data presented here typically form a rough linear trend intermediate between, and overlapping, data from the miogeocline and Nicola Group volcanic rocks. Input of detritus from a North American source into the Quesnel terrane is also supported by a provenance study of sedimentary rocks from the Paleozoic Harper Ranch assemblage of the Quesnel terrane, in places the basement to the Triassic strata, which also shows the North American craton to be a source of detritus (Roback and Walker, 1995).

The regional Nd isotopic study of Patchett and Gehrels (1998) on inboard terranes within the Canadian Cordillera allowed them to speculate that the source of evolved continental detritus in these terranes could be North American, but left the question of the proximity of these terranes to North America unresolved. Our data show the abundant, widespread, and consistent presence of evolved continental material within the Upper Triassic sedimentary record of the Quesnel terrane. Without the ability to distinguish evolved from primitive samples in the field, 16 out of 24 samples in this study show negative εNd_{220} values. From this, it is reasonable to estimate that at least 50% of all sedimentary rocks within the Quesnel terrane of southern British Columbia show evidence for continental affinity. This abundance, along with a lack of correlation between εNd values and grain size or geographic location, can be interpreted to record proximity of the continental source to the Triassic depositional basin. The similarity of this evolved signature to more inboard strata of the North American miogeocline, combined with the geological evidence of a stratigraphic tie of Quesnel terrane strata to rocks of, or tied to, North America, strongly suggests that North America was the source of the evolved detritus.

Other Possibilities

An alternative interpretation, proposed by Ghosh and Lambert (1989), is that a block of continental crust to the west of a Quesnel intra-oceanic arc, having an Nd model age of ~1.9 Ga, contributed the evolved material. That hypothesis could be compatible with the notion of an alpine rift system for the Cordillera as proposed by Struik (1987), in which parts of the North American craton rifted during extension between late Proterozoic and Devonian time, and which, if exposed, may have been a source of detritus for surrounding sedimentary basins. However, such a block has not been observed, and it should be noted that the interpretation of Ghosh and Lambert (1989) was made prior to the availability of any Nd isotopic data from rocks of the North American miogeocline. Limited Nd data are available from Cache Creek terrane rocks outboard of the Quesnel terrane; in Cache Creek clastic sedimentary rocks have generally primitive εNd_T values and coarse-grained rocks are largely primitive (Jackson, 1992; Patchett and Gehrels, 1998). This suggests that local sources west of the Quesnel terrane did not have an evolved continental nature. Further study on sedimentary rocks from the Cache Creek and other outboard terranes is needed to substantiate this suggestion.

Implications

Quesnel Terrane

The data enable conclusions to be drawn about the broad Nd isotopic characteristics of the Quesnel terrane in southeastern British Columbia. Metasedimentary rocks of the Nicola, Slocan and Ymir groups all show a range of evolved and primitive εNd_{220} values; this supports their previously proposed correlation. Our data also show a significant difference in Nd isotopic characteristics between the sedimentary and volcanic facies of Triassic rocks of the Quesnel terrane. All of the geological and Nd isotopic data now available (this study; Smith et al., 1995; Ghosh, 1995) show a prevalence of sedimentary rocks with evolved Nd isotopic values in the east, contrasting with a dominance of volcanic rocks with primitive Nd isotopic values in the west. Thus, the overall Nd isotopic character of supracrustal rocks in the Quesnel terrane in southeastern British Columbia is more evolved in the east and more primitive in the west. This should be taken into account when considering the potential contamination that local rocks could contribute to intrusive igneous bodies (e.g., Ghosh, 1995).

Tectonic Setting

The tectonic setting of the Quesnel terrane has been widely described as that of a Triassic to early Jurassic intra-oceanic arc, which was accreted to the North American continental margin starting in mid-Jurassic time (e.g., Ghosh, 1995; Monger et al., 1982, 1991). However, the evolved Nd isotopic and geochemical features of Triassic metasedimentary rocks of all grain sizes from the Quesnel terrane in southeastern British Columbia are inconsistent with sediment deposition as part of an intra-oceanic arc. Similarly inconsistent are the recent discoveries of older supracrustal successions beneath apparently thin veneers of Triassic rocks of the Quesnel terrane in southeastern British Columbia (Erdmer et al. 2001a, 2001b). Those pre-Triassic strata have been interpreted to be pericratonic in origin, and contain U-Pb and Nd isotope evidence of derivation, at least in part, from a Precambrian source region.

Instead, the interpretation that the Quesnel arc, and other rocks currently assigned to the Quesnel terrane, formed as a continental margin assemblage on ancestral North America is offered, where a Triassic back-arc depositional basin received sediment input from both a primitive magmatic arc and the continent. This interpretation differs from that presented by Ghosh (1995), which was based upon Nd and Sr isotope data from igneous bodies that have intruded the Quesnel terrane in southern British Columbia, and form part of it.

On the basis of their primitive εNd_T and initial $^{87}Sr/^{86}Sr$ values (hereafter Sr_T), Triassic and early Jurassic igneous rocks of the Quesnel terrane (215-190 Ma) were interpreted by Ghosh (1995) to have been emplaced into Paleozoic oceanic crust outboard of North America. Ghosh (1995) interpreted a shift from these primitive εNd_T and Sr_T values to more evolved εNd_T and Sr_T values in mid-Jurassic and younger igneous rocks (<180Ma), to reflect the onset of crustal contamination caused by progressive obduction of the Quesnel terrane onto the continental margin starting in mid-Jurassic time. The crustal contamination observed by Ghosh (1995) in post mid-Jurassic igneous rocks indeed increases from west to east, manifest as a strong eastward decrease in εNd_T and increase in Sr_T. One line of evidence called upon as supportive of an intra-oceanic origin for the Quesnel arc is the appearance of strongly evolved εNd_T values in mid-Jurassic time, and the absence of such values in Triassic to early Jurassic time.

Several points relating to the study of Ghosh (1995) require discussion. The strongly evolved εNd_T values in mid-Jurassic igneous rocks are evident only east of longitude 119-120°W, comprising 23 igneous rock analyses with negative εNd_T values. By comparison, an early Jurassic hornblende andesite from the Rossland Group was the only sample of Triassic to early Jurassic igneous rocks analyzed by Ghosh (1995) east of longitude 119°W (Fig. 3-10a). All remaining Quesnel terrane samples of Ghosh (1995) east of longitude 119°W are Paleozoic samples from a Quesnel terrane basement assemblage or from a separate terrane, including a massive volcanic rock from the Kaslo Group, which has been interpreted as part of the Slide Mountain terrane, and greenschist, greenstone and amphibolite from rocks part of, or correlated to, the Harper Ranch assemblage. Thus, the interpreted shift from primitive to evolved isotopic signatures in igneous rocks in mid-Jurassic time rests entirely on one pre mid-Jurassic datum. Substantially more pre–middle Jurassic isotopic data from east of 119°W are required to verify the notion of an isotopic shift.

Furthermore, late Triassic to early Jurassic granitoid plutons of the Quesnel terrane have εNd_T values comparable with rocks of mid- to late Jurassic age and younger at the same longitude (Fig. 3-10; see Ghosh 1995). It is also apparent that a small but clear decrease in εNd_T from west of 121°W to 119-120°W exists in these Triassic to early Jurassic plutons (Fig. 3-10a), just as in mid-Jurassic and younger igneous rocks at the same longitude (Figs. 3-10b-d). The sole outlier in a general pattern of decreasing εNd_T from west to east in 85 Mesozoic rocks of the Quesnel terrane analyzed by Ghosh (1995) remains the single hornblende andesite from the Rossland Group.

Thus, a pattern of eastwardly more evolved isotopic signatures in igneous rocks of the Quesnel terrane has been a characteristic feature since Triassic time. Such a pattern does not require obduction of an exotic oceanic terrane, but could equally result from the development of the Quesnel arc on an eastwardly thickening wedge of continentally derived material. This is consistent with formation of the Quesnel terrane on or near the edge of the North American passive margin, as required by the isotopic data for Triassic metasedimentary rocks presented here. Any pattern of eastwardly increasing contamination in igneous rocks could have been amplified by contamination from Triassic supracrustal rocks, which are demonstrably intruded. The latter are dominated by isotopically evolved metasedimentary rocks in the east, and by isotopically primitive volcanic rocks in the west.

Conclusions

Nd isotopic and trace element geochemical compositions of Triassic clastic metasedimentary rocks of the Quesnel terrane in southeastern British Columbia show a mixed provenance between a primitive arc and evolved continental crust. The widespread occurrence of clastic sedimentary rocks of a range of grain sizes with evolved compositions within the Quesnel terrane does not support its development as an intra-oceanic arc. These more evolved metasedimentary rocks show Nd isotopic compositions that are indistinguishable from contemporaneous clastic sedimentary rocks of the North American miogeocline. The abundant, consistent and widespread continental signature within Triassic sedimentary rocks of the Quesnel terrane can be interpreted to indicate that the arc was proximal to North America throughout its development. These new data, coupled with geological data describing unconformable relationships between Quesnel terrane rocks and strata tied to or of North American origin, lead to the conclusion that the Quesnel terrane in southeastern British Columbia formed as an arc assemblage on or near the ancient North American margin in late Triassic time.

TABLE 3-1. MAJOR AND TRACE ELEMENT CONCENTRATIONS AND CALCULATED RATIOS

sample	RC99	RC99	RC99	RC99	RC99	RC99	RC99	RC99	RC99	RC99	RC99	RC99
	1	2	3	4	5	6	7	8	9	10	11	12
Major elements (wt. %)												
SiO_2	51.87	64.16	75.52	86.51	74.34	65.07	70.25	74.83	58.51	69.08	72.04	59.73
Al_2O_3	17.08	19.97	6.88	5.20	7.10	18.52	13.38	11.52	16.68	13.77	13.26	17.81
TiO_2	0.918	0.842	0.342	0.260	0.348	0.892	0.654	0.702	0.792	0.670	0.739	0.676
FeO	10.10	4.57	1.36	2.01	2.54	6.64	4.17	3.32	6.95	4.37	3.26	7.04
MnO	0.168	0.021	0.055	0.041	0.093	0.084	0.122	0.112	0.136	0.071	0.032	0.101
CaO	8.18	0.56	9.86	2.99	10.65	0.85	3.38	3.31	8.40	3.80	2.91	4.75
MgO	4.86	1.58	2.21	0.35	1.51	2.83	4.34	1.83	3.57	3.83	2.52	3.25
K_2O	3.04	3.51	0.64	0.53	1.50	3.47	2.66	2.34	1.32	2.77	2.38	2.56
Na_2O	3.42	4.41	2.93	2.06	1.73	1.48	0.91	1.87	3.34	1.51	2.73	3.73
P_2O_5	0.365	0.375	0.190	0.066	0.178	0.172	0.139	0.157	0.285	0.134	0.127	0.349
Trace elements (ppm)												
Ba	1153	1521	135	202	743	671	831	509	769	354	493	1231
Rb	70.72	69.91	18.75	23.75	42.67	150.28	92.65	93.86	34.73	131.17	97.71	66.50
Cs	4.25	3.77	0.83	1.08	2.69	7.31	4.00	5.00	1.41	10.26	7.43	3.34
Sr	602	304	289	57	380	158	174	143	546	155	205	809
Pb	8.6	9.5	7.6	9.3	4.7	17.9	10.4	23.9	6.3	9.9	12.9	7.7
Th	2.9	4.9	3.5	4.9	3.2	13.2	9.4	12.9	3.1	10.1	10.3	3.9
U	1.29	2.90	1.56	1.25	1.86	2.43	1.48	2.75	1.70	2.45	2.43	2.58
$Zr^{\#}$	69	106	188	234	114	192	171	387	96	193	316	95
Nb	2.73	4.22	5.38	5.40	4.31	19.94	12.44	14.89	4.55	13.18	14.55	4.33
Ta	0.18	0.33	0.40	0.40	0.31	1.47	0.97	1.14	0.30	0.98	1.11	0.31
Hf	1.79	2.25	4.56	6.01	2.89	5.61	4.77	9.61	2.72	5.19	8.12	2.53
Y	18.62	26.01	15.84	14.48	22.41	37.11	25.36	38.57	25.15	30.71	31.09	22.77
La	12.60	18.54	12.69	16.32	11.82	41.57	27.00	52.39	14.75	31.61	27.90	15.93
Ce	23.98	30.17	22.61	31.45	19.81	77.00	51.73	97.20	28.10	57.92	52.26	29.46
Pr	3.09	4.12	2.85	3.43	2.85	8.75	5.77	10.81	3.56	6.87	6.29	3.87
Nd	13.70	17.50	11.41	13.48	12.22	33.73	22.49	42.00	15.83	27.02	25.14	17.39
Sm	3.77	4.14	2.64	3.01	3.26	7.49	5.07	8.81	4.13	6.09	5.56	4.34
Eu	1.00	1.20	0.61	0.65	0.65	1.59	1.04	1.94	1.18	1.28	1.18	1.46
Gd	3.86	3.98	2.55	2.72	3.39	6.81	4.57	7.07	4.34	5.53	4.94	4.26
Tb	0.59	0.64	0.40	0.42	0.57	1.12	0.75	1.14	0.69	0.91	0.84	0.67
Dy	3.54	3.98	2.50	2.49	3.58	6.75	4.45	6.63	4.32	5.52	5.22	3.99
Ho	0.72	0.89	0.52	0.50	0.77	1.39	0.91	1.33	0.91	1.15	1.10	0.83
Er	1.88	2.45	1.45	1.37	2.21	3.71	2.46	3.53	2.48	3.06	3.05	2.26
Tm	0.27	0.36	0.22	0.20	0.32	0.55	0.37	0.53	0.37	0.45	0.46	0.33
Yb	1.69	2.23	1.50	1.32	2.20	3.33	2.32	3.30	2.29	2.87	2.91	2.15
Lu	0.26	0.34	0.24	0.22	0.36	0.52	0.36	0.52	0.37	0.45	0.46	0.34
Sc	32.86	23.80	4.64	4.20	11.43	21.68	13.70	11.01	22.94	16.73	12.96	18.46
$V^{\#}$	278	395	43	23	66	120	99	87	210	89	83	264
$Cr^{\#}$	44	146	20	16	30	81	75	49	40	67	52	63
$Ni^{\#}$	17	10	6	10	15	45	37	35	14	58	18	32
$Cu^{\#}$	133	45	15	10	24	40	26	52	70	55	11	109
$Zn^{\#}$	203	47	24	22	51	100	92	55	142	133	52	116
$Ga^{\#}$	17	21	5	4	10	24	17	14	18	18	15	16
Calculated Ratios												
$Eu/Eu^{*\#\#}$	0.80	0.91	0.72	0.70	0.60	0.68	0.66	0.75	0.85	0.68	0.69	1.04
$La_N/Yb_N{}^{\#\#\#}$	5.3	6.0	6.1	8.9	3.8	9.0	8.3	11.4	4.6	7.9	6.9	5.3

Notes: Major element analyses by XRF and normalized to 100% (volatile free). Trace element analyses performed by ICP-MS except thosedenoted by superscript "#" which are perfumed by XRF.

$^{\#\#}Eu/Eu^{*}=Eu_N/(Sm_N{*}Gd_N)^{1/2}$ (Taylor and McLennan, 1985).

$^{\#\#\#}$ Subscript "N" denotes values normalised to chondrite values of Sun and McDonough (1989).

TABLE 1. CON'T

RC99 14	RC99 15	RC99 16	RC99 17	98JU 250	98JU 515	98JU 624	PE99 24	PE99 40	PE99 43	PE99 44	PG99 691
59.95	75.05	60.29	73.86	80.90	75.61	87.23	74.72	64.34	62.33	55.19	62.33
15.89	12.13	16.25	9.71	8.24	11.59	7.08	13.10	20.32	17.97	18.67	21.07
0.942	0.663	0.767	0.570	0.492	0.569	0.450	0.677	1.063	0.938	0.711	0.832
5.84	4.10	6.59	4.05	2.04	2.95	1.57	5.46	6.92	6.88	7.08	7.89
0.057	0.095	0.110	0.092	0.037	0.138	0.028	0.062	0.063	0.074	0.134	0.140
8.29	1.37	7.09	4.92	3.60	1.79	0.26	1.48	0.56	3.55	7.12	0.26
3.32	2.54	3.48	3.07	1.21	3.17	0.30	1.84	2.36	3.50	4.02	2.18
2.28	2.04	2.55	1.85	1.67	2.64	0.87	1.13	2.73	3.11	2.25	3.49
3.09	1.91	2.51	1.60	1.70	1.45	2.10	1.40	1.47	1.48	4.49	1.63
0.354	0.103	0.377	0.271	0.101	0.097	0.096	0.133	0.169	0.157	0.337	0.180
1047	2516	2128	1637	463	1335	244	259	424	627	799	966
53.16	57.12	45.73	46.30	57.8	105.7	32.5	70.2	129.5	145.5	75.8	158.7
1.75	1.67	2.70	2.20	1.86	10.03	1.44	2.58	3.96	9.33	2.51	6.71
787	307	827	363	200	119	129	118	196	230	430	247
4.2	9.4	5.5	9.8	9.9	13.6	7.3	16.4	21.4	19.0	5.8	19.6
5.0	5.5	2.7	3.2	6.8	8.2	6.4	9.9	15.3	14.8	3.4	13.6
1.94	1.85	1.28	2.12	1.70	1.66	1.51	2.36	3.02	2.81	1.62	2.63
156	130	94	88	245	146	363	274	246	242	69	141
10.10	8.11	5.10	6.86	9.79	11.79	9.25	18.04	20.87	21.27	3.45	19.45
0.64	0.59	0.33	0.48	0.74	0.87	0.68	1.25	1.53	1.60	0.22	1.42
3.95	3.65	2.55	2.15	6.12	4.01	8.47	7.36	7.10	7.74	1.94	4.74
26.95	29.52	22.65	24.51	22.84	23.06	19.46	26.17	31.84	40.50	18.84	32.69
26.45	18.69	16.25	15.14	24.96	19.06	22.90	26.92	21.87	47.43	13.70	30.56
47.23	33.60	30.19	22.01	49.86	39.56	45.50	56.48	51.30	91.98	27.38	73.67
5.91	4.29	3.81	3.34	5.32	4.20	4.82	6.04	5.01	10.48	3.40	6.86
23.93	17.47	16.27	14.08	20.74	16.65	18.37	23.66	19.47	41.87	15.21	27.29
5.51	4.44	4.21	3.67	4.46	3.69	3.80	5.29	4.65	9.43	3.94	6.51
1.61	1.40	1.39	0.89	1.01	0.87	0.82	1.19	1.08	1.94	1.23	1.40
5.04	4.60	4.08	3.89	4.19	3.63	3.47	4.47	4.45	7.99	3.69	5.86
0.79	0.79	0.67	0.62	0.65	0.61	0.57	0.76	0.82	1.32	0.58	1.00
4.65	5.12	4.03	3.78	3.98	3.92	3.46	4.56	5.32	7.83	3.48	6.32
0.96	1.11	0.84	0.78	0.82	0.82	0.70	0.94	1.16	1.55	0.71	1.29
2.53	3.11	2.29	2.19	2.19	2.38	1.95	2.80	3.41	4.14	1.90	3.53
0.38	0.48	0.33	0.32	0.34	0.35	0.29	0.46	0.53	0.61	0.28	0.53
2.36	3.16	2.13	2.00	2.12	2.35	1.85	3.18	3.43	3.78	1.74	3.35
0.38	0.54	0.34	0.32	0.35	0.38	0.30	0.52	0.55	0.60	0.28	0.55
19.82	22.94	19.96	13.85	6.8	15.4	5.0	15.8	20.7	24.5	26.9	26.1
179	146	207	111	42	72	33	76	127	99	169	124
77	70	48	142	26	65	25	45	87	82	38	83
27	36	20	86	9	37	9	30	43	42	18	60
40	130	113	56	12	94	6	30	38	17	78	63
89	92	80	120	31	78	16	71	88	106	94	104
17	16	18	10	10	15	9	16	27	21	16	26
0.93	0.95	1.02	0.72	0.71	0.72	0.69	0.75	0.73	0.68	0.99	0.69
8.0	4.2	5.5	5.4	8.4	5.8	8.9	6.1	4.6	9.0	5.7	6.5

TABLE 3-2. ROCK TYPE, Sm AND Nd CONCENTRATIONS, AND ISOTOPIC DATA

Sample	Rock type*	Petrography#	Sm (ppm)	Nd (ppm)	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd**	T_{DM}## (Ga)	eNd_{220}***
RC99-1	siltstone	QP	4.33	18.09	0.1446	0.512758 ± 6	0.89	+3.8
RC99-2	C-rich silty-sandstone	U	3.50	16.09	0.1314	0.512587 ± 11	1.07	+0.8
RC99-3	sandy-siltstone	QR	1.72	6.89	0.1514	0.512220 ± 9	2.30	-6.9
RC99-4	sandy-siltstone	QR	2.09	9.59	0.1316	0.512168 ± 6	1.84	-7.3
RC99-5	sandy-siltstone	QR	2.52	9.30	0.1636	0.512474 ± 11	2.09	-2.3
RC99-6	phyllite (silt)	QR	8.35	36.90	0.1368	0.512096 ± 7	2.11	-8.9
RC99-7	C-rich phyllite (mud-silt)	QR	2.48	10.80	0.1387	0.512114 ± 9	2.12	-8.6
RC99-8	phyllite (silt-sand)	QR	4.75	20.45	0.1403	0.512118 ± 11	2.16	-8.6
RC99-9	phyllite (mud-sand)	U	3.81	16.24	0.1420	0.512738 ± 7	0.90	+3.5
RC99-10	siltstone	QR	7.50	35.70	0.1269	0.512185 ± 7	1.71	-6.9
RC99-11	siltstone	QR	5.55	27.72	0.1210	0.512053 ± 8	1.82	-8.5
RC99-12	phyllite (mud-silt)	QP	4.49	18.84	0.1442	0.512765 ± 11	0.87	+4.0
RC99-14	limey-siltstone	U	4.60	22.03	0.1263	0.512776 ± 8	0.68	+4.7
RC99-15	siltstone	QR	4.07	17.87	0.1378	0.512356 ± 7	1.62	-3.9
RC99-16	sandy-siltstone	QP	3.55	16.02	0.1338	0.512832 ± 7	0.63	+5.6
RC99-17	sandy-siltstone	U	3.52	14.95	0.1424	0.512322 ± 7	1.79	-4.6
98JU-250	sandy-siltstone	QR	4.18	21.10	0.1198	0.512119 ± 7	1.69	-8.0
98 JU-515	siltstone	QR	3.59	17.32	0.1254	0.512124 ± 8	1.79	-8.0
98JU-624	pyritic sandstone	QR	3.96	20.85	0.1148	0.512104 ± 6	1.63	-8.1
PE99-24	phyllite (mud-silt)	QR	6.24	30.87	0.1221	0.512111 ± 12	1.75	-8.2
PE99-40	phyllite (mud-sand)	U	4.56	21.15	0.1303	0.512115 ± 9	1.91	-8.3
PE99-43	siltstone	QR	10.24	43.56	0.1422	0.512092 ± 7	2.27	-9.1
PE99-44	silty-sandstone	QP	3.23	14.04	0.1392	0.512662 ± 8	1.02	+2.1
PG99-691	muddy-siltstone	U	5.96	29.42	0.1225	0.512135 ± 8	1.71	-7.7
8006G###	not available	not available	6.00	33.18	0.1139	0.511902 ± 17	1.92	-12.0
8035A###	not available	not available	2.94	14.34	0.1229	0.511897 ± 30	2.12	-12.4
88GJ-88****	argillite	not available	ND	18.79	0.0978	0.512256 ± 8	1.19	-4.7

Notes: ND - no data

*All rocks are chlorite to biotite grade metamorphic rocks except of PE 99-40 and PE 99-24, which are garnet-grade.

Grain size of detrital particles is given for comparitive purposes.

#QR - quartz-rich group (>40% quartz, 0-<10% plagioclase), QP- quartz-poor group (<30% quartz, up to 40% plagioclase), U-undetermined because too fine-grained

** ± 2 SE

##Based on the model of Goldstein (1984).

***Where $eNd_{(T)} = [(^{143}Nd/^{144}Nd)_{Sample(T)}/^{143}Nd/^{144}Nd_{CHUR(T)})-1]*10^4$(DePaolo and Wasserburg, 1976), values used were $^{143}Nd/^{144}Nd_{CHUR,today} = 0.512638$ (Goldstein, 1984) and $^{147}Sm/^{144}Nd_{CHUR,today} = 0.1966$ (Jacobson and Wasserburg, 1980).

###Data from Ghosh and Lambert (1989).

****Data from Patchett and Gehrels (1998).

Table 3-3. Sample locations

sample	latitude (N)	longitude (W)
RC99-1	50.253	118.742
RC99-2	50.240	118.606
RC99-3	50.235	118.606
RC99-4	50.218	118.549
RC99-5	50.219	118.548
RC99-6	50.167	117.785
RC99-7	50.214	117.720
RC99-8	50.142	117.608
RC99-9	49.407	117.195
RC99-10	49.448	117.176
RC99-11	49.448	117.176
RC99-12	49.283	117.212
RC99-14	50.138	120.284
RC99-15	50.257	120.231
RC99-16	50.528	120.253
RC99-17	50.778	120.323
98JU-250	50.419	119.095
98 JU-515	50.366	119.098
98JU-624	50.400	118.958
98JU-162	50.438	119.138
PE99-24	50.497	119.443
PE99-40	50.506	119.467
PE99-43	50.275	119.157
PE99-44	50.387	119.309
PG99-691	50.451	119.009

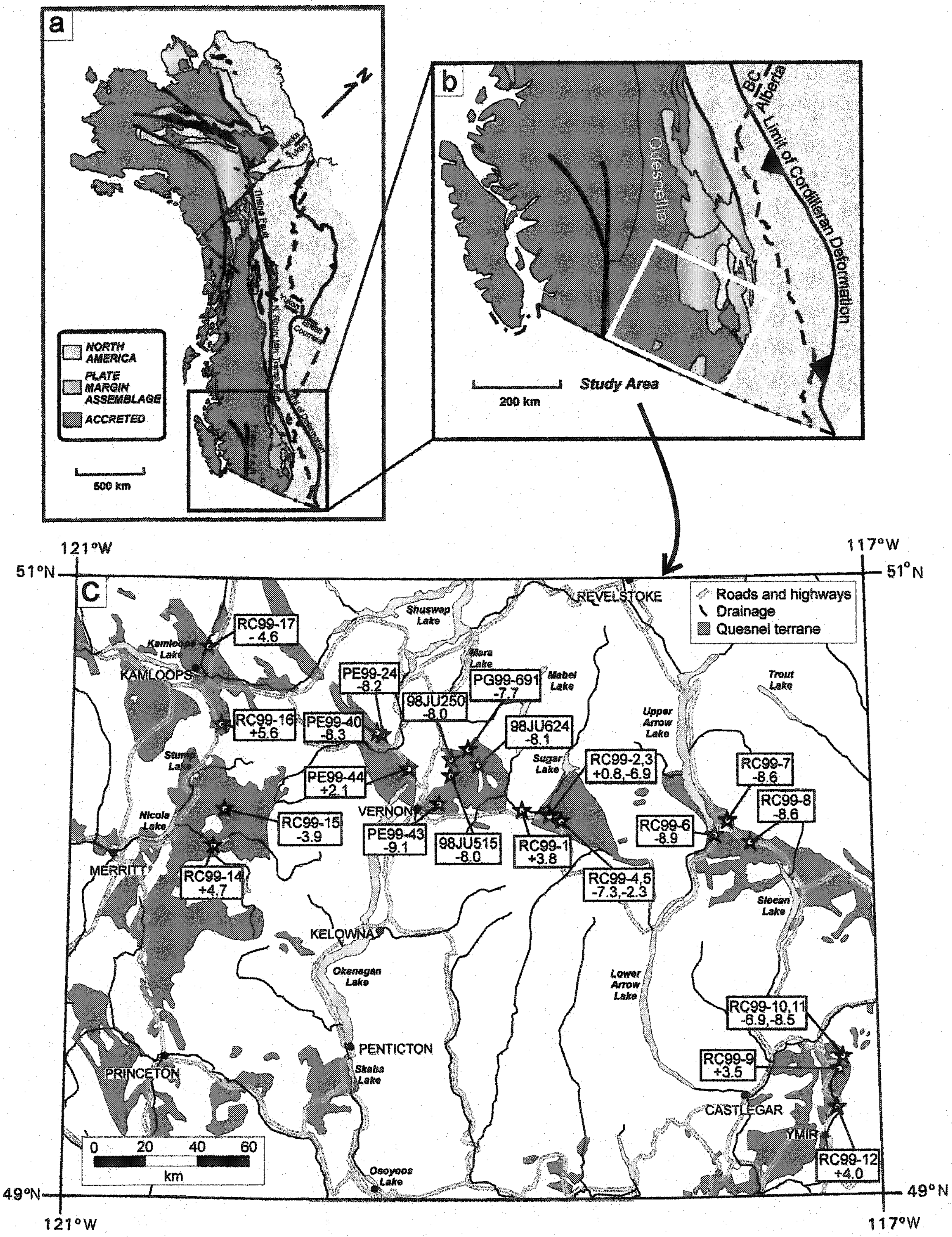

Figure 3-1. Maps showing a) the North American Cordillera in Canada and Alaska, differentiating rocks presently interpreted to be North American, plate margin assemblage, and accreted assemblages; b) outline of the Quesnel terrane and study area; and c) rocks of the Quesnel terrane (in gray), together with sample locations and Nd$_{220}$ values determined in this study (modified from Wheeler and McFeely, 1991). See text for discussion.

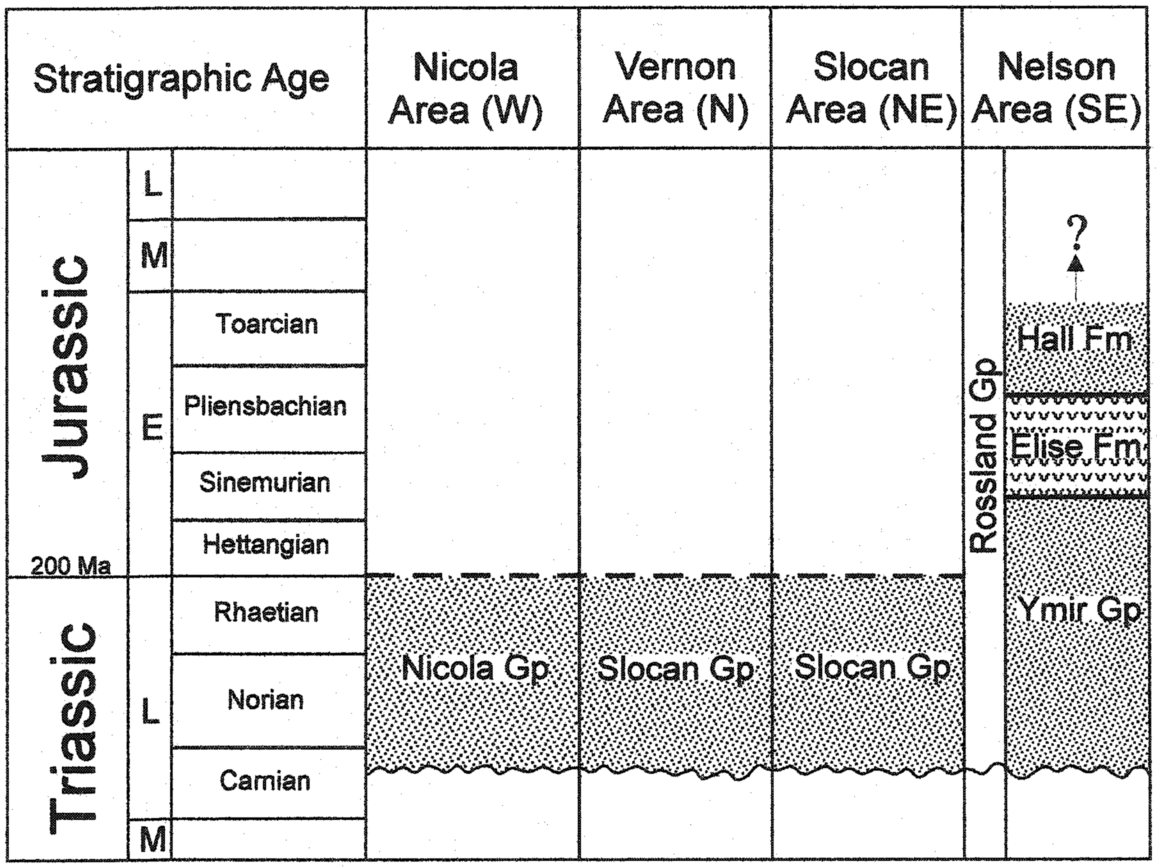

Figure 3-2. Stratigraphic correlation chart of Triassic metasedimentary rocks in southeastern British Columbia (after Little, 1960; Okulitch and Cameron, 1976; Klepacki and Wheeler, 1985; Höy and Andrew, 1988).

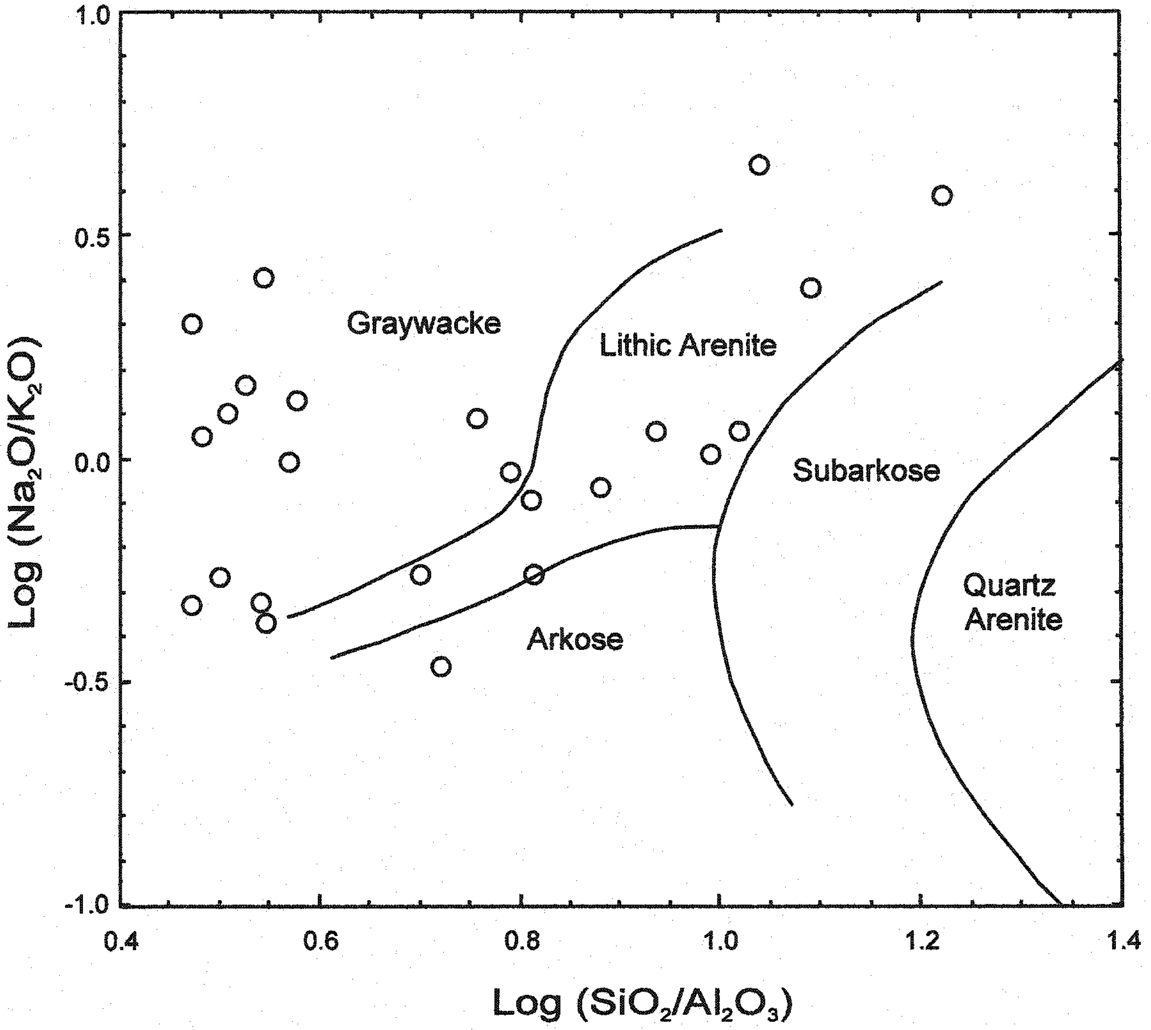

Figure 3-3. Chemical classification diagram of Pettijohn et al. (1987), showing analyzed samples falling in the fields of graywacke (n = 14), lithic arenite (n = 9) and arkose (n = 1).

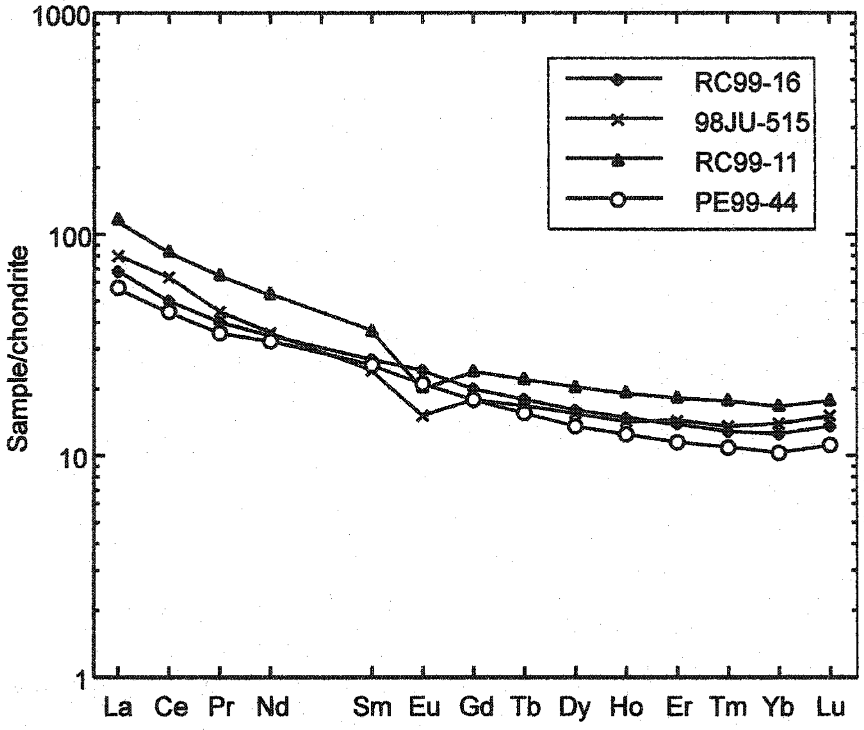

Figure 3-4. Chondrite normalized (Sun and McDonough, 1989) REE plot showing end member examples of primitive (RC99-16, RC99-11) and evolved (98JU515, PE99-44) Triassic metasedimentary rocks in southeastern British Columbia.

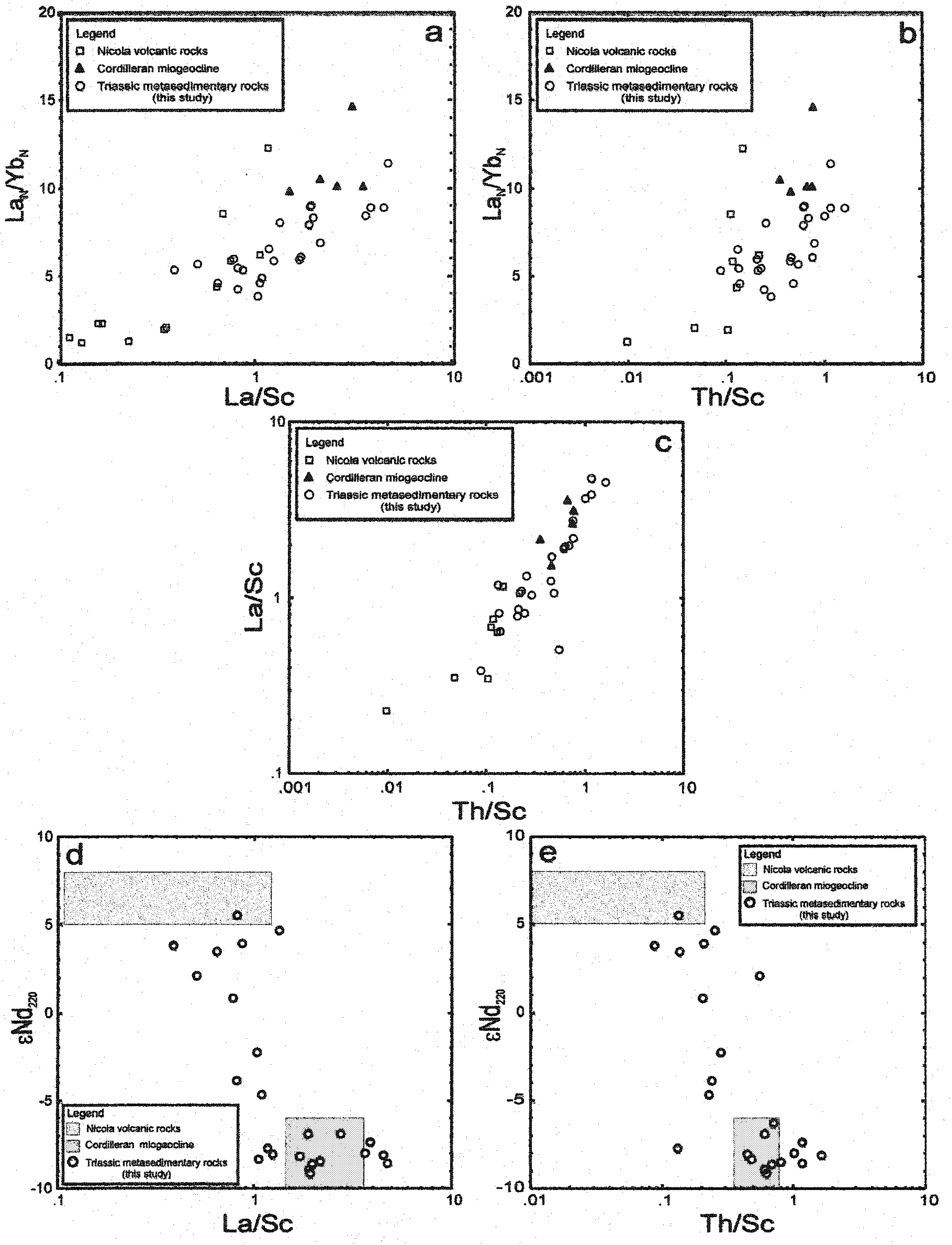

Figure 3-5. Plots a-c: Trace element variation diagrams for Triassic metasedimentary rocks; results overlap and are intermediate between values from the Nicola Group volcanic rocks (Mortimer, 1987) and sedimentary rocks of the North American miogeocline (data from Devonian strata, Garzione et al.,1997). Plots d,e: relationship between trace element ratios and Nd_{220} values of Triassic metasedimentary rocks that both overlap and are intermediate between values for the Nicola Group volcanic rocks (Nd isotopic data from Smith et al., 1995) and sedimentary rocks of the North American miogeocline (Nd isotopic data from Mississippian-Triassic strata from Jackson, 1992; Boghossian et al.1996; and Garzione et al., 1997).

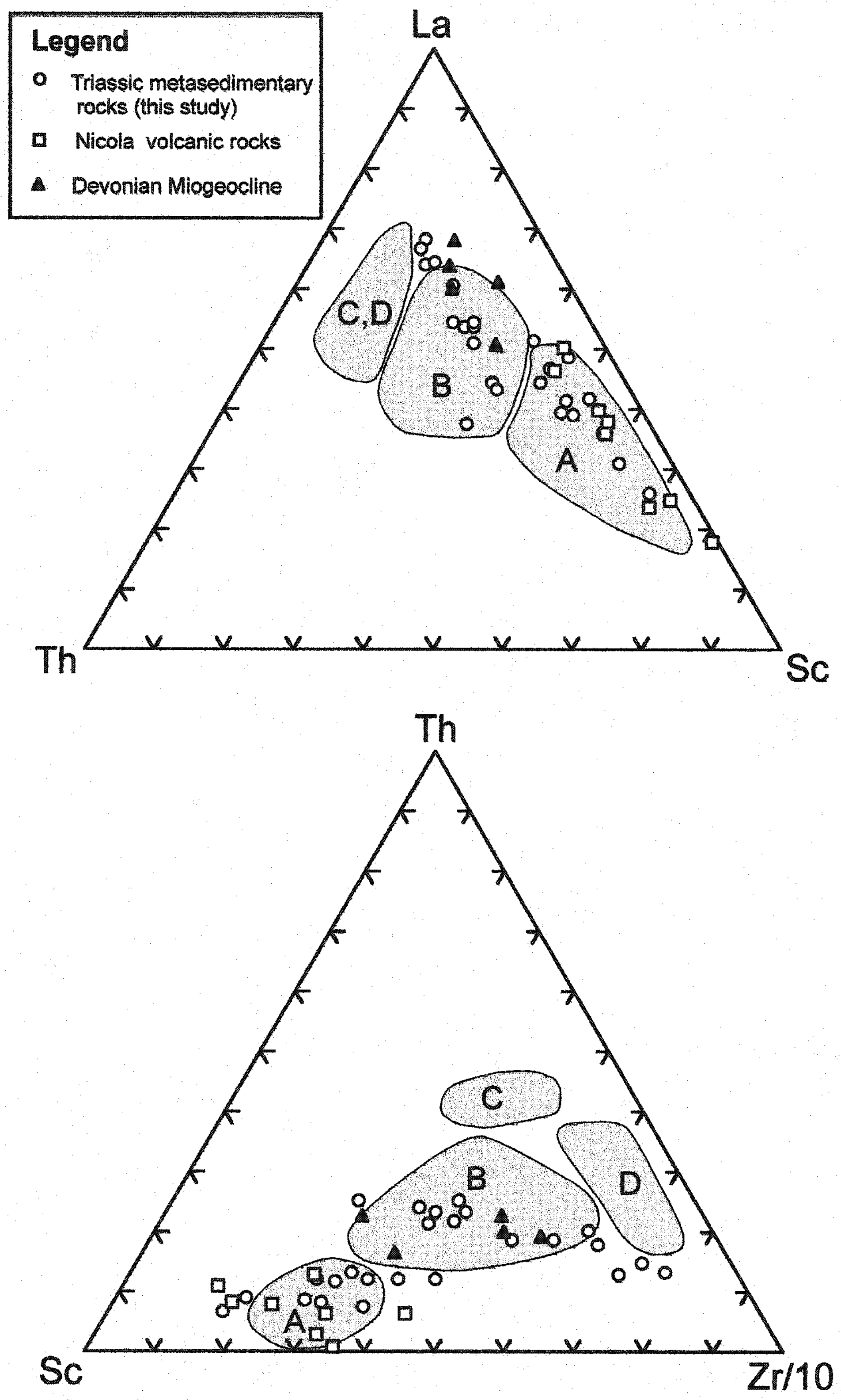

Figure 3-6. Tectonic discrimination diagrams for graywakes from Bhatia and Crook (1986); fields displayed are A: oceanic island arc, B: continental island arc, C: active continental margin, D: passive margin. Plotted for comparisonare data from Nicola Group volcanic rocks, (Mortimer, 1987) and Devonian strata of the North American miogeocline (Garzione et al., 1997).

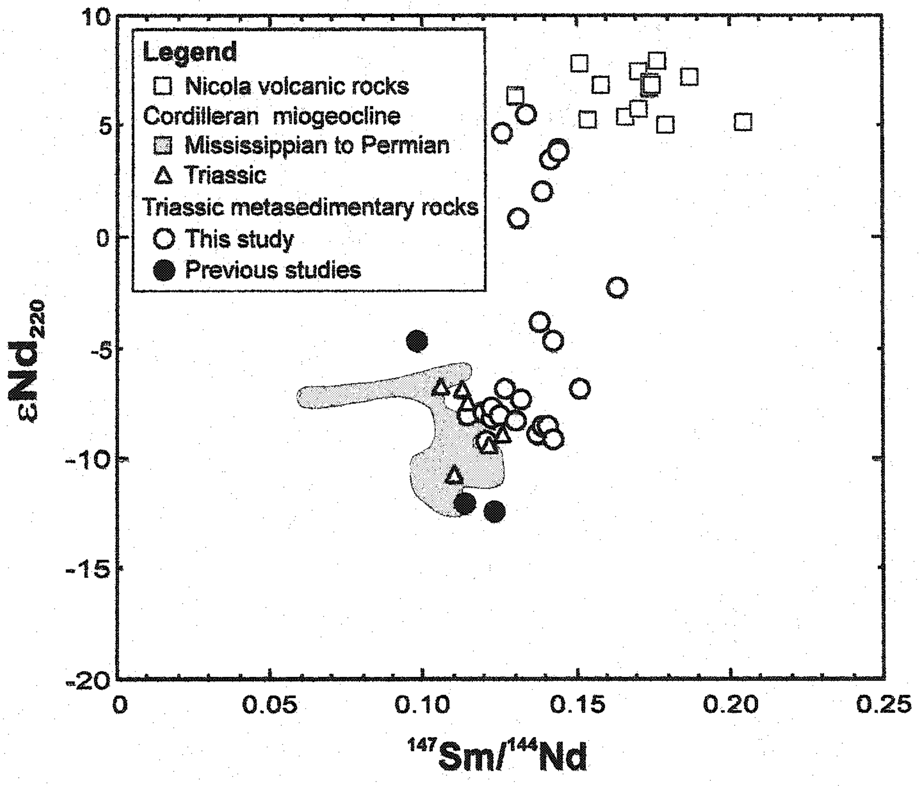

Figure 3-7. Sm-Nd isotopic data from Triassic metasedimentary rocks in southeast British Columbia. Shown for comparison are data from Mississippian to Triassic strata of the Canadian Cordilleran miogeocline (Jackson, 1992; Boghossian et al., 1996; Garzione et al., 1997) and volcanic rocks of the Upper Triassic Nicola Group (Smith et al., 1995). The Triassic metasedimentary rocks overlap the area between miogeocline and Nicola Group values and are compatible with a mixed origin between these sources.

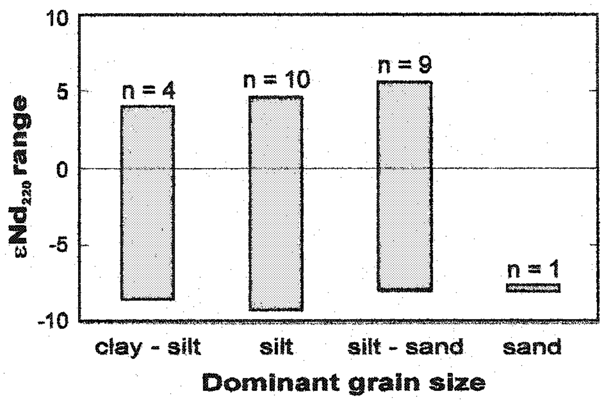

Figure 3-8. Plot of grain size against Nd isotopic composition, showing an absence of correlation in the analyzed samples. Grain size was measured by graduated ocular in thin section.

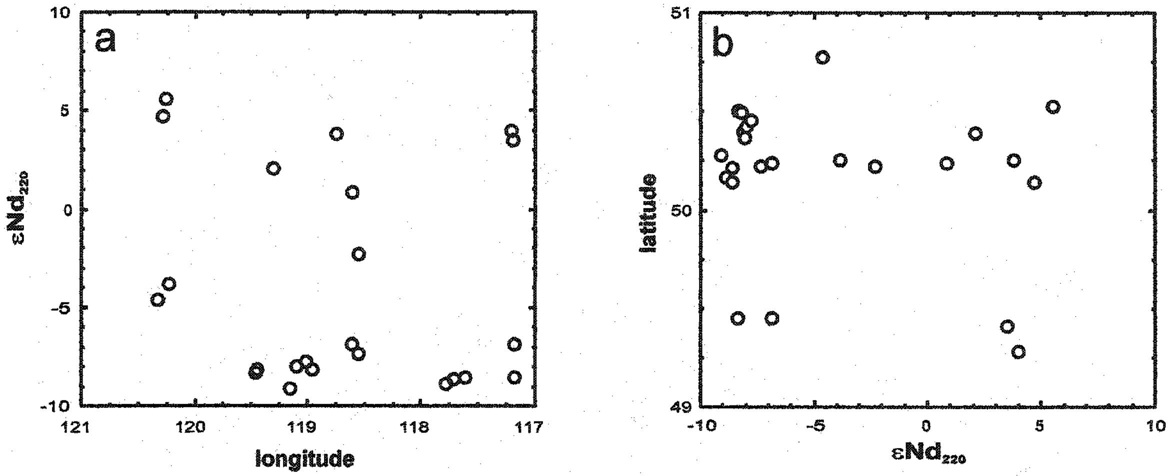

Figure 3-9. Distribution of Nd$_{220}$ values of Triassic metasedimentary rocks in southeastern British Columbia in (a) east-west and (b) north-south directions.

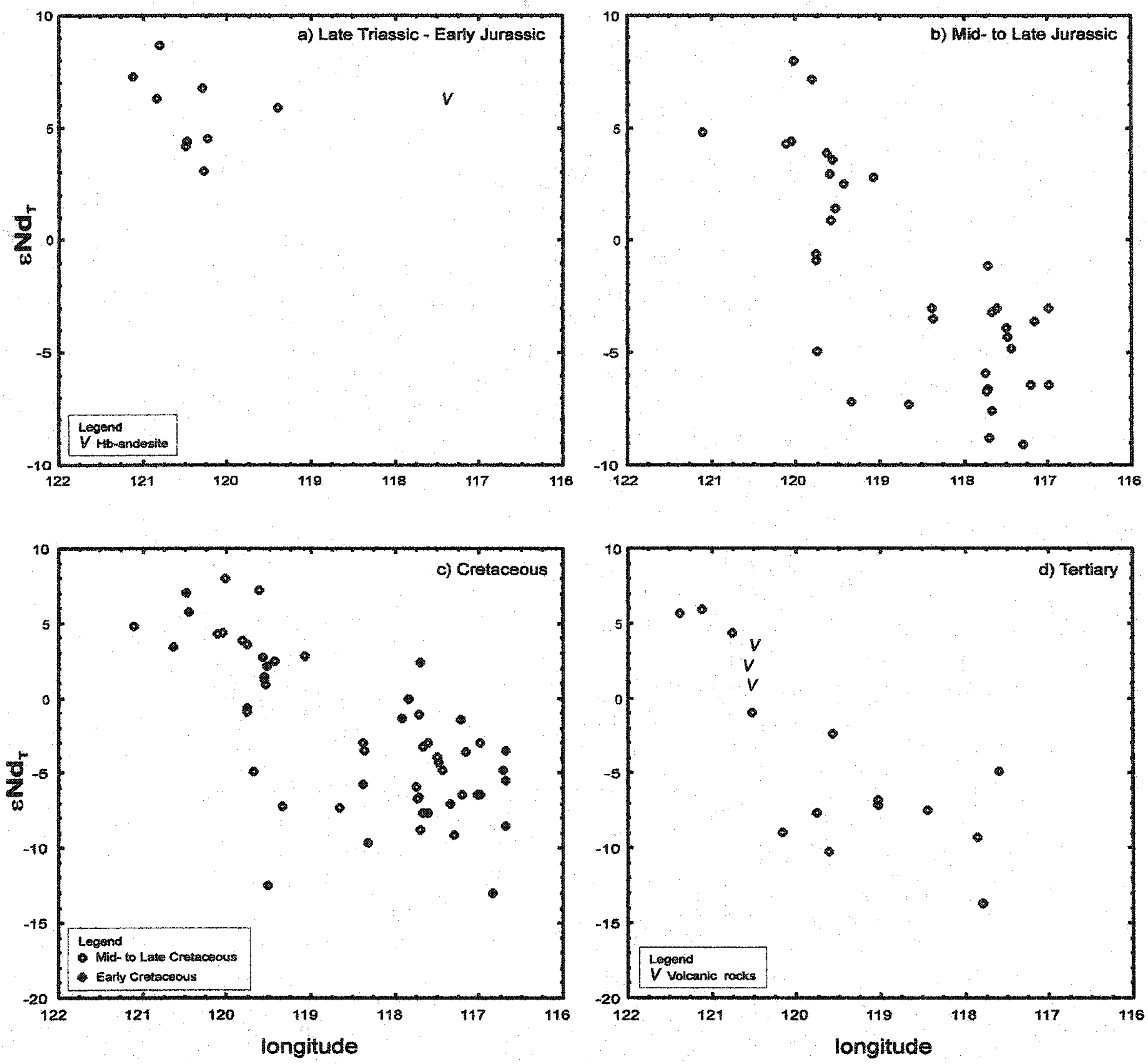

Figure 3-10. East-west distribution of εNd_T values of igneous rocks intruding the Quesnel terrane in southeastern British Columbia from Ghosh (1995). All samples are from intrusive igneous rocks except where noted. Periods are (a) Late Triassic to Early Jurassic, (b) Middle to Late Jurassic, (c) Cretaceous and (d) Tertiary. With the exception of a single volcanic rock (Fig 10a), Nd_T values become consistently more evolved from west to east over all time periods. See text for discussion.

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Chapter 4

Concluding Remarks

This dissertation presents two studies that examine the relationship between strata of the Quesnel "terrane" and ancestral North America in southeastern British Columbia, Canada, to further the understanding of the geological history of the west coast of North America, heretofore poorly understood. New geologic and geochemical data are presented and discussed to place constraints upon the paleogeographic setting in which the Quesnel "terrane" formed, during the Late Triassic - Early Jurassic. To address this objective, field mapping, petrographic studies, structural analysis, U-Pb geochronology, and Nd tracer isotope studies were combined.

Chapter 2 presents the geology of the Silver Star area, a region in which pericratonic North American rocks are in contact with rocks of the Quesnel "terrane". Field studies established that this contact is not exposed in the map area. Mapping suggests that a structural or stratigraphic discontinuity at this boundary is possible, and in that respect was inconclusive toward the main objective of this dissertation. However, indirect evidence, in the form of detrital zircons within Quesnel "terrane" strata, suggests that rocks of the Quesnel "terrane" in this area were derived from Early Jurassic volcanic sources (~183 – 192 Ma) to the east that intrude rocks of the North American margin, and thereby provides a depositional link between metasedimentary Quesnel strata in the Silver Star area and North American rocks.

Chapter 3 presents a regional provenance study of Upper Triassic metasedimentary rocks of the Quesnel terrane, using Nd isotope and trace element compositions. This study demonstrates a mixed provenance for these rocks (εNd_T between –10 to +5.5, La_N/Yb_N between 3.85 and 11.40, La/Sc between 0.38 and 4.76), including a consistent, widespread, and abundant detrital contribution from evolved continental crust, identical in composition to contemporaneous deposits of the Cordilleran miogeocline in British Columbia and the Yukon, Canada. These data also record a detrital contribution to this basin from rocks with a composition identical to the volcanic arc rocks of the Quesnel "terrane" to the west, and suggest that both sources were proximal to the sedimentary basin. This study further establishes evidence for a depositional link, and a case for proximity, between the Quesnel "terrane" and North America.

This dissertation indicates that the Quesnel "terrane" in southeastern British Columbia developed in a paleogeographic setting that was proximal to the North American margin at its present, paleo-equivalent, latitude. This is in conflict with previous interpretations based on paleontologic and paleomagnetic data that described a more southerly origin for the Quesnel "terrane" (e.g. Carter et al. 1991; Taylor et al. 1984; Symons 1983; Irving et al. 1985; Rees et al. 1985; Symons 1985). However, while these data can be used to suggest a more southerly origin, the paleontologic data do not require it, and thus they do not necessarily preclude a parautochthonous origin for these rocks. A parautochthonous interpretation is supported by geologic relationships that describe unconformable contacts between Quesnel strata and rocks of North American origin (Jones 1959; Read and Okulitch 1977; Klepacki 1983; Klepacki and Wheeler 1985; Höy and Andrew 1991; Roback and Walker 1995; Thompson and Daughtry 1996, 1997, 1998), and igneous rocks intruding this "terrane" with Proterozoic inheritance, prior to the purported obduction of the Quesnel "terrane" onto the North American margin (Dostal et al. 2001). These data combine to suggest that the Quesnel "terrane" developed as a distal continental margin arc, overlapping North American strata in the east, and oceanic rocks in the west. These conclusions indicate that the categorization of Quesnel strata as a "terrane" is no longer appropriate, and pushes the boundary between North American and allochthonous rocks further west.

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