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RELATIONSHIP BETWEEN OPHIOLITES AND GOLD-QUARTZ VEINS IN THE NORTH AMERICAN CORDILLERA

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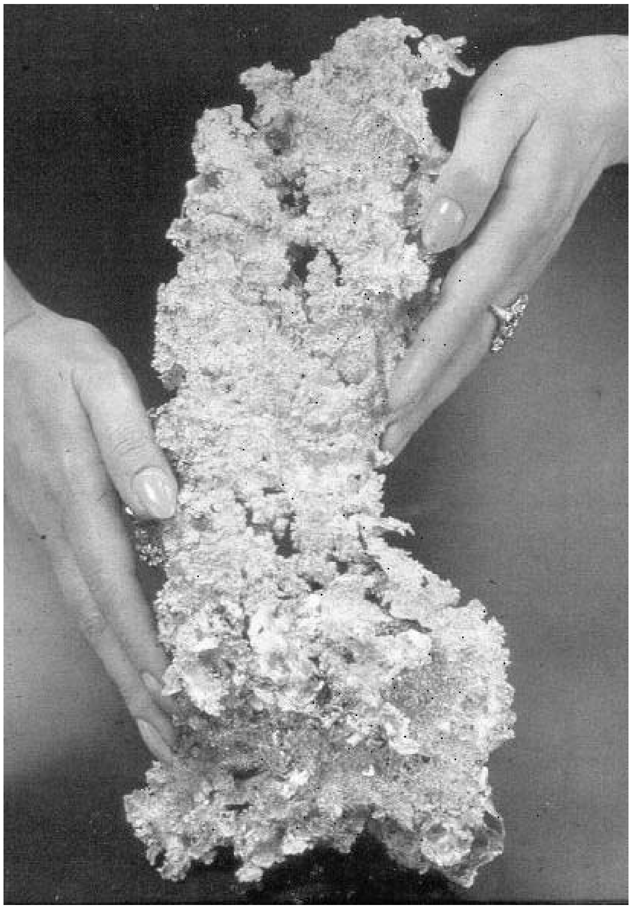

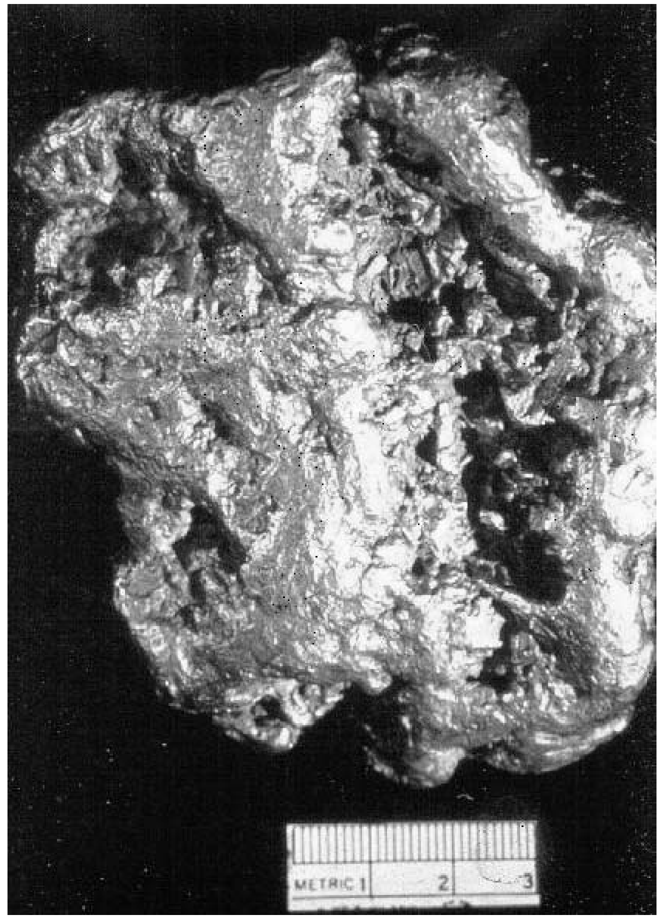

FRONTISPIECE

Left photo: Crystalline lode gold, Eureka mine, Tuolumne County, Mother Lode Belt, measures 15 x 33 cm and weighs 2.1 kilograms (67 troy ounces). This sample currently resides in the Smithsonian Institute (Photo courtesy of Bruce Ballantyne).

Right photo: Placer gold nugget from the Atlin camp (Photo courtesy of Bruce Ballantyne).

Johnston (1940) wrote the following preceeding a discussion on the origin of gold veins at Grass Valley, California and is worthy of consideration by deposit model proponents:

> "*The principal characteristics of the rock formations, fracture systems, vein materials, and wall rock alteration have been set forth. From this body of fact must come a large part of the evidence upon which any explanation of the origin of the deposits is based. But, as much of that evidence is fragmentary and incomplete, it must be supplemented by evidence from other geologically similar districts and interpreted in the light of our broader geological concepts. Thus genetic hypotheses, in a large measure, are a synthesis of knowledge and belief, and it is imperative that they be so regarded*"

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CHAPTER 1
INTRODUCTION

INTRODUCTION

Gold-quartz vein deposits and their derived placers are often spatially associated with carbonate±sericite±pyrite altered ophiolitic mafic and ultramafic rocks known as 'listwanites'. They have historically been of major socio-economic importance in British Columbia and account for a large portion of the 50% of the provinces' gold production from such lodes (Schroeter *et al.*, 2000). An amount that would be significantly greater if placer gold derived from such lodes were included. Districts with spatially associated ultramafic and related ophiolitic rocks that produced significant gold in British Columbia include the Bralorne-Pioneer, Erickson and Rossland lode mining camps, and the Atlin, Cariboo-Barkerville, Dease Lake and Manson Creek placer camps (Figure 1.1). Examples of significant gold producers elsewhere in the North America Cordillera include the Klondike area, Yukon, the Sierra Nevada metamorphic belt of California and the Alaska-Juneau deposit in southeastern Alaska (Figure 1.1).

Cordilleran Mesozoic gold-quartz vein deposits have Archean analogues that are typically referred to in terms of their age 'Archean lode gold', or the nature of their host rocks 'greenstone gold'. In a similar fashion one could refer to the deposits to be discussed as 'Mesozoic lode gold' or 'oceanic lode gold'. Characterizing a deposit type, however, based strictly on its age or the nature of its host rocks, when that deposit spans a range of both these characteristics is restrictive. Deposits of this type are referred to in many ways, such as; gold quartz veins or lodes, mesothermal gold, shear-hosted or shear zone gold, orogenic gold, syn-orogenic veins, Mother Lode gold, etc. and they all correspond to USGS Deposit Model 36b, low-sulphide gold-quartz vein classification of Berger (1986). Ash and Alldrick (1996) provide a more recent deposit description. These deposits occur primarily as quartz veins, stockworks or stringer zones in fault, fracture and shear zones (Boyle, 1979) and are typified by the variability of host rocks which are affected by pervasive carbonatization with localized sericitization and sulfidation marginal to gold-bearing quartz veins.

This study was initiated in 1989 to document the relationship between altered mafic and ultramafic ophiolitic rocks (listwanites) and their associated gold quartz vein deposits in British Columbia. Investigations were conducted in six lode gold or related placer camps throughout the province: Atlin, Stuart - Pinchi Lakes, Rossland, Cassiar (Erickson), Bralorne and Cariboo-Barkerville (Figure 1-1). These camps or deposits provided a regional sample set, including most significant gold producers in the Canadian Cordillera. Investigations focused on characterizing the lithotectonic setting and timing of gold-quartz vein mineralization and relating these to the magmatic and tectonic history of the host oceanic terranes. We present new, and also summarize existing, isotopic age data for the individual camps. Deposits discussed are compared to deposits with significant gold production in the Sierra Nevada metamorphic belt in California and the Juneau Gold belt in Alaska. Deposit-scale features of the gold quartz veins, such as alteration and mineralization styles, and fluid inclusion characteristics have been well documented for most of the deposits discussed. Such data is summarized throughout for both completeness and to demonstrate similarities between the individual deposits.

PREVIOUS WORK

A compilation of previous work in the camps examined or reviewed is provided in subsequent chapters, here we summarize those that are regional in context.

Sutherland Brown *et al*. (1971) were among the first to relate metallic mineral deposits of British Columbia to the lithotectonic subdivisions of the Canadian Cordillera. They recognized the common association of gold and silver with Cache Creek terrane hostrocks and suggested that these metals are related to younger intrusions. Boyle (1979) described the general character of these deposits in the Western Cordillera and suggested that they are related to Mesozoic orogenic activity. Barr (1980) summarized the geology of many of the significant lode gold mines in the Canadian Cordillera and provided a synopsis of their mining and production histories.

Hodgson (1982, 1989, 1993) compared the characteristics of British Columbia gold vein deposits to those of Archean age in the Superior Province of central Canada. He emphasized the spatial relationship of both lode and placer gold deposits in the Cordillera with oceanic rocks.

Nesbitt and co-workers (Nesbitt *et al.*, 1986, 1989; Nesbitt and Muehlenbachs, 1988, 1989; Nesbitt 1988, 1992) studied the isotopic character of mesothermal vein-forming fluids from several gold camps in the Canadian Cordillera and concluded that the bulk mineralizing fluids were of primarily meteoric origin. Based on the isotopic data, they proposed a deposit model that invokes deep circulation of meteoric waters through the crust to the brittle-ductile transition zone from where it is focused upward along major transcurrent fault zones.

Ash and Arksey (1990b) provided a brief synthesis on the origin, tectonic significance and ore characteristics of listwanite-related lode gold deposits in other orogenic belts and related them to similar deposits in British Columbia. Panteleyev, (1992) provided an overview of gold deposits in British Columbia in which he discussed ore genesis, reviewed existing deposit models and described many of the significant deposits. Summaries of the metallogeny of Brit-

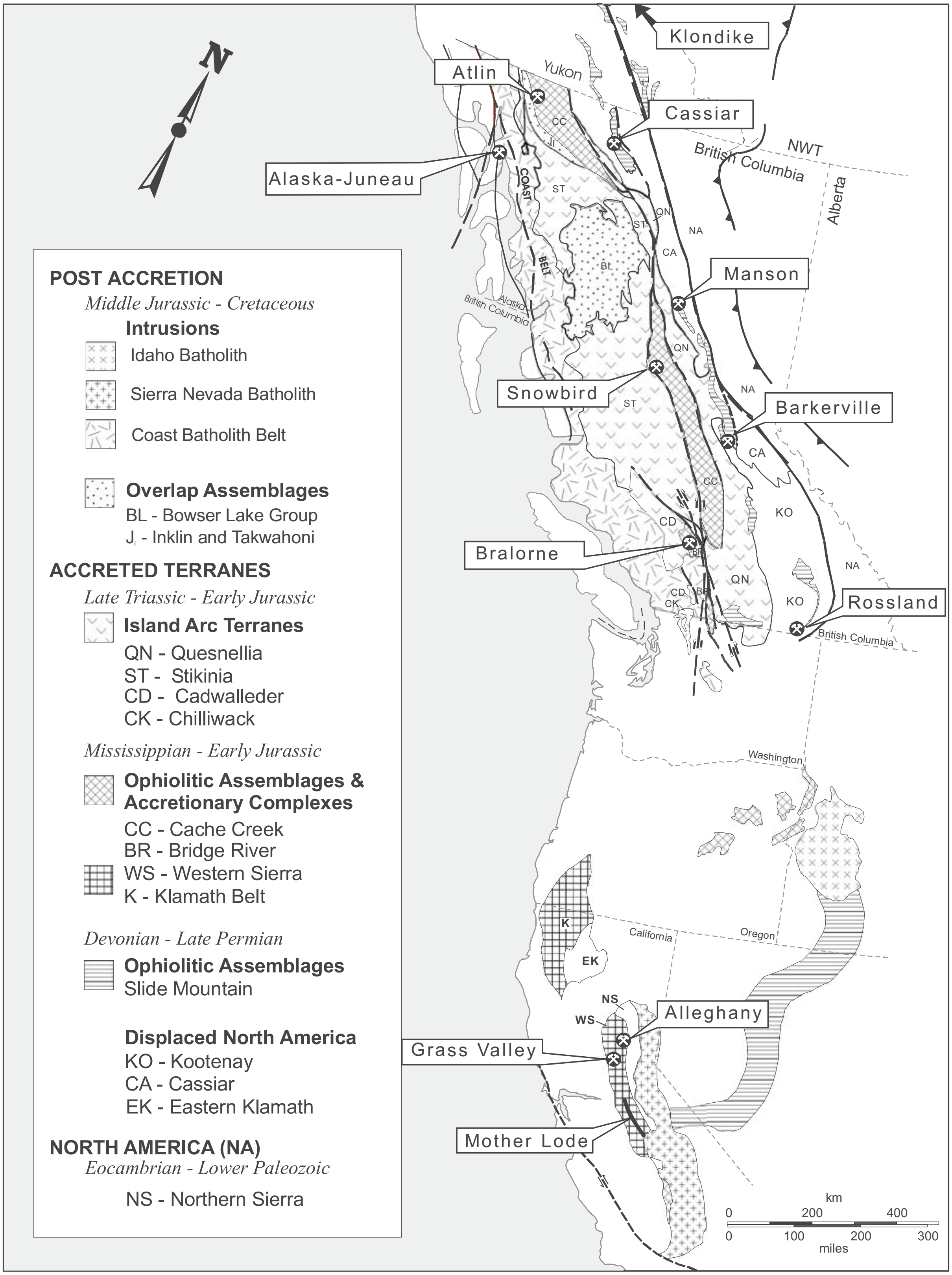

Figure 1.1 Distribution of oceanic terranes in the North American Cordillera, showing significant mesothermal gold-quartz vein camps and locations of study areas discussed in this report (modified fter Wheeler and McFeely, 1991 for Canada and Saleeby and Busby-Spera, 1992 for the Western United States).

ish Columbia that discuss mesothermal gold-quartz vein deposits, include those of McMillan and Panteleyev (1992) and Dawson *et al*. (1991).

REGIONAL GEOLOGICAL SETTING

Gold quartz vein or derived placer deposits discussed in this report are, more often than not, hosted by or in close proximity to ophiolitic rocks. Ophiolites are obducted, usually dismembered, remnants of ancient oceanic lithosphere consisting mainly of crustal igneous and sub-crustal metamorphic mantle rocks (Appendix I). In orogenic belts, like the North American Cordillera ophiolitic assemblages, occur either as allochthonous, dismembered and imbricated structural slices that were transported tectonically across former continental margins, or as imbricated and deformed slices in the central parts of orogens (Williams and Talkington, 1977). Examples of the first include the Bay of Islands ophiolite in western Newfoundland, the Semail ophiolite in Oman, the Zagros ophiolite in Iran and Slide Mountain Terrane ophiolitic rocks in British Columbia. Examples of the second type include central Newfoundland, the India-Asia Indus suture, the Pindus zone and Cache Creek and Bridge River Terrane ophiolitic rocks in British Columbia.

In British Columbia the Slide Mountain and the combined Cache Creek and Bridge River terranes form two distinct north-trending, discontinuous belts of oceanic rocks along the length of the Cordilleran orogen, with the Slide Mountain Terrane along its eastern margin and the Cache Creek and Bridge River terranes along the core (Figure 1.1). Both belts of oceanic rocks are separated by, and are also locally tectonically interleaved with younger Late Triassic to Early Jurassic basinal sequences of Quesnellia. These are dominated by Middle to Late Triassic clastic sedimentary rocks with locally developed Latest Triassic to Earliest Jurassic (Mortensen *et al*., 1995) calcalkaline to shoshonitic submarine lava flow, pyroclastic and hypabyssal-plutonic complexes (Mortimer, 1987; Monger *et al*., 1991; Struik *et al*., 1992; Nelson and Bellefontaine, 1996; Panteleyev *et al*., 1996).

Ophiolitic rocks in the Slide Mountain Terrane consist mainly of rootless nappes and klippen as imbricated and dismembered sheets structurally above displaced parautochthonous Late Proterozoic to middle Paleozoic rocks of the ancient eastern North American margin (Klepacki and Wheeler, 1985; Harms, 1985; Struik, 1986, 1988a, 1988b; Struik *et al*. 1992; Schiarizza and Preto, 1987; Nelson, 1993; Roback *et al*., 1994; Ferri, 1997). They also occur as discontinuous slivers along the faulted contact between Quesnellia and displaced North American rocks (Struik, 1988b; Panteleyev *et al*., 1996). Parautochthonous continental margin rocks include metamorphosed clastic sediments and platformal carbonates, which are represented by the Cassiar and Kootenay terranes. In California analogous continental margin rocks are included in the Northern Sierra Terrane (Edelman and Sharp, 1989; Saleeby, 1990). Over the entire length of the orogen these continental margin sediments are in places overlain and intruded by volcano-plutonic arc complexes that record Late Devonian to early Mississippian, Late Permian and Late Triassic-Early Jurassic volcanic events (Edelman and Sharp, 1989; Monger *et al*., 1991).

In contrast to the more uniform character of the eastern belt Slide Mountain Terrane in which ophiolites are the dominant exotic oceanic rocks , the Cache Creek and Bridge River Terranes are composite oceanic terranes, in which ophiolites are also associated with a much more diverse range of exotic oceanic lithologies that also include; chaotic chert-argillite deposits, remnant ocean islands and minor blueschists. Both these terranes are dominated by a late Paleozoic to Early and Middle Jurassic, tectonically disrupted, chaotic mix of marine pelagic sediments with lesser blocks, lenses and slivers of ophiolite (Monger, 1977a; Monger *et al*., 1991; Ash and Macdonald, 1993; Ash, 1994; Cordey and Schiarizza, 1993; Schiarizza *et al*., 1997). Lithologically this unit is dominated by argillite/phyllite and ribbon chert occurring mainly as mélange and broken formation with lesser limestone, mafic volcanics and subordinate gabbro and ultramafic rocks.

These lithologically diverse oceanic terranes also include distinctive associations of late Paleozoic Tethyan-affinity limestone and mafic volcanic rocks with ocean island petrochemical affinity (Monger, 1975; Saleeby, 1990; Ash and Macdonald, 1993). Blueschist rocks of predominantly Middle Triassic to Middle Jurassic age contribute an additional component and are found intermittently, mainly along the western margin of the central oceanic belt of rocks (Paterson and Harakal, 1974; Paterson 1977; Monger *et al*., 1991; Erdmer *et al*., 1998; Mihalynuk *et al*., 1999).

Although the two belts of oceanic rocks occur in very distinctive lithotectonic regimes, the ophiolitic rocks within both are remarkably similar. They both include dismembered, often imbricated associations of ultramafic mantle tectonite, ultramafic cumulate, gabbro, diabase and mafic volcanic rocks (Monger, 1977a,c; Monger *et al*., 1991). In each ophiolitic lithologies occur as internally imbricated, fault-bounded lenses at highly varied scales and levels of preservation. Though the database is limited, virtually all isotopically dated ophiolitic crustal plutonic rocks indicate late Paleozoic, mostly Permian ages of igneous petrogenesis. This is the case for dated ophiolitic rocks in the northern (Gordey *et al*., 1998) and central (Schiarizza, personal communication, 2000) Cache Creek and Bridge River terranes (Leitch, 1990; Leitch *et al*., 1991; Church, 1995) and in the southern (Greenwood; Church, 1986) and northern (Cassiar, Gabrielse *et al*., 1993) Slide Mountain Terrane. Ophiolitic assemblages also have consistent petrochemical affinities to abyssal oceanic lithosphere, with characteristic MORB signatures in northern (Atlin; Ash, 1994) and central (Stuart Lake; Ash and Macdonald, 1993) Cache Creek and Bridge River Terranes (Bralorne; Church *et al*., 1995; Dostal and Church, 1994) including the Coquihalla Belt (Ray, 1990). Similar abyssal MORB signatures are also typical of southern (Greenwood, Dostal *et al*., 2001 and Rock Creek, Ash, unpublished data), central (Manson Creek; Ferri, 1997) and northern (Cassiar; Nelson, 1993; Ash, unpublished data) Slide Mountain Terrane.

The general abyssal character of the Late Paleozoic ophiolitic rocks throughout the Canadian Cordillera is further confirmed by their general lack of chromite deposits (Roberts, 1988; Ash, 1994). These rocks typically lack vegetation and are usually well exposed. Having been extensively examined for associated mineral deposits like jade (Leaming, 1978), asbestos (Harvey-Kelly, 1995), chromite (Hancock, 1990), magnesite (Grant, 1987) and gold, their absence, due to not yet being identified, seems an unrealistic factor.

Most plate-tectonic reconstructions presented to account for geological architecture of the Canadian Cordillera have traditionally invoked accretion of island arcs and their related basement terranes to the continental margin during recognized periods of orogenic activity (Monger *et al*., 1982, 1991; Monger, 1984, 1993, 1999; Mihalynuk *et al*., 1992; 1994; Ash, 1994; Mihalynuk, 2000). In these terrane accretion models chaotic chert-argillite deposits that dominate the Cache Creek and Bridge River are interpreted as Late Triassic accretionary prisms or subduction-related accretionary complexes, generated by Middle Triassic to Early Jurassic destruction of the late Paleozoic ocean lithosphere. In this model volcanic basinal arc terranes are considered to have developed somewhere offshore, to be subsequently accreted to the continental margin during the Middle Jurassic.

An alternate plate tectonic model proposed by Saleeby (1990, 1992) and Saleeby and Busby-Spera (1992) suggests Mesozoic development of the Cordilleran margin involved formation of extensional fore-arc basins within and upon a previously tectonized Paleozoic, predominantly oceanic basement framework that existed along the continental margin. Belts of younger arc-basinal rocks are viewed as linear zones of in-situ fore-arc spreading that subsequently were affected by inter-arc contraction and basinal collapse.

Interestingly, application of the fore-arc extension model to the Canadian Cordillera offers some compelling alternatives, which address some of the outstanding pitfalls of current plate tectonic models. Previous plate tectonic reconstruction to account for ophiolitic rocks in the Slide Mountain terrane have argued for their development in a back-arc basin setting (Monger *et al*., 1991; Nelson, 1993; Nelson and Mihalynuk, 1993; Mihalynuk *et al*., 1994; Roback *et al*., 1994; Ferri, 1997). A major problem with this scenario involves an adequate explanation for the consumption or destruction of the Slide Mountain ocean basin. Suggestions (Nelson, 1993) for a relatively narrow back-arc basin to account for this ambiguity contradict all available petrochemical data for Slide Mountain metabasaltic rocks which consistently indicate an abyssal (MORB) paleotectonic environment of formation.

An alternate explanation that avoids some of the previous tectonic pitfalls and also accounts for the similarity of the ophiolitic rocks in each belt is to eliminate the Slide Mountain as part of a separately formed oceanic basin distinct from Cache Creek (Figure 1.2). In this model all these late Paleozoic abyssal ophiolitic rocks throughout the Cordillera are considered as parts of the same Late Paleozoic ocean basin. Portions of which were obducted onto the continental foreland in latest Permian-earliest Triassic (Slide Mountain) and portions of which remained as basement along the oceanward side of the Mesozoic continental margin (Cache Creek and Bridge River).

The intervening Late Triassic-Early Jurassic sedimentary-volcanic rocks of the Quesnel Terrane which separates these two belts of ophiolitic rocks could readily be interpreted from existing data as a fore-arc basin sequence. Its development resulting in the Mesozoic separation of the once semi-contiguous oceanic crust.

This alternate view for the origin of Slide Mountain ophiolitic rocks also offers an alternate interpretation for the Harper Ranch Terrane (Monger *et al*., 1991, Nelson, 1993; Ferri, 1997, Dostal *et al*., 2001). Harper Ranch Terrane rocks consist of Late Permian continental arc-volcanics deposited primarily on Early Paleozoic continental margin sedimentary rocks. These are generally found tectonically intercalated with Slide Mountain Terrane and older continental margin sediments and volcanics. The traditional interpretation is that the Late Permian arc-volcanics were deposited above a rifted portion of the continental margin, which migrated westward in response to Slide Mountain basinal development. The need to interpret this as a rifted portion of the continent, and hence its designation as a separate terrane has been to explain Slide Mountain ophiolitic rocks as a separate ocean basin. In this alternate view the Late Permian continental arc volcanic rocks could be interpreted to have formed along the continental margin due to Late Permian, easterly directed subduction. Late Permian subduction would be a necessary precursor to Late Permian-Early Triassic tectonic emplacement of the Slide Mountain oceanic lithosphere as processes of obduction are considered to be linked to active subduction. Cessation of continental arc-volcanism and sedimentation in the Late Permian, also the youngest age of ophiolitic rocks in the Slide Mountain Terrane are also consistent with this scenario.

Although a Middle Jurassic obduction age for Slide Mountain ocean crust is generally advocated (Schiarizza and Preto, 1987; Harms, 1989; Struik *et al*., 1992, Nelson and Bradford, 1993; Murphy *et al*., 1995; Ferri, 1997) there is a range of available evidence to suggest that the Slide Mountain terrane was most likely emplaced during the Late Permian-Early Triassic Sonoma orogeny (Siberling, 1973). The most compelling evidence for this period of emplacement is the relationship between the youngest age of the obducted crust relative to the age of the youngest sedimentary units underlying it. Nowhere is the Slide Mountain ophiolitic assemblage defined as being any younger than Late Permian and nowhere does it overlie rocks younger than that age. This relationship suggests a tectonic emplacement or 'obduction' age of latest Permian to earliest Triassic.

East verging structures of latest Permian to earliest Triassic age have been described in Slide Mountain Terrane rocks by Monger (1977) and Monger *et al*., (1991) (Saleeby and Busby-Spera, 1992). Thrusting of that age is constrained by a Late Permian tonalite intrusion which cross-cuts a bounding thrust fault near the southern end of

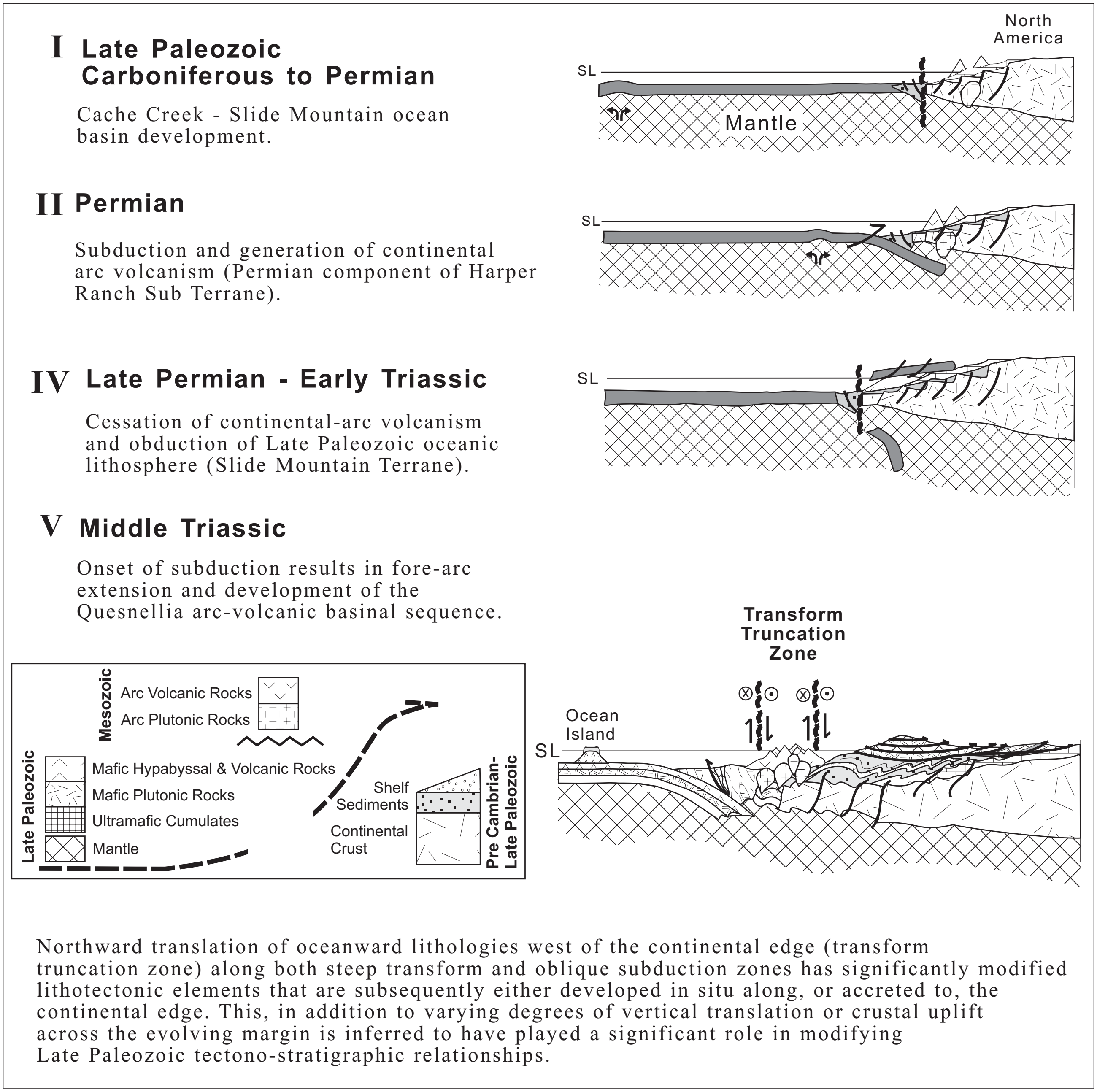

Figure 1.2. Plate tectonic cartoon illustrating possible mechanism of oceanic-continental crustal interaction for the Cordilleran margin during the Late Paleozoic and Early Mesozoic.

the Sylvester Allochthon in the Rapid River area of northern British Columbia (Harms, 1985; Gabrielse *et al*., 1993), which clearly suggests some component of pre-Triassic tectonism within the ophiolitic assemblage rocks.

Further south in the Eureka Peak area of east central British Columbia the basal sedimentary component of the Middle Triassic black phyllite unit of the Quesnel Terrane contains micaceous quartzite suggesting continental margin derivation (Bloodgood, 1990). These continental margin sediments display both concordant and discordant contact relationships with the underlying Crooked Amphibolite, which is a correlative of the Slide Mountain Terrane.

Several significant field relationships recently discussed by Dostal *et al*. (2001), for the Greenwood region of southeastern British Columbia, when interpreted differently, offer compelling evidence for such a viewpoint. The Lexington Porphyry is a *ca.*200 Ma (Dostal *et al*., 2001; Church, 1992) narrow elongate body that intrudes mainly serpentinite along a flat-lying thrust fault within imbricated abyssal, late Paleozoic ophiolitic rocks of the Knob Hill Assemblage (Fyles, 1990). This relationship clearly supports some component of a previously tectonized oceanic basement.

The recognition of similar geochronologic and structural-stratigraphic relations in the Sierra Nevada belt of Northern California in which Late Triassic-Early Jurassic, arc-related plutonic complexes intrude previously accreted late Paleozoic oceanic basement rocks led to questioning the concept of island arcs being accreted during the Late Jurassic Nevadan orogeny (Dilek *et al.*, 1990; Edelman, 1990; Saleeby, 1990, 1992).

Dostal *et al*. (2001) also discuss the tectonic significance of the Middle Triassic (Ladinian) Brooklyn Formation (Church, 1986, Fyles, 1990). This comprises a chert-pebble (sharpstone) conglomerate basal sequence grading upward into a siltstone supported polymictic sedimentary breccia containing rounded to angular clasts of chert, gabbro, basalt and limestone. This relationship of ophiolitic sharpstone conglomerate of Middle Triassic age deposited unconformably on deformed and imbicated late Paleozoic ophiolitic basement clearly supports obduction of Slide Mountain ophiolitic rocks prior to the Middle Triassic. These immature conglomerates most likely represent deposition of previously obducted oceanic crust during the early stages of fore-arc extension related to initiation of the Quesnellia basinal sequence.

It is of note that in the Greenwood area, where Slide Mountain Terrane rocks have been mapped in the most detail (Church, 1986; Fyles, 1990) they provide geological relationships that are possibly better explained by the fore-arc extension, intra-arc contraction model as opposed to the traditional terrane accretion model (Dostal *et al*., 2001). Evidence that either supports or contradicts such a view farther north along the Slide Mountain Terrane is lacking as contacts are generally poorly exposed, and where identified, are mainly tectonic.

The intent of the foregoing discussion is not to critique existing plate-tectonic models or even introduce alternatives. It is simply meant to demonstrate that at the current level of understanding there are alternative explanations for development of the Cordilleran margin. This is an important realization, considering the recent emphasis to assign paleo-tectonic environment(s) of formation to gold-quartz veins (Kerrich and Cassidy, 1994; Haeussler *et al*., 1995; Groves *et al*., 1998; Goldfarb *et al*., 1998; Kerrich *et al*., 2000).

It is particularly intriguing that the fore-arc extension model introduces more of a pre-plate tectonic, eugeosynclinal flavor to the development of the Mesozoic Cordilleran margin. Application of plate tectonics concepts to Cordilleran geology might not be such a complete change from '*geosynclines to crustal collage*', as is commonly envisaged (Monger, 1993; 1999).

Undoubtedly, the current configuration of the Canadian Cordillera evolved through alternating stages of oceanic-continental margin interactions ranging from periods of transform to oblique subduction style plate-tectonic processes. The prevalence of truly exotic accreted elements from those that developed in situ, either within or along the Cordilleran margin during its Mesozoic evolution is a question of more detailed examination. Any reconstruction of the continental margin during the Late Paleozoic must ultimately address relative amounts of lateral and vertical translation that has affected these rocks both along and across the margin sense that time.

Irrespective of its historical mode of construction, the Cordilleran in its present architecture, for the purposes of this discussion, contains ophiolites with associated gold-quartz vein deposits which occur in two very distinct lithotectonic regimes. These are: 1) an eastern regime, which is dominated by lithologies with parautochthonous ties to the North American ancestral margin, and assemblages within it which are usually bounded by relatively flat-lying, low-angle thrust faults; and, 2) a western regime dominated by late Paleozoic abyssal oceanic and lesser continental arc-rocks that are tectonically interleaved with Mesozoic and younger submarine basinal sedimentary and volcanic-arc sequences. In contrast to the eastern lithotectonic regime major bounding structures in the western belt are more often characterized by high-angle cryptic faults.

The rational for this major, regional east-west subdivision of the Cordillera is expanded upon and related to aspects of gold-quartz vein deposits in the concluding chapter following a presentation of data for the individual deposit areas.

In descriptions of the various oceanic terranes in B.C. a number of inconsistencies in the nomenclature are applied to similar geological units for the widely separated regions with similar rocks. Terminology that best describes the lithotectonic elements is used in this report. Existing geographic names are generally retained, but their generic roots (e.g. formation, group) have been changed in some cases to reflect what is considered to be their essential character, and to establish a uniform and consistent nomenclature based on accepted usage in descriptions of accreted oceanic terranes. The terms adopted here are consistent with those applied to the accreted elements of the Semail ophiolite belt in Oman by Lippard *et al.* (1986). The designations 'assemblage" and 'complex' are used as follows:

An **'assemblage'** is an allochthonous structural unit composed of several thrust slices of the same or closely related rock units occurring at the same general structural level.

A **'complex'** is one or more thrust slices of largely unrelated rocks brought together by tectonic processes" (Williams, 1975).

The informal term 'assemblage' is used as a collective term to substitute in some instances for 'group' names that have been used in the past. Terms such as 'group' and 'formation', which imply principles of stratigraphic continuity and superposition, cannot be rigidly applied to accreted oceanic terranes, which are constructed primarily by tectonic processes. We acknowledge that primary stratigraphic sequences may be locally preserved.

SCOPE OF PROBLEM AND APPROACH

Discussion of this deposit type is complicated by recent and historic differences of opinion regarding their origin.

These complications are further compounded by fundamental advances in the understanding of the origin and mode of emplacement of their host rocks (Figure 1.2), advances which evolved completely independent of any consideration of lode gold associations. Undoubtedly, confusion concerning the geological setting of gold-quartz veins has been a factor in the inability to place definitive constraints on their origin.

Possibly no other mineral deposit type has been studied so intensely and generated as much controversy as to the nature of its origin. Boyle (1979) details the history of proposed origins prior to the renewed period of exploration and research interest spurred by the precipitous increase in the value of gold early in 1980 (Figure 1.2). Unlike previous gold rushes that were initiated by significant gold discoveries, this one resulted from a precipitous increase in the metal's monetary value. The proposed origins of the mineralizing fluids including: magmatic, metamorphic, meteoric and mantle sources were revived during the 1980s and underwent the scrutiny of modern day analysis which focused on constraining the nature and source of mineralizing fluids. These data showed that there is a remarkable consistency in the composition and physical character of the mineralizing fluids irrespective of age or geographic location.

Consensus on a genetic model relating to the source of the ore fluid or tectonic environment of formation and the gold remains divided (Perring *et al*., 1987; Hodgson, 1990; Kerrich, 1991, 1993; Jai and Kerrich, 1999; Groves *et al*., 1998; Ridley and Diamond 2000).

An additional obstacle in discussing Mesozoic gold quartz vein deposits is the general uncertain understanding of their host rock origins and emplacement histories. Even though the origin of the deposit would remain a matter of debate, the origin and interpretation of the host rocks, historically a matter of controversy, has undergone some fundamental conceptual changes due to the advent of plate tectonics, circa early 1970 (Coleman, 1977). Associations of mafic and ultramafic rocks along continental margin mobile belts became recognized as remnants of older oceanic crust and underlying mantle (ophiolites) which were emplaced tectonically during continent-continent or arc-continent collision processes. They were not intruded into the accreted package as previously advocated (Figure 1.2).

Although the 'ophiolite model' as initially defined in 1972 evolved to attain consensus (Gass, 1980, 1990), it has not been widely applied when considering the setting and origin of gold-quartz vein deposits in the North American Cordillera. Reasons for the delay in applying the ophiolite model can be attributed to several factors. Firstly, ophiolite research has traditionally focused on describing primary processes of oceanic crustal development. Studies have

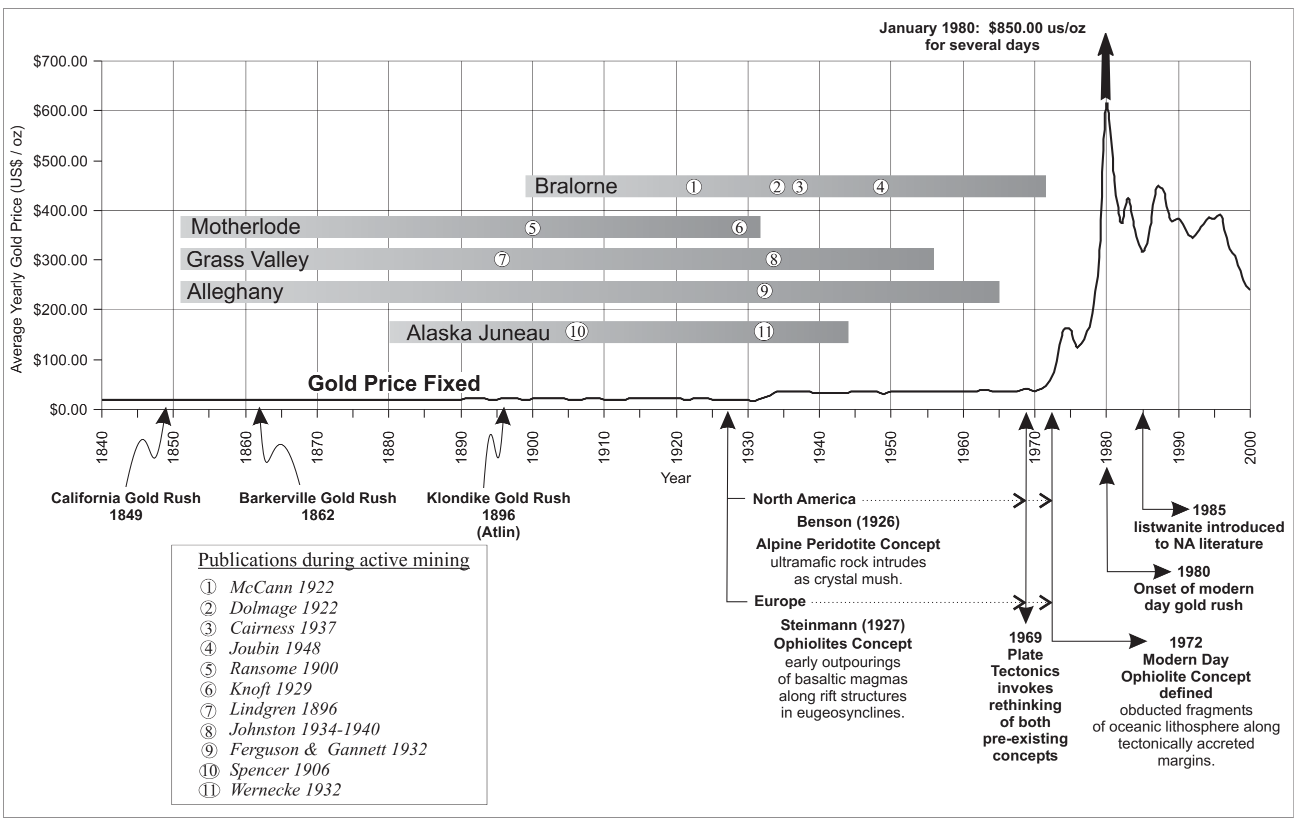

Figure 1.3. Historic yearly averages for the price of gold (US$/oz) compared to evolution of changing ideas for both gold quartz vein deposits and their host rocks. Also depecting periods of significant early gold discoveries, duration of mine life (horizontal bars) and historical references for the significant producing camps.

concentrated on the better-preserved, relatively coherent ophiolites such as Troodos in Cyprus, the Semail in Oman, and the Bay of Islands in Newfoundland. For these intensely studied and well-documented ophiolites there are no known gold-quartz veins. Mineral deposit studies related to ophiolites have focused almost exclusively on primary deposits such as volcanogenic massive sulphide or chromite.

Secondly, the majority of the exploration and research geologists working on gold-quartz veins through the 1980s were not schooled in ophiolite geology. Though achieving general consensus amongst ophiolite researchers, during the 1980s developing ophiolite concepts were not broadly disseminated. In addition, for the preceding 20 years most research and exploration attention in British Columbia had focused on porphyry deposits in volcanic-arc terranes. Most of the renewed exploration and research interest during the 1980s focused on older mining camps with historically significant placer or lode gold production. Published geological descriptions and maps available for the majority of these areas portrayed pre-plate tectonic concepts to characterize relationships between the ultramafic and mafic lithologies associated with the gold-quartz veins. These views so well entrenched in the literature were largely maintained in practice and as a result, the tectonic and inherent economic significance of the carbonate-altered ophiolitic rocks were not always recognized. The relationship between gold-quartz veins and ophiolitic rocks is more completely documented in this report.

Problems in communicating advances in the understanding of these rocks have been further perpetuated by use of various definitions in English language geological dictionaries, that have maintained the pre-plate tectonic concept. In light of these problems of terminology a brief overview of the history and current day understanding of the term ‘ophiolite’ is provided in Appendix I. This overview is not comprehensive but provides appropriate references for more information on individual aspects of the subject.

An additional problem in nomenclature relates to the word listwanite. Originally a Russian term it has been used in varying ways to describe alteration assemblages in ophiolitic gold vein hostrocks. Current definitions for this term are either significantly lacking or even misleading as defined in most geological dictionaries. For this reason the variation of prevailing meanings are reviewed and an attempt is made to more accurately characterize these terms (Appendix I).

When introducing gold deposits and their subdivision into classes, Boyle (1979, page 89) began by stating;

“*The following summary of gold deposits differs somewhat from the commonly accepted classification given in most textbooks on economic geology. This departure may or may not be justified, but it is the writer’s opinion that a classification based on the geological and geochemical setting of gold deposits is much more valuable than any based on their origin be it magmatic, hydrothermal, sedimentary or otherwise. It seems best to state objectively in what types of rocks and structural settings deposits occur. With this clearly set down and a knowledge of the geochemistry of the deposits, it may be possible to discern their origin and more importantly, to predict the environment where one may prospect for similar deposits.*”

Simply put, it would seem much more informative, particularly from an exploration standpoint, to understand not so much where the mineralizing fluids come from, but where they end up and why and what controls their distribution. The general approach as expressed by Boyle is in many aspects similar to that taken in this report except that the deposits herein are viewed within a modern day plate-tectonic framework. Comparisons are made only between Mesozoic deposits of the North American Cordillera.

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CHAPTER 2
NORTHERN CACHE CREEK TERRANE
ATLIN CAMP

INTRODUCTION

The Atlin placer gold camp, located in northwestern British Columbia on the eastern shore of Atlin Lake (Figure 2.1, Photo 1) ranks as the second largest producer of placer gold in the province. Mining has been for most of its history the economic mainstay for the picturesque town of Atlin since the discovery of gold on Pine Creek in 1897 (Mandy, 1936), a discovery which interrupted the intended gold-rush journey for many fortune seekers to the Klondike. During its heyday near the turn of the last century, the former town of Discovery, 12 kilometres east of Atlin on Pine Creek, boasted a population in excess of 10 000.

Reported placer gold production between 1898 and 1946 from creeks in the Atlin area totaled 19 722 kg (634 147 ounces*, Holland, 1950). A number of the larger placers, including those on Otter, Spruce and Pine creeks, continued to produce significant quantities of gold into the late 1980s. During fieldwork in 1991, Otter Creek was the only active placer producer, aside from a number of small-scale operators. Although the total gold production from the area to date is not available, it probably exceeds 1 million ounces and could be significantly greater.

Numerous gold quartz veins occur in the immediate area of the gold placers and are considered to be the source (Aitken, 1959; Ballantyne and MacKinnon, 1986; Lefebure and Gunning, 1988; Rees, 1989; Ash and Arksey, 1990a,b). Many of these occurrences were identified at the turn of the twenieth century following the discovery of placer gold. The only recorded lode gold producer was from the Imperial mine (Figure 2.4) which during 1899 and 1900 produced 268 tonnes of ore with an average gold grade of 13.0 grams per tonne (Bloodgood *et al.*, 1989a).

This chapter discusses the lithotectonic setting and timing of gold-quartz vein mineralization throughout the camp, in the context of the tectonic and plutonic history of the northern Cache Creek (Atlin) Terrane. Initial studies involved 1:25 000-scale mapping of the immediate Atlin area, in an attempt to establish the origin and tectonic setting of the ultramafic and related ophiolitic rocks (Ash, 1994; Ash and Arksey, 1990a, b, c).

PREVIOUS WORK

The first systematic geological mapping of the Atlin area was that of Aitken (1959). Monger (1975; 1977a) mapped ten specific areas of the northern Cache Creek (Atlin) Terrane and provided the first regional overview and tectonic synthesis. Bloodgood *et al.* (1989a, b) conducted 1:50 000-scale geological mapping of the Surprise Lake (104N/11W) and Atlin (104N/12E) map areas. Bloodgood and Bellefontaine (1990) mapped the Dixie Lake (104N/6) and Teresa Island (104N/5) sheets at a similar scale. Lefebure and Gunning (1989) compiled a 1:20 000 geological map of the Atlin mining camp using information obtained chiefly from exploration assessment reports.

Studies of lode-gold mineralization in the Atlin camp have been made by a number of researchers. Newton (1985) studied the mineralogical and geochemical character of listwanitic alteration assemblages from four lode gold properties in the area. Lueck (1985) completed a similar study focusing specifically on the Anna claims. Andrew (1985) describes the fluid inclusion and lead isotope characteristics of some of the mineralized quartz veins. A comparative study of the mineralogical and chemical characteristics of both placer and lode gold was conducted by MacKinnon (1986). Bozek (1989) investigated trace element signatures related to listwanitic alteration halos on the Yellowjacket and Pictou properties, and identified potential pathfinder elements indicative of gold mineralization. Lefebure and Gunning (1988) and Rees (1989), published property descriptions of the Yellowjacket and Pictou lode gold prospects, respectively. Studies of the surfical geology of the camp include those of Black (1953), Proudlock and Proudlock (1976), Levson (1992) and Levson and Kerr (1992).

In addition to these publications, results of a large volume of exploration work conducted in the immediate area are documented in assessment reports filed with the provincial government by mining and exploration companies. These reports include details of trenching, drilling and sampling programs as well as mapping and geophysical surveys.

REGIONAL GEOLOGICAL SETTING

The Atlin map area is located in the northwestern corner of the northern Cache Creek (Atlin) Terrane (Figure 2.2). It contains a fault-bounded package of late Paleozoic and early Mesozoic dismembered oceanic lithosphere (Monger, 1975, 1977a, b, 1984; Tempelman-Kluit 1979), intruded by post-collisional Middle Jurassic, Cretaceous and Tertiary felsic plutonic rocks (Wheeler and McFeely, 1991; Mihalynuk *et al.*, 1992). The terrane is dominated by mixed graphitic argillite and pelagic sedimentary rocks that contain minor pods and slivers of metabasalt and limestone. Remnants of oceanic crust and upper mantle lithologies are concentrated along the western margin. Dismembered

**B.C. Department of Mines records indicate that for this same period 705 229 ounces of gold was sold from the Atlin area suggesting that not all gold production was reported.*

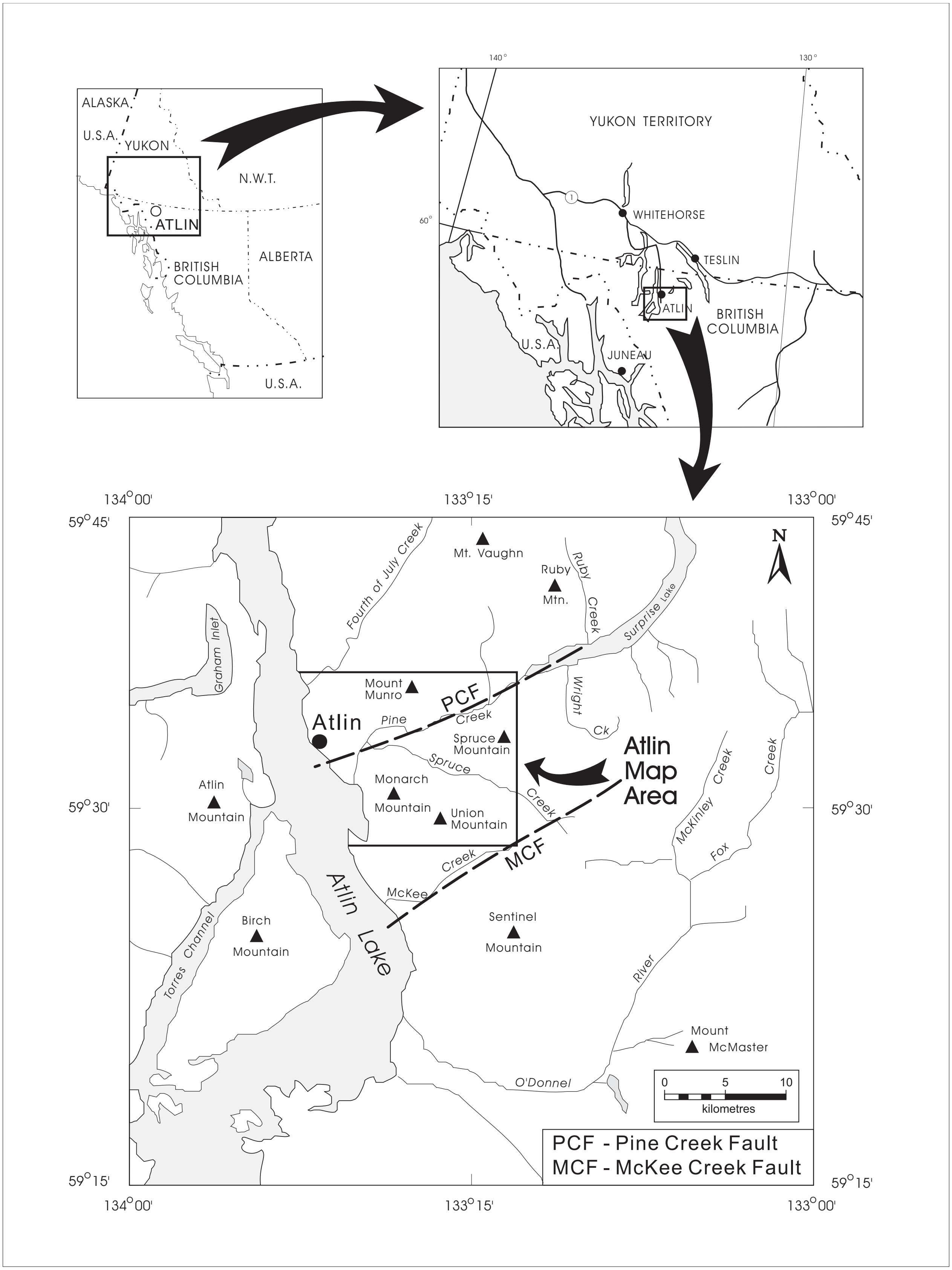


Figure 2.1. Location of the Atlin map area.

Photo 2.1. View looking north over Atlin Lake with Monarch Mountain in the foreground and the town of Atlin at the centre of the photo.

Figure 2.2 Geological setting of the northern (Atlin) Cache Creek Terrane, modified from Monger, 1975.

ophiolitic assemblages have been described at three localities along this margin: from north to south they are the Atlin (Ash, 1994), Nahlin (Terry, 1977) and King Mountain (Leaming, 1980) assemblages. Each area contains imbricated mantle harzburgite, crustal plutonic ultramafic cumulates, gabbros and diorite, together with hypabyssal and extrusive basaltic volcanic rocks. Thick sections of late Paleozoic shallow-water limestone dominate the western margin of the terrane and are associated with alkali basalts. These are interpreted to be carbonate banks constructed on ancient ocean islands within the former Cache Creek ocean basin (Monger, 1977b).

The ages of rocks in the terrane are interpreted primarily from paleontological data. Isotopic age data for oceanic crustal plutonic rocks includes a single U-Pb zircon age of around 245 Ma for peridotite from Cache Creek rocks in Yukon (Gordy *et al*., 1998). Fusulinid-bearing limestones range in age from Carboniferous to Late Permian with Permian faunas dominating (Monger, 1975). Radiolarian cherts range in age from Early Permian to Late Jurassic and give the youngest fossil ages (Cordey *et al.,* 1991; Cordey

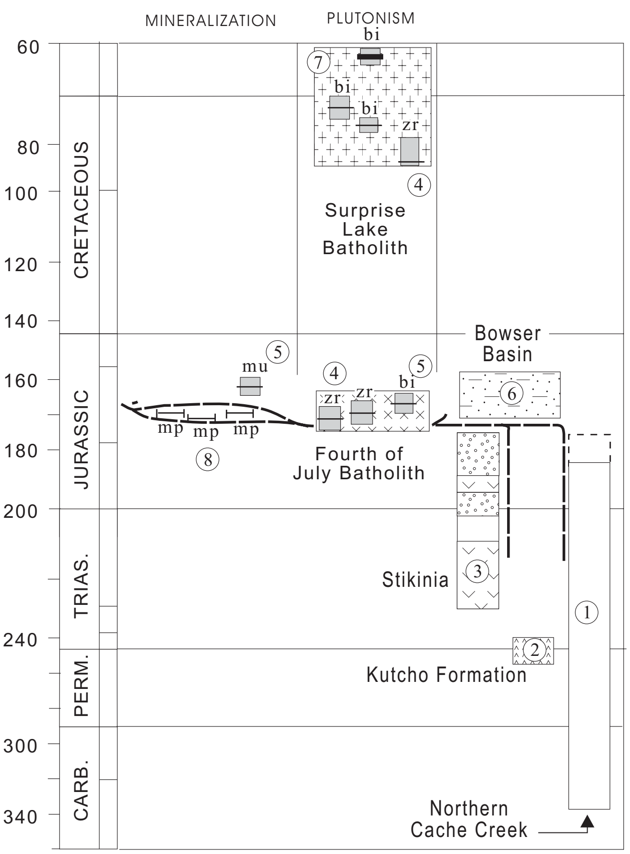


Figure 2.3. Relative age and tectonostratigraphic relationships for lithologies in the Atlin area. **zr** - zircon U-Pb; **mu** - muscovite K-Ar; **mp** - mariposite / fuchsite Ar-Ar; **bi** - biotite K-Ar
Data sources used to constrain age relationships for the elements depicted are;
① Monger 1975; Orchard, 1991, Cordey *et al*., 1991; Cordey 1990a,b; ② Childe *et al*., 1998; ③ Tipper, 1984; Brown *et al*., 1991; ④ Mihalynuk *et al*., 1992; ⑤ Dawson, 1988; ⑥ Ricketts *et al*., 1992; ⑦ Christopher and Pinsent, 1979; and ⑧ this study.

1990a, b). Conodonts give the widest age variation, ranging from early Mississippian to Late Triassic (Orchard, 1991).

The Middle Jurassic timing of emplacement of the northern Cache Creek Terrane over Late Triassic to Lower Jurassic Whitehorse Trough sediments along the Nahlin Fault (Monger *et al*., 1977; Thorstad and Gabrielse, 1986; Mihalynuk, 2000) is well constrained by combined stratigraphic (Ricketts *et al.*, 1992) and plutonic evidence (Gabrielse, 1991; Mihalynuk *et al*., 1992) (Figure 2.3). The youngest sediments affected by deformation related to the King Salmon Fault are Bajocian (Gabrielse, 1991). The earliest sedimentary detritus of Cache Creek affinity recorded in the Bowser Basin is in early Bajocian rocks that are immediately underlain by organic-rich sediments of Aalenian age. They are interpreted to reflect loading along the western margin of Stikinia by the Cache Creek during its initial emplacement (Ricketts *et al*., 1992). The oldest post-collisional plutons that pierce the Cache Creek Terrane to the west of Dease Lake (Gabrielse, 1991) are dated at 173±4Ma by K-Ar methods and in the Atlin area they are dated at 172±3Ma by U-Pb zircon analysis (Mihalynuk *et al.*, 1992) . Considering the age of these plutons relative to the orogenic event, the descriptive term late syn-collisional is preferable.

The northern Cache Creek Terrane to the east is bordered mainly by the Thibert Fault which continues northward along the Teslin lineament. Discontinuous exposures of altered ultramafite along the fault suggest that it has previously undergone significant reverse motion and may be a reactivated thrust or transpressional fault zone. Latest movement on this fault is thought to be dextral strike-slip, of pre-Late Cretaceous age (Gabrielse, 1991).

The terrane is dominated by sub-greenschist, prehnite-pumpellyite facies rocks, however, local greenschist and blueschist metamorphism are recorded (Monger, 1975, 1977b). The terrane is characterized by a northwesterly-trending structural grain, however, in the Atlin - Sentinel Mountain area there is a marked deviation from this regional orientation with a dominant northeasterly trend. Reasons for this divergence in structural grain are poorly understood.

LOCAL GEOLOGY

The geology of the Atlin map area (Ash, 1994; Figures 2.4a and b) is divisible into two distinct lithotectonc elements. A structurally higher, imbricated sequence of oceanic crustal and upper mantle lithologies termed the "*Atlin ophiolitic assemblage*", is tectonically superimposed over a lower and lithologically diverse sequence of steeply to moderately dipping, tectonically intercalated slices of pelagic metasedimentary rocks with tectonized pods and slivers of metabasalt, limestone and greywacke termed the "*Atlin accretionary complex"*. Locally these elements are intruded by the Middle Jurassic (Mihalynuk, *et al.*, 1992) calcalkaline Fourth of July batholith and related quartz-feldspar porphyritic and melanocratic dike rocks.

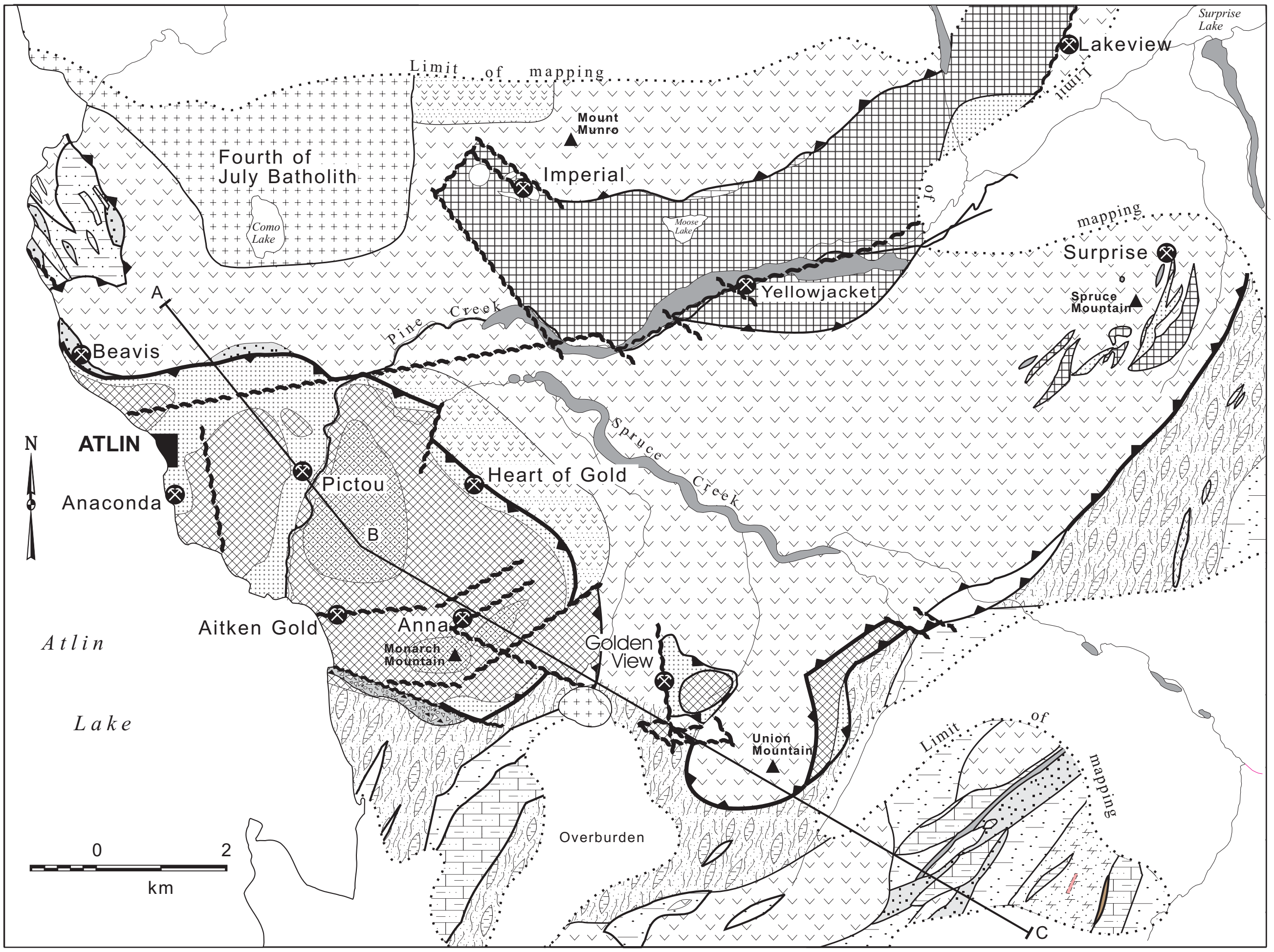


Figure 2.4a. Geology and distribution of lode gold showings in the Atlin camp (simplified after Ash, 1994). Area of gold placers taken from Levson and Kerr (1992). For legend refer to Figure 2.4b.

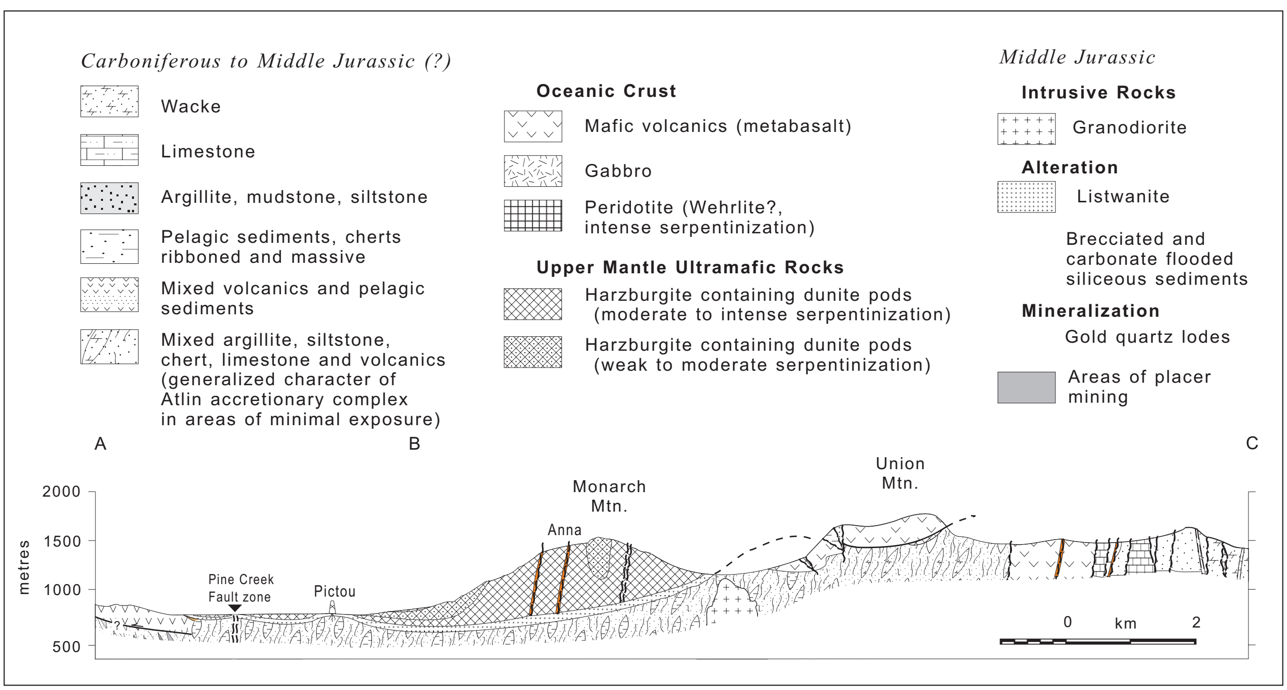


Figure 2.4b. Schematic geological cross-section of the Atlin area. Lines of section illustrated on Figure 2.4a.

ATLIN OPHIOLITIC ASSEMBLAGE

The Atlin ophiolitic assemblage comprises an imbricated sequence of relatively flat-lying, coherent thrust slices of obducted oceanic crustal and upper mantle rocks. Mantle lithologies are dominated by harzburgite tectonite containing subordinate dunite and lesser pyroxenite dikes. The unit forms an isolated klippe that underlies Monarch Mountain and the town of Atlin (Figure 2.4), and is exposed on the northern and southern slopes of Union Mountain. Ductile deformational fabrics indicative of hypersolidus to subsolidus deformation, and the phase chemistry of primary silicates and chrome spinels in the harzburgite (Ash, 1994) indicate a uniform, highly refractory composition and support a depleted mantle metamorphic origin for the unit. The least serpentinized rocks with well preserved primary structures and textures crop out at the highest elevations on Monarch Mountain (Figure 2.4a and b, Photos 2.2 and 2.3). Primary features are less well preserved towards the base of the body and internally, where it is cut by high-angle fault zones, the unit becomes increasingly serpentinized. Serpentinite mylonite fabrics are locally preserved near the base of the body (Photo 2.4). Commonly the basal contact of the harzburgite unit is pervasively carbonatized and tectonized over distances of several tens of meters or more (Photo 2.5).

Oceanic crustal lithologies in the Atlin map area, in decreasing order of abundance, include metamorphosed basalt, ultramafic cumulates, diabase and gabbro with metabasalts dominating. They are generally massive, fine grained to aphanitic and weather a characteristic dull green-grey colour. Locally, the unit grades to medium-grained varieties or diabase. Primary textures locally identified in the metabasalt include flow banding, autobrecciation and rare pillow structures. Although rarely exposed, basalt contacts are commonly sheared or brecciated zones, sometimes intensely carbonatized. Petrochemical investigations of these basaltic rocks (Ash, 1994) indicate that they are similar in composition to basalts of normal mid ocean-ridge settings and the chemistry also suggest a genetic relationship to the associated depleted metamorphic mantle ultramafic rocks.

Serpentinized peridotite displaying ghost cumulate textures and sporadically preserved relict poikilitic texture is suspected to originally be wehrlite. The peridotite forms an isolated thrust sheet which outcrops discontinuously along an east-trending belt 1 to 3 kilometres wide on the south-facing slope of Mount Munro. Extensive exploration drilling along the base of Mount Munro at the Yellowjacket lode gold property indicates that the serpentinized body is in structural contact with metabasaltic rocks along a gently northwest-dipping thrust (Marud, 1988a,b). Along the contact zone hangingwall ultramafites and footwall metabasalts are tectonically intercalated and carbonatized. Projection of this fault across the Pine Creek valley suggests that carbonatized and serpentinized ultramafic rocks on the summit of Spruce Mountain represent a remnant above an extension of the same tectonized and altered basal contact.

Metagabbro is the least commonly seen ophiolitic component in the map area. It crops out on the northern slope of

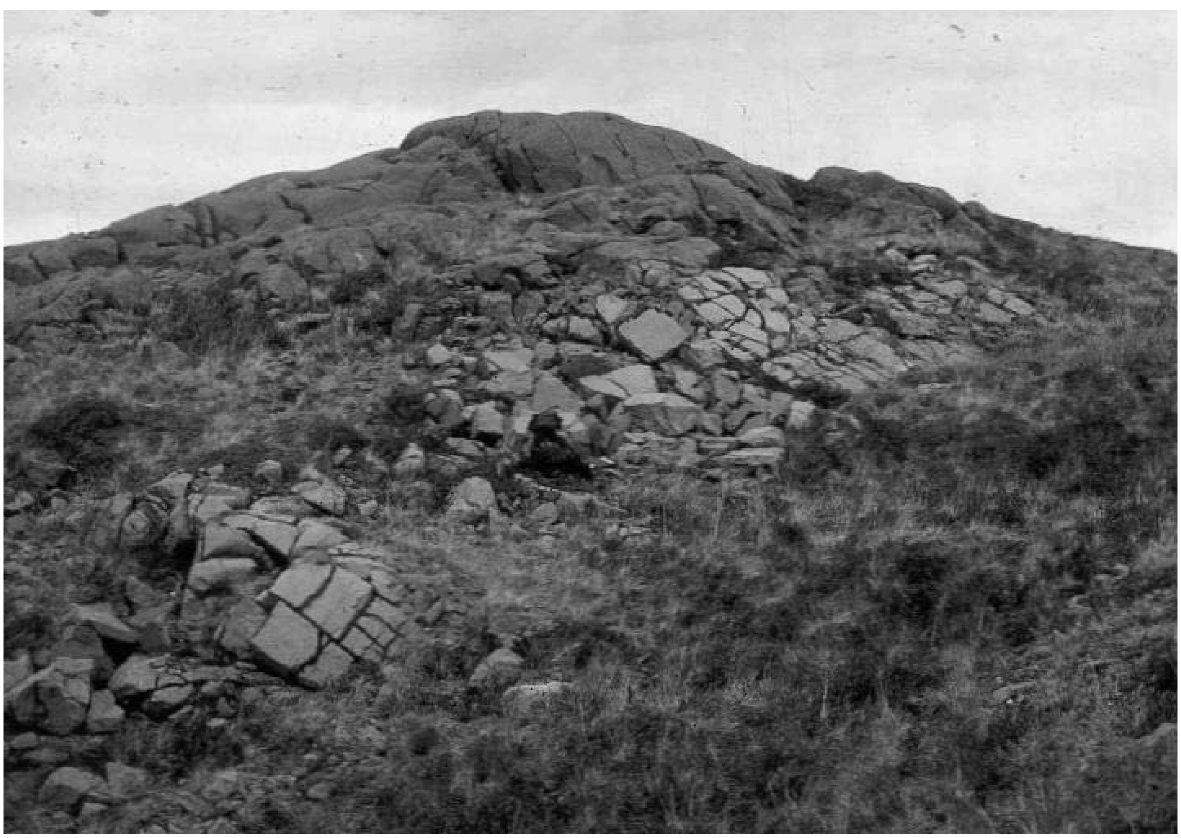


Photo 2.2 Dunite pod in banded harzburgite near the summit of Monarch Mountain. Note: pack sack in centre of photo for scale.

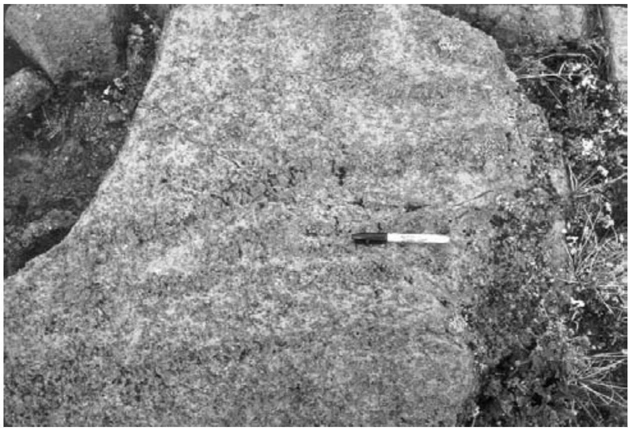


Photo 2.3 Folded pyroxenite dike in harzburgite tectonite near the summit of Monarch Mountain.

Photo 2.4 Serpentinite-bastite mylonite developed in harzburgite near the base of the Monarch Mountain Allochthon.

Union Mountain and along the south-facing slope of Mount Munro. It is abundant in drill core from the Yellowjacket property along Pine Creek, where it occurs as isolated pods and lenses within the Pine Creek fault zone (Lefebure and Gunning, 1988; Marud, 1988 a, b). On Union Mountain, gabbro occurs along the Monarch Mountain thrust as isolated dismembered blocks with faulted contacts.

ATLIN ACCRETIONARY COMPLEX

The Atlin accretionary complex comprises a series of steeply to moderately-dipping lenses and slices of structurally intercalated metasedimentary and metavolcanic rocks that underlie the southern half and northwest corner of the map area. Pelagic metasedimentary rocks dominate the unit and consist of argillites, cherty argillites, argillaceous cherts and cherts with lesser limestones and greywackes. They range from highly mixed zones with well-developed flattening fabric indicative of tectonic melange to relatively coherent tectonic slices. Individual slices range from metres to several hundreds of metres in width. Indications of internal deformation are moderate or lacking; in a few slices original stratigraphy is well preserved. Contact relationships between many of the individual units of the complex have not been established due a lack of exposure, however, most are inferred to be tectonic. Internal bedding within the individual lenses in some places is parallel to the external contacts, but is more commonly strongly discordant. This argues against simple interfingering of different facies.

A common feature throughout the accretionary complex, particularly in areas of moderate overburden, is closely spaced outcroppings of different lithologies with no clearly defined contacts. Such relationships are interpreted to represent areas of mélange in which the exposed lithologies that commonly include chert, limestone and basalt are more competent than the intervening, recessive fis-

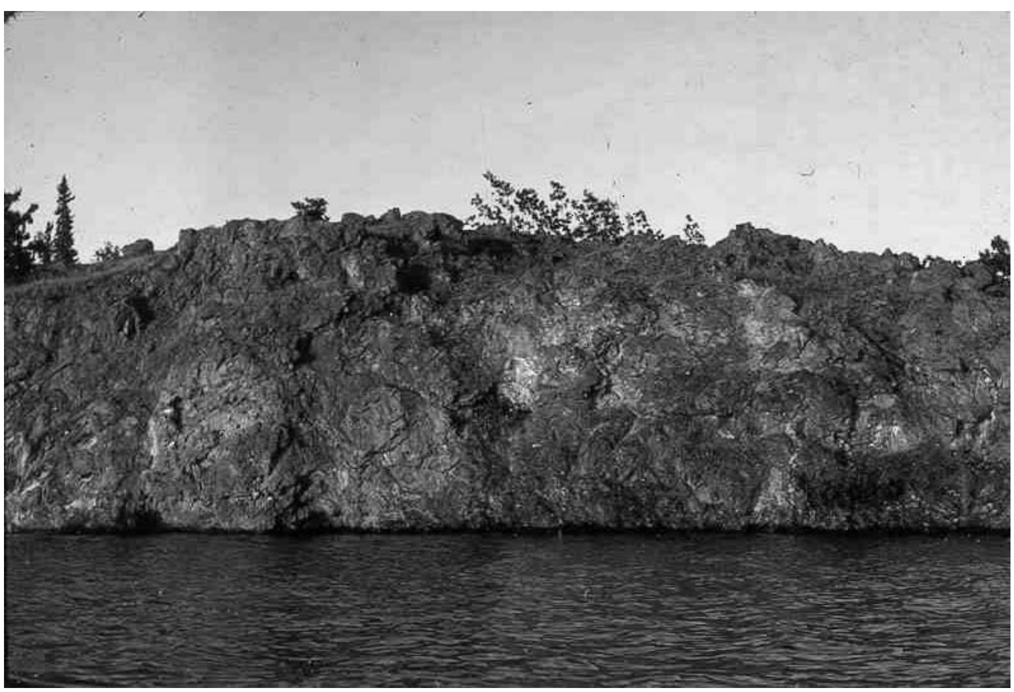


Photo 2.5. Shoreline outcrop of brecciated and pervasively carbonatized harzburgite, shore of Atlin Lake south of Atlin.

sile and argillaceous matrix. Such relationships are confirmed where sections are exposed along road cuts and in areas of trenching.

INTRUSIVE ROCKS

Fourth of July Batholith

The southern extension of the Middle Jurassic Fourth of July batholith (Aitken, 1959; Mihalynuk *et al*., 1992) into the northeastern corner of the map area is the only major intrusive unit exposed in the region. The potassium feldspar megacrystic granite to granodioritic phase of this composite pluton predominates. Pink potash feldspar megacrysts set in a coarse-grained equigranular groundmass of mottled pale green to buff-white plagioclase and grey quartz typifies the unit in this area. Prismatic megacrysts range from 1 to 4 centimetres in length and comprise from 15 to 30% of the unit. Mafic minerals are restricted to the groundmass and consist of both amphibole and biotite, with combined modal abundances of 5 to 20%. Primary clinopyroxene typically mantled by amphibole is a common but minor mafic phase. Accessory magnetite comprises 1 to 2% of the groundmass.

Uranium-lead analysis on zircon from two samples representing distinct phases of this multiphase pluton indicate a range in the age of crystallization from 166.5 to 174 Ma that gives a combined best estimate of 171.7±3 Ma (Mihalynuk *et al*., 1992). A lack of evidence for inheritance in these zircons, combined with low $^{87}Sr/^{86}Sr$ initial ratios, suggest derivation of the magma from a primitive, unevolved source, consistent with thickened oceanic lithosphere and arc rocks.

Biotite from a small stock of orthoclase feldspar megacrystic granodiorite that crops out in the valley midway between Monarch and Union mountains yielded a K-Ar age of 167±3 Ma (Dawson, 1988). This is within error of the Middle Jurassic U-Pb crystallization age reported for the main body of the Fourth of July batholith. The pluton cuts fabrics as well as faulted contacts within the oceanic Cache Creek rocks but itself lacks penetrative fabrics and therefore postdates accretion of the ophiolitic assemblage. The timing of the cross-cutting plutonism gives a minimum age of accretion and imbrication of the oceanic Cache Creek Complex. A similar age and inferred tectonic relationship are reported for a granodiorite stock (K-Ar, biotite of 173±4 Ma) which intrudes sedimentary and ultramafic rocks in the southern part of the northern Cache Creek Terrane near Tachilta Lakes, 60 kilometres northwest of Dease Lake (Stevens *et al*., 1982).

Feldspar ± Quartz Porphyritic Dike Suite

A suite of felsic, two feldspar quartz-porphyritic dikes that are considered to be related to the Fourth of July batholith are sporadically exposed in the map area. They consistently occur near gold bearing quartz veins. Dikes are usually from 0.5 to 2 metres wide, have variable orientations and dip steeply. They lack penetrative deformation and crosscut fabrics and deformed tectonic contacts between all oceanic rocks. Typical dikes consist of randomly oriented, dull white, prismatic plagioclase phenocrysts 1 to 4 millimetres long, set in a grey aphanitic groundmass and comprising from 20 to 50% of the rock. Variable amounts of amphibole and quartz (0 to 20%) also occur as phenocrysts of comparable size. Many of the dikes contain secondary carbonate and sericite from trace to several percent in modal abundance. Feldspar phenocrysts weather a distinctive orange-brown colour due to the effects of carbonate alteration. The groundmass is variably silicified and carbonatized and contains from 3 to 15% fine-grained disseminated pyrite. Altered dikes are commonly anomalous in gold. Lefebure and Gunning (1989) report the occurrence of altered porphyritic dikes in association with gold mineralization at the Beavis, Imperial, Yellowjacket and Anna properties. Rich (1985) reports a similar relationship on the Golden View property. Dikes also occur at the Anaconda showing and have been reported in drill core from the Heart of Gold property (McIvor, 1988a).

GOLD MINERALIZATION IN THE ATLIN CAMP

TECTONIC SETTING

Gold-quartz vein mineralization in the Atlin camp appears to be confined to carbonatized fissure zones within and in close proximity to ultramafic rocks of both the mantle harzburgite and the plutonic oceanic crustal units of the Atlin ophiolitic assemblage. Many of the known gold quartz vein mineralization occurrences are localized along the tectonized basal thrust fault of the harzburgite unit, the Monarch Mountain thrust (Ash, 1994; Figure 2.4a and b). These include the Beavis, Pictou, Heart of Gold, Aitken Gold, Anaconda and Goldenview prospects, which are all located along the annular surface trace of the basal fault contact. Others, including the Goldstar and Anna showings, are hosted by carbonatized fault zones within the harzburgite. These faults are interpreted as second order splays of the Monarch Mountain thrust.

Combined outcrop and drill-hole information indicates that the Monarch Mountain thrust is a relatively flat-lying, gently undulating structure, characterized by a zone of tectonic brecciation and carbonatization several metres to tens of metres wide that affects hangingwall and footwall lithologies. Hangingwall peridotites are the most intensely and pervasively altered due to their reactivity with fluids rich in carbon dioxide. The intensity of alteration in footwall lithologies is highly variable, due to the heterolithic nature of the underlying accretionary complex. Basalts within and adjacent to the basal fault zone are typically carbonatized and, like the ultramafic rocks, are cut by discontinuous silicified shear zones which may be anomalous in gold content. Footwall cherts are subject to brittle fracture and form tectonic breccias commonly cemented by hydrothermal carbonate with lesser silica. Argillaceous rocks within the thrust are intensely sheared and commonly form gouge zones.

The arcuate surface trace of the Monarch Mountain thrust is not exposed on the lower southern and eastern slopes of Monarch Mountain. However, its approximate location is well constrained by outcropping with contrasting lithologies, styles of deformation and carbonate alteration.

Along the northeastern side of the allochthon the thrust trace is completely covered by overburden. Its location is constrained by drill-hole data and ground magnetometer surveys conducted on the Heart of Gold property which covers the contact in this area (McIvor, 1988a). Drill holes straddle and also penetrate the thrust contact. Three holes parallel to the contact spaced 100 metres apart are collared in variably serpentinized harzburgites. The succession of rock types intersected in each hole is generally similar: first serpentinized ultramafics, followed by an interval of carbonatized ultramafic rocks with intermittent carbonatized shear zones. Below this is a tectonically mixed zone of basalt, diabase and sediments, locally cut by felsic dikes, and ending in brecciated cherts or strongly sheared mixed chert and argillaceous footwall lithologies. No anomalous metal concentrations were reported along this contact.

Tectonized and carbonatized ultramafic rocks exposed at the Pictou prospect (Rees, 1989; Bozek, 1989; Minfile 104N 044), 2.5 kilometres east-southeast of Atlin, are interpreted to be the hangingwall of the Monarch Mountain thrust. Rusty-brown weathering, pervasively carbonatized ultramafic rocks are exposed in an elongate outcrop area measuring roughly 12 by 150 metres at the main Pictou showing (Photo 2.6). The altered rocks are intensely fractured and cut by several generations of quartz veining. Vein are typically millimetres to several centimetres in width and locally increase to more than 10 centimetres, but lack continuity. Minor mariposite is locally present in the white quartz veins and veinlets; it is best developed in zones generally less than a metre wide in the altered host rocks. These altered rocks are typically massive with a characteristic grey-green colour due to the presence of finely disseminated sulphides and mariposite.

Ten holes, drilled at various locations throughout the Pictou property (McIvor, 1988 a, b), intersected a succession of rocks with alteration comparable to that described on the Heart of Gold property. A representative section defined by three of these holes is illustrated in Figure 2.5. Each hole initially penetrated several tens of metres of intensely carbonate-altered harzburgite with intermittent zones of silica flooding with associated sulphide and mariposite. This lithology was succeeded down-hole by several tens of metres dominated by carbonate-altered basalt with lesser chert and argillite all cut by faults. Drill logs indicate the boreholes pass downward into unaltered equivalents of these footwall lithologies.

Photo 2.6. Surface exposure of the Pictou property. Note: packsack in centre of photo for scale.

Carbonate-altered ultramafics that crop out on the Pictou property are the exposed portion of an elongate north-northeast-trending band, corresponding to an aeromagnetic low which extends across the ultramafic body. This band is interpreted as the hinge zone of a broad, open antiform (Figure 2.4a and b), presumably produced by post-thrust buckling. Monolithic, pervasively carbonatized ultramafic tectonic breccia, crops out in a vertical cliff face (Photo 2.5). This face is 6 to 8 metres high and extends over a distance of several hundred metres along the shore of Atlin Lake, roughly a kilometre north of the Atlin townsite. The exposure is thought to be part of the hangingwall alteration zone of the Monarch Mountain thrust. The Anaconda prospect (MINFILE 104N 046) is several hundred metres inland from this exposure and the intervening area consists entirely of pervasively carbonatized harzburgite. The showing comprises a sparsely mineralized massive white quartz vein that is partially exposed in a caved trench within an area of thick overburden. Several tens of metres west of the vein a pervasively sericitized feldspar phyric felsic dike with several percent disseminated pyrite is exposed in a roadside outcrop.

The Beavis property (MINFILE 104N 007) is located on the northern edge of the Atlin townsite and covers the northern contact of the Monarch Mountain thrust. This is the only identified mineralization in which gold bearing quartz veins are hosted by accretionary complex sedimentary rocks. Pelagic sedimentary rocks form a strongly tectonized northwest-trending zone several hundred metres wide that separates hangingwall ultramafic rocks from footwall basalts. In this poorly exposed area a series of 15 exploration trenches spaced at 30 to 50 metre intervals exposes the footwall contact and permitted it to be mapped in detail (Figure 2.6) (Photo 2.7). Sheared argillite forms the matrix of the fault zone which also contains lensoid, centimetre-scale chert fragments (Photo 2.8) as well as localized metre-scale blocks of limestone breccia. The unit is highly incoherent and varies from a broken formation to mélange as defined by Raymond (1984). The prominent shear fabric within the argillite trends northwesterly with moderate to gentle dips consistently toward the southwest. Carbonatization of footwall basalts takes place along the contact with the sediments and marginal to undeformed melanocratic and feldspar-phyric dikes related to the Fourth of July Batholith. These dikes are generally steeply-dipping and oriented more or less parallel to the contact and the shear fabric in the sediments. Gold-bearing quartz veins and veinlets are restricted to the margins of these dikes, either within sediments (Photo 2.9) or carbonatized basalts. Ultramafic rocks consisting of serpentinized harzburgite are not exposed in the trenches but crop out several hundred metres to the southwest and along the shore of Atlin Lake (Figure 2.6). The intervening contact zone between the trenches and outcrops of ultramafic rocks forms a broad linear depression

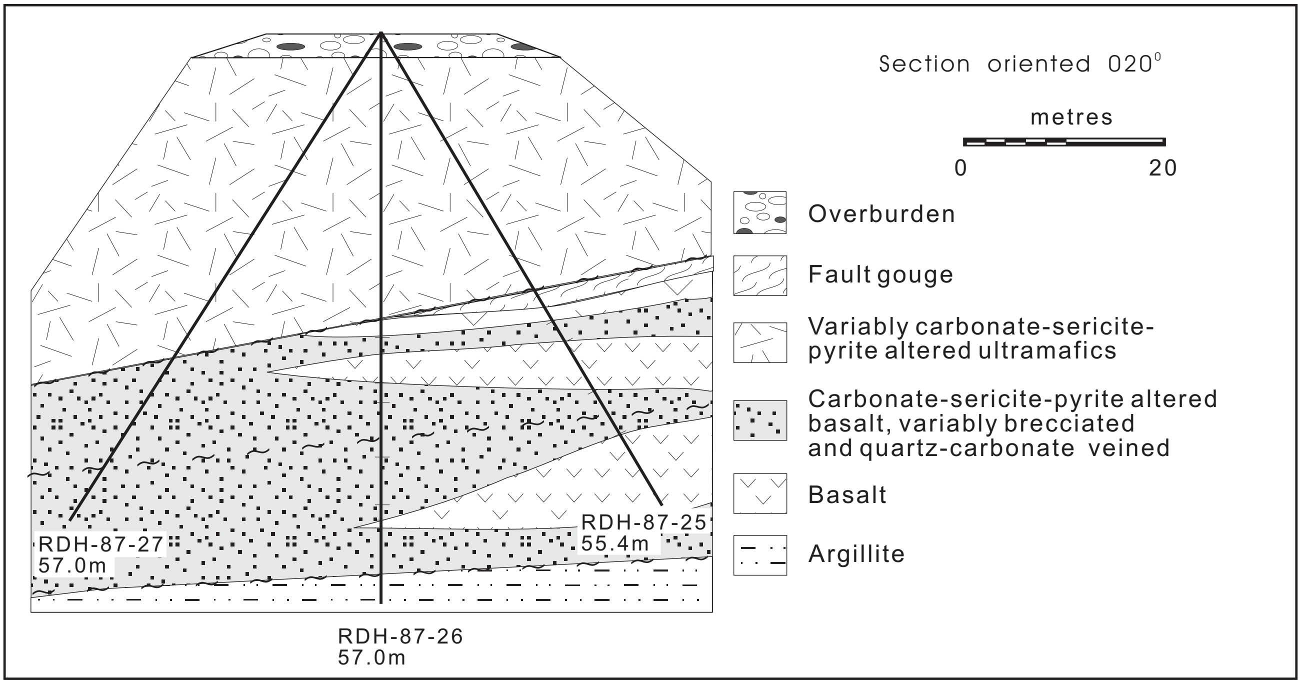


Figure 2.5. Cross-section illustrating the flat-lying character of the Monarch Mountain thrust at the Pictou property.

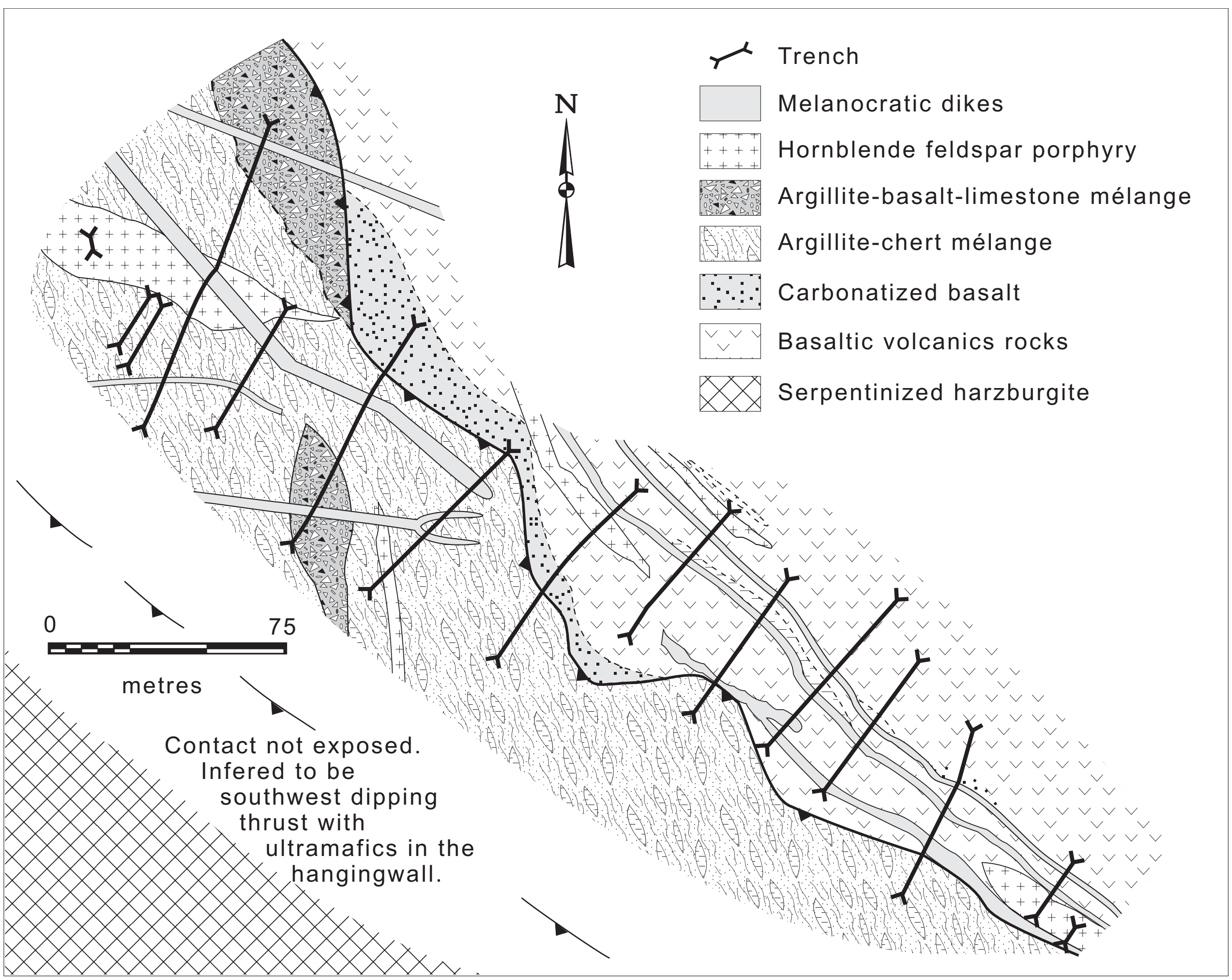


Figure 2.6. Geology of the Beavis prospect. Map location shown on Figure 2.4a.

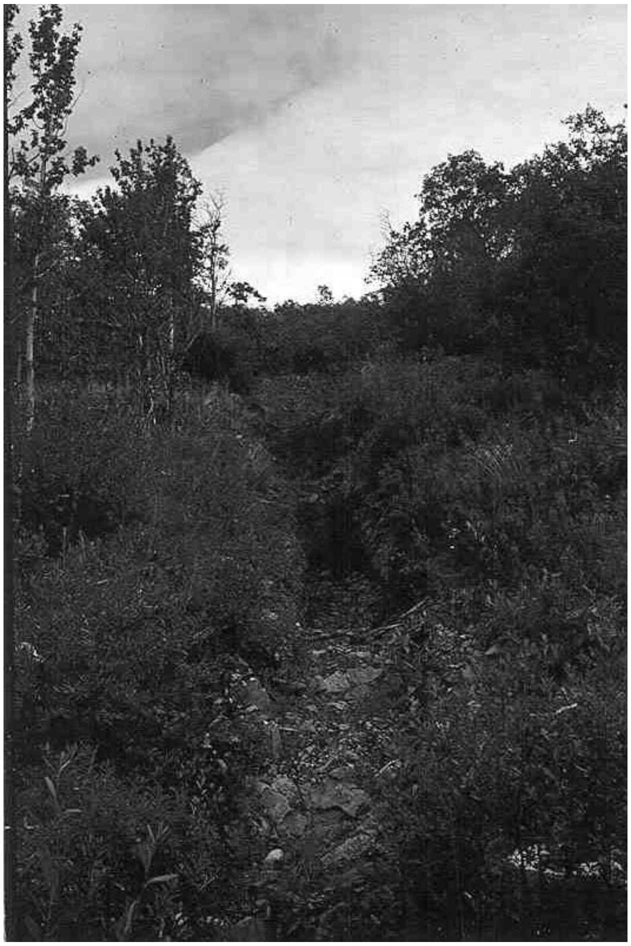


Photo 2.7. Character of trenches mapped at the Beavis Property.

Photo 2.8. Character of argillite-chert broken formation in the Beavis trenches.

devoid of outcrop. The proximity of auriferous quartz veins to the ultramafic rocks suggests that the contact area adjacent to the ultramafic rocks has potential for the development of high-grade ore shoots. An explanation of this relationship is presented in Appendix III, Deposit Characteristics.

Photo 2.9. Detailed relationship between feldspar-porphyritic granodiorite dike (left portion of photo) and quartz vein (centre left) in Beavis trench. Chert-bearing, graphitic argillite broken formation occupies the right half of the photo.

The Golden View showing (MINFILE 104N 042) is located on the western flank of Union Mountain, approximately 6 kilometres southeast of Atlin. It is associated with carbonatized harzburgite along the southern edge of the Monarch Mountain thrust. The showing comprises several quartz veins, 10 to 20 centimetres wide, hosted by carbonatized ultramafic and metabasaltic rocks within the fault zone.

Anna and Aitken Gold are characteristic of lode gold showings hosted by high angle fracture zones within the ultramafic body. The Aitken Gold showing (MINFILE No. 104N019) is a relatively well exposed vein system on the lower western slopes of Monarch Mountain, 3.8 kilometres south of Atlin roughly 50 metres east of the Warm Bay road. Bull quartz veinlets with several percent mariposite form weakly developed stockworks along an east-trending, high angle, variably carbonatized fault zone that cuts variably serpentinized harzburgite. A shallow pit blasted into the hillside exposes several steeply-dipping, anastomosing, quartz-mariposite±carbonate veins 1 to 5 centimetres wide that pinch and swell laterally and vertically (Photo 2.10). Veining is restricted to the core of the fault zone. A characteristic listwanitic alteration halo is developed for several tens of metres on either side of the fault. Alteration passes laterally outward from carbonatized to pervasively serpentinized harzburgite into partially serpentinized harzburgite.

The **Anna** showing (MINFILE 104N 101; Photo 2.11) is located near the plateau of Monarch Mountain, roughly a kilometre west of its summit. The showing occurs along the same northeast-trending, steeply-dipping fault zone that hosts the Goldstar showing. Similar to the Goldstar showing, a listwanitic alteration halo envelops the fault (Lueck, (1985). Quartz fills erratically developed fractures within the pervasively carbonatized fault which grades outward through a variably developed talc-carbonate altered zone into serpentinite. Mariposite is abundant in the strongly altered core; locally it comprises up to 40% of the rock. Abundant, angular, mariposite-rich fragments, from several centimetres to several tens of centimetres in size, are dispersed about a pit blasted 1.5 metres into the fractured and veined core zone. A porphyritic felsic dike, 10 metres in width, that appears to parallel the fault and vein system, has been exposed by trenching near the showing. The ultramafic rocks along the dike contact are talc-carbonate altered and cut by gold-bearing quartz veins.

Lode gold mineralization is also associated with the thrust sheet of ultramafic cumulate rocks along the lower southern slopes of Mount Munro and capping Spruce Mountain. Showings hosted by faults bounding this thrust sheet include the Imperial, Yellowjacket, Surprise and Lakeview. The Yellowjacket showing (MINFILE 043; Lefebure and Gunning, 1988; Bozek, 1989) is associated with the basal faulted contact of this ultramafic body along the Pine Creek valley. The contact between the hangingwall ultramafites and footwall metabasalts is not exposed, but is well defined by 86 exploration drill holes (Marud, 1988 a, b; Marud and Southam, 1988). The zone of thrusting is characterized by up to 15 metres of carbonate alteration that contains intermittent zones of quartz-carbonate veining in both hangingwall and footwall rocks. On the Yellowjacket property the thrust fault is disrupted by a later, east-trending, steeply dipping structure referred to as the Pine Creek Fault. This high-angle fault zone averages approximately 70 metres in width and is described by Marud (1988b) as a fault breccia. It is characterized by strongly broken and fractured rocks, with gouge and rubble zones ranging from centimetres to more than 10 metres wide. The zone contains irregular blocks and lenses of all the lithologies that are typical of the Atlin ophiolitic assemblage, metamorphosed basalt, diabase, gabbro and ultramafics as well as younger felsic rocks. Ultramafic rocks vary from completely serpentinized to completely carbonatized, with or without quartz veining. Along the fault trend on the shore of Atlin Lake a well washed exposure of monolithic tectonic breccia typifies the character of the fault zone within harzburgite tectonite unit (Photo 2.12). Subangular to subrounded blocks of dark brown harzburgite are enveloped by schistose serpentinite.

Marud (1988b) suggested that the later high-angle faulting might be contemporaneous with mineralization along the structure, however, it is more likely that the Pine Creek fault post-dates mineralization. In addition to carbonatized and silicified ultramafic rocks, the fault breccia is dominated by strongly sheared incoherent serpentinite that forms the matrix to the carbonate-altered lithologies. If the serpentinite had been present during the introduction of the CO_2-rich mineralizing hydrothermal fluids one would expect that it too would be altered, or at least show

Photo 2.10a. Exploration adit blasted into quartz veined and carbonatized harzburgite at the Aitken showing.

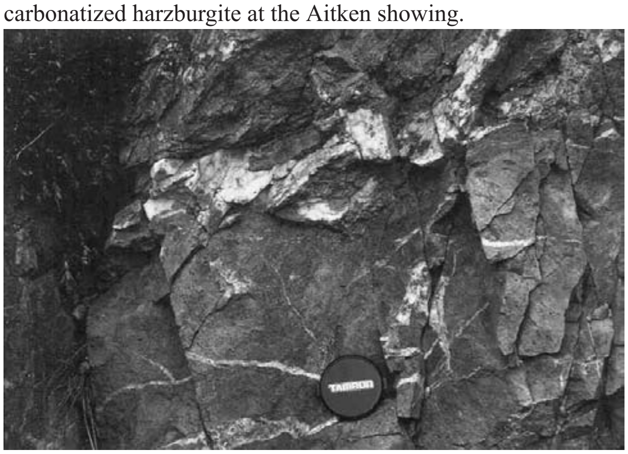


Photo 2.10b. Style of quartz veining in pervasively carbonatized harzburgite at the Aitken showing.

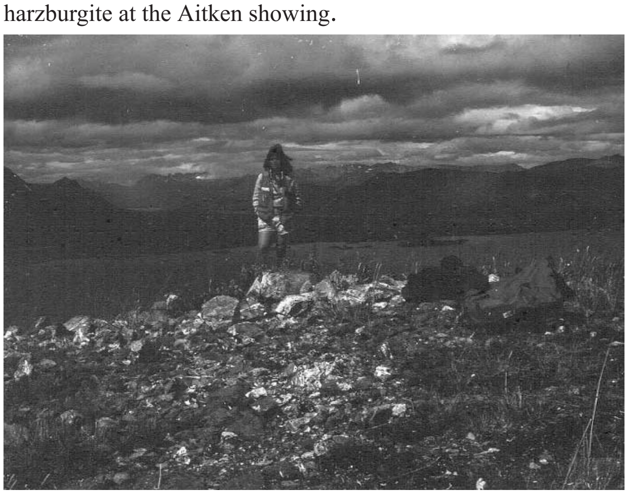


Photo 2.11. Anna showing near the summit of Monarch Mountain.

Photo 2.12. Monolithic serpentinite breccia within the Pine Creek fault zone exposed on the shore of Atlin Lake, north of the Atlin town site. Darker, sub-angular blocks of serpentinized harzburgite in light-grey serpentinite schist.

some degree of carbonate veining. A preferred interpretation is that movement on the Pine Creek Fault resulted in both the development of the serpentinite and the tectonic entrapment of blocks and lenses of carbonatized and mineralized ultramafic rocks that had formed earlier along the basal fault of the ultramafic thrust sheet. Dikes of the Fourth of July batholith affinity that are considered to be coeval with carbonate alteration and associated mineralization. They occur as pods and slivers within the fault zone. This relationship provides evidence that the fault is later than the mineralizing event. Age data presented elsewhere in this chapter provide additional evidence in support of this interpretation.

The **Surprise showing** (MINFILE 104N 076) is located on the northeastern flank of Spruce Mountain approximately 1 kilometre northeast of the summit. The occurrence is a steeply dipping north-trending quartz vein approximately 3.5 metres wide, hosted by carbonatized metabasaltic rocks near a faulted contact with intensely carbonatized ultramafic rocks. Ultramafic rocks form a north-northeast trending lens with a width of roughly 150 metres at the showing and appears to thin significantly to the east. The exposed vein consists of fractured white bull-quartz with randomly distributed clots of euhedral galena, 0.5 to 4 centimetres across, comprising from 1 to 3% of the vein. No mariposite can be seen in the vein where exposed but it comprises up to several percent of the carbonatized wallrocks.

The **Imperial deposit** (MINFILE 104N 008) and **Lake View showing** (MINFILE 104N 009) are hosted by mafic volcanic and plutonic crustal rocks near the carbonatized, faulted borders of the western and eastern ends of the wehrlitic ultramafic body respectively (Figure 2.4a).

The abandoned Imperial mine is located on the southwestern flank of Mount Munro, 8 kilometres northeast of Atlin. Two northwest-trending auriferous quartz veins dip moderately toward the southwest and are hosted by fissures in carbonatized basalt/diabase and gabbro close to their faulted contact with the ultramafic cumulates. The gold quartz veins are associated with pyrite-sericite-carbonate altered feldspar-phyric dikes that are also anomalous in gold. The Lakeview showing is located between Birch and Boulder creeks north of the east end of Surprise Lake, at the eastern end of the ultramafic thrust sheet. A mineralized northwest-trending quartz vein, 2 centimetres to 1 metre wide, dips steeply to the northeast. The vein is hosted by carbonatized metabasalt adjacent to a faulted contact with serpentinized and carbonatized ultramafic rocks.

ALTERATION AND MINERALIZATION

Gold-bearing quartz veins in the Atlin camp are typically associated with carbonatized ultramafic or mafic lithologies. Studies of the alteration mineralogy show that the Fe-Mg carbonate, breunnerite (a type of magnesite with 40-80 weight % Mg) is the dominant carbonate replacing the serpentinized ultramafic hostrocks. Iron-dolomite is the principal vein carbonate and also occurs in the altered host rocks (Newton, 1985; MacKinnon, 1986; Bozek, 1989). The Fe-Mg content of the magnesite shows considerable variability which is considered to result from differences in the primary composition of the host rocks, whereas Fe-dolomite showed much less variation. A marked increase in potassium content adjacent to the gold-bearing veins is a consistent feature. Unlike the broad halo of secondary carbonate, zones of silicification and quartz veining with associated mariposite are restricted or adjacent to the controlling fracture.

Mariposite (Cr-muscovite) is associated with many of the quartz veins, occurring either within the veins or in the pervasively carbonate-altered wall-rocks. Newton (1985) studied samples of mariposite from four different showings throughout the camp and identified a relatively uniform compositional range in the major elements Si, Al, K as well as in Cr. In contrast, measured concentrations of trace elements including Fe, Mg, Ni, Ba and V showed some marked variation between individual groups of samples. All samples contained trace amounts of iron but mariposite from two of the gold vein occurrences contained only Mg, Ba and V with no Ni. Where Ni is present in the other two occurrences it is the only trace element present. These differences can be attributed to differences in the character of the ultramafic rock types that are hosts for the mariposite. Samples characterized by selective trace element enrichment only in Ni from the Discovery and Goldenview occurrences are hosted by harzburgite tectonite. Those enriched in Mg, Ba, and V with no Ni from the Lakeview and Surprise showings are hosted by ultramafic cumulate rocks.

It is well established that Ni, which is refractory during processes of mantle partial melting, is selectively enriched in residual metamorphic harzburgite tectonites relative to genetically associated ultramafic cumulate rocks. Ba and V, in contrast are mobile and would be selectively enriched in the melt fraction produced during partial melting in the derived ultramafic cumulate rocks. The provenance of Mg enriched mariposite in the ultramafic cumulates is less clear cut.

These data, although limited, suggest that trace element compositions of mariposite may be used to determine the original composition of the altered ultramafic rocks in which they are hosted. This relationship deserves to be tested further for consistency, but is one that could be used to potentially characterize small zones of ultramafic rocks lacking recognizable primary textures or mineralogy due to intense and pervasive alteration.

Gold occurs either within quartz veins or in zones of carbonatized, potassium metasomatized and pyritized ultramafic and mafic hostrocks immediately adjacent to the veins. It occurs as free gold and as inclusions in sulphide minerals. Gold-bearing hydrothermal systems are generally low in overall sulphide content, ranging from 2 to 5% where they occur as 1 to 3 millimetre, disseminated grains. At both the Pictou and Surprise showings intensely carbonatized ultramafic rocks form zones containing from 10 to 15% finely disseminated sulphides. At these showings gold is anomalous only in the sulphidized zones; white bull quartz veins are barren. At the Pictou showing Bozek (1989) found that there is a positive correlation between elevated gold and higher concentrations of other metals (Cu, Pb, Zn, Sb, As, Ag). Ballantyne and Mackinnon (1986) examined a number of gold occurrences and reported that associated elements; Ag, As, Ni, Co, Bi, Sb, Te and Pb are consistently present in the gold-bearing quartz veins.

A range of ore mineralogies and gold compositions have been determined by microprobe and scanning electron microprobe (SEM) examination of quartz vein samples from a number of the occurrences (Table 2.1; S.B Ballantyne and D.C. Harris, personal communication, 1992). Sample analyses were conducted at the Geological Survey of Canada, Ottawa on samples collected by S.B Ballantyne. All samples are from quartz veins in outcrop or dump material except for the Yellowjacket, which is from drill core. The most notable relationship is the wide variation of sulphide minerals between prospect. An increased number of sulphides present in vein systems hosted in ultramafic rocks (Anna and Pictou) suggest inheritance of metallic elements that are primary to the host ultramafic, *e.g.* Ni, and account for some of the additional sulphide minerals. In contrast, samples from veins hosted by mafic hypabyssal-volcanic rocks such as those at Discovery, Goldenview, Surprise display limited variation in sulphide mineralogy.

The composition of individual gold grains is relatively uniform, but wide variations are possible, even within the same vein sample (*see* Lakeview and Anna). Neither copper nor mercury was detected in the gold grains analyzed.

AGE OF MINERALIZATION

A number of researchers in the Atlin area have attempted to establish the age of the gold mineralization. Based on lead isotope data for galena from quartz veins, An-

TABLE 2.1
GOLD COMPILATION AND SULPHIDE MINERALOGY OF SELECTED QUARTZ VEINS IN THE ATLIN CAMP

Mineral Occurrence	Mineralogy (generally in decreasing order of abundance)	Average Gold Composition Fineness Range
Anna	pyrite galena gersdorffite (NiAsS) bismuthimite (Bi_2S_2) tetradymite (Bi_2Te_2S) sphalerite chalcopyrite pyrrhotite millerite	native gold 844 (835-855) electrum 625 in Fe-Mn dolomite gangue
Discovery Shuksan	pyrite galena pyrrhotite	native gold 885
Goldenview Little Spruce Creek	pyrite chalcopyrite galena	 N/A
Surprise Spruce Mtn.	galena pyrite	N/A
Lakeview Sharon Birch Creek	galena pyrite sphalerite hessite (Ag_2Te) tetradymite (Be_2Te_2S)	native gold with hessite 809 electrum with galena 708 (769-792)
Yellowjacket Pine Creek	pyrite gersdorffite (NiAsS) rammelsbergite ($NiAs_2$) millerite	electrum 766
Pictou Atlin airport	pyrite freibergite $[(Ag,Cu)_{12}(Sb,As)_4S_{13}]$ chalcopyrite gersdorffite (NiAsS) rammelsbergite ($NiAs_2$) sphalerite acanthite (Ag_2S) millerite	 N/A
Beavis Atlin Lake	pyrite chalcopyrite sphalerite rutile	electrum 774 (770-784)

Gold Fineness: approximately [Au/(Au+Ag)] * 1000 drew (1985) proposed a Triassic age. Rees (1989) concluded that mineralization occurred during the period of post-magmatic high-angle faulting associated with the Pine Creek Fault.

In an attempt to establish the timing of listwanitic alteration considered to be attendant with gold mineralization, samples of Cr-muscovite were collected from five gold showings in the camp. Three of the samples were taken from listwanite alteration zones within or marginal to the harzburgite body at the Anna, Aitken Gold and Pictou showings. The other two were collected from the basal fault zone of the other ultramafic thrust sheet, at the Yellowjacket and Surprise prospects. Mariposite from the Anna and Goldstar showings occurs in quartz veins and was sampled from blasted pits, to avoid the effects of weathering. The sample from the Yellowjacket was obtained from quartz in drill core supplied by Darcy Marud, formerly of Homestake Mining Company. Mariposite from both the Surprise and Pictou showings was taken from pervasively carbonatized altered ultramafic rocks adjacent to the quartz veins in which there is no visible mariposite.

Results of Ar-Ar Dating

Mariposites from the Surprise, Aitken Gold, Yellowjacket and Pictou lode gold showings (Figure 2.1) were analyzed at Dalhousie University by the conventional ^{40}Ar/^{39}Ar step-heating method described in Appendix II. Age spectrum plots are shown in Figure 2.7.

Samples for the Surprise, Yellowacket and Aitken Gold showing yielded fairly consistent ages over the major portions of the gas released. There is a tendency for apparent ages to decrease at the highest extraction temperatures. Because these concentrates are fine-grained and relatively impure, irregular spectral features may be produced by irradiation-induced recoil of ^{39}Ar out of micas and into other, perhaps more argon retentive phases. To compensate for this effect, total gas ages (employing all but the low-age first steps) have been calculated to give the preferred ages indicated in Figure 2.7. These are respectively 168±3, 171±3 and 167±3 Ma. The spectrum obtained for the sample from the Pictou showing is more variable and yields a preferred age of 165±4 Ma. This spectral variation and overall lower apparent ages may both be a consequence of the relatively finer-grained nature of this sample.

Results of K-Ar Dating

Initially K-Ar dating was conducted at The University of British Columbia on mariposite from the Surprise, Pictou, Warm Bay and Anna showings. The analytical data and calculated ages for these hydrothermal micas are given in Table 2.2. The ability to obtain a sufficient amount of mariposite separate needed for K-Ar dating (1 g) proved to be a problem for the majority of the samples. The fine-grained nature of the mineral and a specific gravity similar to that of hydrothermal carbonate, made mineral separation by heavy liquids difficult. Sufficient mariposite to provide a homogeneous clean mineral separate was obtained only from the Surprise showing. It gave an apparent age of 171±6 Ma; an age which is in excellent agreement with the calculated ^{40}Ar-^{39}Ar plateau ages. The other three

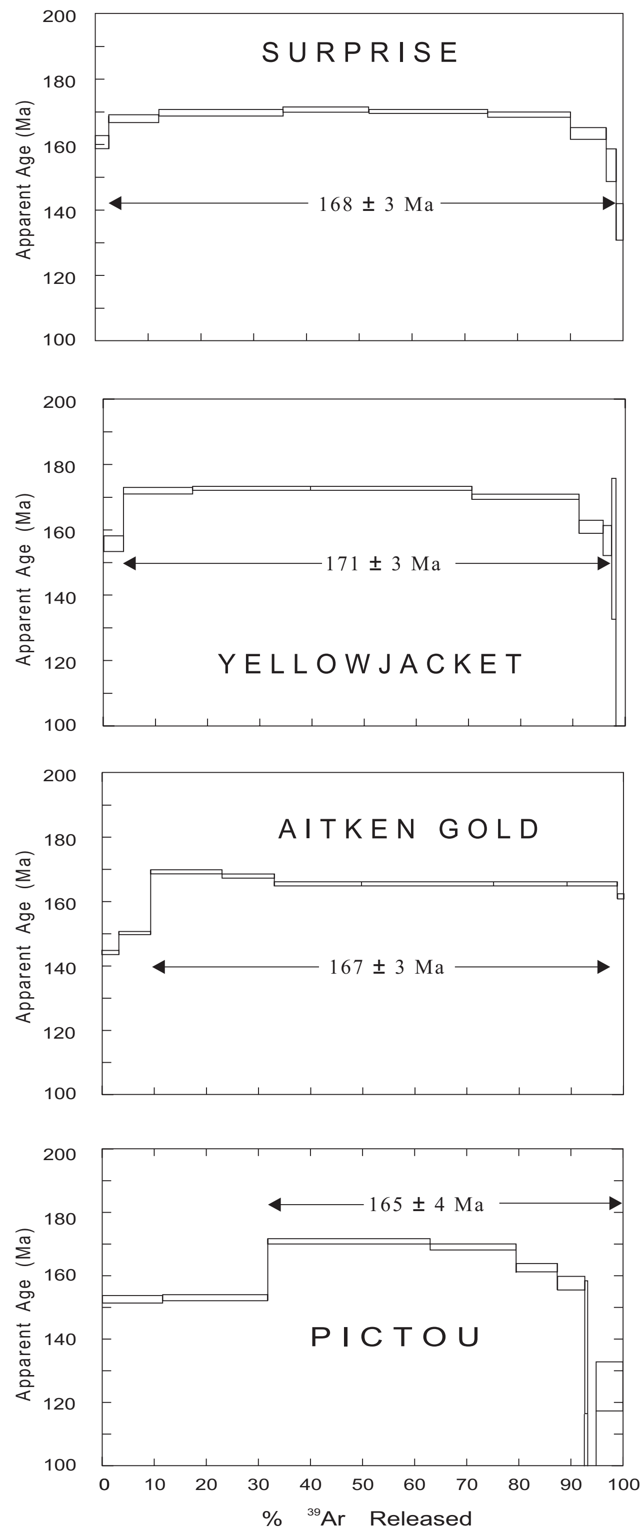


Figure 2.7. ^{40}Ar-^{39}Ar apparent age spectra of mariposite from four lode gold showings in the Atlin camp. Sample locations shown on Figure 2.4.

TABLE 2.2
K-Ar MINERALIZATION AGES FOR SELECTED GOLD SHOWINGS IN THE ATLIN CAMP

Showing	K (%)	Rad. Ar^{40} (%)	SampleType	Age (Ma)
Anna	0.41	70.4	WR (Marip)	169 ± 6
Aitken Gold	3.32	91.7	WR (Marip)	156 ± 5
Pictou	0.18	53.8	WR (Marip)	121 ± 4
Surprise	7.09	95.7	MS (Marip)	171 ± 6
FJB Stock[1]			MS (Sericite)	160 ± 2

[1]Age reported by Dawson (1988)
MS - Mineral Separate, WR - Whole Rock
All age dates reported where obtained by Joe Harakal and D. Runkel, The University of British Columbia.

samples taken for K-Ar dating failed to provide sufficient mariposite separate and were treated as “whole rocks”. This approach had limited success and gave a range of apparent mineralization ages with questionable reliability. The Anna showing was dated at 169±6 Ma which is in agreement with the $^{40}Ar/^{39}Ar$ data presented above. The Aitken Gold sample gave an apparent K-Ar age of 156±5 Ma years. This is inconsistent with the apparent $^{40}Ar/^{39}Ar$ date for the same sample, which shows a remarkably uniform plateau, consistent with the other dates, with no indication of a thermal event at 156 Ma. The K-Ar date is therefore considered suspect due to these conflicting data combined with the nature of the sample used. A 121±4 Ma K-Ar cooling age obtained from the Pictou sample (Table 2.3) is markedly discordant with the other mariposite ages. The low potassium content of the analyzed sample suggests that it was relatively deficient in mariposite. This sample provides the most discordant of all the Atlin Ar-Ar plateau ages which may be due to the very fine-grained nature of the hydrothermal mica.

The isotopic data indicate that the formation of mariposite and attendant gold mineralization throughout the Atlin camp is Middle Jurassic in age. The consistency of uniform plateau ages, without indications of significant resetting suggests that the mineralizing episode was a single, relatively short-lived event.

The age data establish a synchronous relationship between gold mineralization (167 to 171 Ma) and intrusion of the late syn-orogenic Fourth of July batholith (166-172 Ma). A direct genetic relationship between gold mineralization and the spatially and temporally associated felsic magmatism appears likely, but remains equivocal.

SOURCE OF PLACER GOLD

The gold veins described above have been widely accepted as the source of the abundant gold won from Tertiary and Quaternary placer gravels (Aitken, 1959; Monger, 1975; Ballantyne and MacKinnon, 1986; Lefebure and Gunning, 1988; Rees, 1989; Ash and Arksey, 1990a). Two convincing lines of evidence support this relationship:

- The coarse, free gold in the veins is similar physically and chemically to the gold recovered from the placer gravels (MacKinnon, 1986; Ballantyne and MacKinnon, 1986).
- The two most productive placer gold streams, Spruce Creek and Pine Creek, drain erosional windows through the basal fault zones of the ultramafic thrust sheets that are hosts for most of the gold mineralization throughout the camp.

Historically, significant economic concentrations of placer gold are restricted to streams in the Pine Creek and McKee Creek watersheds (Figure 2.1). It appears that preferential erosion through flat-lying mineralized thrust contacts in both these areas was accelerated along high-angle, post-accretionary fault zones. This interpretation is supported by the presence of fault breccia zones within both these valleys. The fault breccia along the Pine Creek Fault on the Yellowjacket property has been described previously. A similar tectonic breccia, with lenticular inclusions of various competent lithologies in a sheared and flaggy argillaceous matrix has been recognized at the headwaters of McKee Creek (Photo 2.13a, b). As at the Yellowjacket, the breccia contains isolated tectonic inclusions of altered feldspar-phyric dike rock. Because intrusion of these dikes is interpreted to be coeval with vein mineralization, it can be concluded that movement on the fault postdates the gold mineralization.

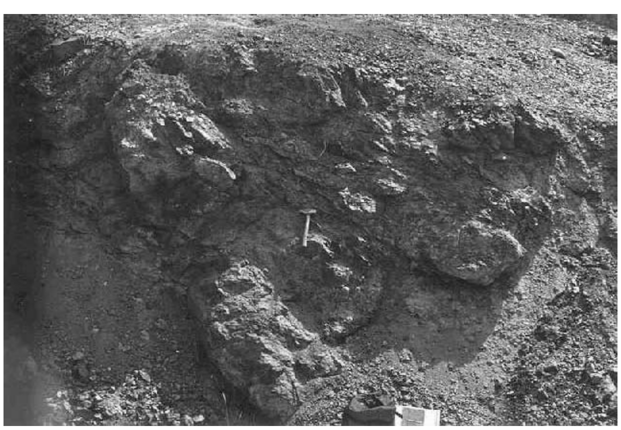



Photo 2.13.a, b. Tectonic melange within the McKee Creek fault zone, headwaters McKee Creek (Photo courtesy of Mitch Mihalynuk).

SUMMARY

The northern Cache Creek terrane in the area of the Atlin placer gold camp is lithotectonically divisible into both ophiolitic assemblages and accretionary complexes. Gold veins are only found within or immediately adjacent to the ophiolitic assemblage rocks.

Occurrences of gold quartz vein mineralization throughout the camp are localized along pervasively carbonatized fissure and fracture zones within and marginal to serpentinized mantle tectonite and ultramafic cumulate rocks of the Atlin ophiolitic assemblage.

Gold quartz veins are poorly and erratically developed within the ultramafic rocks and more commonly occur as random fracture fillings. Wider, more continuous tabular fissure veins have been identified only in the mafic igneous crustal components (gabbro, diabase) of the Atlin ophiolitic assemblage where immediately adjacent to carbonatized ultramafic rocks.

Ages of hydrothermal Cr-muscovite (mariposite) associated with the gold mineralization suggest a limited interval of vein formation between 171 and 167 Ma. This age of mineralization is consistent with the timing of Middle Jurassic magmatism at around 171 Ma. There is also a consistent spatial association between known gold vein occurrences and high level dikes and stocks. Both mineralization and magmatism appear to closely follow Middle Jurassic orogenic activity.

Placer deposits within the camp are situated in stream valleys cutting erosional windows through the carbonatized relatively flat lying thrust faults within the Atlin ophiolitic assemblage. The placers are considered to be derived from quartz lodes previously contained within the ophiolitic crustal rocks.

Variations in the trace element composition of Cr-muscovite as defined by Newton (1985) appear to be related to differences in the primary composition of the altered ultramafic host. These data, although limited, suggest that the trace element compositions of mariposite may be used to determine the original composition of the altered ultramafic rocks in which they are contained. This relationship deserves to be tested further to determine if it can be used to characterize small zones of ultramafic rocks that lack recognizable primary textures or mineralogy due to intense and pervasive alteration.

CHAPTER 3
CENTRAL CACHE CREEK TERRANE
SNOWBIRD DEPOSIT

INTRODUCTION

The central Cache Creek Terrane (Figure 3.1) or Stuart Lake belt of Armstrong (1949) has no recorded gold production from lode deposits. However, there are a number of significant showings and some placer gold has been recovered from small streams throughout the belt (Holland, 1950). Most placer gold (about 7800 oz or 242 000 g) has been obtained from the northern end of the central Cache Creek Terrace primarily from Vital and Tom creeks. Minor placer production (330 oz; 10 265g) is also recorded from the southwestern end of Stuart Lake on Sowchea and Dog creeks.

The Snowbird prospect, located at the southwestern end of Stuart Lake, is a shear-hosted gold-quartz vein occurrence with historic antimony production. As it is readily accessible and the only documented occurrence of its type in the region, it was selected for investigation. The deposit was mined for antimony over half a century ago, and has been periodically evaluated for its gold potential. Although gold-bearing intersections have been obtained in drill core (Game and Sampson, 1987a), no mining for gold has taken place.

Investigations in the region were conducted over two 2-week periods in 1989 and 1991. Mapping of a northwest-trending belt to the southwest and northeast of Stuart Lake to provide a database suitable for mineral potential evaluation was conducted over a 3-week period in 1993 (Ash and Macdonald, 1993; Ash *et al*., 1993) and helped to establish the regional setting of the deposit. This chapter describes the lithotectonic setting of the Snowbird deposit and presents data on the age of mineralization and spatially associated felsic intrusive rocks. Major element analyses of these rocks are presented and used to characterize their composition.

PREVIOUS WORK

Earliest published geological maps of the region are those of Armstrong (1942a, 1944), which focused on a north-trending belt, 20 kilometres wide, centred on the Pinchi fault zone. Armstrong (1949) also conducted the first systematic mapping of the region. He subdivided the Cache Creek rocks into two units: limestones, and a mixed sedimentary suite of argillites and cherts with subordinate mafic volcanics. Ultramafic rocks throughout the belt were referred to as the 'Trembleur intrusions', which he interpreted to be later crosscutting plutons consistent with concepts widely held before the development of plate tectonic models. Subsequently, Rice (1948) produced a 1:506 880-scale geological compilation and mineral occurrence map for the Smithers - Fort St. James area.

Paterson (1973, 1974, 1977) mapped and described the geology of the Pinchi Lake area and determined that the lithologies are consistent with those of a dismembered ophiolite suite. He suggested that the Pinchi fault may represent a fossil oceanic transform, a view consistent with current interpretations for the development of these units in British Columbia as well as for regionally correlative rocks along the Western Sierra Nevada metamorphic belt (Saleeby, 1990, 1992).

Ross (1977) documents the detailed structural history of ultramafic rocks underlying Murray Ridge, southeast of Pinchi Lake. He defined three generations of deformation in the residual harzburgite and concluded that the two earlier fabrics were generated by mantle transport and the later fabric by high-level structural emplacement (obduction). Whittaker (1982a, b; 1983a, b) and Whittaker and Watkinson (1981; 1983; 1984; 1986) present detailed petrological and phase chemistry data for the majority of the larger ultramafic bodies in the region which support the interpretation that they are obducted fragments of oceanic uppermost mantle material.

Ash *et al*. (1993) and Ash and Macdonald (1993) subdivided the central Cache Creek into accretionary complex and ophiolitic assemblage rocks on the basis of lithological and tectono-stratigraphic relationships. They also demonstrated petrochemically that mafic volcanic rocks associated with thick sequences of Paleozoic limestone along the Pinchi Fault are of ocean island affinity and distinct from MORB mafic volcanic rocks typically associated with other ophiolitic assemblage rocks, a relationship consistent with that previously described by Monger (1977a,b) for the northern Cache Creek Terrane.

Subsequent to 1992 fieldwork in the area (Ash and Macdonald, 1993; Ash *et al.*, 1993) the region has been remapped as part of the Nechako Plateau NATMAP Project (Struik and MacIntyre, 1997, 1998, 1999). NATMAP researchers in the immediate Stuart Lake area have adopted a more traditional stratigraphic approach to these oceanic rocks (Struik *et al*., 1996; Cordey and Struik, 1996; Orchard and Struik, 1996; Orchard *et al*, 1997; Letwin and Stuick, 1997; Struik *et al*, 1997; Sano and Struick, 1997; Orchard *et al*, 1997; Whalen and Stuick, 1997; Sano, 1998), for maintaining use of the outdated term 'Cache Creek Group' for this tectonically constructed package of oceanic rocks. For reasons discussed in Chapter 1 it is advised that such usage be discontinued, as a stratigraphic approach to these rocks is misleading.

We maintain that the lithotectonic subdivisions in the following text are valid as they adequately separate economically significant oceanic crustal and upper mantle

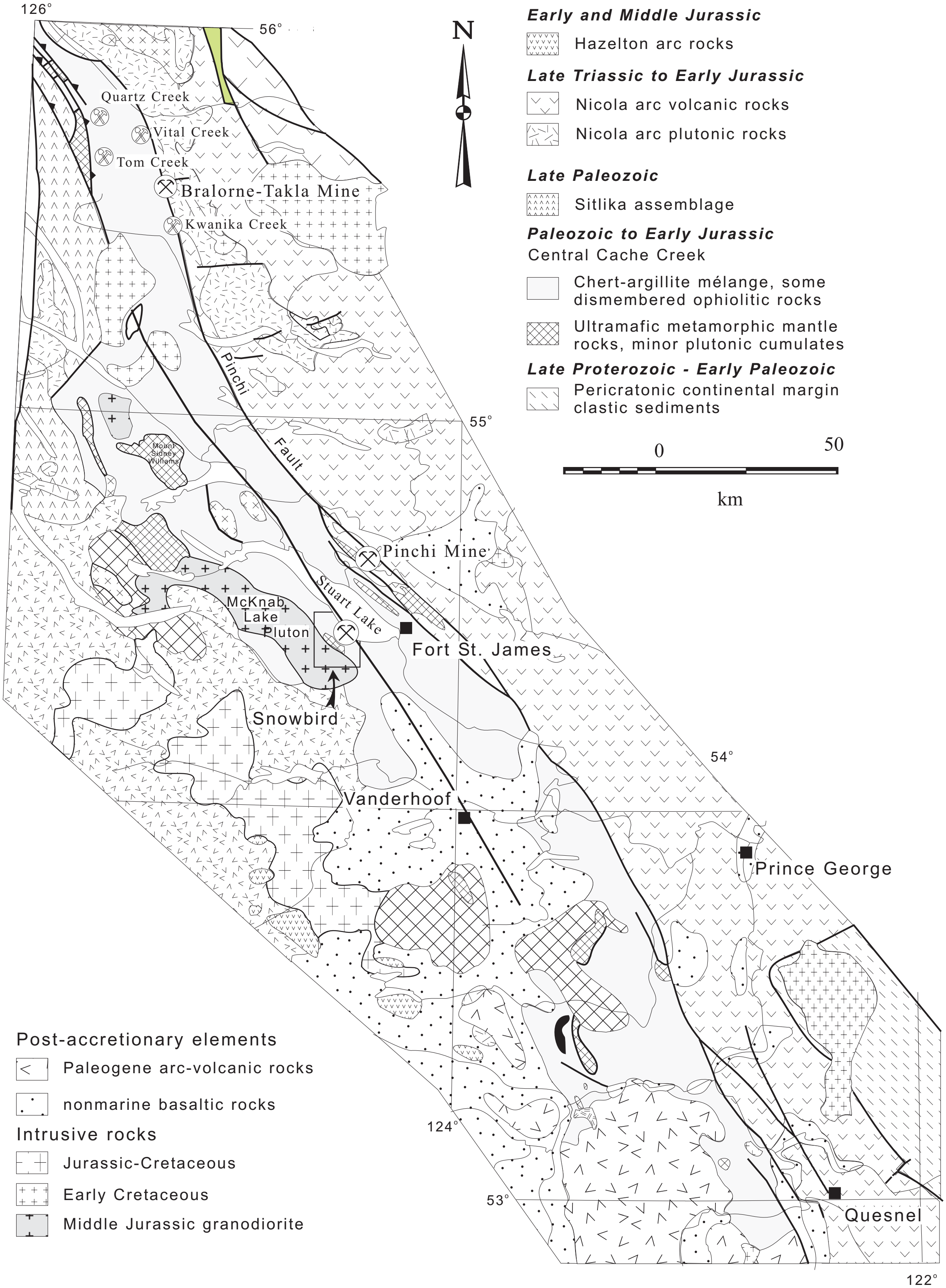


Figure 3.1. Regional geology of the central Cache Creek Terrane (modified after Wheeler and McFeely, 1991).

rocks from the largely accreted and tectonically disrupted, sedimentary-dominant sequences. It also places units into a distinctive lithotectonic framework, which addresses both their origin and tectonic construction.

The geology of the Snowbird-Sowchea area has been mapped and in part compiled at a 1:10 000-scale by Callan (1991). The area of the main showing has been mapped in greater detail (Heshka, 1971; Game and Sampson, 1987a, b). Previously published descriptions of the deposit include those of Armstrong (1949), Faulkner (1988) and Faulkner and Madu (1990). Fluid inclusion and isotope data on mineralized quartz-carbonate veins have been presented by Madu *et al*. (1990).

REGIONAL SETTING

The central Cache Creek Terrane forms a northwest-trending belt, 450 kilometres long, that average 60 kilometres wide (Figure 3.1). The belt is bounded by faults and comprises a tectonically intercalated package of pelagic and siliciclastic sediments with lesser limestones, subordinate oceanic crustal volcanic-plutonic and mantle metamorphic lithologies. Similar to the northern Cache Creek Terrane, these rocks are divisible into two broad lithotectonic elements that include an accretionary complex and ophiolitic assemblages. In accord with the former Stuart Lake designation of Armstrong (1949) for the belt, we use the terms 'Stuart Lake accretionary complex' and 'Stuart Lake ophiolitic assemblage' to distinguish between the two.

In addition to these lithotectonic elements, as in the northern Cache Creek, a third and distinct association of thick, Late Carboniferous limestone sequences associated with alkali basalts that characterize accreted remnant ocean island(s) are also present along the western margin of the belt. Recently documented facies changes within the Mount Pope limestone sequences (Sano and Struik, 1997; Sano, 1998) support an ocean island origin as initially suggested by Ash and Macdonald (1993), based on the petrochemial character of associated volcanic rocks.

The topographically highest areas throughout the belt are commonly underlain by relatively large ultramafic bodies such as the Murray Ridge, Mount Sydney Williams and Rubyrock ultramafites (Figure 3.1). These consist of residual harzburgite tectonite with subordinate dunite and pyroxenite, or their serpentinized equivalents. The rocks are interpreted to represent residual upper mantle material tectonically emplaced into its present position. Most of these rocks are associated with oceanic mafic plutonic gabbro and basaltic volcanic units with characteristic MORB chemical signatures that collectively comprise remnants of dismembered oceanic crust and upper mantle (*i.e.* ophiolites). These remnants commonly display characteristic inverted ophiolite stratigraphies (Appendix 1) and are interpreted to be structurally emplaced above the Stuart Lake accretionary complex. The accretionary complex dominates the poorly exposed lower-lying areas of the belt. It comprises variably metamorphosed and deformed argillaceous and siliceous sedimentary rocks with lesser pods and slivers of limestones and mafic volcanics (Photo 3.1 and 3.2).

The age of the central Cache Creek Terrane is constrained almost entirely by paleontological data. A single U-Pb ziron date of 257±5 Ma on gabbro underlying the Mount Sidney Williams ultramafic body (P. Schiarizza, personal communication, 2000) provides a Permian age for these ophiolitic rocks. Limestones throughout the belt contain fusulinids that range in age from Pennsylvanian to Late Permian (Armstrong, 1949; Thompson, 1965). Conodonts from massive carbonate of the Mount Pope sequence near Fort St. James are dominantly Late Carboniferous in age but locally are as young as Early Permian (Orchard, 1991; Orchard and Struik, 1996; Orchard *et al.*, 1997, 1998). Cherts from Stuart Lake accretionary complex yield late Norian conodonts (Orchard, 1991) and Middle to Late Triassic radiolaria (Cordey, 1990a,b; Cordey and Struik, 1996). Fossil evidence thus places the upper age limit of the central Cache Creek at Latest Triassic which is notably older than the northern Cache Creek Terrane from which Early Jurassic fossils are identified (Cordey *et al*., 1991).

Cache Creek oceanic rocks are intruded by Middle Jurassic quartz diorite, tonalite and lesser granodiorite. Several Early Cretaceous medium to coarse-grained granite to

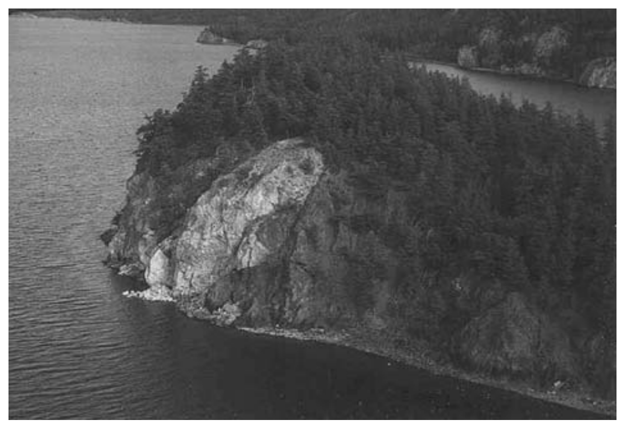


Photo 3.1 Limestone block in sheared fine grained siliciclastic and pelagic sediments exposed along the northwest end of Battleship Island in the south eastern end of Stuart Lake.

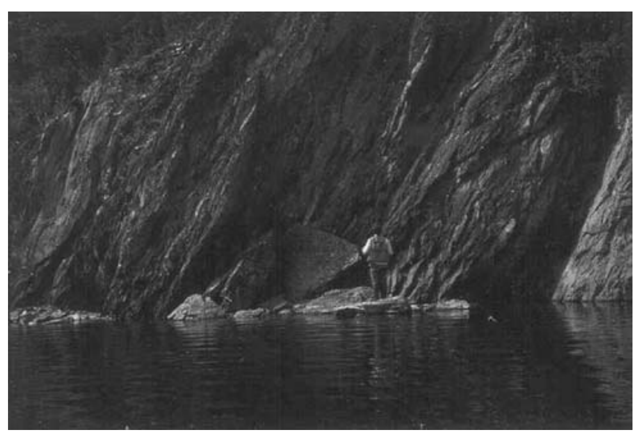


Photo 3.2. Accretionary complex siliciclastic sedimentary rocks exposed on island in the center of Stuart Lake displaying irregular planar fabric.

granodiorite intrusions also intrude the Stuart Lake complex, but are restricted largely to the northern portion of the belt (MacIntyre and Schiarizza, 1999).

Along its eastern margin, the belt is separated by the Pinchi fault zone from the early Mesozoic Takla Group rocks of the volcanic-plutonic arc terrane of Quesnellia . Paterson (1977) described the zone in the Pinchi Lake area as a series of elongate fault-bounded blocks of contrasting lithology and metamorphic grade. The fault is interpreted to be a high-angle transcurrent structure (Gabrielse, 1985) that records a protracted history of displacement. Patterson (1973, 1977) describes a belt of glaucophane-lawsonite-bearing mafic metavolcanics and metasediments within and parallel to the Pinchi fault zone with blueschist grade metamorphism. Four K-Ar dates on muscovite from these blueschists range from 212 to 218 ± 7 Ma, indicating a Late Triassic metamorphic age (Paterson and Harakal, 1974). Armstrong (1966) referred to the Pinchi fault as the Pinchi mercury belt, as it is a strongly carbonatized zone with mercury mineralization occurring intermittently along most of its exposed length (Armstrong, 1942a,b, 1949, 1966; Rice, 1948). The Pinchi mine (MINFILE No.039K049) is the only significant mercury producer; production during two periods of operation (1940-44, 1968-75) totalled 6.28 million kilograms (182 296 flasks) of mercury from 2.03 million tonnes of ore milled (I.A. Paterson, personal communication, 1992).

Contact relationships along the western margin of the central and southern parts of the belt are poorly defined, as they are masked by Tertiary volcanic rocks and thick drift cover. To the north, the western boundary of the belt is marked by the Vital fault, an easterly-dipping thrust which places Cache Creek rocks over the Sitlika assemblage (Paterson, 1974; Monger *et al*., 1978; Childe and Schiarizza 1997; Childe *et al*., 1998; Schiarizza *et al*., 1998). The Sitlika is an enigmatic sequence of Permian to Jurassic volcano-sedimentary rocks, which shows similar lithologic and tectonostratigraphic relationships to the Kutcho Formation along the southeast boundary of the Atlin Terrane (Thorstad and Gabrielse, 1986). These rocks are tentatively included with the Cache Creek Terrane (Gabrielse, 1991) and are considered to be related to the destructive stage of the Cache Creek ocean basin. The Sitlika assemblage is separated from arc-volcanic and plutonic rocks of Stikinia by the Takla fault to the west.

LOCAL GEOLOGY

The area surrounding the Snowbird property is underlain by oceanic crustal and sedimentary rocks that are intruded by Middle Jurassic tonalitic to quartz dioritic plutons (Figure 3.2). The area is dominated by pelagic sediments with lesser limestone, metabasalt, ultramafic and gabbroic units that form northwest-trending belts consistent with the regional structural grain of the central Cache Creek Terrane. The McKnab Lake pluton is exposed along the western property boundary. A smaller, satellite intrusion of altered quartz diorite to tonalite composition, the Snowbird Stock, cuts Cache Creek sedimentary and metavolcanic rocks on the peninsula near the west shore of Stuart Lake. There are also dikes in the area of the main Snowbird showing. Both the large intrusions are relatively undeformed elongate bodies, oriented parallel to the regional structural grain.

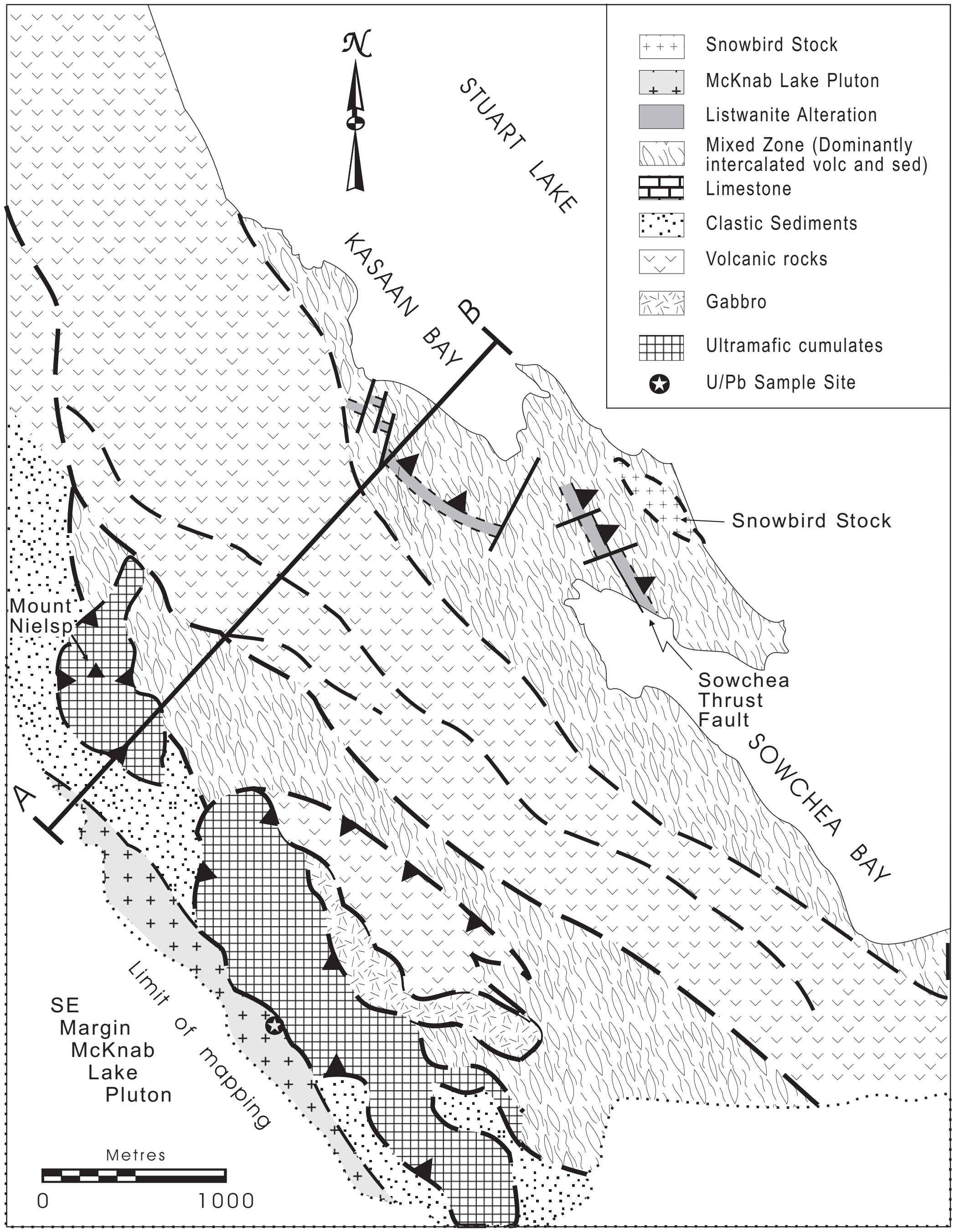
ACCRETIONARY COMPLEX ROCKS

Sedimentary rocks in the central Cache Creek Terrane are dominated by fine grained siliciclastic and pelagic sediments including siliceous argillite, mudstone, siltstone and chert, with lesser greywacke. Siliciclastic sediments are grey to black and vary from massive to well-cleaved. Cherts are pale grey to buff-white and massive to locally banded. The central low-lying area between the Snowbird deposit and the ophiolitic assemblage rocks to the east was interpreted by Game and Sampson (1987) to be underlain by a belt of continuous limestone. This interpretation is based on selective exposure of resistant limestone blocks within the recessive siliceous argillites in this area of poor bedrock exposure. Similar resistant limestone blocks occur along a northwest trending ridge to the east of the Snowbird main showing, characterize this relationship (Photo 3.3). These limestones are typically light to dark grey, buff weathering, locally mottled and massive to laminated and commonly contain crinoids. The origin of these small limestone blocks within the deposit area is permissive. Large enclaves of pale grey limestone are clearly visible on the northwest end of Battleship Island roughly 5 kilometres to the northeast (Photo 3.1) close to the thick Mount Pope limestone sequences along the eastern margin of the central Cache Creek Terrane. It is likely that these limestone blocks throughout the deposit area are also derived from this belt. It is unknown whether the dispersal of the limestone was a primary oceanic olistormal feature or resulted from later tectonism. Isolated occurrence of alkali volcanic basalt to the immediate north of the Snowbird are considered to also be derived from the belt to the east by a similar mechanism.

OPHIOLITIC ASSEMBLAGE ROCKS

Metabasalt forms several prominent hills to the north and northwest of the main Snowbird showing and is also poorly exposed in the lowland area to the west. Basalts crop out in the area of the main Snowbird showing and are found in drill core, above and below the Sowchea thrust fault. These rocks are typically grey green, fine grained, aphanitic and massive. Locally, however, brecciated and rare pillowed structures are present. In some exposures the fine-grained aphanitic metabasalt grades into a slightly coarser grained, paler weathering diabasic phase of the unit. Petrochemistry of these metavolcanic rocks indicates that they are tholeiitic subalkaline basalts of normal mid-ocean ridge (N-type MORB) character (Ash and Macdonald, 1993). Contacts between the metabasalts and the sedimentary rocks are poorly exposed. They are inferred to be primary contacts, which have been subsequently tectonized.

Metagabbro forms an isolated, fault-bounded belt along the western boundary of the property and cuts metabasalt locally. The western belt of metagabbro appears to form an isolated thrust slice with ultramafic rocks in the hangingwall and a footwall of mixed metasedimentary and metabasaltic rocks. These are equigranular, medium to coarse-grained, to locally very coarse grained (i.e.



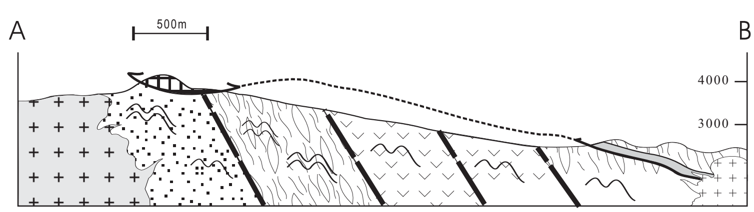


Figure 3.2. Geological setting of the Snowbird gold-stibnite deposit.

Photo 3.3 Resistant limestone block in fissile siliceous argillite exposed on ridge west of the main Snowbird showing.

Photo 3.5. Cumulate olivine and intercumulate pyroxene display poikolitic texture in ultramafic cumulates rocks on Mount Nielsp.

varitextured, Photo 3.4). These rocks are typically retrogressively metamorphosed to greenschist mineral assemblages and are typically well fractured and locally veined.

Ultramafic rocks are best exposed near the southwestern boundary of the property within a klippe at the higher elevations of a northwesterly trending ridge (Figure 3.2). The summit of Mount Nielsp to the north is also interpreted as an isolated klippe of ultramafic rocks. In this area the ultramafic rocks are structurally underlain by a locally distinctive bedded clastic sedimentary succession, which has been interpreted to be Triassic and possibly Early Jurassic in age (Struik *et al.*, 1996).

Partially serpentinized, dunitic to wehrlitic ultramafic cumulate rocks are the dominant lithologies in both outcrop areas. The rocks vary from tan to dark brown (Photo 3.5) and typically display a relict poikolitic texture with cumulate olivine, intercumulate pyroxene and minor cumulate chromite. Olivine comprises from 80 to 95% of the unit and individual 1 to 3-millimetre euhedral grains are 40 to 75% serpentinized. Relict grains appear as isolated kernels surrounded by mesh-textured antigorite, as serpentinization has developed along pre-existing grain fractures. Association of secondary magnetite with serpentinization is minor to rare. Relict pyroxene was not identified in thin section, as the intercumulate phase is completely replaced by fibrous aggregates of talc. The relict cumulate poikolitic texture is, however, well preserved. Chrome spinel is a minor accessory phase, comprising less than 1% of the rock. Its habit is highly variable, forming 0.3 to 2-millimetre, subhedral to euhedral grains that are typically associated with the altered intercumulate phase. Flat-lying, scaly serpentinite shear fabrics are locally well developed throughout the unit (Photo 3.5).

The most southwesterly klippe is closely associated with the metagabbroic unit. Contact relationships between the two are poorly exposed, however, the development of incoherent serpentinite with local carbonatization along discrete shear zones near the contact suggests it is faulted. The transition downhill from ultramafic to mafic cumulate rocks into mafic volcanics displays a characteristic inverted ophiolite stratigraphy (Appendix I) and can be interpreted to be the result of tectonic stacking. Ultramafic rocks also form slivers or tectonic lenses within the Sowchea thrust fault. These rocks range from completely serpentinized to completely carbonatized and lack any relict primary textures or mineralogies that indicate the original protolith.

Photo 3.4. Varitextured gabbro on ridge southeast of Mount Nielsp..

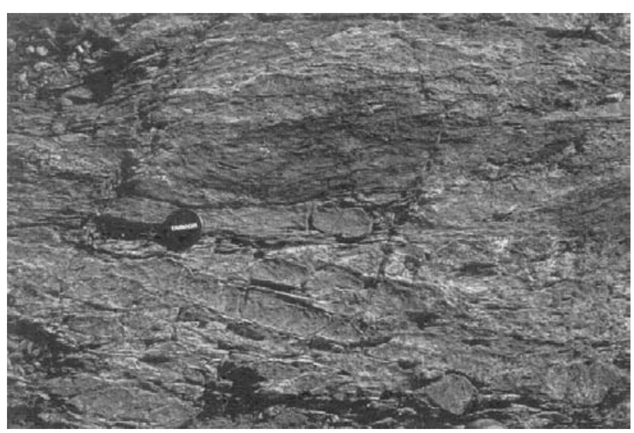


Photo 3.6. Flat-lying serpentinite scaly fabric developed in untramafic cumulate rocks on ridge southeast of Mount Nielsp.

INTRUSIVE ROCKS

McKnab Lake Pluton

The name Shass Mountain pluton was introduced by Ash and Macdonald (1993) to describe the elongate northwest-trending granitic body exposed between Stuart Lake and the Sutherland River (Figure 3.1). This name was applied after mapping the western margin of the intrusion (Ash *et al*., 1993) since the pluton was shown to underlie Shass Mountain (Rice, 1948; Armstrong, 1949). Subsequently, Letwin and Struik (1997) show that the Shass Mountain area is not underlain by the intrusion but consists of ultramafic and mafic plutonic to volcanic and sedimentary rocks of the Cache Creek Terrane. Not surprisingly, these units on Shass Mountain display comparable lithotectonic relationships to those described above for ophiolitic rocks forming the high ground to the west of the Snowbird prospect. As a result these authors suggest that the intrusion be renamed after McKnab Lake, situated within the outcrop area of the pluton, roughly 13 kilometres southeast from the summit of Shass Mountain. The name McKnab Lake pluton is hereby adopted and replaces 'Shass Mountain' as used in previously by Ash *et al.* (1993) and Ash and Macdonald (1993).

The McKnab Lake intrusion is roughly 56 kilometres long and up to 16 kilometres wide. It consists of medium to coarse-grained, equigranular white to buff-white weathering quartz diorite to tonalite (Photo 3.7). The pluton is mostly massive and isotropic but locally displays well-developed flow fabrics near its intrusive contact margins. The orientation of the fabric is consistently parallel to the intrusive contact and is characterized by a penetrative foliation defined by alignment of mafic minerals. Mafic xenoliths are common near the margins of the pluton and include hornfelsed sedimentary country rocks and, more commonly, melanocratic, medium to coarse-grained amphibole-rich cognate xenoliths. In less deformed parts of the intrusion, xenoliths are angular and range from several centimetres to several tens of centimetres across. In foliated areas near the intrusive contact, mafic xenoliths are strongly attenuated within foliation planes and visually emphasize the fabric. Locally, they are strongly attenuated, giving the unit a banded or striped appearance.

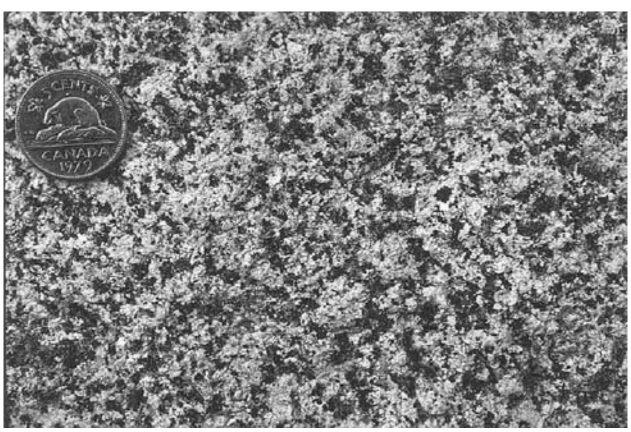


Photo 3.7. Medium-grained, equigranular tonalite characteristic of the McKnab Lake pluton.

Primary minerals in the intrusion, in decreasing order of abundance, are plagioclase, quartz, amphibole and biotite. Both felsic and mafic minerals show little or no sign of alteration in thin section. Plagioclase occurs as 1 to 3-millimetre, lath-shaped subhedral to euhedral grains which comprise from 40 to 60% of the rock. Quartz is typically anhedral, comprising from 20 to 40% of the rock and occurs as both individual 1 to 3-millimetre anhedral grains and as larger 3 to 5-millimetre grains which poikilitically enclose plagioclase, hornblende and biotite. Mafic mineral content varies from 15 to 35%. Hornblende, which forms 0.5 to 5-millimetre euhedral to subhedral grains, is usually the dominant mafic mineral, however, locally biotite occurs in greater abundance.

Major element whole rock data for samples collected along most of the eastern margin of the body are plotted (Figures 3.3a and b) using the discernment diagrams of Debon and Le Fort (1983). Figure 3.3a calculates relative abundances of quartz, potassium feldspar and plagioclase. A sample from the McElvery Lake pluton east of the North Arm of Stuart Lake and a sample from the Snowbird stock are also included. The Snowbird sample is distinct, due primarily to the pervasive sericite-carbonate-pyrite alteration. Collectively the data display a broad range in quartz with a limited variation in alkali content indicating a compositional range from diorite to tonalite with most being quartz diorite to tonalite.

Figure 3.3b characterizes the aluminous character of the pluton. An apparent cluster of the data into two separate fields might reflect two distinct phases of the pluton, however, it is considered more likely that the gap in data is due to an incomplete representative range in the current sample population. The data, irrespective of the gap, displays a relatively uniform evolutionary trend with a limited increase the in the range of parameter A = Al-(K+Na+2Ca). This parameter is particularly sensitive to alteration and shows a limited progressive increase which correlates with a corresponding reduction in mafic mineral content suggesting that the trend is primary. It also suggests that pluton has not been significantly affected by post magmatic alteration.

Age of the McKnab Lake Pluton

The McKnab Lake pluton was grouped with the Topley intrusions by Armstrong (1949). Based primarily on relative age groupings, as defined by K-Ar isotopic data, Carter (1981) subdivided the Topley intrusions into the Topley (173 to 206Ma) and Francois Lake (133 to 155 Ma) intrusive suites. Based on an apparent K-Ar age of 144 Ma for a sample collected from the northeast corner of Camsell Lake near the centre of the Mcknab Lake pluton, Carter (1981) included this body with the Francois Lake suite.

A sample of quartz diorite for U-Pb dating was collected from the southeastern corner of the pluton roughly 4.5 kilometres south-southeast of the main Snowbird showing (Figure 3.2). Sample processing, analysis and age determinations were conducted at the Royal Ontario Museum geochronology laboratory by Robert Tucker. Three different morphological types of zircon were separated from the sample; relatively large (ca. 75 micron) clear, colourless, sharply faceted, short prismatic grains; clear, colourless,

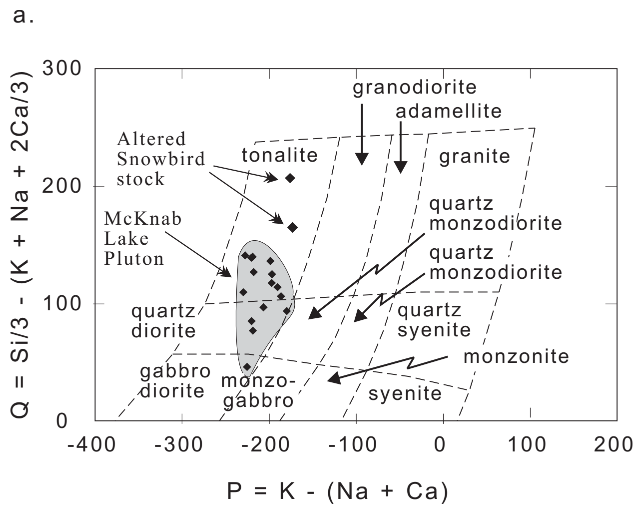


Figure 3.3a. Classification of the McKnab Lak plutonic rocks based on relative abundances of quartz, potassium feldspar and plagioclase as calculated on the basis of major element chemistry (after Debon and Le Fort, 1983).

long prismatic (aspect ratio 4:1) needle-like grains; and generally small (50 um) clear, colourless, sharply faceted, short prismatic grains. Three zircon fractions were analyzed, including one of each type. All grains selected for isotopic analysis were treated by air-abrasion polishing to minimize the presence of secondary lead loss and surface-correlated common lead. The two fractions of short prismatic zircons (types 1 and 3 above) were analyzed for inherited lead. The third fraction of long, needle-like zircons was analyzed to eliminate potential sources of inheritance and also, to test the overall reliability of the determination. No significant component of inherited lead was detected in any fraction (within a resolution of ±4 Ma), nor was there any detectable component of secondary lead loss in these young, low-uranium (84-43 ppm) grains. All analyses are concordant with reproducible $^{206}Pb/^{238}U$ ages ranging between 165.07 Ma and 165.5 Ma (Figure 3.4, Table 3.1), and the age of granodiorite emplacement is taken as the mean $^{206}Pb/^{238}U$ age of 165.7+2/-1 Ma. This age was calculated using the internationally accepted half-lives and isotopic abundance ratios of uranium as cited in Steiger and Jäger (1977).

Snowbird Stock

The Snowbird stock is an oblong, altered tonalite body, roughly 1 kilometre long and up to 200 metres wide, which intrudes deformed pelagic sediments and metabasaltic rocks between Stuart Lake and the main Snowbird showing (Figure 3.5). This intrusion was referred to as the “granite zone” by Faulkner and Madu (1990). This usage is discontinued here as petrographic work and potassium feldspar staining indicate that the intrusion is potassium deficient and therefore not granite. Petrological examination of two samples from the Snowbird stock suggests that its relict primary mineralogy is similar to that of the Mcknab Lake pluton 5 kilometres to the west. A finer grain size and a dull brown to flesh-tone weathering appearance clearly distinguish it from the larger intrusive body. Disseminated 2 to 4-millimetre pyrite cubes, varying in abundance from 1 to 3%, produce diagnostic, rusty brown weathering pits on exposed surfaces (Photo 3.8). Thin sections of several samples show that secondary sericite and carbonate are also present. Primary quartz and feldspar occur in roughly equal proportions varying from 40 to 45 modal percent. Mafic minerals, which comprise from 10 to 20 modal % of the rock are pervasively carbonatized and weather orange brown.

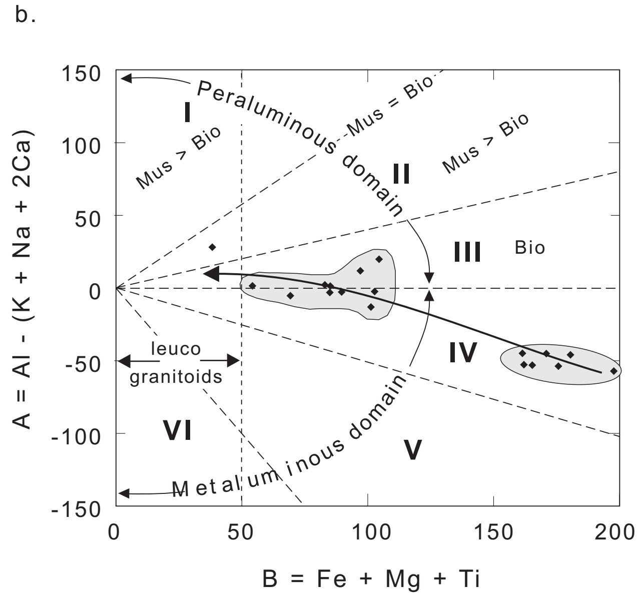


Figure 3.3b Characteristic mineral diagram depicting the aluminous character of the McKnab Lake plutonic rocks. Mus = muscovite, Bio = biotite (after Debon and Le Fort, 1983).

Alteration Age

Sericite from the intrusion was dated using conventional ^{40}Ar-^{39}Ar step-heating method (Appendix II) in order to determine the timing of potassium metasomatism. The location of the dated sample is designated Ar4 on Figure 3.5 and the apparent age spectrum is shown in Figure 3.6. The data for this samples produce a plateau made up of steps 6 through 12 inclusive which indicate an age of 157±3Ma.

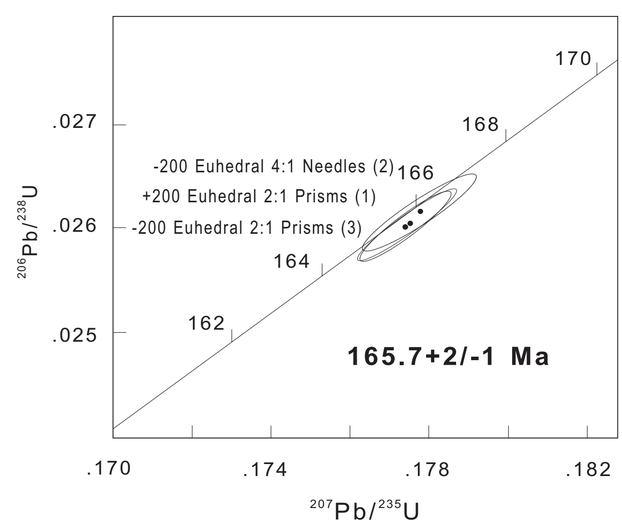


Figure 3.4. Uranium-lead concordia plot for the McKnab Lake pluton. Error ellipses indicate 2 sigma uncertainty. Sample location shown in Figure 3.2.

TABLE 3.1
URANIUM-LEAD ANALYTICAL DATA FOR THE McKNAB LAKE PLUTON

Fraction	Wt (mg)	U (ppm)	Pb* (ppm)	$^{206}Pb^{**}/^{204}Pb$	Pb*** (pg)	Isotopic ratios $^{206}Pb/^{238}U$	Isotopic ratios $^{207}Pb/^{235}U$	Isotopic ratios $^{207}Pb/^{206}Pb$	Apparent ages $^{206}Pb/^{238}U$	Apparent ages $^{207}Pb/^{235}U$	Apparent ages $^{207}Pb/^{206}Pb$
1	0.16	84.3	2.22	9849.88	2.24	0.0261	0.1775	0.049462	165.60	165.88	169.80
2	0.25	67.4	1.73	18370.33	1.50	0.026	0.1774	0.049462	165.52	165.80	169.79
3	0.1	43.1	1.12	3766.94	1.95	0.026	0.1777	0.049426	165.97	166.11	168.08

*Radiogenic Pb
**Measured ratio, corrected for spike and Pb fractionation (0.1 %/AMU)
***Total common Pb in analysis based on blank isotopic composition.

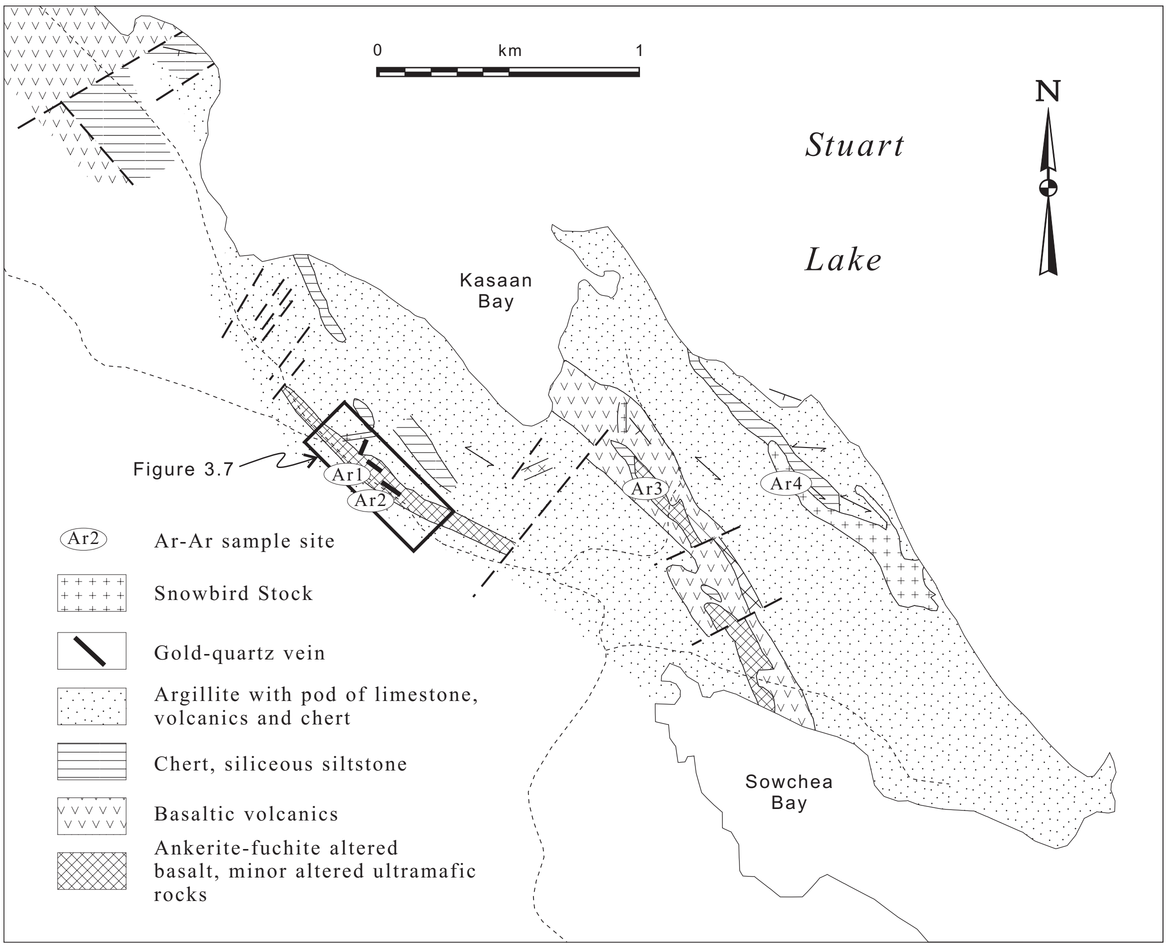


Figure 3.5. Local geology of the Snowbird gold-stibnite deposit (modified after Game and Sampson, 1987a and b).

This Middle Jurassic age alteration age for the stock is from 5 to 10 million years younger than the McKnab Lake pluton. A U-Pb age for the Snowbird stock is needed to refine relative age relationships between hydrothermal alteration and magmatism.

Lack of penetrative foliation within the Mcknab Lake pluton or its satellite Snowbird stock indicates that the intrusion postdates regional penetrative deformation of the more deformed rocks which it intrudes. The Middle Jurassic age therefore provides an upper limit on the age of accretion of the oceanic rocks in the central Cache Creek terrane.

SNOWBIRD DEPOSIT

The early history of the Snowbird deposit, as briefly reviewed below, is taken from Armstrong (1949). The property was first staked in 1920 and initially referred to as the McMullen group; it derives its current name from the Snowbird claim block covering the main showing (Photo 3.8). It was mined for antimony between 1939 and 1940,

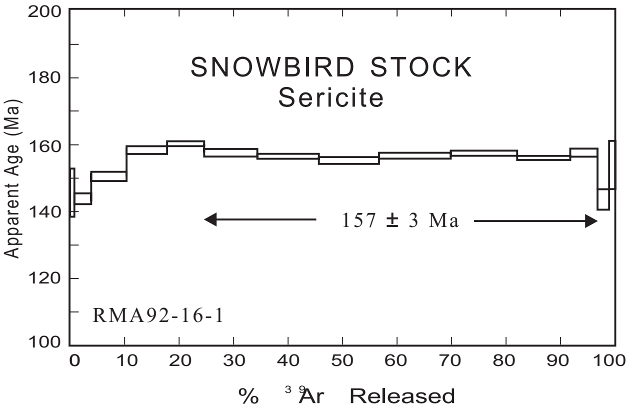


Figure 3.6. Apparent age spectra plot of muscovite from the Snowbird stock. Sample location A4, Figure 3.5.

producing roughly 77 tonnes of handpicked ore grading 60% antimony. Mine development during that period included the sinking of a 45-metre inclined shaft and an unknown amount of drifting. The property was dormant from 1940 until 1963 when its gold potential was first explored. This work is summarized in assessment reports filed with the British Columbia Ministry of Energy and Mines (Heshka, 1971; Poloni, 1974; Dewonck, 1980; Game and Sampson, 1987a).

VEIN MINERALIZATION

Mineralized gold-quartz-carbonate veins on the Snowbird property are hosted by the Sowchea shear zone (Armstrong, 1949), a prominent northwest-trending thrust fault zone which dips from 40° to 50° northeast. Armstrong (1949) suggested that the fault zone was of regional extent based on the presence along strike to the north and south of the main Snowbird showing of similar styles of deformation with associated pervasive carbonate alteration. These rocks, as projected along strike from the Snowbird property crop out 19 kilometres south on Tsah Creek and along Tachie and Middle Rivers to the north. The inferred extent of the Sowchea fault, as defined by Armstrong, is illustrated on Figure 3.1.

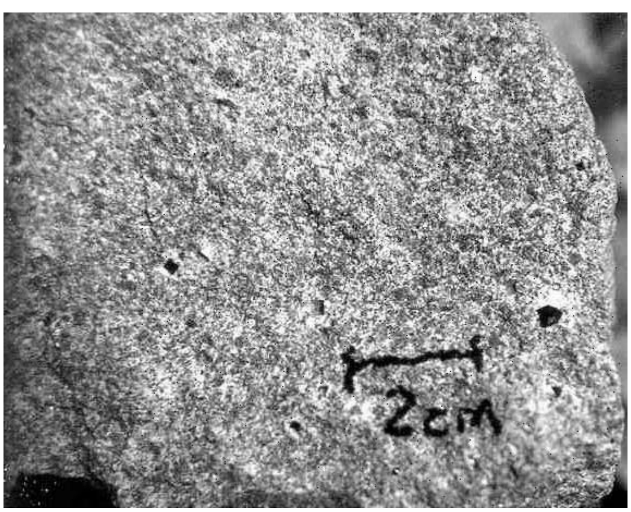


Photo 3.8. Pervasively carbonate-sericite-pyrite altered quartz diorite-tonalite of the Snowbird stock.

The character and orientation of this structure on the Snowbird property is well documented from both drill-hole data and a semi-continuous surface exposure excavated by stripping (Figure 3.7, Photo 3.8). Assessment reports indicates that 57 diamond-drill holes, totalling roughly 5000 metres, have been drilled on the property. Most holes were collared in the hangingwall of the Sowchea shear zone and the vein system. The fault zone is up to several tens of metres wide and is characterized by intense carbonatization, brecciation and shearing. Armstrong interpreted the structure as: “a zone of faulting, shearing and brecciation that provided channelways for later carbonatizing and mineralizing solutions”. Pervasively carbonatized ultramafic rocks and mafic volcanic rocks occur as tectonic slivers within intensely sheared graphitic and variably pyritized argillite.

Two cross-sections of the mineralized shear zone, depicting the Main and Pegleg veins (Figure 3.7), illustrate the down dip extension of the shear-hosted vein system as well as the lithologic variability of footwall and hangingwall rocks. Rock types above and below the shear zone are lithologically heterogeneous, dominated by siliciclastic and pelagic sedimentary rocks and lesser volcanics, ultramafic rocks and limestones. Siliciclastic sediments close to the shear zone are characteristically intensely sheared, highly fissile and easily desegregated. Orientation of the foliation fabric in the sediments above the shear zone parallels the dominant northwesterly structural grain in the area. Dips of the foliation are variable and appear to reflect tight to open folding. Axial planes of the inferred folds are parallel to the Sowchea fault zone, suggesting that folding of the sediments was contemporaneous with fault movement.

Basalts and possibly ultramafic rocks within the fault zone have been altered to aggregates of mainly ankerite and magnesite, respectively. These are buff-cream coloured, rusty orange-brown weathering rocks cut by a network of white dolomite and quartz veinlets.

Mineralization at the Snowbird is hosted by three quartz-carbonate veins, the Main, Pegleg and Argillite veins. The Main and Pegleg veins are hosted within the Sowchea shear zone. The Argillite vein follows a high-angle cross-fault perpendicular to the main shear zone. Metallic vein minerals include gold, stibnite, arsenopyrite, chalcopyrite and pyrite (Armstrong, 1949). Stibnite is the dominant sulphide, occurring as a massive, grey, fracture-filling phase while other sulphide minerals are only sporadically developed. The Argillite vein is reported (Armstrong, 1949) to have included a body of massive stibnite 10 metres long by 10 centimetres wide that was mined out by the Consolidated Mining and Smelting Company of Canada, Limited.

Semi-continuous, sheeted veins of bull white quartz from less than 1 to 5 centimetres in width occur within a broad, strongly sheared and altered contact zone between hanging wall basalt and footwall siliciclastic sediments at the Main and Pegleg veins (Photo 3.8 and 3.9). Quartz veins are usually contained within the ankerite altered basaltic

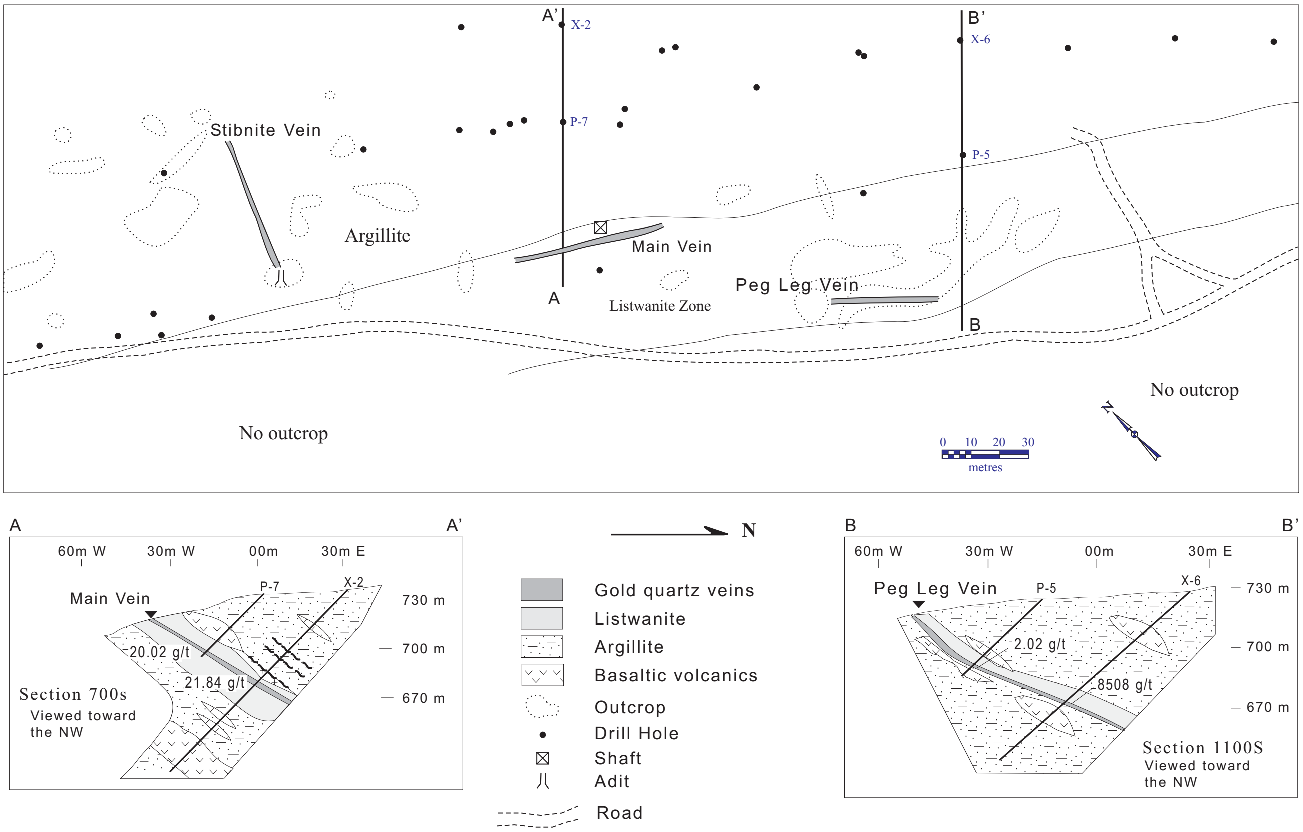


Figure 3.7. Detailed geology and drill-hole locations for the Snowbird main showing with cross-sections of the Main and Pegleg veins as defined by drill-hole data (map and sections modified after Game and Simpson, 1987a).

rocks where they form semi-continuos stringer zones that locally merge producing vein segments over 15 to 30 centimetres in width. A thicker vein segment of the Main vein contains a lens of semi-massive stibnite up to 4 centimetres wide. Veins are also developed in gouge-filled fissures within the faulted contact zone between the sedimentary and volcanic rocks (Photo 3.9).

Significant gold values occur in drill core vein intercepts along the shear zone, either within, or adjacent to quartz-carbonate-mariposite-altered ultramafic or volcanic rocks. Gold values are highly erratic, with no definable continuity. Game and Sampson (1987a) reported that significant gold intersections on the Main vein are all associated with massive stibnite. One 10-centimetre intersection, in contact with listwanite, contained visible gold with assay values of 8500 g/t gold and 2900 g/t silver. Fluid inclusion studies on the quartz-gold-stibnite veins (Madu *et al.,* 1990) suggest that they formed from low salinity, CO_2-rich aqueous fluids at temperatures greater than 240^{o} C and in excess of 80 000 kilopascals (0.8 kilobar) pressure.

Age of Mineralization

Mariposite concentrates from three samples of quartz-carbonate-mariposite listwanite were dated by the conventional ^{40}Ar-^{39}Ar step-heating method (*see* Appendix II for analytical techniques) in order to establish the timing of alteration and gold mineralization. Two of the dated samples are from ankerite-mariposite listwanite marginal to the Main vein (samples Ar1 and Ar2, Figure 3.5). A third sample was collected from ankerite mariposite altered and quartz veined mafic volcanic rocks exposed east of the Snowbird main showing (sample Ar3, Figure 3.5). The age spectrum of the dated samples is shown in Figure 3.8.

All three spectra have similar shapes. Apparent ages in each increase to relatively uniform value (~162-165 Ma) before decreasing towards the ends of the gas release. Because these concentrates are fine-grained and only ~90% pure, some spectral features may be cause by irradiation-induced recoil (*see* earlier discussion). Consequently, total gas ages (employing all but the low-age first steps) have been calculated to give the preferred ages indicated in Figure 3.8. These range from 161 to 163 Ma, only slightly lower than the above plateau values. These data suggest that hydrothermal alteration and associated gold mineralization at the Snowbird deposit occurred during the Middle Jurassic, between 160 and 165 Ma. The isotopic age data indicate that, alteration and mineralization at the Snowbird gold-antimony property are within error, only slightly younger than the magmatic age of the McKnab Lake pluton and the regionally defined Middle Jurassic orogenic event (Figure 3.9).

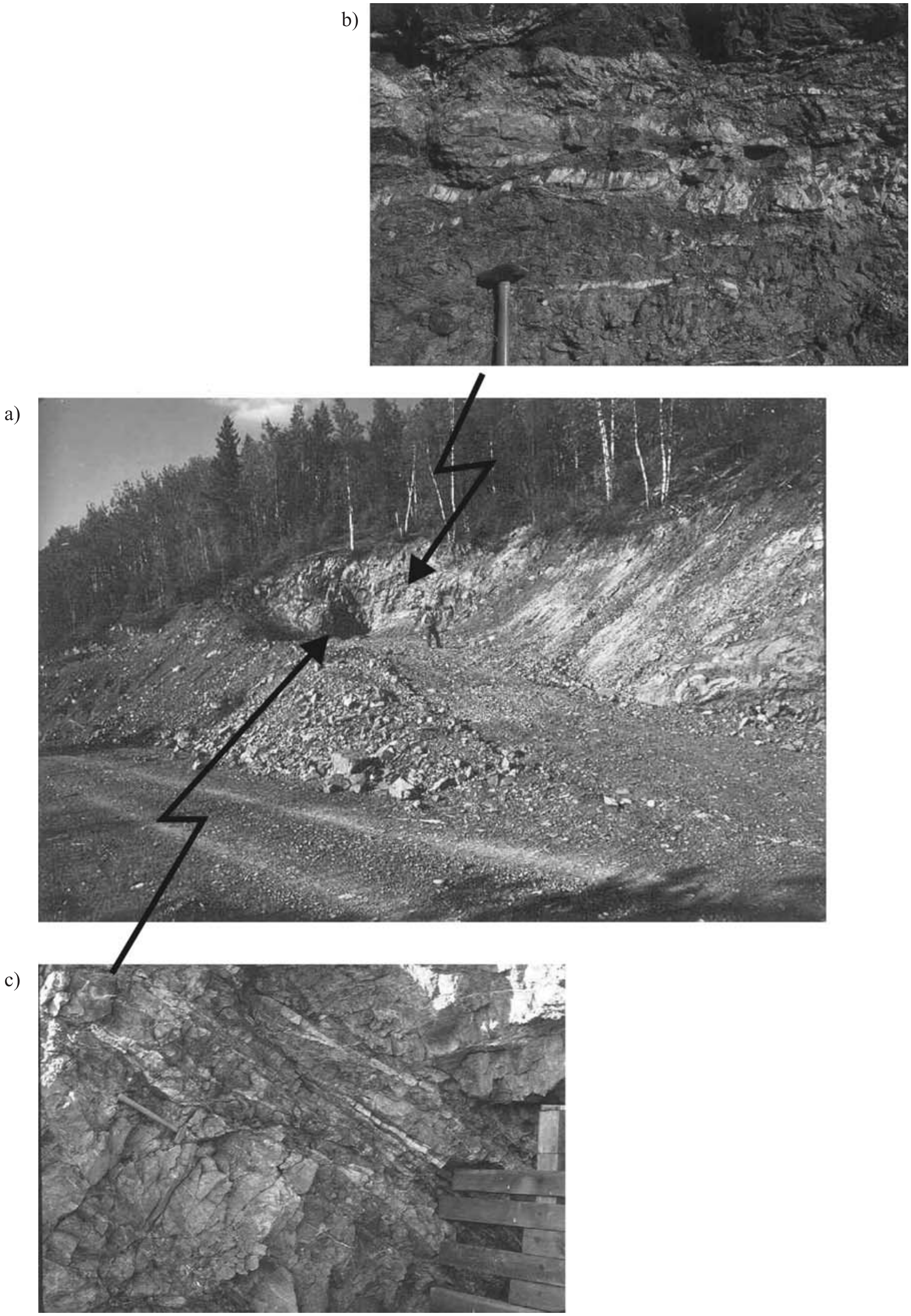


Photo 3.9a. Snowbird showing - view of the Main vein shaft looking north. b) Thicker quartz vein segment with massive stibnite along the fracture vein core. c) Sheeted quartz veins in ankerite mariposite altered basalt, north face of the Main vein portal.

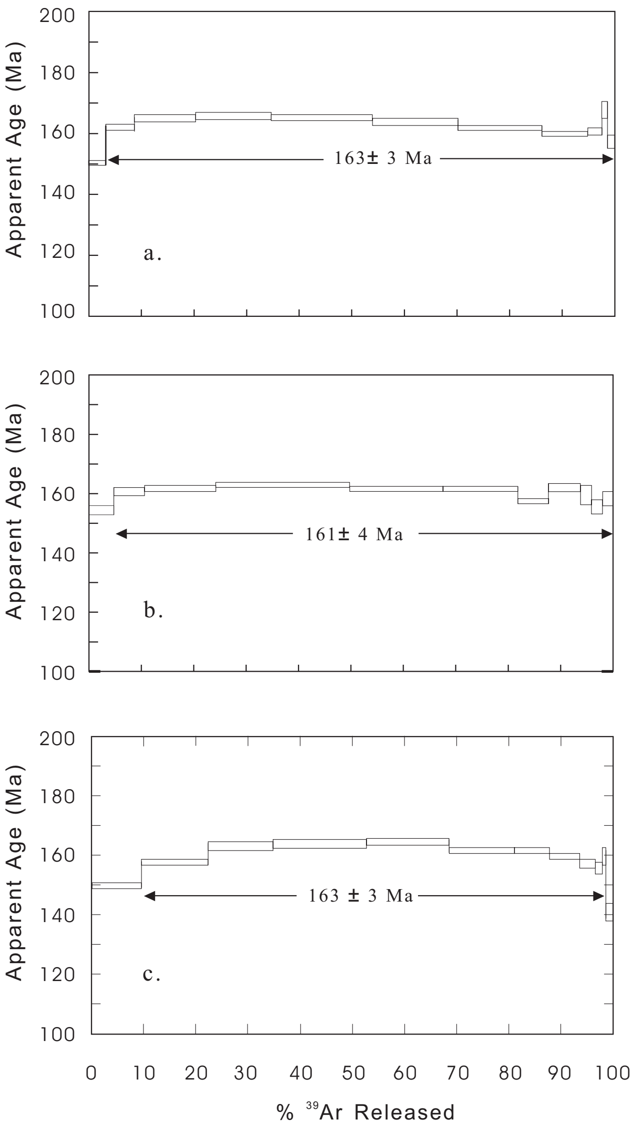


Figure 3.8. Apparent age spectra plots for mariposite/fuchsite separated from listwanite samples discussed in text. Sample locations for a, b and c designated as Ar1 to Ar3 respectively.

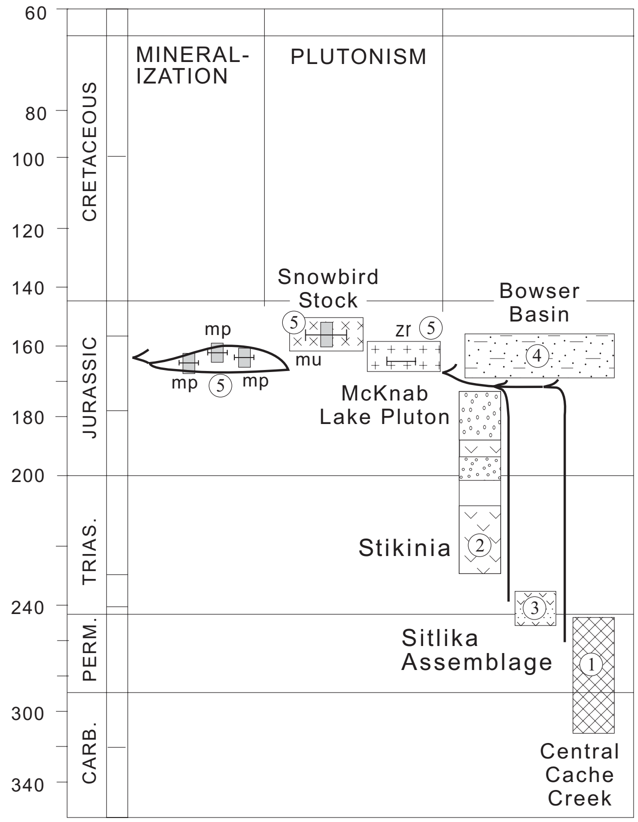


Figure 3.9 Relative age and tectonostratigraphic relationships for lithologies in the Central Cache Creek Terrane.
zr - zircon U-Pb; mu - muscovite Ar-Ar; mp - mariposite / fuchsite Ar-Ar; b - biotite K-Ar
Data sources used to constrain age relationships for the elements depicted are:
① Orchard, 1991, Cordey *et al.,* 1991; ② Tipper, 1984; Brown *et al.*, 1991; ③ Paterson, 1974; Monger *et al.*, 1978; Childe *et al.*, 1998 ④ Ricketts *et al*., 1992 and ⑤ this study.

SUMMARY

The central Cache Creek Terrane, similar to the Atlin area of the northern Cache Creek Terrane, is divisible into:

1. A tectonically intercalated package of oceanic upper crust, pelagic sediments and limestones the 'Stuart Lake accretionary complex' and,
2. Obducted fragments of oceanic crust and upper mantle lithologies which form relatively coherent thrust sheets that typically overlie the accretionary complex with marked structural discordance. This assemblage of units is referred to as the 'Stuart Lake ophiolitic assemblage'.
3. A third and distinct component includes thick limestone sequences that are spatially associated with alkali basaltic volcanic rocks which are the interpreted to be rem-

Photo 3.10. Looking south at sheeted quartz veins in hanging wall basalt in gouge zone along contact with footwall sediments at the Pegleg vein.

nants of ancient ocean islands (Ash and Macdonald, 1993; Orchard *et al.,* 1997, 1998).

The Sowchea shear zone contains tectonic slivers of ultramafic oceanic plutonic or metamorphic mantle rock. It is interpreted to be a thrust fault, related to accretion of oceanic rocks, and is referred to as the 'Sowchea thrust'. The regional extent of the structure as previously advocated by Armstrong (1949) is suggested by the presence of pervasive carbonatization with attendant gold vein mineralization.

The large northwest-trending felsic Intrusion west of Stuart Lake, the McKnab Lake pluton, is a Middle Jurassic (165.7+2/-1 Ma) post collisional pluton. Compositionally, the quartz diorite to tonalite pluton displays a relatively broad range in quartz and mafic mineral content but with a corresponding limited range in both alkali and aluminum contents.

The northwest-trending tonalite stock on the peninsula east of the main Snowbird showing is a satellite of the McKnab Lake pluton, which was subject to pervasive sericite alteration at roughly 157 Ma.

Gold quartz vein mineralization at the Snowbird deposit is hosted by the Sowchea thrust fault. Hydrothermal Cr-mica associated with vein mineralization yield Ar-Ar ages between 162 and 165 Ma and are contemporaneous with, or immediately followed structurally controlled felsic magmatism, shortly following Middle Jurssic orogenic activity.

CHAPTER 4
BRIDGE RIVER TERRANE
BRALORNE-PIONEER CAMP

INTRODUCTION

The Bralorne-Pioneer gold mine in southwest British Columbia (Figure 4-1) is historically the largest lode gold producer in the province. The Bridge River mining camp in which the Bralorne- Pioneer deposit is located, has enjoyed a long and profitable mining history starting in the mid - 1800s with the discovery of placer gold on Cadwallader Creek and Bridge River. The first lode claims at Bralorne were located in 1896. Production soon followed and continued periodically throughout the 1900s until final closure in 1971 (Bellamy and Saleken, 1983). During this period the Bralorne-Pioneer mine produced over 113.4 tonnes (4 000 000 oz) of gold from 7 million tonnes of ore at an average recovered grade of close to 20 g/t (0.57 ounces per ton) (Leitch, 1990). Exploration has continued throughout the 1980s and 1990s to delineate additional gold-quartz veins.

The area was visited during a 6-day period in 1991. Active underground drilling at that time by Levon Resources to delineate the subsurface extension of the Peter vein enabled underground access by way of the main portal on level # 8 of the Bralorne mine (Photo 4.1). This provided a near continuous section through Bridge River sedimentary rocks into the southwest part of the Bralorne gabbro-diorite igneous complex and allowed direct observation and sampling of the vein system. We are grateful to Jim Miller-Tait for providing a review of the surface and underground geology at the Bralorne mine.

This chapter summarizes the lithotectonic setting of gold quartz veins in the Bralorne-Pioneer deposit with an emphasis on the ophiolitic character of the host rocks. It is the most significant gold producer in British Columbia and is a type example of the deposits under discussion. New Ar-Ar age data of hydrothermal vein micas associated with gold vein mineralization is reported and a revised terminology for host rocks of the Bralorne-Pioneer gold quartz veins is introduced.

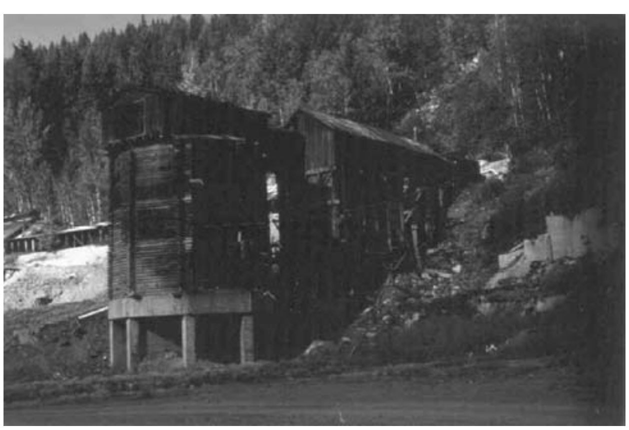


Photo 4.1. Main portal to the Bralorne mine in 1991.

PREVIOUS WORK

Studies of the Bralorne-Pioneer vein system were done either prior to 1950 when the mine was a major producer or during the gold rush of the 1980s when historically productive deposits such as this were afforded considerable exploration and research attention. McCann (1922), Dolmage (1934), Cairnes (1937) and Joubin (1948) published the classic works of the pre-1950 period. The most recent and comprehensive publications on the deposit have resulted primarily from doctoral research on the Bralorne-Pioneer mine by Craig Leitch (Leitch and Godwin, 1986, 1987,1988; Leitch *et al.*, 1989, 1991; Leitch, 1990). The geology of the Bridge River camp including detailed descriptions of the individual deposits have been part of studies by the British Columbia Ministry of Energy and Mines (Church, 1987a, b; Church and Pettipas, 1989; Church *et al*., 1988; Church, 1995; Sebert, 1987). A description of the geology of the Bralorne camp is given by Bellamy and Saleken (1983), with abbreviated summaries provided by Barr (1980) and Panteleyev (1992). Our current understanding of the regional geology as summarized below, is primarily from Schiarizza *et al.* (1997) and references therein.

REGIONAL GEOLOGICAL SETTING

The Bralorne-Pioneer mine is situated within the southeastern Coast Belt (Figure 4.1) (Monger, 1986; Journeay, 1990). This structurally complex belt is dominated by abyssal oceanic rocks with subordinate sedimentary and arc volcanic rocks and younger sedimentary basin fill sequences, all intruded by Late Cretaceous to Eocene felsic plutonic rocks (Schiarizza *et al*., 1997). Lithotectonic units and structures of the southeastern Coast Belt extend southward into the Cascade fold belt and form a strongly tectonized zone between the Intermontane Belt and a western zone that includes the western Coast Belt and Wrangellia Terrane (Monger *et al*., 1990).

The tectonic history of the region is complex, with recognition of earlier tectonic events complicated by structural disruption and intercalation of all the lithologies by Cretaceous and Tertiary faulting. It records a protracted and varied magmatic, depositional and deformational history extending from late Paleozoic to Middle Tertiary (Schiarizza *et al*., 1997).

Gold quartz vein deposits at the Bralorne-Pioneer mine are hosted within Late Permian (Leitch and Godwin, 1988; Leitch, 1990) ophiolitic basement rocks that occur as tec-

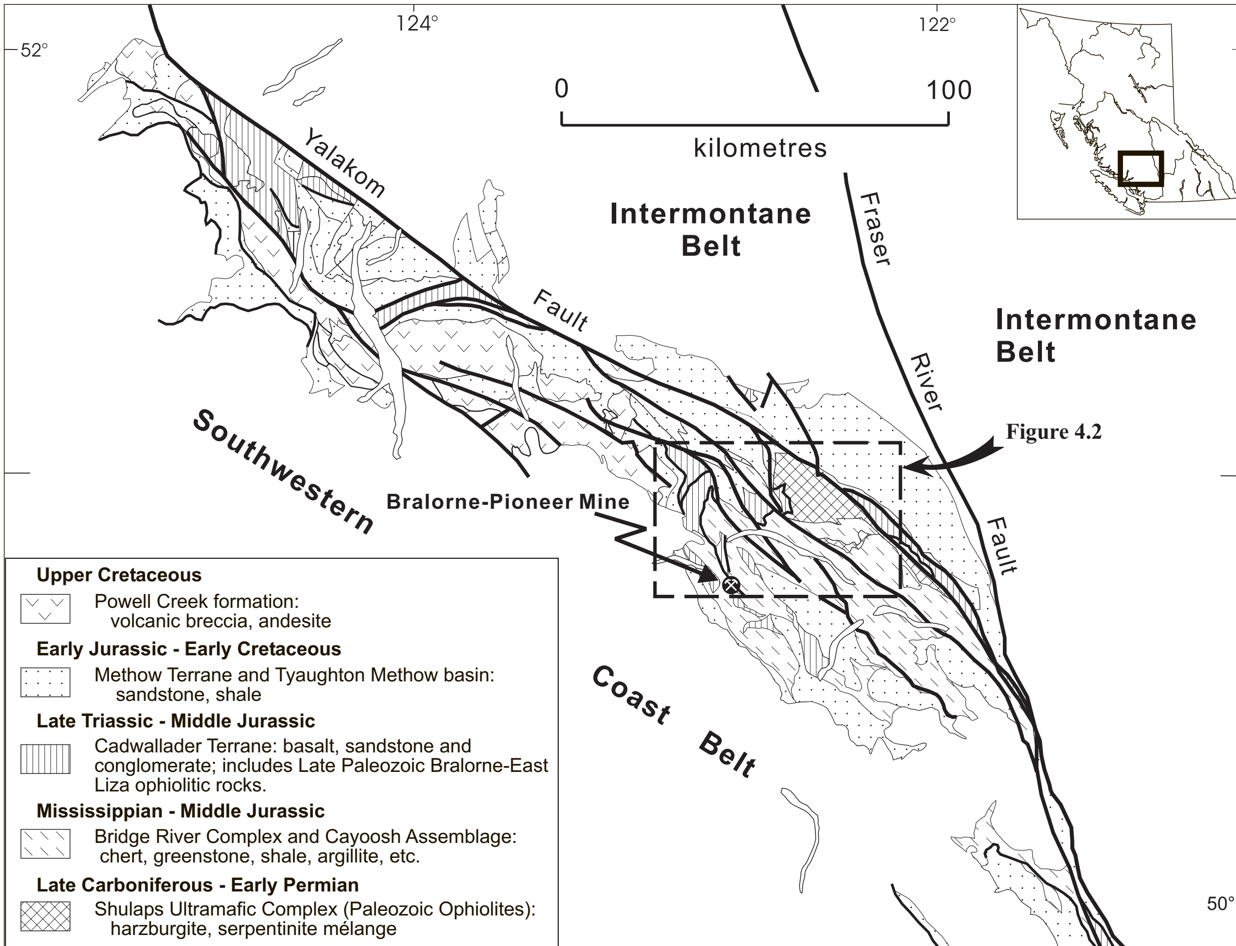
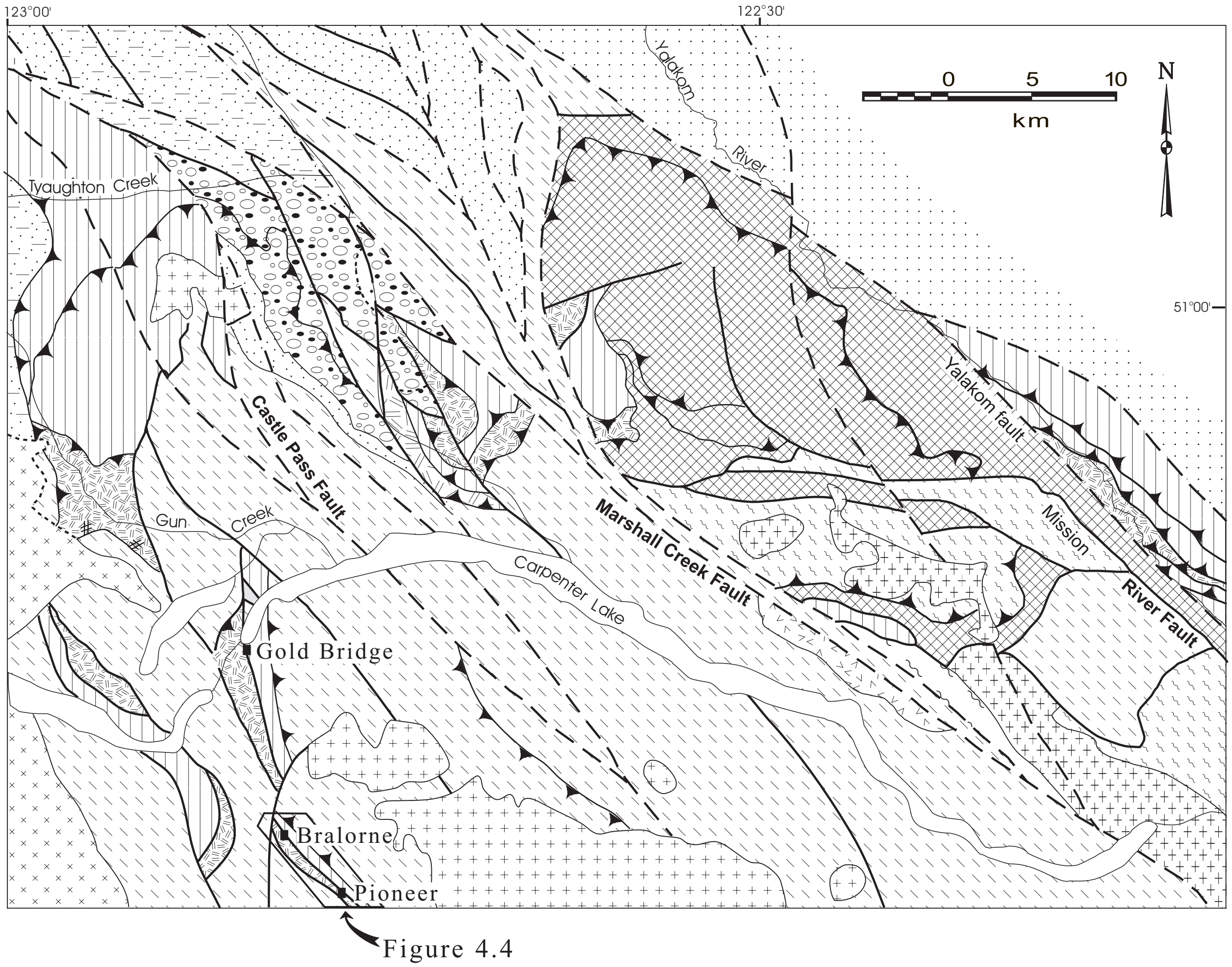


Figure 4.1 . Location and regional geological setting of the Bralorne Pioneer mine (after Schiarizza and Garver, 1995).

tonic fault bounded lenses within the Bridge River Terrane (Schiarizza *et al.*, 1997; Figure 4.2). Like the Cache Creek Terrane, the Bridge River Terrane is dominated by a highly disrupted belt of Late Paleozoic to Early Mesozoic (Cordey and Schiarizza, 1993) chaotic chert-argillite deposits with lesser mafic volcanics, subordinate limestone, sandstone, conglomerate, serpentinite, gabbro, and minor Late Triassic blueschists, termed the Bridge River complex. Unlike the Cache Creek Terrane, however, the Bridge River Terrane is internally imbricated by Cretaceous and Tertiary faulting with Late Triassic to Early Jurassic volcanic arc sediments and lesser volcanic rocks of the Cadwallader arc-terrane (Rusmore, 1987; Rusmore *et al.*, 1988; Schiarizza *et al.*, 1997).

Terminology and lithotectonic subdivision of units throughout the Bralorne region have recently undergone fundamental changes. Ophiolitic assemblage and accretionary complex rocks were previously included in the Bridge River Terrane (Potter, 1986; Monger, 1977a; Wright *et al.*, 1982; Monger, 1984; Wheeler and McFeely, 1991). Subsequently the ophiolitic assemblage rocks were separated from the Bridge River Terrane and included in a distinct lithotectonic unit called the East Lisa Complex (Schiarizza *et al*., 1997). Based on regional correlations it has recently been suggested that sedimentary and volcanic Cadwallader arc-terrane rocks are most likely stratigraphically tied to ophiolitic assemblage rocks. Based on this relationship ophiolitic assemblage were included as part of the Cadwallader Terrane. In this view the Bridge River Terrane and Bridge River complex are considered one and the same Schiarizza *et al*. (1997). The Bridge River Terrane, however, contains mafic volcanic with lesser diabase and gabbro as isolated tectonic lenses and serpentinite as narrow bodies along fault zones (Schiarizza *et al.*, 1997). Both the ophiolitic assemblage rocks and chert-argillite deposits are late Paleozoic in age and share a comparable abyssal oceanic origin. This provides a strong lithologic and temporal link between the ophiolitic and accretionary complex rocks. Differences between them are considered largely a function of scale, relating to varying degrees of tectonic disruption and attenuation of individual ophiolitic components. We maintain previous terrane terminology and include both the disrupted chert argillite succession of the Bridge River complex with ophiolitic assemblage rocks as part of the Bridge River Terrane. It cannot be ruled out, and is considered likely that the late Paleozoic abyssal basement rocks were already accreted along the North American continental margin prior to deposition of the Late Triassic volcanic arc rocks of the Cadwallader Terrane. We therefore view the Bridge River Terrane as



Paleogene volcanic rocks

Plutonic Rocks

Eocene (48-43 Ma)

Mission Ridge pluton and Rexmount porphyry

Latest Cretaceous (69-67Ma)

Bendor suite

Late Cretaceous (92Ma)

Dickson McClure suite

Early and/or Late Cretaceous

Silverquick and Powell Creek formations: conglomerate, shale, volcanic breccia

Early Cretaceous

Taylor Creek Group: shale, conglomerate

Middle Jurassic - Early Cretaceous

Relay Mountain Group: sandstone, shale

Early Jurassic - Early Cretaceous

Methow Terrane/Basin: sandstone, shale

Late Triassic to Middle Jurassic

Cadwallader Terrane

basalt, sandstone, conglomerate

Bridge River Accretionary Complex

Mississippian - Middle Jurassic

Chert, greenstone, argillite

Bridge River Schists: biotite-quartz schist

Ophiolitic Assemblages

Late Carboniferous - Early Permian

Bralorne-East Liza Complex (greenstone and gabbro)

Shulaps Ultramafic Complex (harzburgite, serpentinite mélange)

Figure 4.2. Geological setting of the Bralorne-Pioneer deposit (after Schiarizza and Garver, 1995).

consisting of both ophiolitic assemblage rocks and chaotic chert-argillite deposits, with the younger Late Triassic volcanic arc rocks as a distinct and possibly overlapping lithotectonic element.

DEPOSIT GEOLOGY

Permian ophiolitic assemblage rocks hosting the Bralorne-Pioneer mine were termed the 'Bralorne block' by Leitch (1990) and Leitch *et al*. (1991) (Figure 4.4). The term "block" is preferable to previous usage of "Bralorne intrusions" as it more adequately characterizes the relative age and tectonic relationships between this structurally bounded plutonic-volcanic complex and its surrounding rocks. It eliminates misconceptions that these rocks are an igneous suite that intrudes the adjoining rocks of the Bridge River complex and Cadwallader Terrane, a prevailing view of most early descriptive works.

Contact and age relationships as well the chemical composition of the individual units (Leitch *et al.*, 1991; Church *et al.*, 1995; Dostal and Church, 1994) establish that the Bralorne block is a differentiated suite of oceanic crustal ultramafic and mafic to felsic plutonic and cogenetic basaltic volcanic rocks. It can be subdivided into: an extrusive component of volcanic rocks, a transitional component of hypabyssal medium to fine-grained dikes that contain plutonic screens, a variably differentiated, multiple magmatic, mafic to felsic plutonic suite of gabbro, diorite and trondhjemite, and an ultramafic cumulate suite of dunite, peridotite and pyroxenite. Table 4.1 identifies the component parts of an oceanic crustal section with reference to the historical nomenclature for the various lithologies.

The 'Bralorne ophiolite', is a preferred term than 'Bralorne block' to describe this tectonically emplaced, recognizably dismembered segment of Early Permian ocean crust. In addition to highlighting the tectonic character this term properly characterizes the associated lithologies within the block and alludes to their origin within an oceanic spreading center.

Host rocks for the primary producing veins of the Bralorne-Pioneer mining camp are the mafic to felsic, gabbro-diorite-trondhjemite crustal plutonic section of the Bralorne ophiolite. Veins within the ophiolitic rocks have been long recognized for their overall regularity, size and continuity (Cirkel, 1900). To a lesser, though significant degree, veins continue into competent massive metabasalt, the main Pioneer fissure vein being the most notable example. The massive, medium to fine-grained, granular texture typical of host rocks in the area of the Pioneer mine, combined with the fact that the unit has survived as a competent entity suggest that it is more likely hypabyssal rather than volcanic in origin. Notably the ultramafic portion of the Bralorne ophiolitic assemblage is recognized as the least favourable unit for quartz vein development. Cairnes (1937) writes;

"*Probably the least favourable rock for quartz veins is serpentine. Fissures rarely persist in this rock for any appreciable distance and mostly feather out abruptly on reaching it. This feature is well shown in Pioneer and Bralorne mine workings and is in more ways than one of economic significance, for some of the richest ore and most extensive shoots in these mines end against the serpentinite bodies.*"

VEIN MORPHOLOGY AND MINERALOGY

Subsidiary fault sets related to movement along the major faults bounding the Bralorne ophiolite control the morphology and distribution of mineralized veins (Leitch *et al*., 1991). The block is cut by sets of en-echelon, mineralized faults formed in compressional and tensional shears related to sinistral transpressional movement along the Fergusson thrust to the northeast and the Cadwallader fault to the southwest (Figure 4.3). Three types of shear veins are recognized within the Bralorne-Pioneer deposit and include fissure, tension and cross veins.

Fissure veins, including Veins 51, 55 and 77 at Bralorne (Figure 4.3) and the Main vein at the Pioneer mine, are the richest in the camp. They are also the widest and most continuous of the three vein types (Joubin, 1948). They have been traced continuously for up to 1500 metres along a strike of roughly 110^{o} and to a depth of 1800 metres down their steep northerly dip (Joubin, 1948; Leitch 1990). The fissure veins are commonly ribboned. They have an average

TABLE 4.1
COMPONENT PARTS OF THE BRALORNE OPHIOLITE
AND ASSOCIATED HISTORICAL NOMENCLATURE

Oceanic Crustal Rocks of the Bridge River Ophiolitic Assemblage in the Bralorne Block	Corresponding Units of the Bralorne Block
Upper crustal, basaltic to andesitic extrusive igneous rocks	Pioneer volcanic rocks (greenstone)
Dike transition between extrusive and intrusive complexes	Hybrid greenstone - diorite
Mid-crustal, differentiated gabbroic to trondhjemitic, multiphase plutonic complex	Bralorne diorite / Bralorne soda granite / Sumner gabbro / related minor phases
Transition from mid-crustal mafic plutonic complex to lower crustal ultramafic plutonic suite	Hornblendite
Ultramafic-cumulate plutonic suite	President ultramafics (cumulate phases only)

width of 1 to 1.5 metres but often pinch and swell, ranging from several centimetres to seven metres in width (Bellamy and Saleken, 1983; Leitch, 1990).

Tension veins are generally less continuous than the fissure veins at usually about 500 metre strike lengths with similar dip extensions. They are also usually not as rich as the shear veins (Joubin, 1948). They are hosted by fault sets that strike roughly 250^{o} and dip about 75^{o} northwest (Leitch 1990) and appear to form oblique splays off the fissure veins. Veins consist of massive white quartz with erratic high gold values. They are characterized by open-space filling textures commonly including pockets of drusy to cockscomb quartz between widely spaced and slickensided septae (Joubin, 1948). Examples of this vein type include the 75 and 83 veins at Bralorne, and the 27 vein at Pioneer. Cross veins are subeconomic and are interpreted to be connecting structures between the fissure and tension veins.

Ore and alteration mineralogy of the Bralorne-Pioneer veins has been described by McCann (1922), Dolmage (1934), Cairnes (1937), Joubin (1948), Stevenson (1958), Church (1987, 1995) and Leitch (1990) and is summarized here. Quartz is the dominant gangue mineral along with minor calcite, ankerite, sericite, clay-altered mariposite and talc. Most of the gold-quartz veins have a low metal content with sulphide minerals restricted mainly to altered wallrock septa but sulphides can be highly concentrated locally. Sulphide assemblages consist primarily of pyrite and arsenopyrite with lesser marcasite, pyrrhotite, chalcopyrite, sphalerite, galena and rare tetrahedrite. Pyrite is the most abundant sulphide and occurs mainly as disseminated crystals in both veins and altered wall rocks. Arsenopyrite occurs as disseminated, well-formed, pyramidal crystals and as minute acicular grains, mainly in veins but also in altered wall rock. Sphalerite and to a lesser extent galena are locally conspicuous in the veins, whereas chalcopyrite is comparatively scarce but can be locally significant.

Ore shoots with mainly free gold occur in the most fractured and deformed parts of the veins, notably at the intersections or junctions of vein-bearing fissures (Cairnes, 1937). Well-ribboned quartz is characteristically better grade than adjoining massive quartz. Vein septa are relatively narrow dark films, streaks or bands composed of one or more of sulphide, sericite and chloritic minerals occurring over ribboned widths of 2 to 3 centimetres. Native gold occurs sparsely disseminated throughout the vein quartz or concentrated between ribbons in the quartz. Along the face of the ribbons native gold is commonly associated with minute, acicular crystals of arsenopyrite. Quartz breccias are also relatively rich, and bands of gouge and crushed vein matter may contain high grades. Native gold also occurs in massive, white quartz or coarsely crystalline calcite and rich pockets of such material are common in the western mine workings close to the serpentinite contact. In this area there is spectacular ore where native gold occurs together with masses of arsenopyrite. The richness of the ore shoots in the western mine workings compared to the remainder of the deposit is aptly described by Cairnes (1937, page 123) who writes:

"Altogether, four principal ore shoots are referred to by James, namely, a west-end shoot, a west shoot, and two easterly shoots. The west-end shoot rakes approximately with the intersection of the vein fissure and the serpentinite and extends back for several 100 feet from this intersection This is a high grade shoot and has provided exceptionally rich pockets. In a stope from 8-level, two tons alone produced $200 000 (9685 ounces) worth of gold. Another pocket yielded 400 pounds of gold from 900 pounds of ore."

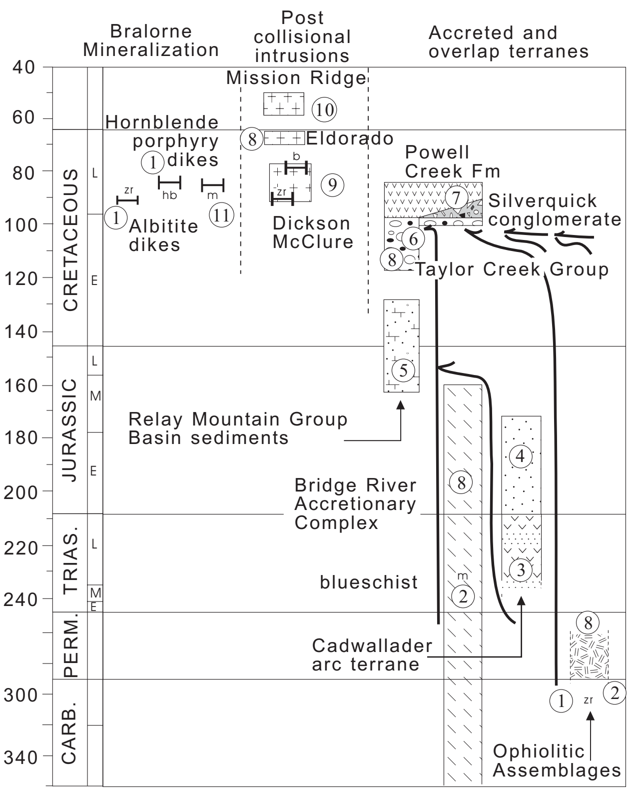


Figure 4.3. Relative age and tectonostratigraphic relationships for lithologies in the Bralorne region. zr - zircon U-Pb; hb - hornblende K-Ar; m – mariposite Ar-Ar
Data sources used to constrain age relationships for the elements depicted are:
① Leitch *et al*., 1991; ② Archibald *et al*., 1990; ③ Rusmore, 1987; ④ Umhoepher, 1990; ⑤ Jeletzky and Tipper, 1968 ⑥ Garver *et al*., 1989; ⑦ Glover and Schiarizza, 1987; ⑧ Schiarizza *et al*., 1997; ⑨ Parrish, 1992; ⑩ Coleman, 1989; 11 this study.

Wall rock alteration associated with vein mineralization is widespread and commonly intense. Alteration envelopes range from less than 0.1 to 10 metres in width, and in places coalesce into broad zones up to 50 metres wide. Although somewhat variable, there is a consistent zoning of alteration minerals from regionally metamorphosed wall rock into the vein core over average distances of 5 metres. The metamorphic assemblage of chlorite-epidote in the country rock reflects subgreenschist to greenschist facies typical of the regional metamorphic grade (Schiarizza *et al*., 1990, 1997). This grades through a buff-coloured, carbonate (calcite)-albite±sericite zone into an inner, cream-coloured,

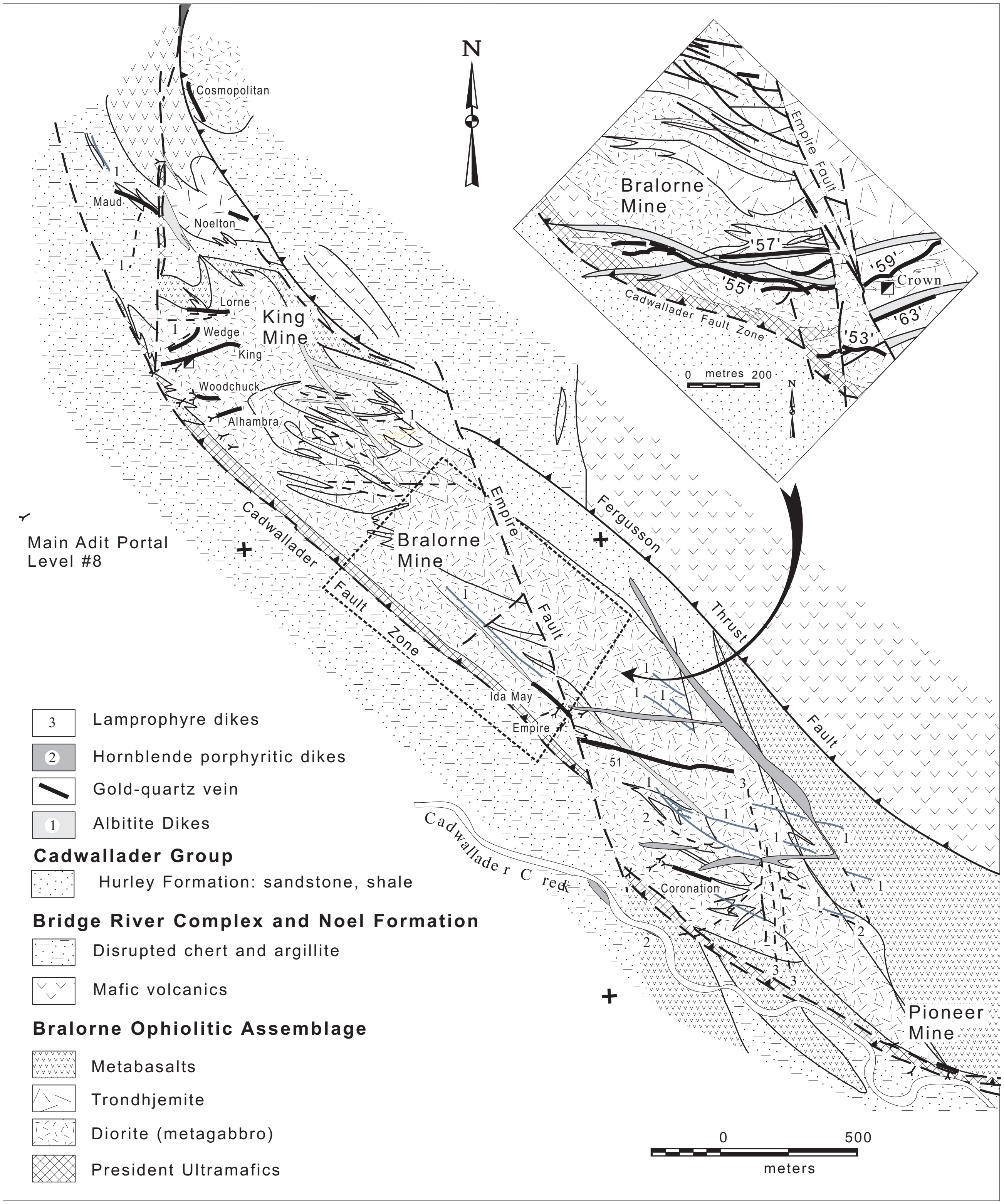


Figure 4.4 Geology of the Bralorne-Pioneer mine area. Simplified after Leitch *et al*. (1991).

quartz-sericite±fucshite-carbonate (ankerite) zone (Cairnes, 1937; Leitch, 1990). This alteration sequence is common in both the oceanic hostrocks of the deposit and in albitite dikes which intrude structures hosting the gold bearing veins (Leitch 1990). Fluid inclusion studies (Leitch *et al.,,* 1989) indicate that the Bralorne-Pioneer deposit is a mesothermal vein system formed at about 5 to 7 kilometres depth (1.25 to 1.75 kb) and 300^{o} to 400^{o} from low-salinity CO_2-rich fluids.

AGE OF MINERALIZATION

The age of gold quartz vein mineralization at the Bralorne-Pioneer mine is currently constrained indirectly from the ages of felsic dikes that both predate and postdate the mineralizing event (Leitch, 1990; Leitch *et al*., 1991). Gold quartz veins are spatially and temporally related to intrusion of albitite and hornblende porphyry dikes, coeval with the Early to Middle Cretaceous magmatic phases of the Coast Plutonic Complex. Pre to syn-mineralization albitite dikes have a U-Pb zircon age of 91.4±1.4 Ma; syn - to postmineral hornblende porphyry dikes have a K-Ar whole rock age of 85.7±3 Ma. Both the veins and co-structural dikes form en echelon sets subsidiary to the regional scale bounding shear and fault zones and appear to be related to movement along these faults.

In an attempt to directly determine the timing of hydrothermal activity, efforts were made to collect chrome-bearing micas associated with gold-quartz vein mineralization for Ar-Ar isotopic dating. A sample of carbonate altered and quartz veined massive metabasalt rock with visible mariposite was found in waste dumps along the west side of Cadwallader Creek directly across from the dilapidated Pioneer Mine (Photo 4.2). The contents of the mine dumps are relatively uniform and appear to be representative of the local vein host rocks. Rock types contained within the dumps consist on average of 50 to 60% medium to fine-grained, massive, equigranular grey-green basalt/diabase, 25 to 30% pink felsic dike rocks and 15 to 20% brown weathering carbonate-altered basalt (Photo 4.3a and b).

The spectrum (Figure 4.5) for this sample is unusual. The first step obtained at a laboratory extraction temperature of 650^{o} C yielded 75% of the total gas release at an apparent age of 87 Ma. The subsequent steps have much lower ages, ranging from ~50-60 Ma. As discussed above, for a fine-grained impure sample such as this, redistribution of ^{39}Ar by recoil may produce irregular spectral features. In this case, the total gas value, here 79 + 4 Ma, is the most reliable age estimate. This may be interpreted as a lower limit to the time of mineralization.

Photo 4.2 Remains of the Pioneer mine along Cadwallader Creek in 1991.

Photo 4.3a. Waste dumps from Pioneer Mine along the west side of Cadwallader Creek.

Photo 4.3b. Detail of altered varieties of diabase from the Pioneer Mine.

Several additional samples were collected from the North vein, both along the Main Adit Level No. 8 and also at surface roughly 1 km north of Bralorne where a shallow tunnel had been recently driven along the Cosmopolitan vein. Samples were taken from green, sheared and clay-altered zones marginal to pervasively hydrothermally altered felsic dikes along the mineralized quartz-vein structure. The material collected was dull green and amorphous, which on sampling was broken into 0.5 to 1.5 cm chips. A mineral which is indicated by Cairnes (1937, page 54) to be fairly prevalent throughout the vein system;

"*...most of the veins contain a conspicuous, light green, flaky to amorphous mineral referred to, in general as mariposite and presumed to be a chromium-bearing potash mica very similar in composition to the potassium-magnesium mica, alurgite.*"

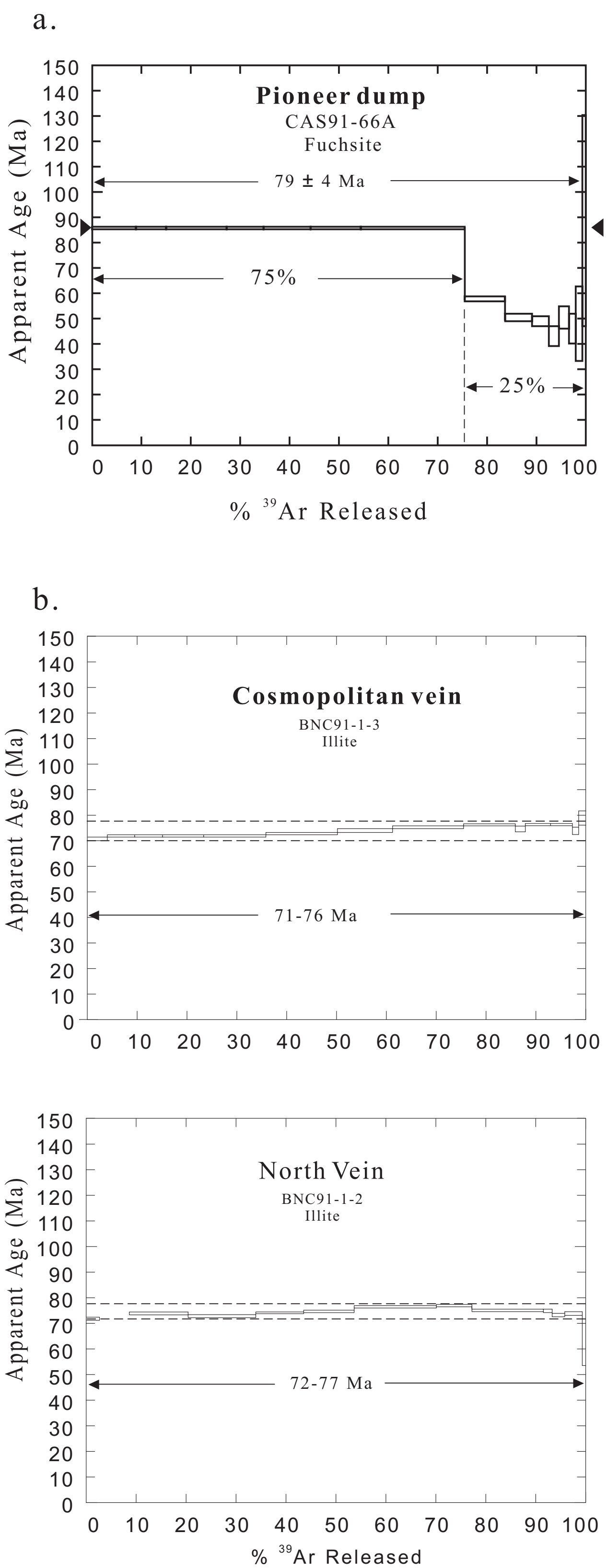


Figure 4.5. Ar-Ar age spectra of mariposite in quartz veined and carbonate altered diabase from the Pioneer dump.

Examination of this mineral by XRD analysis at The University of British Columbia by Mac Chandry with the BC Geological Survey determined it to be chrome-bearing illite.

Independently, Neil Church (personal communication, 1992) collected similar samples of fine-grained, green chrome-bearing illite from the area along the Level 8, Main Portal. These samples were processed by heavy liquids and provided separates, which he had isotopically dated by Ar-Ar at Dalhousie University (Appendix II). Results of these analyses are presented in Figure 4.5b. The two samples yielded spectra of similar shape, both with ages increasing from approximately 70 to 80 Ma over the gas released. These data suggest that the altered fault gouge zones from which the dated mineral was sampled underwent movement and accompanying hydrothermal activity at approximately 70 Ma. This is interpreted to be a post mineralization event producing alteration of preexisting mariposite.

RELATIONSHIP TO TECTONISM

Gold-quartz veins are hosted within a fault system related to a regional, mid to Late Cretaceous, east to west directed, contractional tectonic event. This tectonic activity internally imbricates and stacks late Paleozoic oceanic lithosphere with arc volcanic and sedimentary rocks (Cadwallader Terrane) as tectonic slices within and on top of late Paleozoic to mid Mesozoic transform-subduction accretionary complex rocks (Bridge River accretionary complex) and the overlying basin-fill sequence (Relay Mountain Group) (Schiarizza *et al*., 1997). Major orogenic activity at that time is recorded by a contractional event that is temporally constrained by the mid Cretaceous syn-orogenic flysch sedimentation in the Taylor Creek Group (Garver *et al*., 1989) suggesting uplift of ophiolitic rocks at that time (Garver *et al*., 1989; Calon *et al*., 1990; Macdonald, 1990; Schiarizza *et al.*, 1997). In addition related structures are cross-cut by the 92 Ma Dickson McClure suite of intrusions.

Gold veins are both spatially and temporally related to felsic, albitite and hornblende porphyry dikes (Leitch, 1990) which are coeval with early magmatic phases of the Coast Plutonic Complex (Parrish, 1992; Figure 4-3). These are associated with regional-scale, Cretaceous contractional tectonics related to emplacement of the Bridge River ophiolite assemblage (Schiarizza *et al*., 1989, 1997). These various geological and age constraints indicate that gold mineralization, dike intrusion and movement along the Bralorne fault zone was contemporaneous with mid to Late Cretaceous orogenesis.

SUMMARY

- The Bralorne-Pioneer mine is historically the largest lode gold producer in British Columbia. Gold-quartz veins hosted in the Bralorne ophiolite produced over 124 400 kilograms (4 million ounces) of gold at an average grade 18 grams per tonne (0.57 oz/ton) from a roughly 15 square kilometre area.

- The term ‘Bralorne ophiolite’ is introduced to designate the late Paleozoic oceanic crustal component that is host to gold-quartz veins at the Bralorne-Pioneer mine.
- Gold-quartz veins are hosted almost exclusively within the more competent mafic to felsic crustal plutonic and locally hyperbyssal portion of the ophiolitic assemblage. Notably, the veins are not well developed in altered ultramafic rocks but the richest and most spectacular gold ore is found where veins are adjacent to the ultramafic rocks.
- Gold-quartz veins are spatially associated with synmineral to postmineral albitite and hornblende porphyry dikes. Both the mineralizing event and dike intrusions are fault controlled. Mineralization is interpreted as syn-kinematic and structurally controlled by fault sets related to westerly directed transpressional movement along the Fergusson and Cadwallader faults bounding the Bralorne ophiolite. Felsic dike rocks display a consistent temporal and co-structural spatial association with gold quartz vein mineralization and suggests they may be genetically related.

CHAPTER 5
SOUTHERN SLIDE MOUNTAIN TERRANE
ROSSLAND GOLD CAMP

INTRODUCTION

The Rossland mining camp in southwestern British Columbia (Figure 5.1) ranks historically as the second largest lode gold producer in the province. Between 1894 and 1957 the camp produced more than 73 860 kilograms of gold, 107 000 kilograms of silver and 54 295 tonnes of copper (Fyles, 1984). Most of this gold was recovered from copper-gold sulphide fissure veins contained within Early Jurassic Rossland Group hypabyssal, subvolcanic rocks marginal to the Middle Jurassic Rossland monzonite (Höy and Dunne, 2001). Appreciable gold (1060 kilograms) has also been recovered from gold-quartz veins associated with ultramafic and mafic hypabyssal or volcanic rocks on the O.K., I.X.L. and Midnight Crown-granted claims to the southwest of the sulphide-rich vein system. Fyles (1984) reports that between 1899 and 1974, 10 492 tonnes of ore were mined from these veins with an average grade of 101 grams per tonne gold and 14 grams per tonne silver. Some of the veins have exceptionally high gold grades. The Snowdrop vein, for example, produced only 6 tonnes of ore but had an average grade of 1150 grams per tonne gold. Drysdale (1915) indicates that during September 1893 the three owners of the mine extracted 6 kilograms ($4000.00 = 193.7 ounces) of gold in one week by means of a hand mortar alone. This chapter discusses the character, origin, and tectonic setting of associated ultramafic rocks and their bearing on the genesis of the gold-quartz veins.

During the 1991 field season three weeks was spent in the Rossland area. Investigations focused primarily on mapping the ultramafic rocks to determine their type, origin and possible relationship to the spatially associated gold-quartz veins. Two isolated ultramafic bodies, one to the immediate west of Rossland and the other several kilometres to the southwest, were mapped at 1:10 000 scale (Figure 5.2). Dan Wehrle is gratefully acknowledged for providing several days of his time to give an overview of Rossland mine geology.

Aspects of the tectonic and lithologic controls of gold-copper sulphide-rich vein mineralization in the Rossland camp are part of an on-going study by Höy and Dunne (2000) and are summarized here for the purposes of comparison. A number of their unpublished dates have been used to help constrain geological relationships in the area.

PREVIOUS WORK

The first comprehensive overview of the geology and mineral deposits of the Rossland camp was presented by Drysdale (1915) which built on the earlier work of Brock (1906). More recent studies of the camp have been conducted by Thorpe (1967), Fyles (1984) and Höy *et al*. (1992). Most of this research, as well as descriptive reviews of the camp (Barr, 1980; Panteleyev, 1992) have focused specifically on the copper-gold sulphide vein mineralization. Gold-quartz vein deposits on the O.K., I.X.L. and Midnight claims have been described by Drysdale (1915) and Stevenson (1936). The regional geology has been described by Little (1963, 1982), Höy and Andrew (1991a, b) and Höy and Dunne (1997). Regional 1:100 000-scale geological and mineral deposit compilation maps for the Rossland-Trail area have been published by Andrew *et al*. (1991) and Höy and Dunne (1998).

GEOLOGICAL SETTING

Ultramafic rocks and spatially associated gold-quartz veins are exposed along a regional tectonic boundary which separates late Paleozoic continental margin slope and rise sedimentary rocks of Mount Roberts Formation to the west (Little, 1982) from the Early Jurassic Rossland Group arc volcanic rocks (Höy and Dunne, 1997) to the east (Figure 5.1) . This boundary is interpreted as an eastward directed thrust fault (Hoy and Andrew, 1991b) related to late Early to Middle Jurassic collision of the eastern edge of Quesnellia with the North American craton between 184 and 174 Ma (Murphy *et al.*, 1995; Colpron *et al*., 1996).

Ultramafic rocks, of probable ophiolitic affinity are considered correlative with the Permian Kaslo Group or preferably “Kaslo Assemblage”, and part of the oceanic Slide Mountain Terrane.

The late Paleozoic Mount Roberts Formation consists of metamorphosed, lower greenschist to amphibolite grade siliceous clastic rocks including grey to black siltstone and slate, argillaceous quartzite, argillite and lithic greywacke, with lesser limestone, conglomerate and volcanic rocks (Little, 1982; Hoy and Dunne, 1997; Roback *et al*., 1994). It is included with the Harper Ranch subterrane (Monger *et al.*, 1991) and contains Early Proterozoic and Archean detrital zircons suggesting that the unit is in part derived from the adjacent North American craton (Roback and Walker, 1995).

The Early Jurassic (Sinemurian) Rossland Group (Little, 1982; Höy and Dunne, 1997) in the Rossland area is dominate by mafic and intermediate volcanic and volcaniclastic rocks locally interbedded with marine sediments consisting of siltstone and argillite. Hypabyssal, subvolcanic intrusions that occur as augite porphyritic sills and dikes (*e.g.* Rossland sill) are also a component part of the Rossland Group and the primary host for the richest Cu-Au sulphide veins.

Both the Early Jurassic Rossland Group and late Paleozoic Mount Roberts Formation are affected by two major

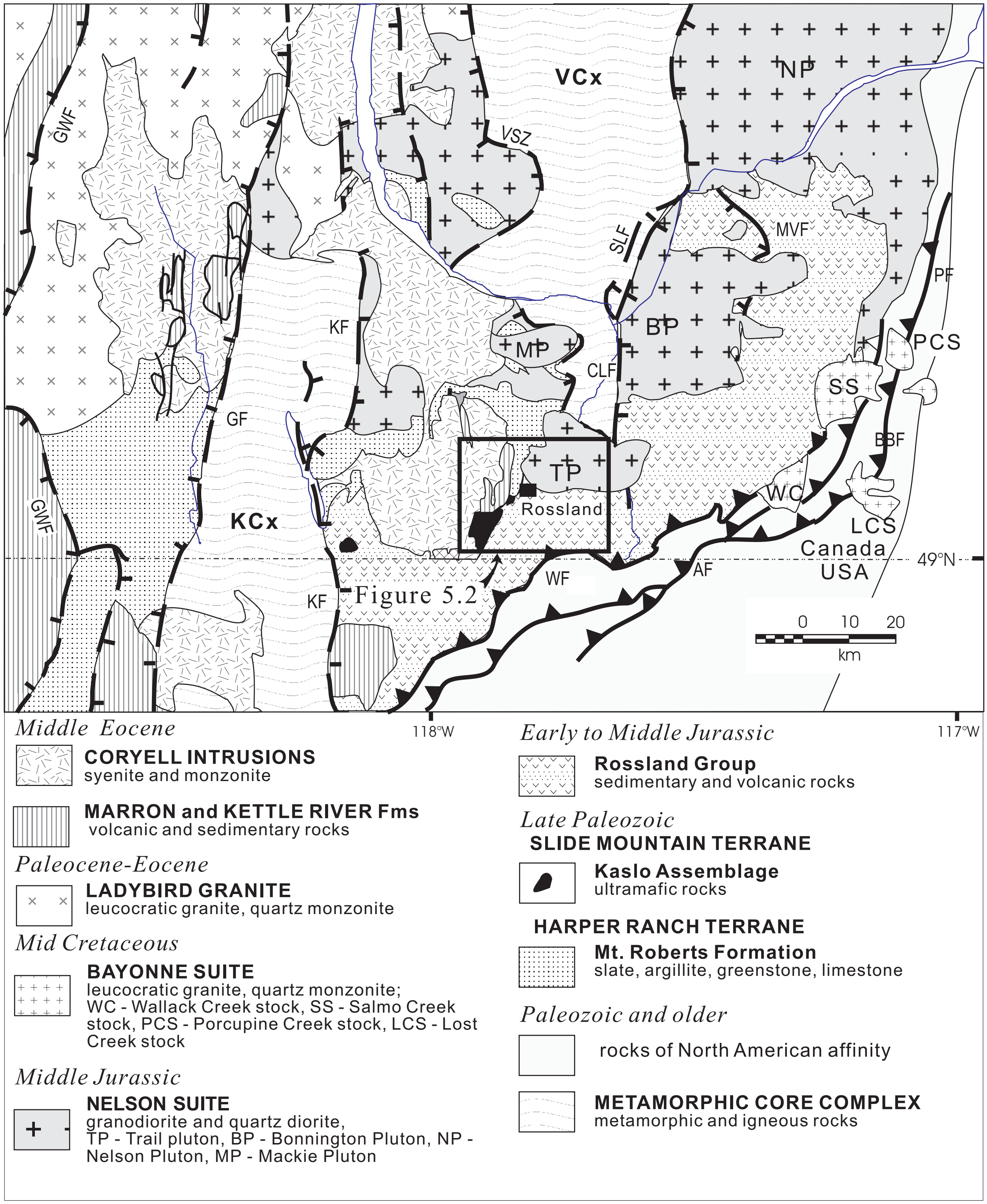


Figure 5.1. Regional setting of the Rossland mining camp (modified after compilation by Wingate and Erving, 1994 and Ghosh and Lambert, 1995). GF-Gramby fault, KF-Kettle River fault, GWF-Greenwood Fault, SLF-Slocan Lake Fault, WF-Waneta Fault, AF-Argillite Fault, PF-Porcupine Fault, MVF-Mount Verde fault, CLF-Champion Lake Fault, AF-Argillite Fault, BBF-Black Buff Fault, VCx-Valhalla Complex, KCx-Kettle Complex.

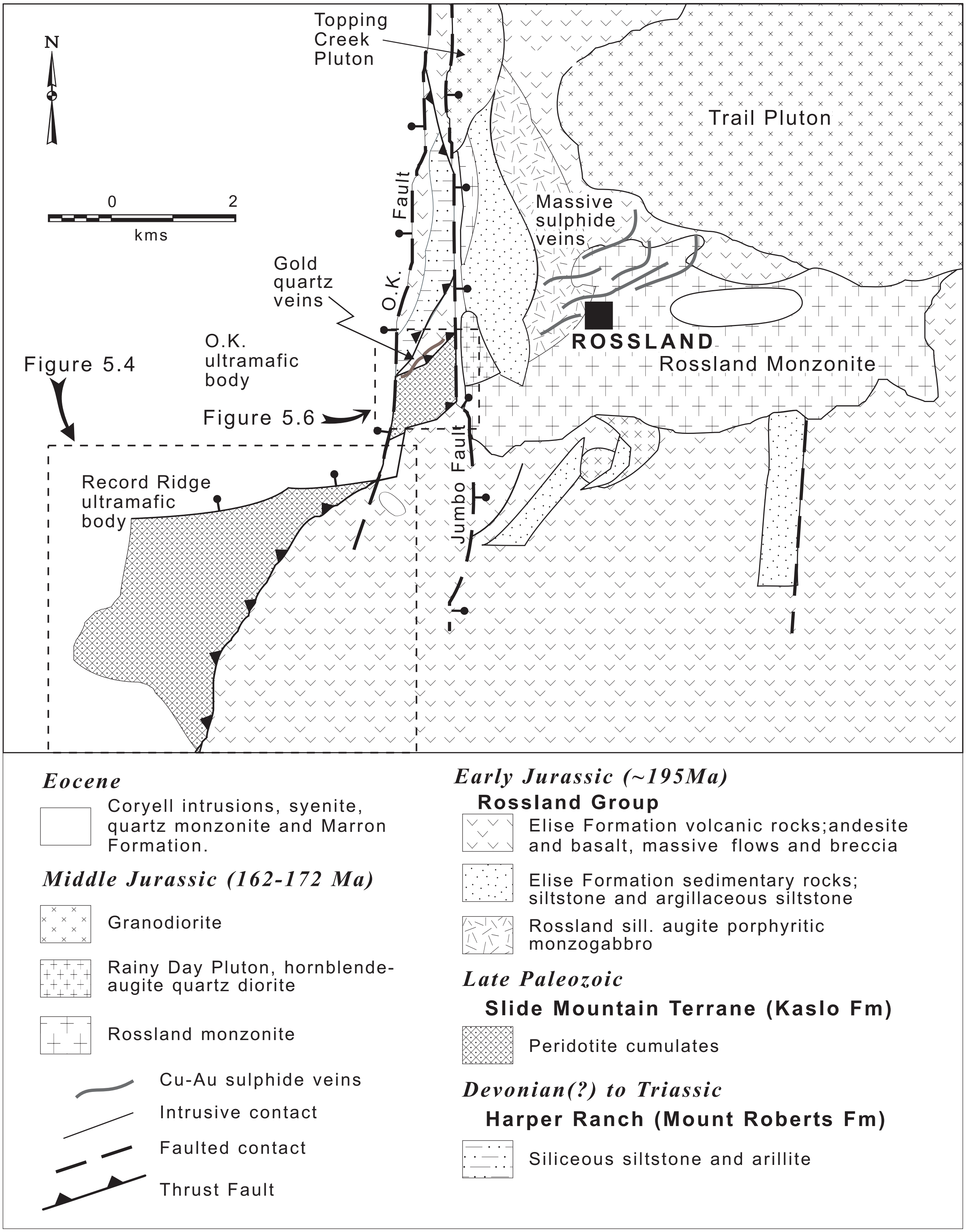


Figure 5.2. Geological map of the Rossland gold camp (after Little, 1982; Fyles, 1984; Höy and Andrew, 1991b).

episodes of post-collisional magmatism in the Rossland area. The earliest post-collisional intrusions belong to the Middle Jurassic Nelson suite and are intimately associated with mineral deposits in the Rossland camp. These occur as batholiths, plutons, stocks and dikes that range in composition from granodiorite, which is dominant, to quartz diorite, diorite and monzonite (Little, 1982). Available age constraints indicate that they formed during a roughly 10 Ma period of magmatic activity between *ca.* 172 and 162 Ma (Ghosh, 1995; Höy and Dunne, 1997, 2001) subsequent to middle Jurassic accretion of Quesnellia to the North American craton (Figure 5.3) (Murphy *et al,* 1995; Colpron *et al*., 1996; Höy and Dunne, 1997).

The Middle Eocene Coryell Intrusions and related Marron volcanics (Little, 1982; Ghosh, 1995) are the latest magmatic episode recorded in the vicinity of the Rossland mining camp. These rocks form a large batholith, which underlies a vast area west of the camp (Figure 5.1 and 5.2). They also occur as dikes and small stocks that intrude all older lithologies and form a north-trending linear, dike-like body along the Jumbo fault. Coryell intrusions include syenites, granites, quartz monzonites and monzonites with quartz monzonite being dominant.

ULTRAMAFIC ROCKS

RECORD RIDGE ULTRAMAFIC BODY

The Record Ridge ultramafic body (Figures 5.2 and 5.4) underlies an area of approximately 6.2 square kilometres, 7 kilometres southwest of the town of Rossland. It extends from the southern tip of Record Ridge, south to the foot of Mount Sophia and east to Ivanhoe Ridge and is the larger of the two ultramafic bodies mapped. Unlike the smaller ultramafic body to the north, there are no known lode-gold prospects associated with the Record Ridge ultramafic body; however, it provides more extensive exposure and variation in rock types and is therefore more informative in defining the nature and possible origin of these units. Mapping was facilitated by an assessment report map of the immediate area (Morrison, 1980), which provides details of outcrop distribution.

The Record Ridge body comprises variably serpentinized and locally carbonatized ultramafic cumulates. Rock types include dunite, pyroxene-bearing dunite, olivine-bearing wehrlite and wehrlite, each type varying simply as a function of the relative proportion of cumulate olivine (65-100 modal percent) to intercumulate pyroxene (0-35 modal percent) (Figure 5.5). Disseminated chrome spinel is present in all the ultramafic rocks, usually as minor, subhedral to euhedral accessory grains (< 1 to 3 %). Within the dunite, concentrations of chrome spinel increase to over 5 modal percent locally. Areas with 5% chrome spinel or more have been mapped separately and are designated as chrome-bearing dunites. Contact relationships between all these ultramafic rock types are everywhere gradational.

Within the ultramafic body a mappable transition exhibiting a reduction in the modal abundance of cumulate olivine and chromite, combined with an increase in the modal abundance of intercumulate pyroxene, defines a differentiated stratigraphy towards higher elevations that corresponds to an east-west transition. The exposed lower and eastern parts of the ultramafic body are dominated by dunite with localized areas of chrome dunite and chrome bearing dunite (Photo 5.1). This unit grades upward through clinopyroxene-bearing dunite into olivine wehrlite (Photo 5.2) with localized concentrations of wehrlite.

Cumulate layering, defined by alternating 1 to 2 centimetre chromite-rich (50 to 80 %) and chromite-poor planar bands (Photo 5.3), was identified at three separate localities within the dunite. Layering is typically randomly oriented with limited lateral extent up to several metres.

Contacts of the ultramafic body were not identified in outcrop. Along its northern, western and southern margins the ultramafic rocks are covered by Middle Eocene rhyolitic volcanic rocks of the Marron Formation or intruded by co-

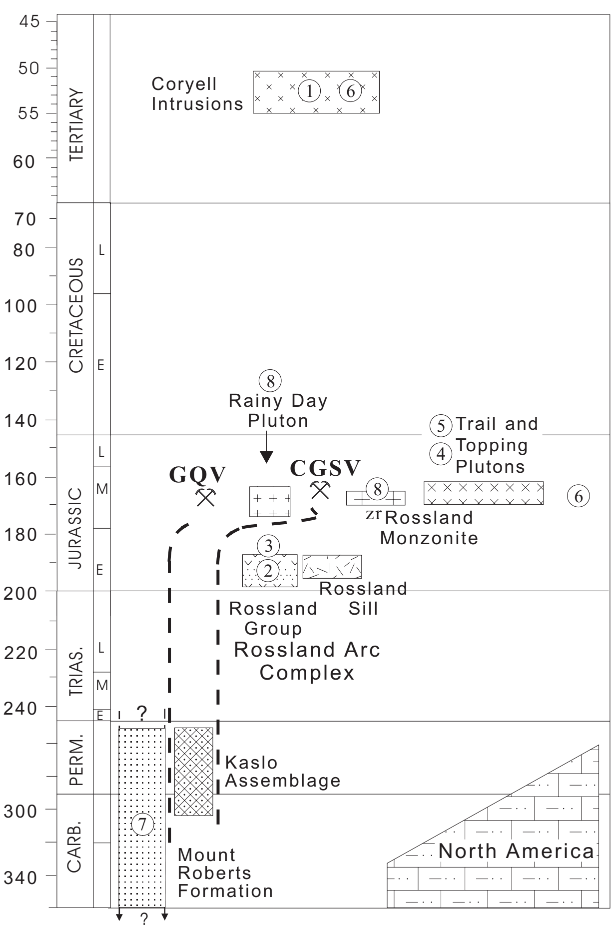


Figure 5.3 Relative age and tectonostratigraphic relationships for lithologies in the Rossland camp.
GQV - gold quartz veins; **CGSV** - Cu-Au sulphide fissure veins
Data sources used to constrain age relationships for the elements depicted are as listed following;
① Little 1982; ② Tipper, 1984; Höy and Andrew, 1991a; ③ Höy *et al*., 1992; Höy and Dunne, 1997; ④ Fyles, 1984; ⑤ Corbett and Simony, 1984; ⑥ Ghosh, 1995; ⑦ Roback and Walker, 1995; ⑧ Höy and Dunne, 2001.

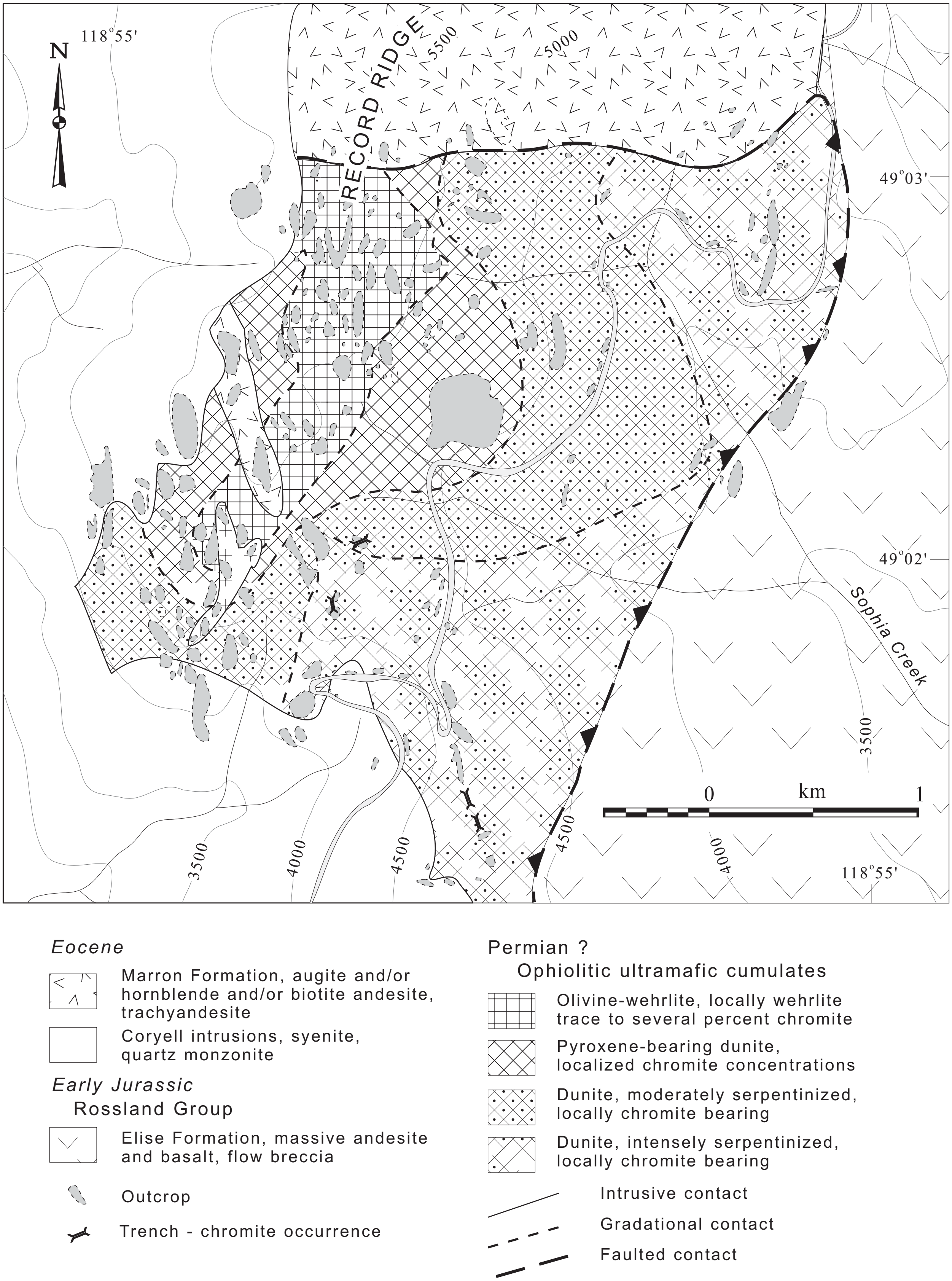


Figure 5.4. Geology of the Record Ridge ultramafic body.

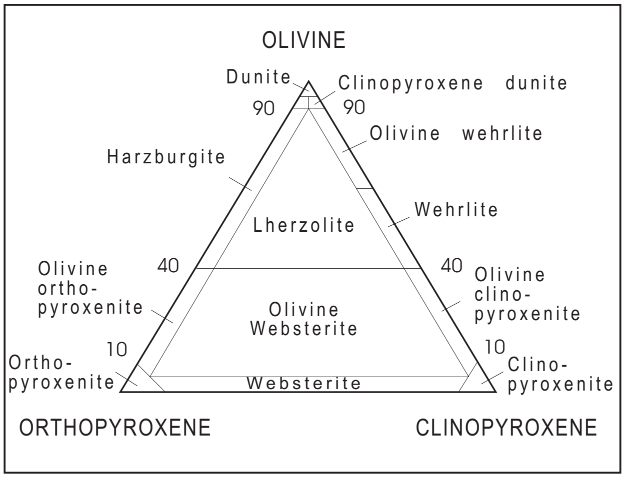


Figure 5.5. Classification and nomenclature of ultramafic rocks in the olivine-orthopyroxene-clinopyroxene prism (after Streckeisen, 1975).

eval Coryell subvolcanic plutonic rocks (Little 1982). The inferred northern contact of the body is marked by a linear topographic depression which Fyles (1984) interpreted as a faulted contact. A minor increase of alteration intensity in the ultramafic rocks towards the contact suggests that the fault has been affected by only limited movement or is restricted to late, high level brittle faulting. The lobate nature of its western and southern margins, combined with the presence of small isolated ultramafic bodies that are possibly zenoliths or rafts within the Coryell batholith several kilometres to the south (Little, 1982), suggest an intrusive relationship. Along its eastern margin the body is in contact with massive fine-grained, aphanitic mafic volcanic rocks correlated with the Rossland Group by Little (1982) and Höy and Andrew (1991a). This contact is not exposed but the presence of fish-scaled serpentine with localized carbonate-altered shear zones near the margin of this body indicates a faulted contact.

O.K. ULTRAMAFIC BODY

The O.K. ultramafic body is the smaller, but economically more significant of the two ultramafic bodies examined (Figure 5.6). It underlies an area of approximately 1.0 square kilometre roughly two kilometres west-southwest of Rossland in the valley of Little Sheep Creek between O.K. Mountain and Deerpark Hill. Data and linework illustrated in Figure 5.6 is taken directly from an air photo of the immediate map area investigated and therefore is not immediately transferable to existing topographic base maps.

The ultramafic rocks are similar to the larger Record Ridge body and consist of variably serpentinized olivine-bearing cumulates with variable contents of intercumulate pyroxene. A lack of continuous exposure as well as the limited size of the body preclude recognition of any systematic variation in the rock types that might indicate a primary magmatic stratigraphy as defined in the larger body to the south. The dominant lithology consists of olivine wehrlite with erratically distributed, localized areas of dunite and pyroxene-bearing dunite.

Photo 5.1. Chrome bearing dunite, on the eastern slope of Record Ridge.

Photo 5.2. Olivine wehrlite, displaying textural character of intercumulate pyroxene and cumulate olivine.

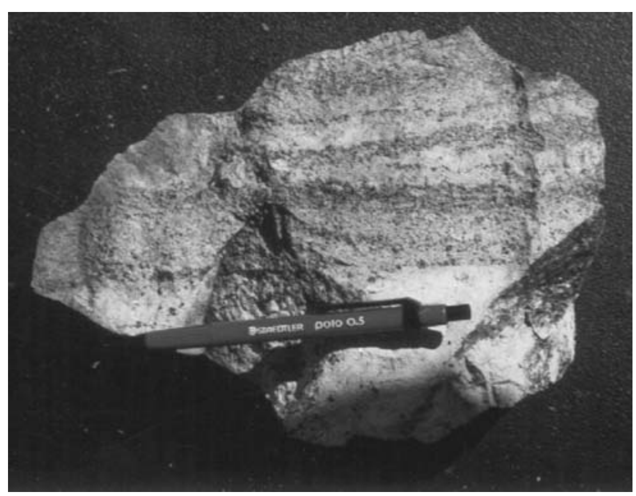


Photo 5.3 Cumulate chromite layering in dunite. From trench in showing No. 2, Figure 5.3.

The western margin of the body is faulted against Marron volcanic rocks along the O.K. fault (Fyles, 1984), a late, steeply-dipping structure. Ultramafic rocks exposed near this fault contact are characterized by a slight and localized increase in the degree of serpentinization, with little or no shearing, suggesting limited or localized high level fault displacement. To the east, the body is in part against a linear north-trending dike-like intrusion of Coryel rocks along the Jumbo fault. Siliceous siltstones correlated with the Mount Roberts Formation by Fyles (1984) and mafic metavolcanic rocks of uncertain association crop out farther south along the eastern margin. Their distribution is erratic in this poorly exposed area and their contact relationship with the ultramafic rocks is not well defined, but is inferred to be tectonic. The presence of serpentinized ultramafic rocks, separate from the main O.K. body, between these sediments and the adjoining mafic volcanic rocks to the southeast suggests that this is most likely a tectonic contact. Based on this relationship the belt of siliciclastic metasediments along the southeast margin of the ultramafic body are tentatively correlated with the Mount Roberts assemblage.

Along its northern contact, the O.K. ultramafic body is faulted against Mount Roberts siltstones to the west and fine-grained aphanitic mafic metavolcanic rocks correlative with the Rossland Group (Little, 1982; Höy and Andrews, 1991a; Höy *et al.*, 1992) to the east. Fyles (1984) mapped these rocks as greenstones of unknown age and correlation and distinguished them from Rossland Group volcanics. Close to the contact, these mafic metavolcanic rocks host the majority of the gold-quartz veins in the Rossland Camp.

In the north the ultramafic-metavolcanic contact is not well exposed but Stevenson (1936) has described the nature of the contact in underground workings. He writes:

"A contact zone intervenes between the black serpentine and the andesite; it is best seen in the second and third crosscuts to the north from the main fault-drift in the lower O.K. adit. The zone strikes roughly east and varies from 20 to 30 feet in width. Over this width irregular areas of hard, chocolate-coloured andesite are interspersed with irregular areas of serpentine."

Hard, chocolate coloured andesites as described by Stevenson (1936) are interpreted to be carbonate altered mafic volcanic rocks.

A large pit excavated to serve as a holding pond near the entrance to the O.K. No. 350 adit exposes brecciated ultramafic rocks close to the metavolcanic contact (Photo 5.5). The breccia consists of blocks of talcose serpentinite ranging from several centimetres to several tens of centimetres in size within a schistose talc-serpentine matrix (Photos 5.6a and b). The more massive blocks contain from 2 to 5 % disseminated euhedral pyrite. Blocks of schistose talc±carbonate rock are also common in several dumps located near the portal of the O.K. lower adit, which transects the faulted contact. The altered ultramafic rocks adjacent to the faulted contact, and mafic volcanic rocks within it, reveal a carbonatized fault zone. Unfortunately quartz-carbonate-mariposite listwanite for potential dating was not identified in outcrop or in dumps.

ORIGIN OF THE ULTRAMAFIC ROCKS

Suggestions as to the origin of the ultramafic rocks in the Rossland camp have varied. Early workers (Brock, 1906; Drysdale, 1915) interpreted them to be altered augite porphyrite stocks. Little (1982) was the first to suggest that they are most likely contemporaneous with the Paleozoic, oceanic Mount Roberts Formation, and part of an ophiolitic assemblage. Fyles (1984) interpreted the ultramafic rocks to be much younger, possibly of Late Cretaceous age, inferring that they are post- collisional intrusions. Höy and Andrew (1991b) recognized that the ultramafic rocks are most probably tectonically emplaced.

Mapping confirms that these rocks are plutonic with well-preserved primary cumulate textures. Similar rock types are found in ophiolitic and Alaskan-type ultramafic complexes. The close association of the ultramafic rocks in the Rossland camp with both arc volcanic rocks and oceanic sedimentary and possibly volcanic rocks suggests that either association is possible; field evidence is insufficient to draw any firm conclusions. In order to discriminate between these alternatives, massive chromitite collected from the Record Ridge ultramafic body was analyzed for the com-

Photo 5.4. View looking towards the northwest over the Little Sheep Creek Valley depicting the setting of the IXL, Midnight.

Photo 5.5. Entrance No. 8 level portal to the IXL mine.

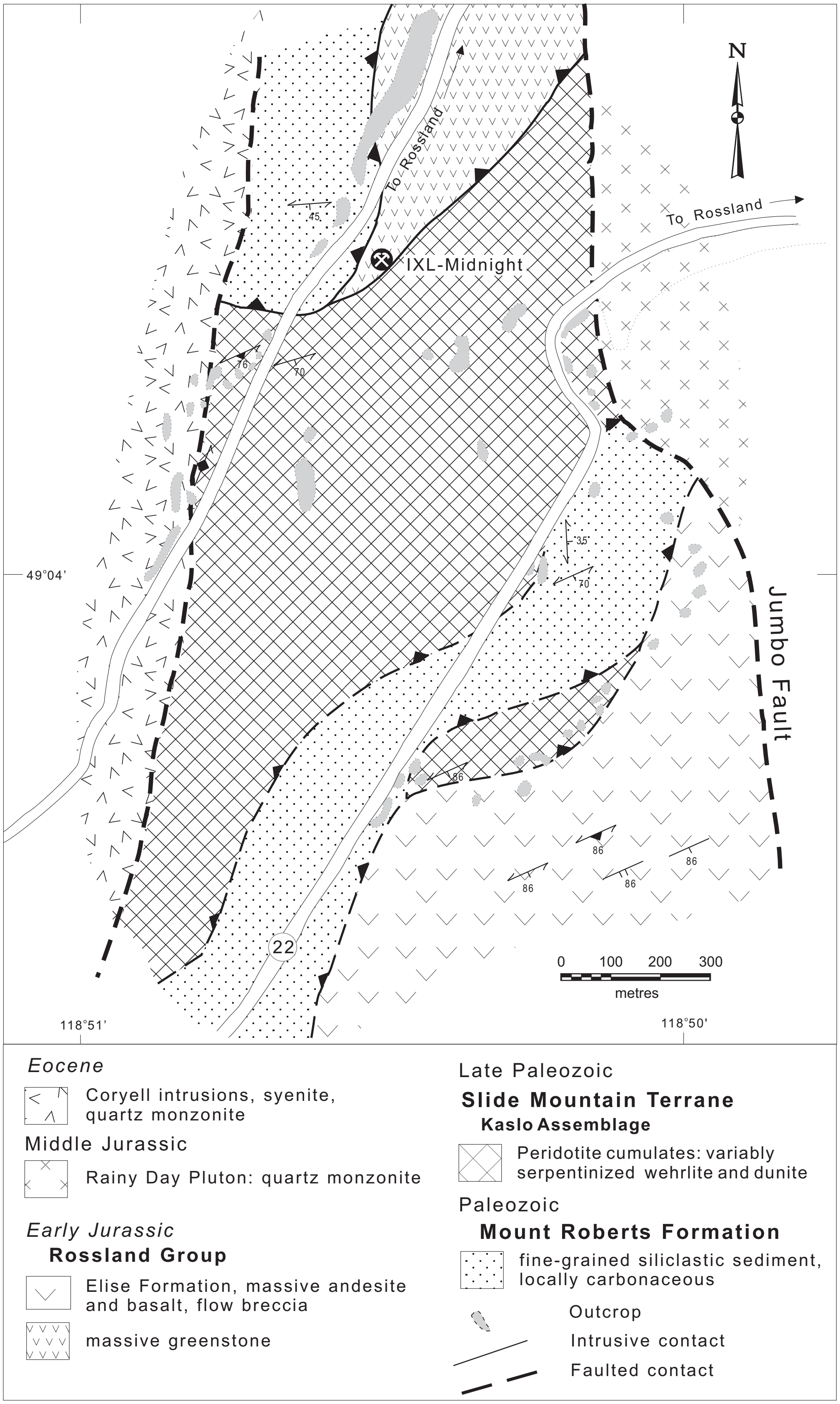


Figure 5.6. Geology of the O.K. ultramafic body.


Photo 5.6 a and b. Carbonatized ultramafic tectonic breccia with disseminated pyrite near the entrance to No. 8 level portal at the I.X.L. mine.

plete suite of platinum group elements (PGEs); the relative abundances of these elements have distinctive signatures in rocks of the two possible affinities. Platinum group element abundances in the massive chromitite (Figure 5.7) show an enrichment in osmium, iridium and rhodium relative to platinum and palladium, a feature consistent with the PGE abundances of ophiolitic chromitites (Agiorgitis and Wolf, 1978; Economou, 1986; Legendre and Augé, 1986; Naldrett and von Gruenewaldt, 1989). Alaskan-type chromitites are characterized by the reverse relationship in which platinum and palladium are enriched relative to the other PGEs.

Petrographic study of the ultramafic rocks provides additional evidence in support of an ophiolitic affinity. Intercumulate orthopyroxene has been identified in a number of thin sections. Orthopyroxene is a common minor intercumulate phase in ophiolitic ultramafic cumulates but is characteristically absent in Alaskan-type complexes due to their strongly alkaline composition. The geochemical and petrological character of these ultramafic rocks suggests that they are most likely ophiolitic in origin and implies formation within the lower plutonic crust at an oceanic spreading centre. The present crustal level of these rocks and their juxtaposition with both sedimentary and subaerial volcanic rocks can only be the result of tectonic processes.

The tectono-stratigraphic character of the ultramafic rocks is compatible with that of the adjacent Mount Roberts Formation. Bedding attitudes in the Mount Roberts Formation, in its type locality along the lower east-facing slope of O.K. Mountain and Mount Roberts immediately to the north of the O.K. ultramafic body, indicate that the unit is homoclinal with bedding tops facing west (Little, 1982; Hoy and Andrew, 1991a). The magmatic stratigraphy defined within the Record Ridge ultramafic body indicates a similar relationship and provides evidence for a common tectonic history for the two oceanic units.

It is considered possible that the small isolated occurrence of massive metavolcanic rocks hosting the gold quartz veins may also be ophiolitic. If determined to be ocean floor basalts as opposed to arc volcanics, they should also be included with the Kaslo assemblage.

The tectonic implications of the ultramafic rocks as ophiolitic is that their current surface position marks the presence of a transcrustal fault, presumably related to suturing of oceanic crust during collapse of the Rossland arc complex in Middle Jurassic time.

LATE SYN-COLLISIONAL MAGMATISM

A number of distinctive intrusive bodies belonging to the Nelson Intrusive Suite are present in the local Rossland area. The Rainy Day quartz diorite (Fyles, 1984), situated several hundred metres east of the O.K. ultramafic body is the most proximal late syn-collisional intrusion to the

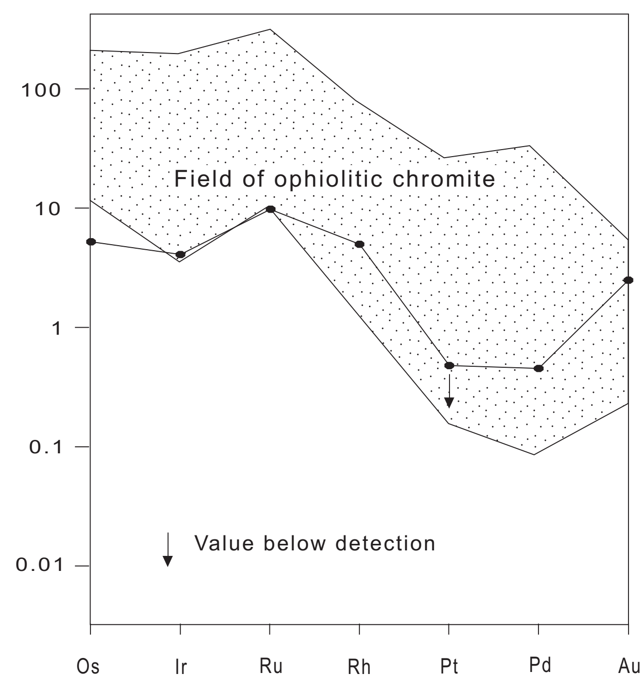


Figure 5.7 Normalized platinum group element abundances of massive chromitite from the Record Ridge ultramafic body compared to the field of PGEs in ophiolitic chromite. Normalizing values are mantle abundances from Barnes *et al.* (1988); arrow indicates abundance of element below detection limits.

gold-quartz vein mineralization. Fyles (1984) described the porphyritic marginal phases of the Rainy Day pluton as being highly fractured with a network of intersecting veinlets which he considered as indicating the presence of endogenous late-stage fluids. The age of the body is poorly constrained by U-Pb dating (Höy and Dunne, 2001) which gives a broad estimate between 174.6±3.6 and 166.3±1.4 Ma. Contact relationships with the adjoining Rossland monzonite (Figure 5.2) may provide additional age constraints. Fyles (1984) identified, though not definitively, dike-like masses of quartz diorite that appeared to extend from the Rainy Day pluton into the Rossland monzonite which is dated at 167.1±0.5 Ma (Höy and Dunne, 1997, 2001).

The Rainy Day pluton has been traditionally interpreted (Brook, 1906; Little, 1982; Fyles, 1984; Höy and Andrew, 1991a, b; Andrew *et al*., 1991) as a satellite stock of the larger Trail pluton to the northeast of Rossland (Figure 5.2). Available U-Pb zircon data for this larger granodiorite body (Corbett and Simony, 1984) and for an isolated, north-trending linear satellite stock (Fyles, 1984), referred to informally as the Topping Creek pluton (Figure 5.2) indicate coeval ages at *ca.* 163 Ma. These ages are within the ca. 172 to 162 Ma range defined for the magmatic suite regionally (Ghosh, 1995).

The late Early to Middle Jurassic contractional event that imbricates Mount Roberts Formation, Kaslo Assemblage and Rossland Group rocks is bracketed by regional considerations (Murphy *et al.*, 1995; Colpron *et al*., 1996) between late Early Jurassic and Middle Jurassic (186 to 174 Ma). On the basis of relative timing between magmatism and tectonism the Middle Jurassic Nelson suite may be typified as late syn-orogenic.

LODE GOLD MINERALIZATION

There are two distinctive styles of gold vein mineralization in the Rossland camp: copper-gold sulphide-rich fissure veins and gold-quartz veins (Drysdale, 1915; Fyles, 1984; Höy and Dunne, 2001). The two distinctive styles of vein mineralization are separated by the north-trending Jumbo Fault (Fyles, 1984) (Figure 5.2). This is a lithologically and structurally complex north-trending fault zone that has been affected by later faulting and episodic felsic intrusion subsequent to the Middle Jurassic thrusting.

The setting of the latter vein type is the primary focus of this discussion. The character of the sulphide rich copper-gold veins is described in detail by Höy and Dunne (2001) and only briefly described here for purposes of comparison.

MASSIVE PYRRHOTITE-CHALCOPYRITE FISSURE VEINS

Sulphide-rich veins of the Rossland camp are hosted mainly in fissure zones cutting Early Jurassic Rossland Group, and hypabyssal subvolcanic intrusives (*e.g.* Rossland sill). Most of the veins are associated with, and thought to be genetically related to, irregular tongue-like protrusions that emanate from the Rossland monzonite into the Rossland Group subvolcanic augite porphyry (Fyles, 1984). These tongues are co-structural with the vein fissures, with veins occurring along the margins of the intrusive contacts or just beyond the termination of the tongues.

The ore in the veins consists mainly of massive pyrrhotite and chalcopyrite with lesser pyrite and minor arsenopyrite, with combined sulphide minerals comprising from 50 to 70% of the vein. Sulphides occur as either well defined veins or as sheeted zones of irregular lenses or tabular bands with intervening zones of barren vein material. These are associated with a gangue of altered country rock with quartz and locally a little calcite.

The range in metal values of the veins as reported by Drysdale (1915) is 12.4 to 37.3 grams (0.4 to 1.2 ounces) gold, 0.7 to 3.6% copper and 9.3 to 71.5 grams (0.3 to 2.3 ounces) silver characterizes the nature of the Rossland vein occurrences.

Höy and Dunne (2001) further refine the camp zonation model of Thorpe (1967) and demonstrate a metal zonation in which the structural style, mineralogy and tenor of the Cu-Au sulphide veins is considered to vary due to the combined effects of depth of formation, proximity to the syngenetic Rossland monzonite and nature of the host rocks.

GOLD-QUARTZ VEINS

Gold-quartz vein mineralization in the Rossland camp on the Midnight (082FSW119), I.X.L (082FSW116) and O.K. (082FSW117) Crown-granted claims is hosted by massive greenstone and ultramafic rocks adjacent to the faulted and brecciated northern margin of the O.K. ultramafic body.

The following is summarized after Drysdale (1915) and Stevenson (1936) which are the only published descriptions of the geology in the largely inaccessable underground workings. The veins are several centimetres to 2 metres wide and follow a series of east to northeast-trending, moderately to steeply (35-75°) south dipping fissures. Visible gold is reported from most of the veins and typically occurs erratically distributed in rich pockets. The majority of the veins are contained in carbonate-altered massive greenstone, however, Drysdale (1915) reports that in 1906 the O.K. and I.X.L. furnished very rich gold-quartz ore from a vein in serpentinite but the vein lacked continuity and did not extend into the lowest levels of the mine. He reports that the average gold grade was close to an estimated 63 g/t (1.84 oz/ton; reported as $38.00 per ton). An average analysis from part of a typical ore car shipment from the mine some time during the 1890s is reported by Drysdale (1915) as; silver 0.85%, gold 140 grams (4.5 ounces) and copper 2.5%. This high-grade gold character of the ore shoots or pockets is well documented (Drysdale, 1915; Stevenson, 1935; Fyles, 1984). Sulphide minerals, including chalcopyrite, pyrite and galena are uncommon but locally have concentrations of 10 to 15% where they occur as individual 2 to 6-millimetre grains or in polymineralic lenses, 1 to 4 centimetres in size. Ankeritic carbonate is the only other gangue mineral in addition to quartz and occurs both in irregular zones within the veins and less commonly in veinlets in the altered wallrocks.

AGE AND ORIGIN OF GOLD MINERALIZATION

Various interpretations of the age and origin of Cu-Au sulphide veins have been presented throughout the long history of exploration and study in the Rossland camp, and are reviewed by Fyles (1984). Although all previous workers have consistently interpreted the veins to be intrusion related, there has been some inconsistency as to which of the local intrusions is genetically related to the vein mineralization. Drysdale (1915) suggested that the immediate association of granodioritic tongues within and alongside the mineralized vein fissures was strong evidence for a genetic association between the two. Thorpe (1967) proposed that gold-copper sulphide mineralization is related to the Rossland monzonite and/or the Trail and Rainy Day plutons.

Thorpe and Little (1973) argued that the Rossland monzonite was related to the Cu-Au sulphide veining in order to account for the camp scale mineral zoning, a view which is supported by more recent constraints defined by Höy and Dunne (2001). Fyles (1984) concluded that the pattern of mineral zoning possibly results from a complex interplay with more than one source for the metals and a succession of structural events, as well as the composition, temperature and confining pressure of the mineralizing fluids.

The timing of gold-quartz veining has been consistently interpreted to be coeval with the Cu-Au sulphide veining in the main Rossland camp. These gold-quartz veins have been viewed to form at a higher structural level, as a lower temperature, more distal expression of the overall mineral zonation pattern (Thorpe, 1967; Fyles, 1984; Höy and Dunne, 2001).

The faulted and altered contact between the O.K. ultramafic body and the massive mafic volcanic rocks is considered to be of Middle Jurassic age (Höy and Dunne, 2001) and places a lower age limit on vein formation. The widespread association of similar vein systems in which late syn-orogenic intrusive rocks are temporally and spatially associated with vein mineralization along the terrane collisional boundaries, as discussed in other chapters, adds support to this view. The relatively high copper content of the gold-quartz veins (Drysdale, 1915) relative to the trace abundances found in other gold-quartz veins described from other camps is atypical. This might suggest a metal signature that is consistent with that in the sulphide rich veins and provides additional evidence for a possible genetic link between the two vein types.

Currently the gold-quartz veins are at a lower topographic elevation than the Rossland sulphide veins, however, restoring Eocene motion on the Jumbo Fault situated between the two deposit types may solve this current contradiction.

The immediate genetic association of the gold-quartz veins with intrusive rocks is speculative.

Stevenson (1936) indicates that a small intrusion of medium-grained monzonite to diorite is intersected at several levels on the O.K. and I.X.L. adits. The rock consists of light-green chloritic hornblende and white feldspar. The only relationship indicated (Stevenson, 1936) between the gold-quartz veins and the intrusion is that the quartz vein dies out on entering the diorite. Clearly, definitive age constraints of gold-quartz veining are needed to confirm their timing and potential genetic association with the Cu-Au sulphide veins. Existing relationships, however, support such a view of coeval vein formation.

SUMMARY

- Gold quartz-veins in the Rossland camp are associated with listwanite altered ultramafic rocks assigned to the Late Paleozoic Kaslo Assemblage. These are located along a terrane collisional boundary between continental margin sedimentary rocks of the Mount Roberts Formation and volcanic arc rocks of the Early Jurassic Rossland Group.
- Ultramafic rocks consisting of magmatic cumulates are exposed in two distinct bodies along this faulted boundary. These rocks appear to be mineralogically and chemically comparable with an ophiolitic origin and are interpreted to be remnants of late Paleozoic, lower ocean crust. They have been emplaced, in the solid state, by tectonic processes and delineate a transcrustal fault zone.
- Gold-quartz vein fissures are best developed in massive greenstone near the faulted and carbonate-altered contact with the O.K. ultramafic body. Veins are poorly developed in the altered ultramafic rocks but veins with the richest gold ore shoots are along side or near contacts with the ultramafic rocks.
- Little’s (1982) proposal that the ultramafic rocks might comprise some type of dismembered ophiolite suite is supported by this study. In light of this, we propose that the ultramafic rocks comprise a component of the Kaslo Group or preferably “Kaslo assemblage”. Massive greenstone in contact with the ultramafic rocks hosting the gold quartz veins, which are distinctive from Rossland Group volcanics and only found along the terrane-bounding zone, may also be part of this ophiolitic assemblage. Petrochemistry of these rocks is required to confirm any potential genetic association between the two igneous units.
- Gold-quartz veins appear to have formed late in the orogenic episode, and are inferred contemporaneous with the development of the sulphide-rich fissure vein system. Both mineralized vein systems are considered to be genetically related to intrusion of the spatially associated, late-syn collisional Middle Jurassic Nelson Plutonic Suite. Cu-Au sulphide veins show a close spatial and likely genetic association with the Rossland monzonite (*see* Höy and Dunne, 2001 for a detailed discussion).

- Intrusive rocks of the Rossland arc complex, mainly the Rossland sill, acted to provide competent host rocks for development of continuous vein fissures.
- This veined and mineralized competent structural block being situated adjacent to a terrane-bounding suture is consistent with relationships for other gold vein deposits discussed in this study.

CHAPTER 6
CENTRAL SLIDE MOUNTAIN TERRANE
BARKERVILLE GOLD CAMP

INTRODUCTION

The Barkerville gold camp in east-central British Columbia (Figure 6.1) is historically the largest placer gold-producing district in the province. Conservative estimates place placer gold production at 4 million ounces (124 tonnes; Schroeter and Lane, 1991). The initial discovery of gold on Lightning and Williams Creeks in 1861 is attributed to Billy Barker after whom the historic town of Barkerville is named. Gold-quartz veins were identified in the area shortly after the discovery of placer gold in 1861 but did not attract much attention until the yield of alluvial gold began to seriously diminish in 1875-76 (Johnston and Uglow, 1926). From this period many repeated unsuccessful attempts were made to profitably mine the veins. It was not until 1933 that profitable mining was initiated and attributed to the enthusiasm and persistent endeavor of Fred M. Wells (Skerl, 1948), presumably the namesake of the local community of Wells. Schroeter and Pinsent (2000) report that the total lode gold produced from the camp is 38 321 529 grams (1 226 289 ounces).

Placer gold in the camp occurs in the same area as two distinct styles of lode gold mineralization: massive pyritic lenses referred to as ‘replacement ore’ and gold-quartz veins. In both deposit types native gold occurs as fine blebs and fracture fillings in pyrite but the gold in the bedrock deposits is not similar to the coarse nugget gold historically recovered from placers. This disparity between the textural style of free, coarse gold found in the placers compared to the predominantly fine flour gold found in lodes was recognized in early studies of the camp (Johnston and Uglow, 1926):

page 224, *“The occurrence of large amounts of coarse, nuggety gold, gold crystals, and mammillary gold in the placers and the apparent general absence of coarse gold in the auriferous veins of Barkerville area are the main apparent difficulties in the way of accepting the view that the placer gold is detrital.*

page 216, *“There can be little doubt, therefore, that the gold of the placers was derived from the auriferous quartz veins, the main problem being to determine how the placer gold could have been derived from quartz veins of such character as those found in the Barkerville area”.*

In an attempt to explain this enigma, these authors proposed that the increased grain size of the placer gold resulted from oxidation and dissolution of gold in the quartz veins, followed by its redeposition in placer gravels near the base of the zone of oxidation. Eyles and Kocsis (1988) proposed a mechanism of supergene reprecipitation to account for the increased size of the placer grains. They suggested that gold in quartz veins was affected by deep, tropical weathering in the Tertiary and was concentrated in the near-surface environment by supergene enrichment. Knight and McTaggart (1989) analyzed fine-grained gold from both lodes and placers and demonstrated that the composition of the two gold types is more or less the same, indicating that supergene enrichment, which should have produced pure or near-pure gold, was not the operative process. They offered no alternative explanation.

In this chapter we discuss the regional geological setting of the Cariboo-Barkerville area and relate characteristics of the individual deposit types to the regional tectonic framework. We present an alternative view for the source of the coarse, nugget gold in the placers, and offer an explanation for the difference in its physical character in contrast to that found in associated lodes. Aspects of the regional geology and deposit characteristics are extracted primarily from published sources. Refinements for the lithotectonic setting of the Barkerville area and related lode gold deposits are introduced.

PREVIOUS WORK

The regional geology of the Cariboo area has been documented by Struik (1981, 1986, 1988a,b). Published descriptions of the camp geology and associated lode gold deposits include those of Johnston and Uglow (1926), Hanson (1935), Skerl (1948) and Sutherland Brown (1957). Later studies have focused largely on the Mosquito Creek mine (Andrew, 1982; Andrew *et al.*, 1983; Alldrick, 1983; Robert and Taylor, 1989). More recent deposit studies focused on comparing the geochemical signatures of the individual deposits (Ray *et al*., 2001) and characterizing the nature of the vein fluids (Dunne and Ray, 2001).

The placer geology of the camp was initially described by Bowman (1889, 1895) and has more recently been studied by Levson and Giles (1993).

GEOLOGICAL SETTING

The Barkerville Camp consists of deformed and variably metamorphosed Proterozoic to late Paleozoic continental slope and rise sedimentary rocks that are tectonically overlain by a relatively undeformed, flat-lying imbricated succession of late Paleozoic ophiolitic assemblage rocks (Figure 6.2). The underlying North American strata comprise late Proterozoic to Paleozoic Barkerville (Kootenay) and Cariboo (Cassiar) terranes (Struik, 1988a). Variably metamorphosed, deformed and folded clastic sedimentary rocks dominate both these terranes. The Cariboo Terrane has two main subdivisions: a lower sequence of Proterozoic and Cambrian grit, limestone, sandstone and shale and an

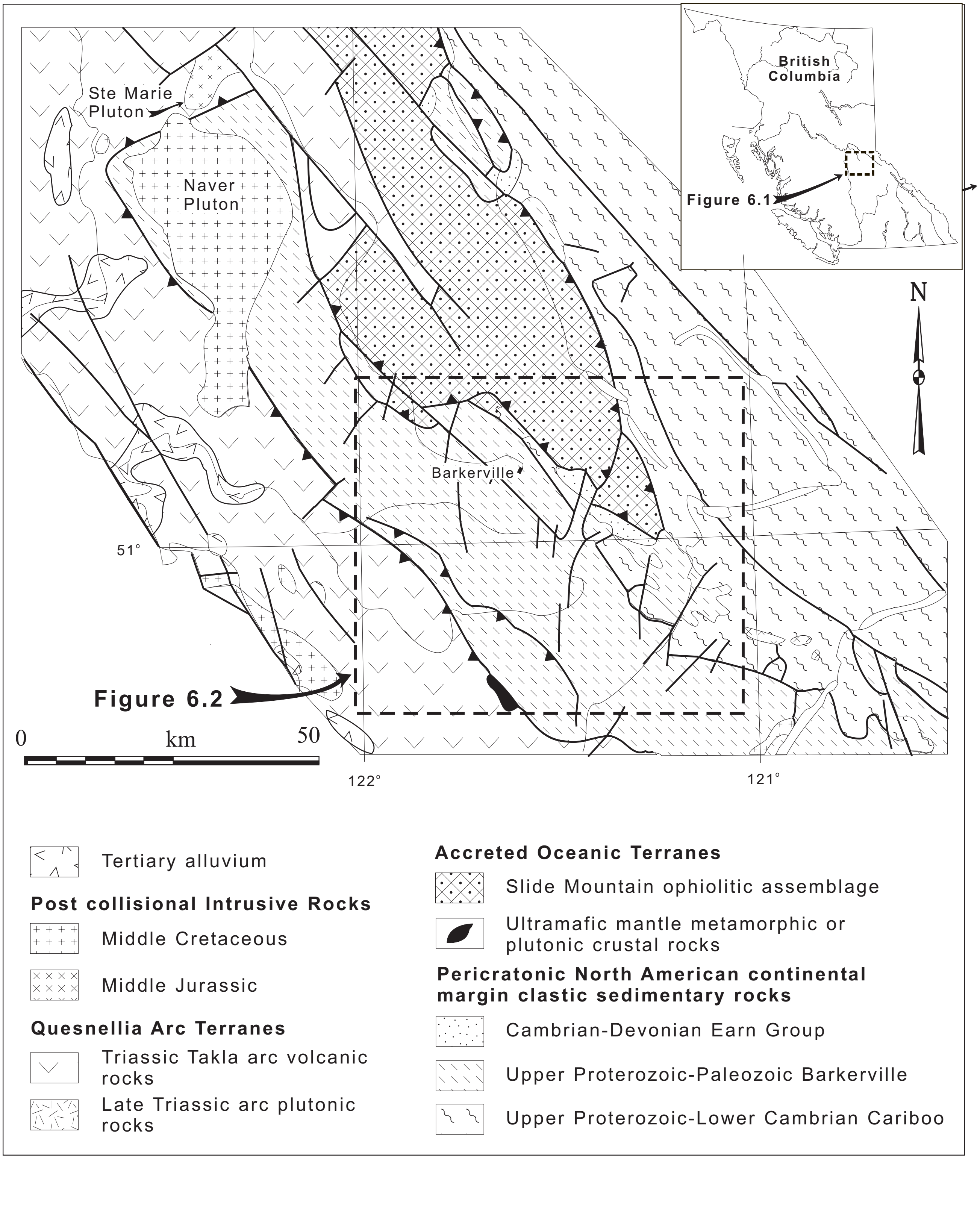


Figure 6.1. Regional geological setting of the Cariboo placer gold camp (after Wheeler and Mcfeely, 1991).

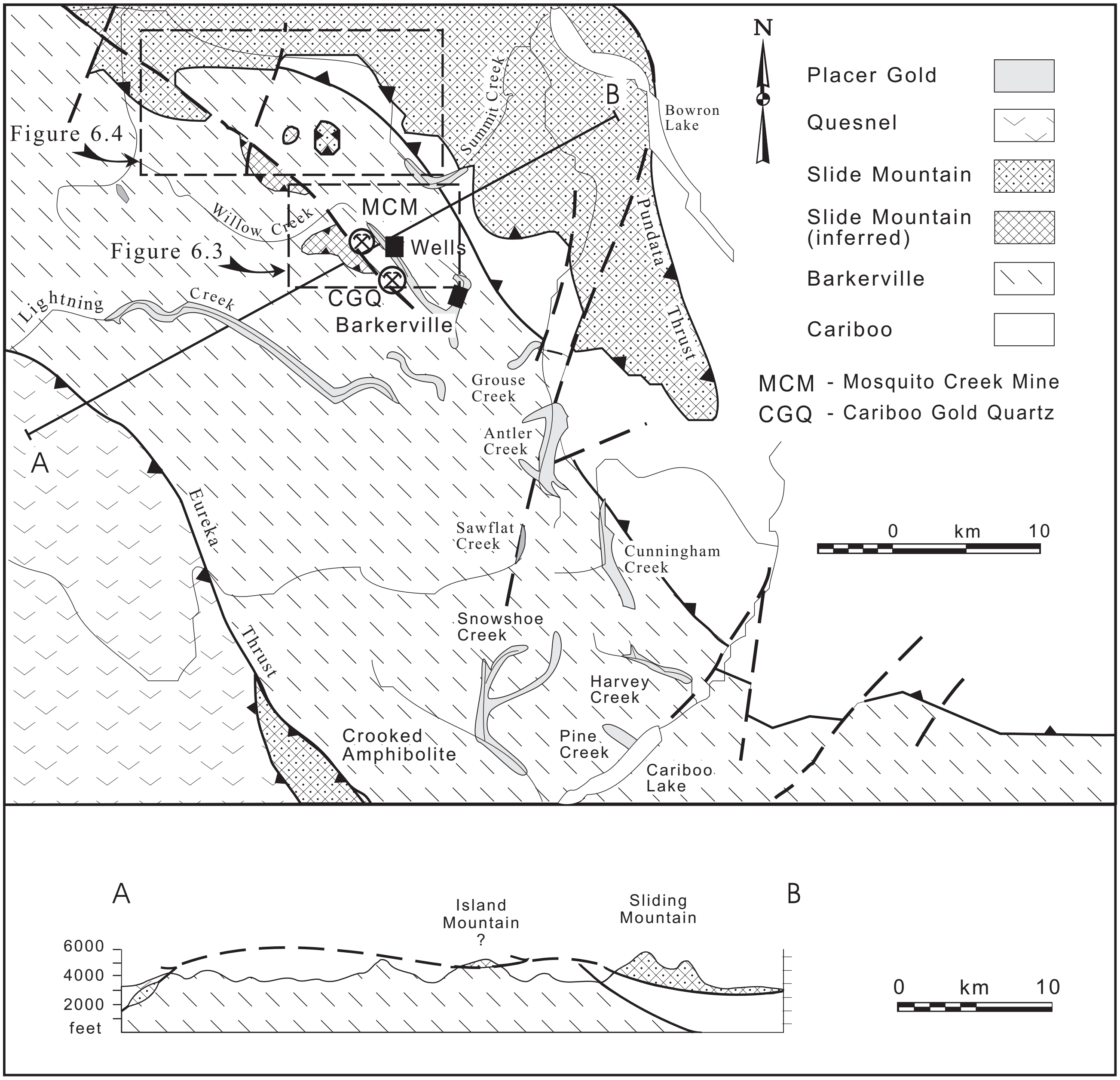


Figure 6.2. Distribution of placer gold deposits in the Cariboo camp (after Struik, 1988).

unconformably overlying sequence of basinal shale, dolostone, wacke and limestone. Barkerville Terrane rocks, which host the majority of the lode-gold occurrences in the region, are generally of higher metamorphic grade and are dominated by variably metamorphosed, commonly schistose varieties of grit, quartzite, pelite and subordinate limestone.

Sutherland Brown (1957) describes the structure of these bedded sediments as being closely compressed into north westerly-trending, complex folds that are overturned to the southwest and plunge at shallow angles to the northwest. Within the Barkerville camp he defines the Snowshoe synclinorium which is flanked by the Island Mountain and Cunningham anticlinoria to the west and east respectively. Metamorphosed limy shales and siliceous mudstones that comprise black siliceous phyllite, slate, argillite and limestone in the Island Mountain anticlinorium are the primary hostrocks for lode gold deposits.

Ophiolitic rocks of the central Slide Mountain Terrane consist of two lithotectonic elements in the Cariboo area (Figure 6.2). The larger bodies are to the immediate east of the Barkerville camp. Twenty kilometres west of the camp, the Crooked amphibolite (Struik, 1986; Panteleyev et al., 1996) occurs as relatively thin, discontinuous tectonic slivers of ultramafic and mafic volcanic rocks along the Eureka thrust fault. This is a west-dipping structure that separates

*Use of the term Antler asssemblage as opposed to Antler Formation is suggested using the rationale discussed in Chapter 1.

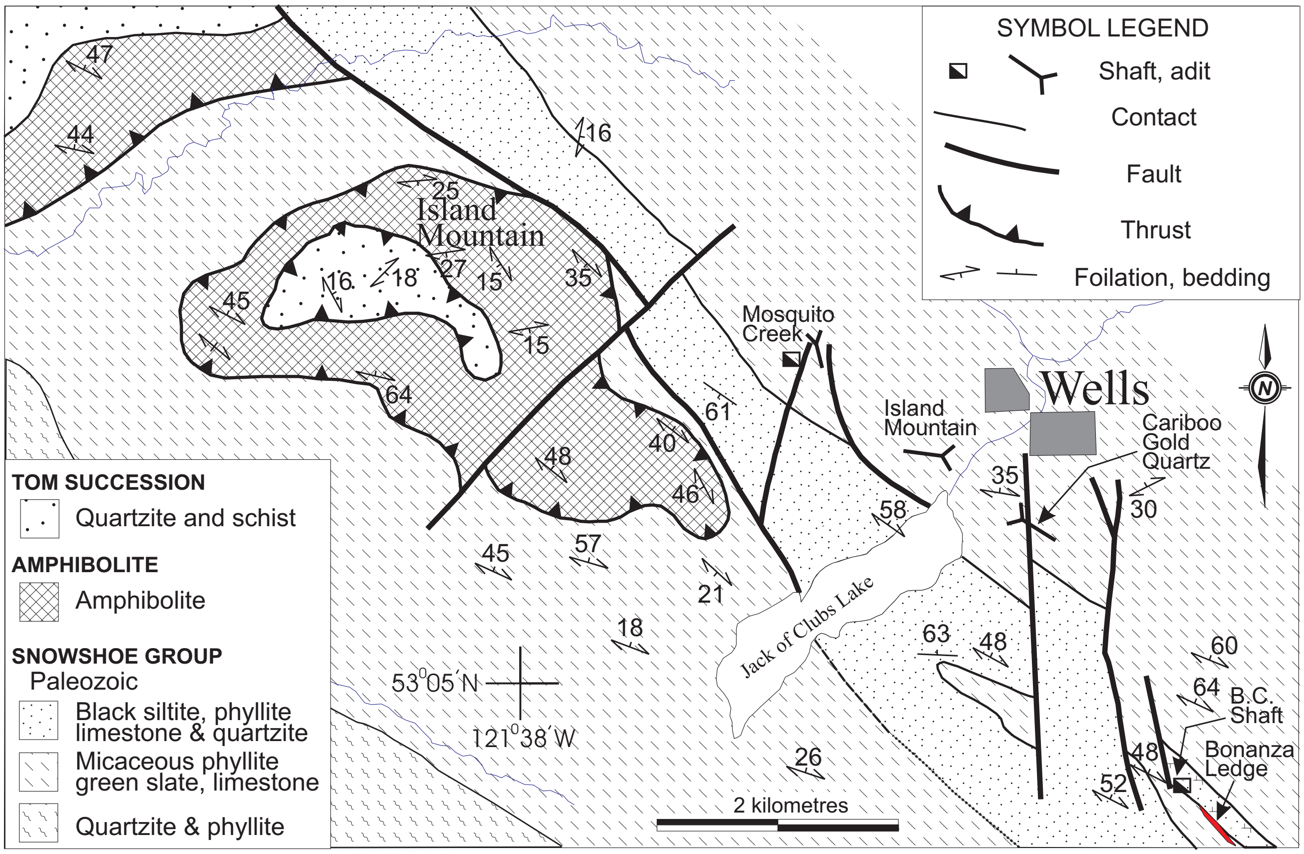


Figure 6.3. Simplified geology of the Wells area, from Alldrick (1983) as modified after Struik (1982).

Quesnel arc volcanic and derived sedimentary rocks in the hangingwall to the west, from footwall North American rocks of the Barkerville subterrane (Struik, 1986).

East of Barkerville, Slide Mountain Terrane rocks are locally assigned to the Antler assemblage* and comprise a series of internally imbricated early Mississippian to Early Permian oceanic crustal volcanic and pelagic sedimentary rocks, which sit structurally above displaced North American rocks of both the Barkerville and Cariboo terranes along the Pundata thrust (Struik, 1981). Struik and Orchard (1985) have established from fossil evidence that at least three thrust imbricates are present within the overlying Antler ophiolitic assemblage. Ophiolitic rocks are dominated by metabasalt and pelagic sediments with lesser mafic plutonic and ultramafic rocks. Sedimentary units commonly include interbedded chert and argillite with lesser slate and greywacke (Sutherland Brown, 1957; Struik, 1986, 1988a, b). Struik (1988a) has correlated the Crooked amphiblite with the Antler assemblage and suggests that both the Pundata and Eureka thrust faults are most likely part of a continuous structure now separated by erosion (Figure 6.2). This interpretation is consistent with that of earlier workers. Hodgson *et al.* (1982) write:

"... in the Cariboo Camp Sutherland Brown (1957) has suggested that the outcrop of Slide Mountain to the east of the camp is the erosional remnant of a thrust slice which was transported from the west, which suggests that Slide Mountain volcanic rocks may have been present structurally not far above the Cariboo deposits at the time they formed."

Similar tectonic relationships in which Antler ophiolitic assemblage rocks form klippen on areas of high ground to the west of, and locally within the camp is considered highly likely. The strongest case can be made for the amphibolite unit capping Island Mountain, 2 kilometres west of and structurally above sedimentary host rocks of the Mosquito Creek mine (Figures 6.2 and 6.3; Photo 6.1). At this location the amphibolite forms a well-defined klippe that truncates steeply folded bedding in the underlying sedimentary rocks (Alldrick, 1983 and personal communication 2000). Struik (1982, 1988a) called this unit the Island Mountain amphibolite and designated it to be part of the upper Paleozoic Snowshoe Group of the Barkerville Terrane, however an alternate correlation with the Crooked Amphibolite was also considered a possibility. Amphibolite is lithologically distinct from local Barkerville rocks which consist almost entirely of metasediments. This amphibolite is, however, directly correlative with metamorphosed igneous lithologies of Slide Mountain ophiolitic crustal rocks.

The suggestion that the Island Mountain amphibolite is metamorphosed Slide Mountain Terrane is further supported by comparable structural settings of the amphibolite units and Antler ophiolitic rocks east and north of the camp

(Figure 6.4). In a regional context the footwall contact of the amphibolite and the trace of the Eureka thrust appear to be part of the same shallowly northward-dipping, terrane bounding suture. The dip of the structure is also consistent with the shallow northwest plunge of major folds in the underlying deformed metasedimentary rocks (Sutherland Brown, 1957).

Immediately northwest of the camp listwanite alteration at Mount Tom is associated with the amphibolite (Struik, 1988a) (Figure 6.4). The lithotectonic setting of the listwanite is consistent with that of the nearby Antler assemblage rocks and suggests the outcrop is an altered remnant of this unit, within and possibly above the Pundata-Eureka thrust. It is also significant that this rare remnant of the carbonate altered hangingwall is directly on trend with the Barkerville gold belt.

Recently obtained petrochemical data for the amphibolite unit on Island Mountain (Ray *et al*., 2001) supports the above contention. These rocks have a compositional range consistent with that of tholeiitic ocean-floor basalts which is consistent with the distinctive abyssal character of Slide Mountain Terrane ophiolitic rocks in general (see Chapter 1).

This reinterpretation of the Island Mountain amphibolite places the position of the terrane collisional suture directly above the known zone of lode gold mineralization. It also suggests this thrust contact originally was above areas of historic placer gold creeks, which now occur in erosional windows through this flat-lying terrane-bounding suture zone (Figure 6.2).

LODE GOLD DEPOSITS

Lode gold has been recovered from two distinctive styles of mineralization in the Barkerville camp: gold-quartz veins and massive pyritic lenses. In both deposit types gold occurs primarily as fine disseminations and as fracture fillings in pyrite. Although free gold has been documented (Skerl, 1948) it is not common and usually occurs erratically as fine particles. Both styles of gold mineralization are intimately associated and occur within a narrow northwest-trending belt along the high ground on the east-facing slope of Pleasant Valley. Both styles of gold mineralization are confined to metamorphosed sedimentary rocks of the Barkerville Terrane and are hosted within an overturned anticline of the Snowshoe Group, immediately below the Pundata thrust fault.

Hanson (1935) introduced the term 'Barkerville Gold Belt' to describe this zone of intermittent mineralization which he defines as being less than 1.5 kilometres wide and extending over a distance of 15 kilometres. Gold has been mined from both the Cariboo Gold Quartz and Mosquito Creek (formerly Island Mountain) mines. Skerl (1948) described these deposits as consisting of numerous small, steeply inclined north trending quartz veins grouped into various zones, each of which is centered on a north-south fault. Massive pyritic lenses occur together with the veins

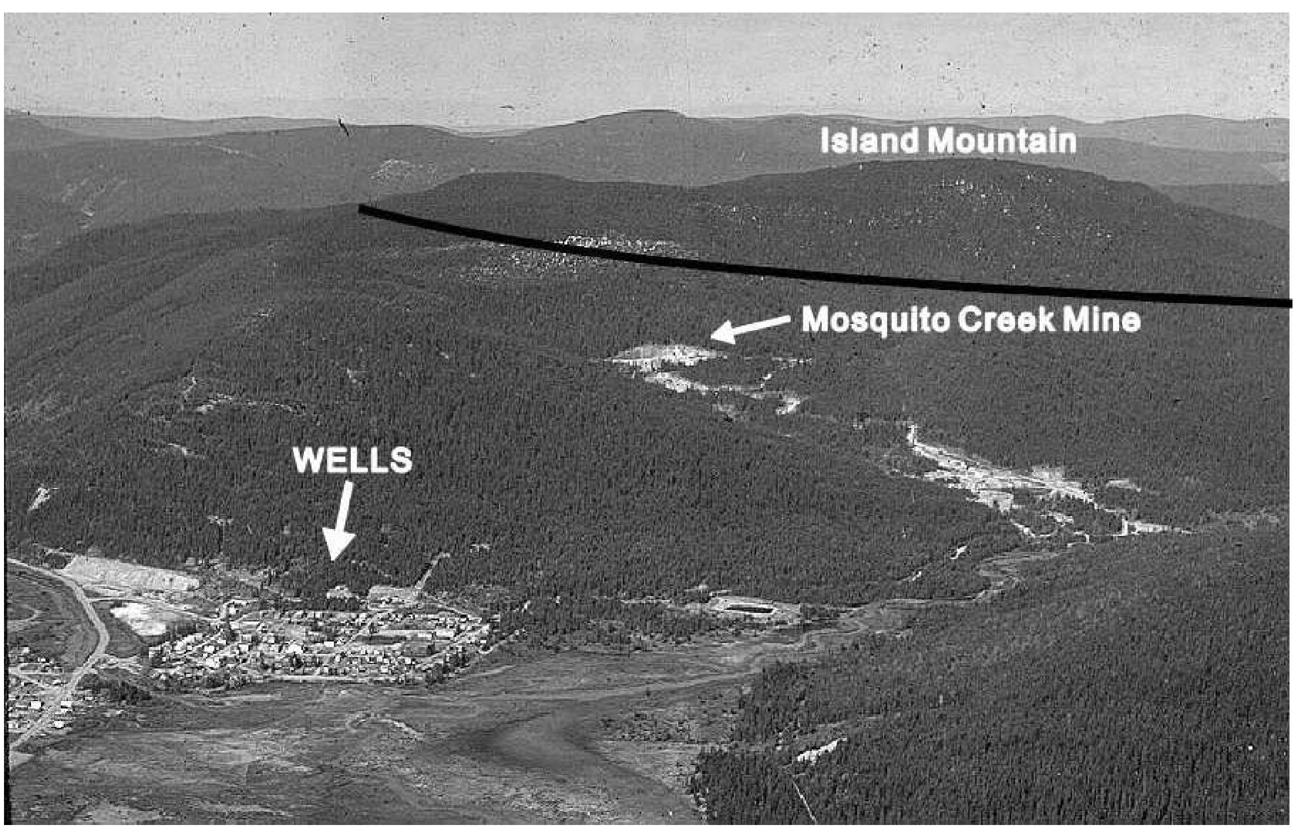


Photo 6.1.The town of Wells and Island Mountain in 1982 viewed from the east illustrating the approximate position of the thrust faulted contact of the Island Mountain amphibolite above the mine workings.

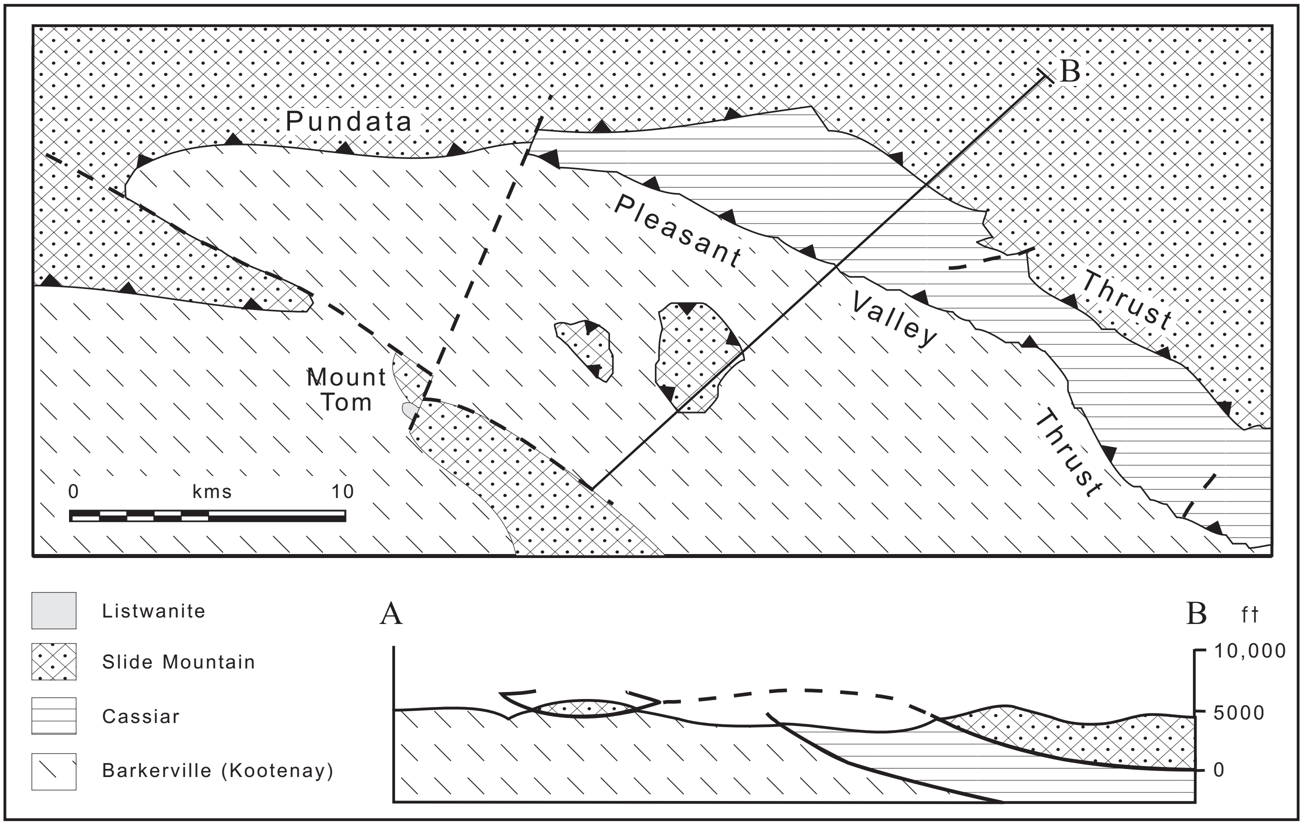


Figure 6.4. Detailed tectonic relationship between Antler ophiolitic assemblage and Barkerville Terrane rocks along the northern margin of the Cariboo placer camp (after Struik, 1988).

and are arranged like wings on each side of veins where they pass through carbonate horizons (Skerl, 1948; Sutherland Brown, 1957). The mined zone has a vertical extent of around 300 metres but veins are developed intermittently along a northwesterly-trending ridge for over 5 kilometres. A projected east-west section (Figure 6.5) shows the restricted vertical extent of ore and clearly mimics the redefined position of the Pundata-Eureka thrust fault. In some of the zones the amount of gold mined and estimated to be present was recognized to steadily diminish with depth. In the No. 3 zone, for example, a gold content of 933 kilograms (30 000 ounces) at the top level diminished down to 187 kilograms (6000 ounces) in the bottom level. Similarly in zone No. 4 the ore grade was better than average near surface but dwindled down to non-economic amounts at 120 metres below the surface.

The following deposit descriptions are summarized primarily from Skerl (1948) and Sutherland Brown (1957).

GOLD-QUARTZ VEINS

Most quartz veins are steep to vertical and generally less than 50 centimetres wide, however, veins up to several metres in width are not uncommon. Stopes consist of many sub-parallel veins and averaged from 15 to 60 metres in width. Ankerite is present in many veins and is a dominant alteration mineral in the calcareous wall rocks, whereas alteration of slate is commonly limited to disseminated euhedral pyrite. Veins of economic grade contain considerable pyrite which is the host to most of the gold. Skerl (1948) reported that the veins contain from 5 to 15% pyrite. Sutherland Brown (1957) indicates a somewhat higher value of 15 to 25% pyrite for ‘ore grade’ with veins assaying from 30 to 60 g/t (1 to 2 oz/ton) gold. Pyrite is either the only sulphide mineral or is the dominant sulphide in association with minor galena, sphalerite, schelite, pyrrhotite, arsenopyrite, chalcopyrite and lead bismuth sulphides. Pyrite forms scattered euhedral disseminations or occurs as streaks (ribboned structures) along the margins or in the center of quartz veins. Visible gold occurs as fine particles and is erratically distributed throughout the veins. Skerl (1948) reports that free gold at the Cariboo Gold Quartz mine was mainly associated with hair-like crystals of the lead and bismuth sulphide cosalite (2PbS, Bi_2S_3) and less commonly with more massive galeno-bismutite (PbS, Bi_2S_3).

AURIFEROUS PYRITIC LENSES

Due to uncertainty as to the origin of these deposits a more descriptive and less generic term is adopted to describe the massive pyritic lenses. The auiferous lenses were first described in 1933 (Hanson 1935) as stratabound, being restricted to the Snowshoe limestone between the Baker and underlying Rainbow members of the Barkerville Terrane. The shape of these lenses range from tabular to cylindrical depending on the folded character of the altered sedimentary host rocks.

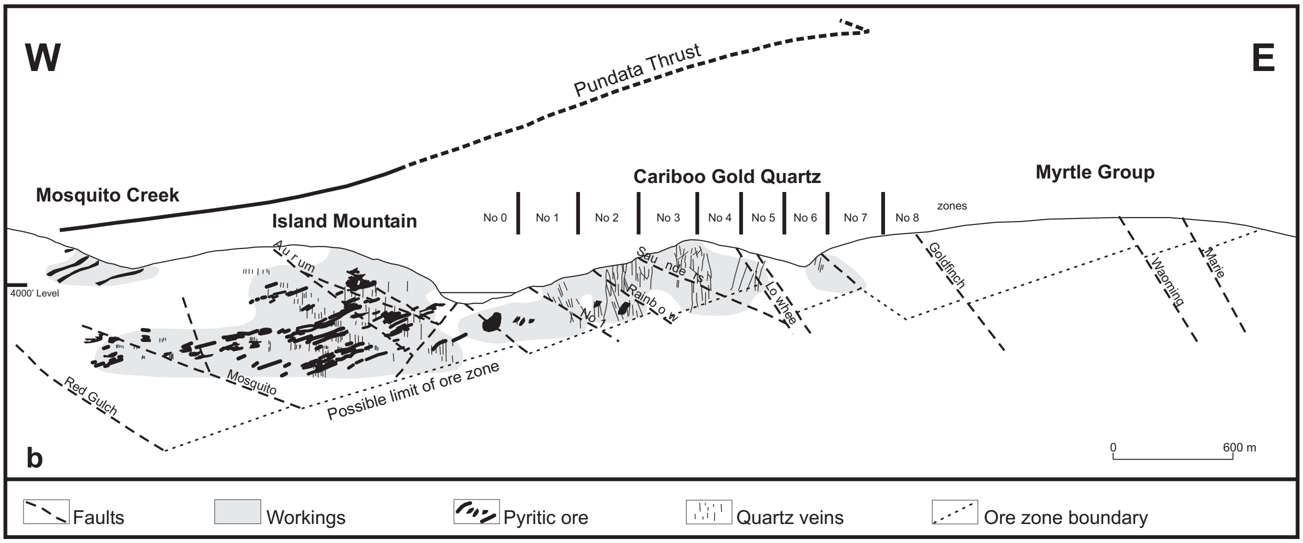


Figure 6.5. Vertical section along 5 000N of mines in the Cariboo camp showing major faults and possible trend of ore zones (after Skerl, 1948 and Poulsen *et al*., 2000).

Pyritic ore lenses are massive to semi-massive with associated fine-grained gold. Free gold, or lead and bismuth minerals have not been found in the massive pyritic lenses. Lenses can be as much as several hundred metres long by several metres in cross-section. The grain size within the massive crystalline sulphides is variable and generally the finer-grained the better the gold grade. Finer-grained pyrite may contain gold values up to 170 g/t (5 oz/ton) whereas the coarser ore, greater than 0.7 millimetres, has comparatively low gold content around 3.5 g/t (0.10 oz/ton).

Lenses are commonly enveloped by coarse grey ankerite in which pyrite is sporadic and coarser-grained relative to that in the massive pyrite zones. Within these ankeritic envelopes minor galena, sphalerite and scheelite can be present. Quartz is not normally identified within the pyritic lenses but bands of ankerite are common.

The auriferous pyritic lenses were considered by most workers to have formed by hydrothermal replacement of limestone during the mineralizing event that produced the gold-quartz veins and were referred to as "pyritic replacements" (Hanson, 1935), or "replacement ore" (Skerl, 1948; Sutherland Brown 1957; Alldrick, 1983). Structural mapping (Robert and Taylor, 1989; Robert, 1996), suggests that the massive pyritic ore was deformed prior to formation of the gold quartz veins and is therefore considered earlier. However, the geometry and overall distribution of the 'wings' of massive pyrite on the sides of veins in preferred calacareous lithologies, tends to favor a hydrothermal replacement origin contemporaneous with quartz vein development. If the sulphide lenses were primary there would be some degree of randomness in the distribution of the lenses. In addition, the ankerite alteration envelopes surrounding the tails of the pyritic lenses where they peter out appear to represent a hydrothermal front diminishing away from the fluid conduit (current vein). Sulphide replacement of the limestone may have preserved a pre-existing structural fabric during metasomatism. Detailed examination of metal content and alteration mineralogy in both the massive pyritic lenses and quartz veins might shed light on their origin.

AGE OF MINERALIZATION AND RELATIONSHIP TO TECTONISM

Current constraints for the timing of gold-quartz vein mineralization in the Barkerville camp is provided by two independent conventional K-Ar isotopic age dates on sericite obtained from quartz-carbonate-sericite vein material at the Mosquito Creek mine. Alldrick (1983) reported an age 139±5 Ma which is coeval with a 141±5 Ma date provided by Andrew *et al.* (1983). This apparent Early Cretaceous age is considerably younger, by at least 30 Ma than the period of Middle Jurassic tectonism (Figure 6.6).

The timing of obduction of the oceanic Antler assemblage onto the North American margin is not well constrained as discussed in the first chapter. Evidence of the regionally well-defined Middle Jurassic tectonic event (Murphy *et al*., 1995) is indicated by metamorphic ages (Figure 6.6). Metamorphic sphene in Barkerville Terrane orthogneiss to the south-southeast of the camp has been dated by U-Pb at 174±4 Ma (Mortensen *et al.*, 1986). A K-Ar metamorphic whole-rock age on phyllite is coeval with the sphene age at 179±8 Ma (Andrew *et al.*, 1983). The Ste. Marie pluton north-northwest of the camp (Figure 6.1) is an undeformed multiphase intrusion which has been dated by U-Pb zircon methods at 167±2 Ma and is interpreted to pierce the Eureka thrust fault at depth (Struik *et al.*, 1992). This Middle Jurassic intrusive date therefore provides a minimum age for the development of the terrane-bounding suture. However, as indicated in Figure 6.6, and discussed elsewhere, it is considered more likely that the Slide Mountain Terrane was obducted onto the North American margin in Late Permian to Early Triassic time. It is possible that earlier obducted ophiolitic Slide Mountain rocks and underlying continental margin rocks underwent fore-arc extension during middle to Late Triassic subduction. This resulted in the development of Quesnellia arc volcanic complexes and deposition of regionally extensive basinal shale sequences. This basin then collapsed during regionally extensive Middle Jurassic orogenic activity.

ASSOCIATED FELSIC INTRUSIONS

No major plutons occur locally in the area of the Barkerville gold camp, however, a suite of intensely carbonate-altered felsic dikes, referred to as the ‘Proserpine dikes’, occur throughout the camp (Johnston and Uglow, 1926; Sutherland Brown, 1957; Struick, 1988a). These dikes are exposed in prospect trenches and underground workings, commonly in association with gold-quartz veins, and in some instances altered dikes host the veins. Johnston and Uglow (1926, page 15) described these dikes:

“*A large number of brownish weathering sills and a few dykes occur cutting the various members of the Cariboo series. They are usually not more than a few feet thick but in two or three places a thickness of 30 or 40 feet was observed. Owing to the covering of glacial drift and vegetation it was impossible to follow them along their strike, except for a very short distance.... Quartz porphyry, felsite, aplite, and quartz latite are prevalent types. Their outcrops are characteristically iron-stained, due to the oxidation of disseminated pyrite and siderite. Since they occur to a very large extent as sills and since the intruded rocks are equally oxidized in most cases, their outcrops and boundaries are not very clearly delineated.... A noteworthy characteristic of almost all of these intrusives is their irregular spotty replacement by siderite; and it is largely due to the oxidation of this mineral that they owe their typical brownish colour. In many cases, as at the Waverly pit just mentioned, the felsite is so completely replaced by siderite that specimens of it closely resemble ferriferous crystalline limestone.... Many of the sills are seamed with a network of quartz veins , some of which carry iron and lead sulphides with gold values.*”

and Sutherland Brown (1957):

“ ...The Proserpine dikes are felsites that in general are so ankeritized that they weather a characteristic reddish-brown. They are usually aphanitic but may be microporphyritic. No dike is fresh; most are highly ankeritized, and many are schistose. Commonly the dikes and their adjacent wall rocks are so highly ankeritized it is difficult to distinguish one from the other in the field..... The feldspars are highly sericitized and the mafic minerals entirely altered. The original fine-grained texture has been largely obliterated by the development of large ankerite porphyroblasts and by muscovite or fuchsite, and quartz, and are indistinguishable from similarly altered sedimentary rocks.”

These dikes as described, are comparable to dikes associated with gold-quartz veins at the Atlin, Bralorne and Fort

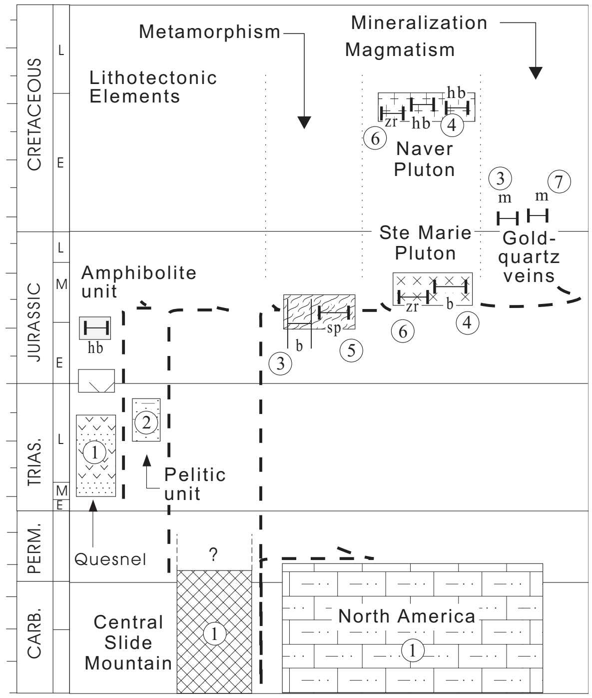


Figure 6.6. Relative age and tectono-stratigraphic relationships for lithologies in the Cariboo-Barkerville camp.
zr - zircon U-Pb; sp - sphene (titanite) U-Pb; m - muscovite K-Ar; hb - hornblende K-Ar; b - biotite K-Ar
Data sources used to constrain age relationships for the elements depicted are:
① Struik 1988; ② Bloodgood, 1990; ③ Andrew, 1982; Andrew *et al*., 1983; ¯ ④ Hunt and Roddick, 1988; ⑤ Mortensen *et al.*, 1986; ± ⑥ Struik *et al*., 1992; and ⑦ Alldrick, 1983.

St. James areas. Analogous features include; post-dating deformation, high level porphyritic textures, carbonate-sericite-pyrite alteration and locally elevated gold values. Isotopic dating of both primary magmatic and secondary alteration minerals from the dikes would clarify geological relationships. A genetic association between dikes and the gold veins is considered likely as has been previously suggested by Johnston and Uglow (1926):

“*The mineralization of the veins, including the formation of the gold, cannot be definitely attributed to the effect of any observed petrological agent, but the mineralogy and structure of the deposits suggests that the metallic minerals owe their origin to emanations from intrusive rocks, whose location is inferred to be at comparatively short depths below the lowest exposed member of the Richfield formation, and of whose presence there the Proserpine quartz porphyry sills may be a manifestation.*”

SOURCE OF PLACER GOLD

Gold in the Barkerville lode deposits is fine-grained compared to the coarse gold typical of the coincident Cariboo placer deposits. A suggestion offered here is that the coarse placer gold was derived from Slide Mountain ophiolitic crustal rocks which had previously structurally overlain Barkerville rocks, similar to the geological setting to the immediate northeast of Barkerville (Struik, 1988a, Figure 6.3).

The type of gold-quartz vein mineralization in accreted oceanic rocks (pre-existing Slide Mountain rocks) are more likely to have generated the coarse, nugget gold as these rocks are characteristically hosts for this style of gold deposit elsewhere in the North American Cordillera.

Additional but indirect support for a gold source somewhere close to and structurally above the present topographic surface is provided by the physical character of the nuggets and their erratic distribution.

"*The source of placer gold in Upper Antler Creek and its erratic distribution have been questions in dispute ever since the early discoveries."(Johnston and Uglow, 1926, page 59).*

"*An especially puzzling feature in the distribution of the placer gold on Upper Antler Creek is the fact that the rich pay streak commenced abruptly near the mouth of Victoria Creek and although dilligent search has been made for its continuation in upper parts of the Creek and its tributaries, no gold lead at all comparable to it in richness has been found.*" (Johnston and Uglow, 1926, page 60).

"*Many of the nuggets, also, are too large to be transported any great distance by streams, and it is probable that they have moved vertically downward nearly as far as they have been transported horizontally.*"

SUMMARY

Placer gold in the Barkerville camp occurs within an erosional window through a collisional suture zone that has emplaced Slide Mountain ophiolitic assemblage rocks onto deformed continental rise and slope sediments of the ancestral North American margin. This structure is regarded to be the transcrustal suture that acted as a conduit or structural trap for the mineralizing fluids. Such a fault zone is fundamental to the development of gold-quartz vein deposits, previously thought to be uncharacteristically absent in this area (Robert and Taylor, 1989). In this respect, the concentration of placer gold can be regarded to be primarily the result of mechanical rather than chemical processes.

Lode gold mineralization in the Barkerville camp is hosted in metasedimentary rocks that form the footwall below the collisional suture zone. The laterally extensive, steeply dipping veined zones exhibit a limited vertical range of mineralization.

Differences in the physical character of placer gold compared to that in the lodes is attributed to differences between the hostrocks of the veins that determined the styles of vein mineralization. Veins hosted by footwall metasedimentary rocks below the pre-existing suture zone contain fine gold. It is inferred that ophiolitic rocks in and above the eroded suture carried coarse free gold that is characteristic of that found in the placers.

The observed spatial association of the co-structural, hydrothermally altered Proserpine felsic dikes with gold quartz veins suggests the two might be genetically related (Johnston and Uglow, 1926). The age of these dikes is unknown. Both late Early Cretaceous and Middle Jurassic plutonic rocks are known to occur regionally. One, or both, of these magmatic episodes may be related to Proserpine diking. Age determinations for both the magma crystallization (U-Pb zircon) and alteration (Ar-Ar sericite) of these dikes would help define possible temporal relationships between magmatism and gold mineralization.

A re-examination of rocks at the summit of Island Mountain, as well as other summits in the camp, may prove valuable in further constraining regional tectono-stratigraphic relationships. These would help broaden the regional exploration potential for similar styles of gold beyond the limits of the Barkerville camp.

CHAPTER 7
NORTHERN SLIDE MOUNTAIN TERRANE
CASSIAR GOLD CAMP

INTRODUCTION

The Cassiar camp, is situated in northern British Columbia, a few kilometres east of the abandoned Cassiar townsite and asbestos mine. It includes mines on Table Mountain (Erickson and Cusac) and at Quartz Rock Creek (Taurus), The camp encompasses a north-trending belt over a distance of about 12 kilometres of productive east to north-east-trending gold-silver-bearing quartz veins (Figure 7.1, Photo 7.1). During its decade-long production history from 1979 to 1988, a combined total of 8 524 000 grams (274 055 ounces) gold and 5 472 300 grams (175 938 ounces) silver were produced from quartz lodes (Schroeter and Lane, 1991). Boronwski (1988) reports that total production from the camp was roughly 490 000 tonnes grading approximately 15.6 grams (0.5 ounce) per tonne gold and 11.3 grams per tonne silver mostly from the Erickson mine. Significant amounts of gold have also been recovered from placers on McDame Creek and its tributaries. Holland (1950) reports that from the initial discovery of placer in 1874 until 1950, reported recovery was 2 021 700 grams (65 000 ounces). Since that time small-scale operations have recovered gold during seasonal placer mining.

Investigations in the Cassiar camp in the course of this project were conducted for approximately one week in 1989. In the following pages, we summarize the lithotectonic setting of mesothermal gold-quartz vein deposits in the Cassiar camp. A conventional K-Ar isotopic age on mariposite from listwanite and an Ar-Ar age on sericite from quartz are presented and discussed. Matt Ball graciously provided several days of his time to review both the underground and surface geology of the mine, which contributed significantly to our understanding of the deposit geology. Andre Panteleyev provided several unpublished Ar-Ar age dates of hydrothermal vein mica from the camp which represents a significant contribution to the following discussion.

PREVIOUS WORK

The geology of the area has been mapped at a variety of scales. It was first investigated as part of a Geological Survey of Canada regional 1:4 mile mapping program of the McDame map sheet (Gabrielse, 1963). Gordey *et al*. (1982) mapped a west-trending belt across the Sylvester allochthon. A larger area of the allochton has been subsequently mapped at a 1:50 000 scale (Nelson and Bradford, 1993). More localized mapping in the area of the Cassiar camp has been conducted by Diakow and Panteleyev (1981), Panteleyev and Diakow (1982) and Harms (1989).

The detailed geology and characteristics of vein morphology, alteration and mineralization in the camp are well documented (Mandy, 1936, 1938; Panteleyev, 1980, 1983, 1992; Diakow and Panteleyev, 1981; Panteleyev and Diakow, 1982; Hopper, 1984; Dursell, 1986; Sketchley, 1986; Sketchley *et al*., 1986; Gunning, 1988; Boronowski, 1988; Anderson and Hodgson, 1989; Nelson and Bradford, 1989; 1993; Panteleyev *et al*., 1997). Most of this work has focused on the central part of the camp, near the Erickson mine, and provides a wealth of detailed information. Production at the mine coincided with the period when mesothermal gold-quartz vein deposits in general were afforded considerable research attention. More recent exploration activity concerned with the potential for bulk tonnage ore has been reviewed by Panteleyev *et al*. (1997).

REGIONAL SETTING

Gold-quartz vein deposits of the Cassiar camp are hosted by late Paleozoic (Gabrielse *et al*., 1993) oceanic crustal volcanic, plutonic and mantle metamorphic rocks of the Sylvester ophiolitic assemblage (Harms, 1989). These oceanic rocks occur as individual thrust-bounded slices which form part of an imbricated stack of fault-bounded lithotectonic units of predominantly oceanic crust-mantle and sedimentary rocks and subordinate arc-volcanic and continentally derived sedimentary rocks that comprise the Sylvester allochthon (Gabrielse and Mansy, 1980; Gordey *et al*., 1982; Harms, 1984, 1985, Harms *et al*., 1989; Nelson and Bradford, 1989, 1993). This oceanic assemblage is a vast, composite, klippe resting on the basal Sylvester fault (Harms, 1989) above displaced ancestral North American continental margin rocks (Figure 7.2). The timing of obduction of the Sylvester assemblage is poorly constrained. Harms (1985) suggested an age between Late Triassic and Early Cretaceous (Figure 7.3) constrained by the upper age of the Table Mountain sediments and the oldest age of hydrothermal sericite within the imbricating structures. A Middle Jurassic emplacement age is, however, most generally advocated (Struik *et al*., 1992; Nelson and Bradford, 1993). Whether or not the Middle Jurassic compressional event is related to obduction of the Slide Mountain terrane or is due to telescoping of a Late Triassic rifted fore-arc basin that was constructed on previously accreted oceanic basement, remains to be resolved. Harms (1985) reported a tonalite intrusion cross-cutting a slice-bounding fault near the southern end of the Sylvester Allochthon in the Rapid river area yielded late Permian zircons which indicates pre-Permian tectonism within the ophiolitic assemblage. This is a rare and possibly unique observation that provides the only evidence for pre-Late Triassic tectonism in oceanic Slide Mountain terrane in the Canadian Cordillera, known to the author. An obduction age

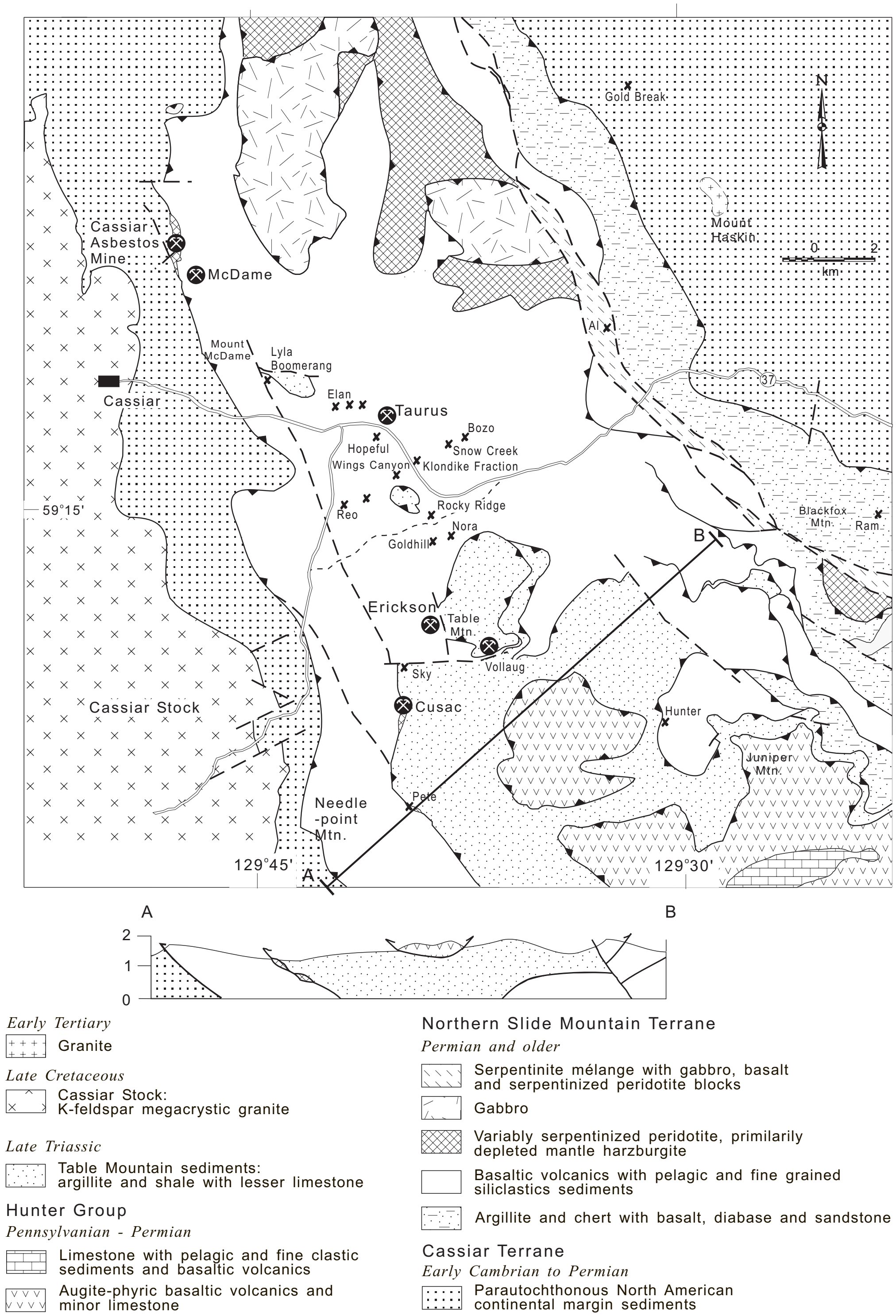


Figure 7.1. Geology of the Cassiar gold camp, after Harms (1989) and Nelson and Bradford (1993). Generalized cross-section of the Erickson mine area is from Harms (1989).

Photo 7.1. View to the south overlooking Needle Point Mountain.

of Late Permian would explain why there are no younger rocks in the Slide Mountain terrane and why it does not overlie rocks anywhere that are younger than Late Permian.

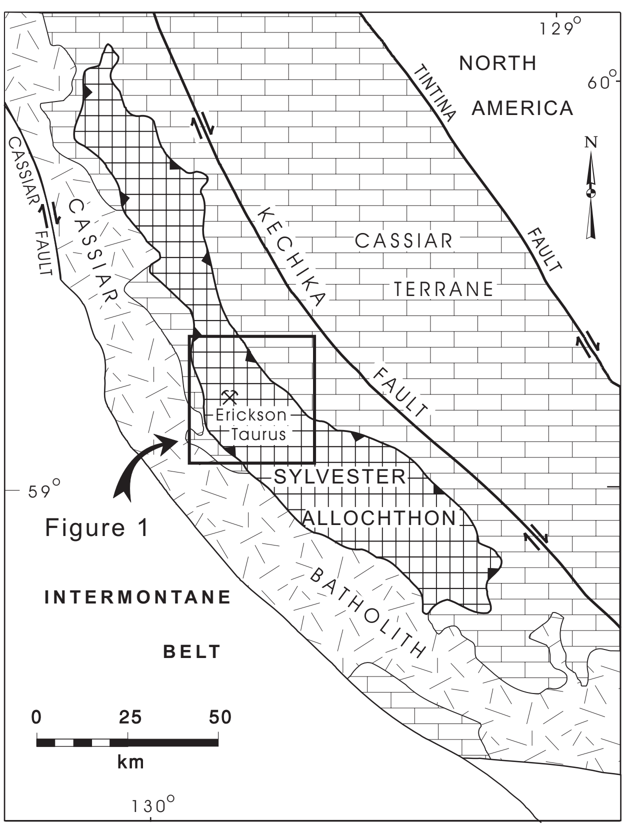


Figure 7.2. Location and regional geological setting of the Cassiar camp.

POST-COLLISIONAL MAGMATISM

Several episodes of post-collisional felsic magmatism have affected rocks of the Sylvester assemblage (Figure 7.3). The earliest identified intrusive event is evidenced by the north-trending Early Cretaceous Cassiar batholith which extends along, and in part cuts, the western margin of the Sylvester allochthon (Figure 7.2). It is a composite batholith including quartz monzonite, granodiorite and granitic phases (Gabrielse, 1963). Potassium-argon isotopic data for biotite and amphibole give a range of mid Cretaceous ages between 109 and 89 Ma (Baadsgard *et al*., 1961; Wanless *et al.*, 1968, 1970, 1972; Panteleyev, 1985).

A small quartz monzonite body near Cassiar, the Troutline Creek stock, intrudes North American platformal sedimentary rocks between the Cassiar batholith and the Sylvester allochthon and is considered to be part of a discrete magmatic suite independent of the Cassiar Batholith (Panteleyev, 1983). Mica and hornblende K-Ar dates indicate a Late Cretaceous age of intrusion which is coeval with a recently obtained U-Pb ziron age of 73±0.5 Ma (A Panteleyev and R. Friedman, personal communication 2000).

The small stocks at Mount Reed and Mount Haskin are products of Early Tertiary magmatism. They intrude North American strata along the eastern periphery of the Sylvester allochthon. Biotite K-Ar ages range from 51.4 to 48.8 Ma (Christopher *et al*., 1972).

DEPOSIT GEOLOGY

Gold-quartz veins in the Cassiar camp are hosted by a gently dipping thrust zone, 300 to 400 metres wide, which immediately underlies Late Triassic Table Mountain sedimentary rocks (Photo 7.2). This thrust zone comprises a sequence of narrow imbricated metabasaltic slices, roughly 100 metres thick, separated by thinner, discontinuous tec-

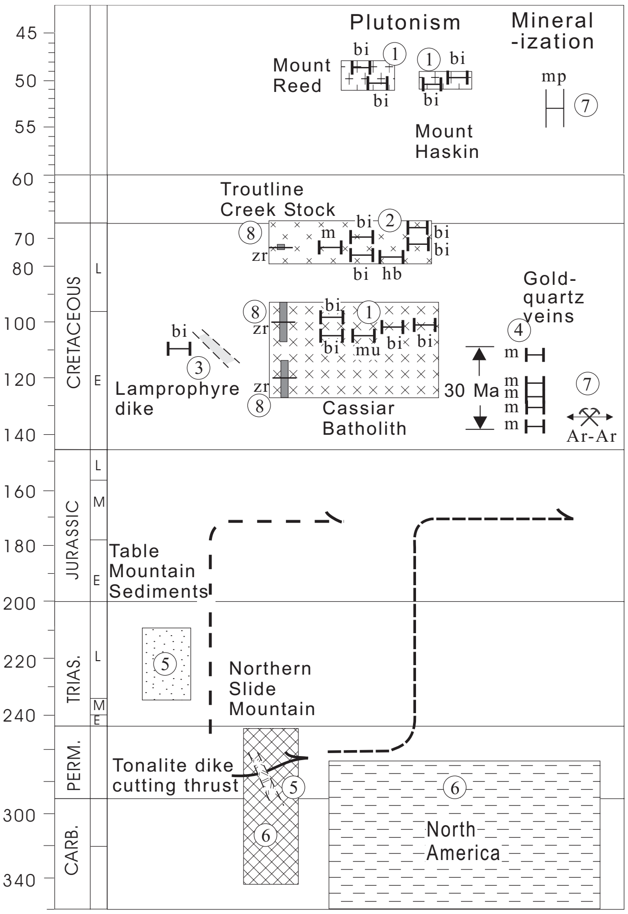


Figure 7.3. Relative age and tectonostratigraphic relationships for lithologies in the Cassiar camp.
m - muscovite K-Ar; **hb** - hornblende K-Ar; **bi** - biotite K-Ar; **mp** - mariposite/fuchsite K-Ar
Data sources used to constrain age relationships for the elements depicted are;
① Christopher *et al*., 1972; ② Panteleyev, 1985; ③ Panteleyev, personal communication 1991; ④ Panteleyev and Diakow, 1982; Sketchley *et al.*, 1986; ⑤ Harms, 1989; ⑥ Nelson and Bradford, 1989, 1993; Gabrielse *et al.*, 1993 ⑦ this study and ⑧ A. Panteleyev and R. Friedman, personal communication, 2000).

tonic slivers of variably listwanite-altered ultramafic rocks (Figure 7.4).

Metabasalts are the dominant rock type throughout the map area and are typically grey-green, massive and aphanitic. Where they contain gold-quartz veins the rock is converted to orange-brown weathering ankerite (Photo 7.3). Locally in outcrops and extensively in underground mine workings, pillow structures and pillow breccias are well preserved. Major, trace and rare-earth element analysis of these mafic volcanic rocks suggest that they are mid-ocean ridge basalts (MORBs; Ash, unpublished data). The ultramafic rocks are either intensely serpentinized or variably carbonatized, making recognition of their protolith lithology difficult. Nelson and Bradford (1989) have suggested that they are attenuated tectonic slivers of the Zus Mountain ultramafic thrust sheet which crops out at a similar

Photo 7.2. Flat-lying thrust contact between hanging wall graphitic black argillite and footwall carbonate altered ultramafics in the area of the Sky vein (photo courtesy of Andre Panteleyev).

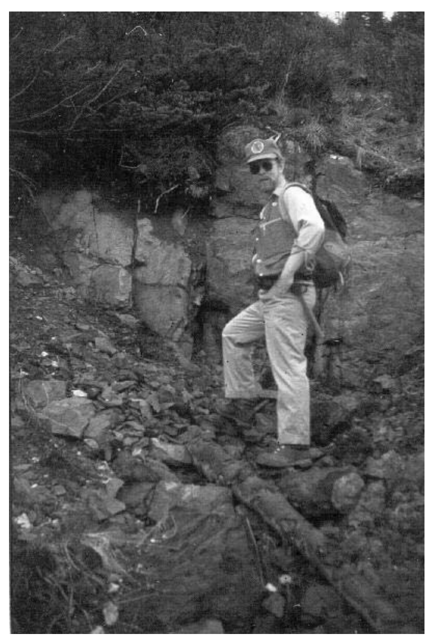


Photo 7.3. Example of relatively unaltered massive basaltic diabase/volcanic in faulted contact with orange-brown weathering carbonate altered equivalent (photo courtesy of Andre Panteleyev).

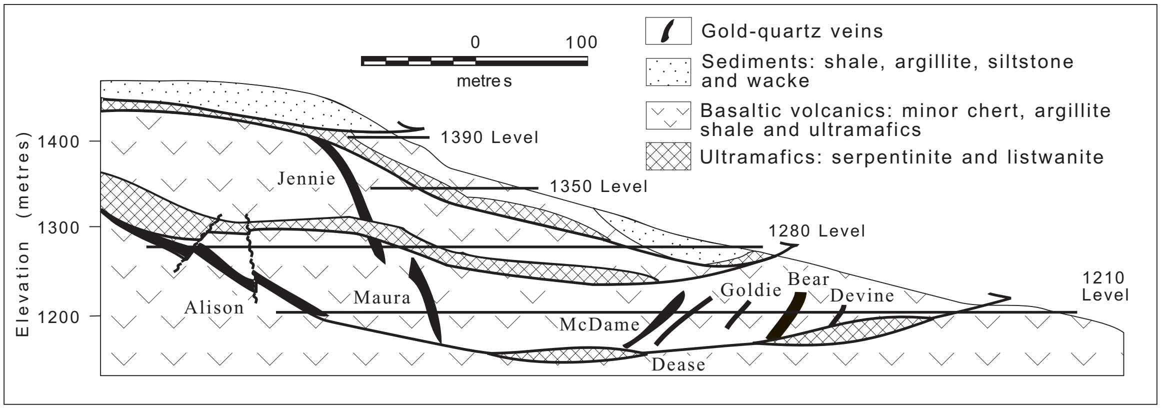


Figure 7.4. Schematic cross-section of the Erickson mine compiled after Sketchley, 1986; Boronowski, 1988 and Anderson and Hodgson, 1989).

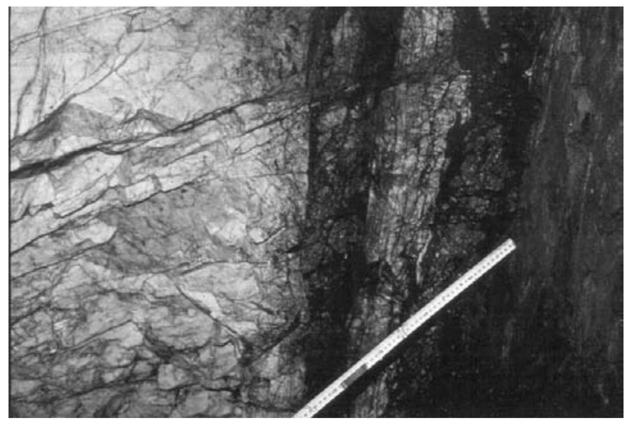


Photo 7.4. Massive bull quartz of the Jenni vein (photo courtesy of Joanne Nelson).

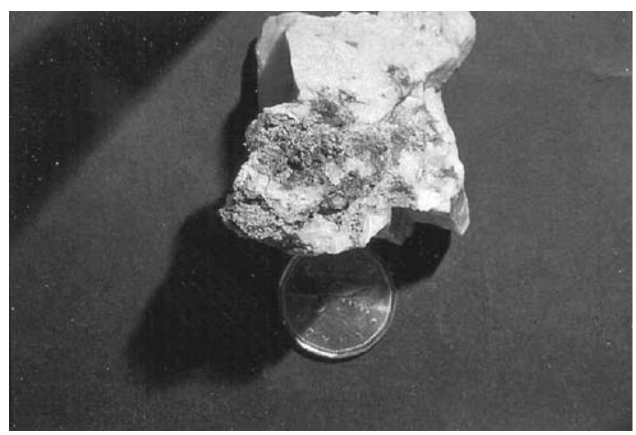


Photo 7.5 Native gold in quartz from the Eileen vein, Erickson mine (photo courtesy of Joanne Nelson).

tectonostratigraphic level to the north. Zus Mountain ultramafic rocks consist of plutonic and metamorphic lithologies representative of an ophiolitic crust-mantle transitional suite. It has been argued (Anderson and Hodgson, 1989; Nelson and Bradford, 1993) that the Cassiar vein deposits, although fitting the overall classification for mesothermal veins in terms of morphology, mineralogy and alteration characteristics, are unique because they lack evidence of an association with a deep crustal fault. We contend that the presence of ophiolitic crustal and upper mantle lithologies within the zone of mineralization implies that it was part of a deeply rooted, through-going crustal fault, during and most likely subsequent to, obduction of the Sylvester allochthon.

Gold-bearing veins are commonly white crystalline quartz (Photo 7.4) with locally laminated, ribboned and brecciated textures. They pinch and swell along strike and are typically 1 to 2 metres wide but locally can be up to several metres in width. Productive veins are commonly from 100 to several hundred metres in strike length, with the Vollaug and the Elan veins having persistent strike lengths of 2600 and 1500 metres, respectively. Down-dip extent of the veins vary from several tens to several hundreds of metres. Most trend easterly with minor deviations. Differences in both structural style and hostrock lithology have led to a twofold subdivision of the vein system (Panteleyev and Diakow, 1982; Boronowski, 1988). Tensional veins (Type 1 veins of Panteleyev and Diakow, or steeply dipping veins of Boronowski) occupy steeply-dipping dilational fractures in sheared metabasalt and are typically truncated by the low-angle thrust faults. These are the most common and economically the most significant vein type. Fissure veins (Type 2 veins of Panteleyev and Diakow, or gently dipping veins of Boronowski) occur along the low-angle thrust faults in association with listwanite-altered ultramafic rocks and hangingwall argillites in the upper part of the thrust zone.

The following description of the vein mineralization is taken primarily from references cited at the beginning of this chapter. Gold was the primary metal recovered in the camp, with silver as a significant byproduct, although it was the dominant precious metal derived from tetrahedrite in some veins. A variety of mineralization styles are evident. Gold is most common as free gold in quartz or along graphitic or micaceous fractures but a significant amount also occurs as either fracture fillings or disseminated blebs within sulphide grains. Sulphides are generally disseminated and comprise from 1 to 3% of vein material, locally increasing to 5 to 10%. Pyrite is the dominant sulphide and is usually associated with tetrahedrite, sphalerite, chalcopyrite and lesser galena and arsenopyrite. In type 1 veins, gold is most commonly found associated with pyrite and vuggy quartz whereas gold within ribboned quartz; is dominant in type 2 veins.

Wallrocks are pervasively carbonatized with variable sericite and pyrite alteration. Metabasaltic rocks hosting the type 1 veins display relatively uniform alteration envelopes, from 1 to 15 metres wide depending on vein width. Sketchley (1986) identified ankerite, siderite, dolomite, quartz, sericite, kaolinite, pyrite, carbon and minor titanium oxides from the alteration assemblage in the metabasaltic rocks. Carbonatization of ultramafic rocks is most commonly manifest as schistose talc-serpentinite, talc-carbonate and quartz-carbonate-mariposite alteration assemblages (listwanite suite, Appendix III). The dominant hydrothermal carbonate is iron-rich-magnesite. Locally, throughout the listwanite, abundances of schistose mariposite-quartz-sulphide rock, with subordinate carbonate, produce visually striking, bright-green exposures.

Studies of primary fluid inclusions in quartz veins indicate that the mineralizing fluids were moderately saline and rich in carbon dioxide, with homogenization temperatures ranging from 250° to 300°C (Hopper, 1984; Dursell, 1986; Nelson, 1990). By using an arbitrary load pressure of 6300 kilopascals, Dussell calculated an entrapment temperature of 350°C. He proposed that gold was transported as a gold bisulphide complex $Au(HS)^2$ with deposition triggered either by decreasing sulphur and oxygen or increasing iron activity or some combination of these mechanisms, all of which relate to fluid-wallrock reactions and fluid degassing.

AGE OF GOLD MINERALIZATION

The age of mineralization for the Cassiar gold veins has been traditionally interpreted at 130 Ma (Panteleyev, 1985; Sketchley, 1986), the mean apparent age of potassium-argon isotopic analysis of hydrothermal sericites that range between 115 and 137 Ma (Figure 7.3). A number of recent Ar-Ar isotopic age determinations on similar hydrothermal sericites from throughout the camp (A. Panteleyev, personal communication) indicate that the age is slightly older than initially interpreted. Six samples of hydrothermal sericite were dated (Layer and Drake, 1997). Four of the dated samples have well defined plateaus with only slight amounts of Ar loss and identical ages between 133 and 135 Ma indicating an age of mineralization at *ca*. 134 Ma. The two other samples were slightly to significantly older than the 134 Ma age, however those samples showed evidence of Ar loss with less well defined plateaus (Layer and Drake, 1997).

Additionally a quartz vein sample with sericite from the Quartzrock Creek area was provided by Andre Panteleyev and dated as part of this study (Appendix II). The age spectrum for this sample (Figure 7.5) has a steep gradient; apparent ages increase rapidly from approximately 100 Ma to approximately 132 to 136 Ma. A plateau age of 132 to 136 for the last 8 steps is clearly consistent with a 134 Ma mineralization age indicated above.

A sample of carbonatized ultramafic rock with abundant mariposite collected from a trench exposure of listwanite marginal to the Eileen vein was analyzed by conventional K-Ar methods at The University of British Co-

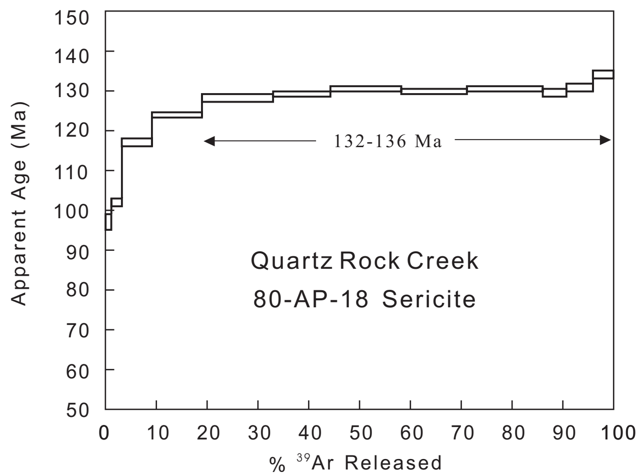


Figure 7.5. Ar-Ar age spectra plot for sericite in quartz vein from the Quartz rock Creek area.

lumbia. The mariposite yielded an apparent K-Ar age of 52.6 ±2.1 Ma. This age is significantly different fron the ca. 134 Ma mineralization ages defined by hydrothermal sericites, and so probably reflects resetting by a later thermal event perhaps related to intrusion of the Mount Haskin and Mount Reed stocks which are coeval with the K-Ar mariposite age (Figure 7.3). This suggests that fault zones within the Sylvester allochthon were reactivated during the Early Tertiary and channeled fluids that either deposited new micas, or reset pre-existing vein micas.

RELATIONSHIP TO MAGMATISM

In contrast to gold-quartz vein mineralization described previously, there is no defined magmatic episode coeval with vein mineralization in the Cassiar camp. Nelson (1990) presented two indirect lines of evidence to suggest that a pluton might be present at depth. An actinolite-epidote metamorphic assemblage within metabasaltic rocks, that defines a broad zone consistent with the distribution of the vein system, is interpreted by Nelson to result from contact metamorphism related to an underlying intrusion. Its existence was indirectly supported by the presence of granodioritic inclusions in a lamprophyre dike. An Ar-Ar age determination on hornblende from these clasts produced a well defined plateau at 76.4 Ma, suggesting that the inclusions may be related to the Troutline Creek Stock. A similar lamprophyre dike elsewhere which cuts the ophiolitic assemblage rocks (A. Panteleyev, personal communication, 1991) returned a biotite K-Ar date of 110±8.0 Ma suggesting that there are two distinct episodes of lamprophyre diking.

It is possible that there are earlier, cryptic phases of the Cassiar Batholith coeval with vein mineralization that are currently unrecognized. The Sierra Nevada Batholith which is associated with the Mother Lode belt in California provides a possible analogy. Both these gold camps are in accreted oceanic terranes spatially associated with, and locally intruded by, large composite batholiths. Although the bulk of the Sierra Nevada Batholith is late Cretaceous in age it also includes Early Jurassic phases that were only detectable by U-Pb dating of zircon. All K-Ar systematics of older phases of the intrusion were effectively reset by the latest and dominant magmatic event. More detailed evaluation of the various phases of the pluton by U-Pb dating may constrain the possibility of a similar relationship in the Cassiar Batholith.

SUMMARY

- Gold-quartz vein mineralization in the Cassiar camp is hosted almost exclusively by ophiolitic crustal volcanic, hypabyssal and mantle metamorphic rocks of the Sylvester ophiolitic assemblage along a terrane collisional suture zone. This suture is inferred by the presence of pervasively listwanite altered ultramafic rocks within the imbricated zone of vein mineralization thought to be derived from upper mantle lithosphere.
- The best developed veins in terms of thickness and continuity are hosted by competent mafic metabasaltic volcanic and hypabyssal rocks. Vein thickness and continuity is generally poorly developed in the ultramafic rocks. However the highest gold grades are found in quartz veins immediately adjacent to the listwanite-altered ultramafic rocks.
- Economic concentrations of gold are found only in the quartz veins or in peripheral fractures and highest values occur in the deformed parts of the veins associated with concentrations of sulphide minerals.
- The limited thickness of suitable ophiolitic gold quartz vein hostrocks within this regionally flat-lying imbricated sequence restricts the vertical extent of productive gold veins.
- Unlike other gold quartz vein camps described previously in this work there is no defined magmatic episode coeval with the gold-quartz mineralization. In addition, there has been no described spatial association between felsic dike rocks and gold quartz veins in any of the mined vein systems in the Cassiar camp.
- An early Cretaceous age of ca. 134 Ma is suggested by isotopic data of hydrothermal vein micas for the age of gold vein mineralization in the Cassiar camp.

CHAPTER 8
OTHER SIGNIFICANT GOLD-QUARTZ VEIN DEPOSITS, NORTH AMERICAN CORDILLERA

INTRODUCTION

Gold-quartz vein deposits of the famous Grass Valley, Mother Lode and Alleghany districts in northeastern California and the Alaska-Juneau deposit of the Juneau gold belt in southwestern Alaska (Figure 1.1) are discussed briefly to aid in the comparison with those in British Columbia. These U.S. deposits appear to have a similar origin and occur within a similar orogenic setting. They are also the most significant Cordilleran gold producers (Figure 8.1) and are commonly used and referred to as type examples for this class of Paleozoic gold-quartz vein deposit (Boyle, 1979; Kerrich and Wyman, 1990; Schroeter and Lane 1991; Goldfarb *et al*., 1998). More importantly, these include mines for which there is ample detailed description of the geological setting and character of the veins, published during active mining periods (Figure 1.3). This chapter emphasizes the lithotectonic setting and relevant geological history of the host terranes relative to the timing of gold-quartz vein mineralization. A more detailed examination of the character of the veins is given in Appendix III.

CALIFORNIA GOLD-QUARTZ VEINS

Total gold recovered from California gold deposits is estimated in excess of 100 million ounces[1], with sixty percent recovered from placers and the remainder from lodes (Clark, 1970). Peak annual production was almost 4 million troy ounces in 1852, less than five years after the initial discovery of placer gold at the edge of the South Fork of the American River at Sutter's Mill, Coloma, by John Marshall in 1848. In 1849, the year of the '49ers', more than 90 000 people made the journey to California's gold fields.

Significant lode-gold production from the belt was from three main regions that included the Grass Valley and Alleghany districts, and the Mother Lode belt (Figures 8.1 and 8.2). Although the Mother Lode gained the most notoriety and is often used to characterize these gold deposits, the Grass Valley district was the most productive gold-quartz vein mining district in both California and the North American Cordillera as a whole.

PREVIOUS WORK

Early descriptive works on the individual gold camps include those of Knopf (1929) for deposits along the Mother Lode belt; Lindgren (1896) and Johnston (1940) for Grass Valley; and Ferguson and Gannett (1932) for Alleghany deposits. Clark (1970) and Albers (1981) presented summaries of the production and setting of the California gold quartz vein deposits. Recent, detailed studies have focused in large part on the Alleghany District and emphasize hydrothermal fluid and alteration characteristics of the vein systems (Coveney, 1981; Wittkopp, 1983; Böhlke and McKee, 1984; Böhlke, 1988, 1989; Böhlke and Irwin, 1992). Landefeld and Silberman (1987) and Landefeld (1988) described the lithotectonic setting of gold veins along the Mother Lode Belt relative to the ages of magmatism and mineralization. Böhlke and Kistler (1986) and Weir and Kerrick (1987) summarize fluid characteristics and mineralization ages for most of the significant gold camps. A recent overview of California gold vein deposits is presented by Bohlke (1999).

The Sierra Nevada metamorphic belt is one of the most intensely studied areas of oceanic terrane rocks within the North America Cordillera. The ophiolitic character and tectonic history of these rocks has been recognized for some time (Moores, 1970; Irwin, 1977; Saleeby, 1982) and has become relatively well established (Edelman and Sharp, 1989; Dilek, *et al.*, 1990; Edelman, 1990; Saleeby, 1990, 1992; Saleeby and Busby Spera, 1992). Interpretations regarding overall plate tectonic construction, however, remain a matter of debate (Dickson *et al*., 1996; Saleeby, 1999).

REGIONAL GEOLOGICAL SETTING

Gold-quartz vein deposits of California are mainly within the Sierra segment of the Western Sierra-Klamath belt (Saleeby and Busby-Spera, 1992) (Figure 8.2 and inset map). The belt consists of highly disrupted late Paleozoic marine sedimentary and ophiolitic rocks interleaved with early and late Mesozoic submarine volcanic-arc and basinal terranes (Saleeby, 1990, 1992; Saleeby and Busby-Spera, 1992). The eastern faulted margin of the belt is referred to as the Foothills Suture (Saleeby, 1982), which separates rocks of oceanic origin to the west from those of continental margin affinity to the east (Figure 8.2).

Continental margin rocks are assigned to the Northern Sierra Terrane and consist of the latest Proterozoic to Silurian Shoo Fly Complex which is unconformably overlain by a near-continuous, Late Devonian to Middle Jurassic succession of predominantly volcanogenic strata (Edelman and Sharp, 1989). The Shoo Fly Complex is an internally deformed and imbricated, southwest-verging thrust sequence of mainly Ordovician to Silurian metamorphosed sandstone, siltstone and shale. It is considered as continental

1 Böhlke (1999) indicates total estimated gold production for California to 1995 is on the order of 115 million ounces.

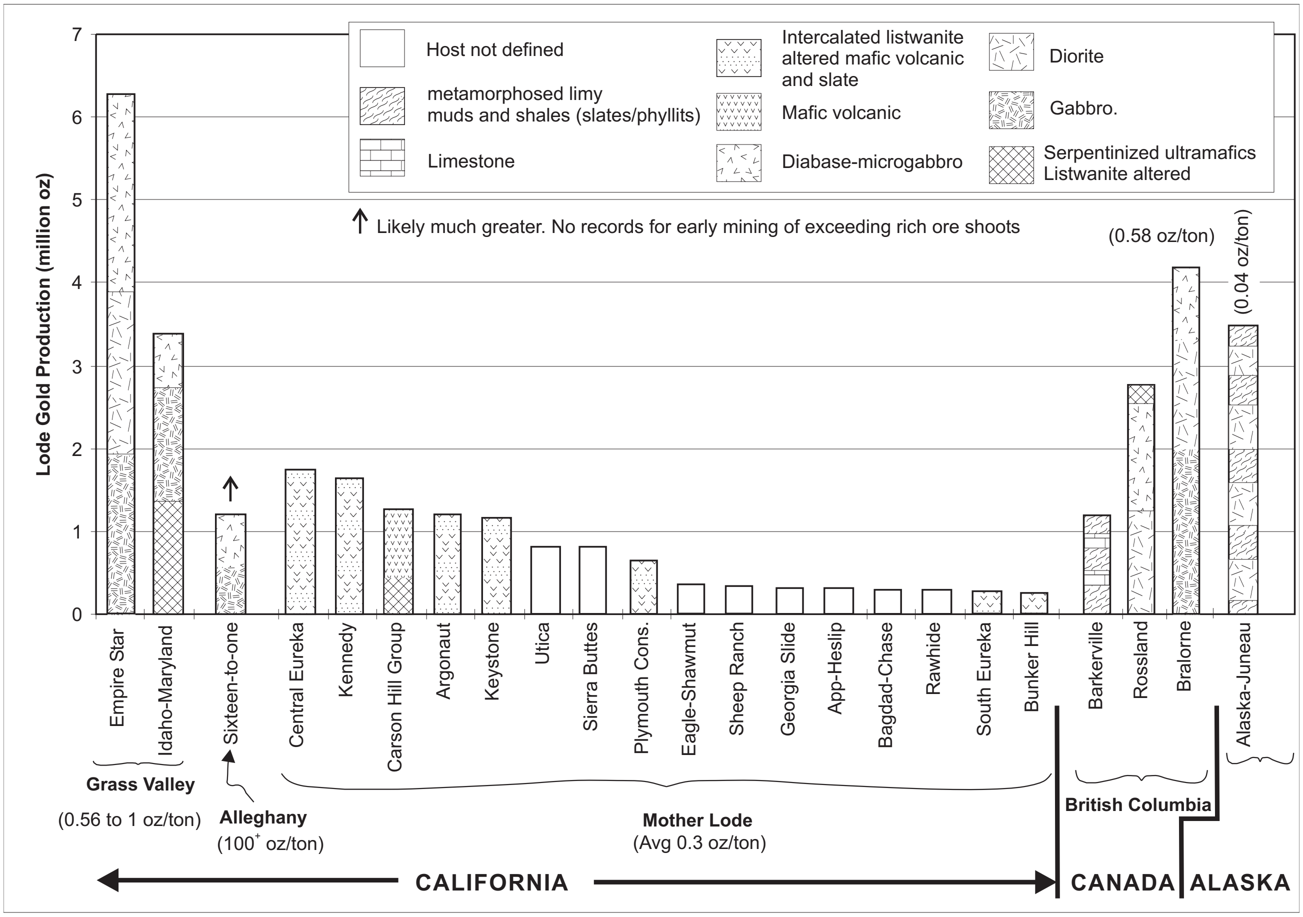


Figure 8.1. Significant gold-quartz vein producing mines of California compared to other significant North America Cordilleran gold producers. Data sources for the areas indicated are: California deposits (Clark, 1970), Bralorne-Pioneer mine (Leitch, 1990), Alaska-Juneau (Fredericksen and Miller, 1989), Barkervill and Rossland (Schroeter and Lane, 1991). Production figures for California converts the dollar value to ounces using a value of $20.67 US per ounce. Production figures given in all cases are estimates. In many instances complete production records do not exist. Individual mines are indicated for California deposits, whereas gold production for all other camps includes all mines and are therefore not directly comparable.

slope-and-rise strata built outboard of the ancient North American miogeocline. The Sierra City mélange forms the structurally highest thrust sheet of the complex and includes blocks of serpentinized peridotite, gabbro, massive and pillowed basalt, chert, limestone and sandstone within a sheared sedimentary matrix (Saleeby, 1992). Plagiogranite from the mélange with a Late Precambrian age (U-Pb, 600±10 Ma), suggests that it is part of a disrupted vestige of an ophiolite sequence. It is interpreted as basement for continental rise strata deposited off the ancient passive margin (Saleeby, 1990). Three major unconformity-bounded sequences of Late Devonian-Pennsylvanian, Permian, and Late Triassic to Middle Jurassic ages are recognized within the overlying volcanic strata (Edelman and Sharp, 1989).

In the predominantly oceanic Western Sierra belt three distinctive lithotectonic elements are recognized (Saleeby, 1990), each hosting significant gold vein deposits. These include from oldest to youngest (Figure 8.3):

(1) A highly disrupted basement framework consisting of; a) late Paleozoic abyssal ophiolitic fragments; b) chaotic late Paleozoic to early Mesozoic chert-argillite deposits; c) subordinate late Paleozoic Tethyan-affinity limestone with associated blocks of mafic alkali basalt and; d) sporadic Triassic blueschist slabs and blocks.

Within this lithotectonic framework gold-quartz vein deposits appear to be preferentially associated with ophiolitic rocks, for example; in the Alleghany district along the Feather River belt, as well as those in the central Mother Lode along the Tuolumne belt.

Chaotic chert-argillite deposits, termed the Calaveras Complex form a fairly continuous belt along the length of the Sierra Nevada. Similar rocks are also found intercalated within ophiolitic rocks in the Tuolumne River belt. Similar to Cache Creek and Bridge River complexes in British Columbia , the chert-argillite units are typically devoid of gold-quartz vein deposits except near their contacts with ophiolitic rocks.

(2) Late Triassic to Early Jurassic submarine lava flow and pyroclastic sequences with overlying cherty, tuffaceous and epliclastic strata, or hypabyssal-plutonic complexes

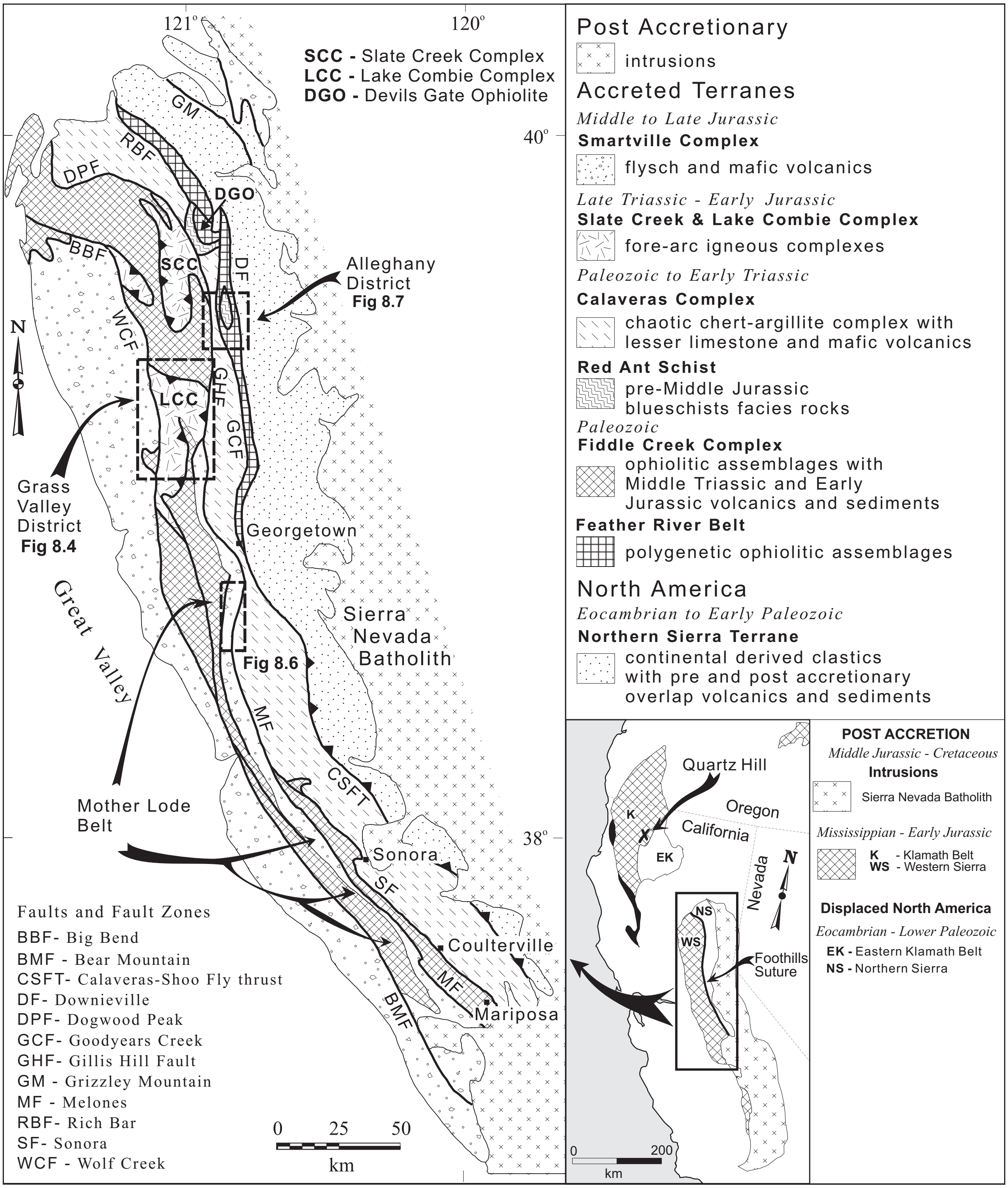


Figure 8.2. Geology and distribution of significant gold-quartz vein camps in the Western Sierra Nevada metamorphic belt, California. Compiled after Edelman and Sharp (1989).

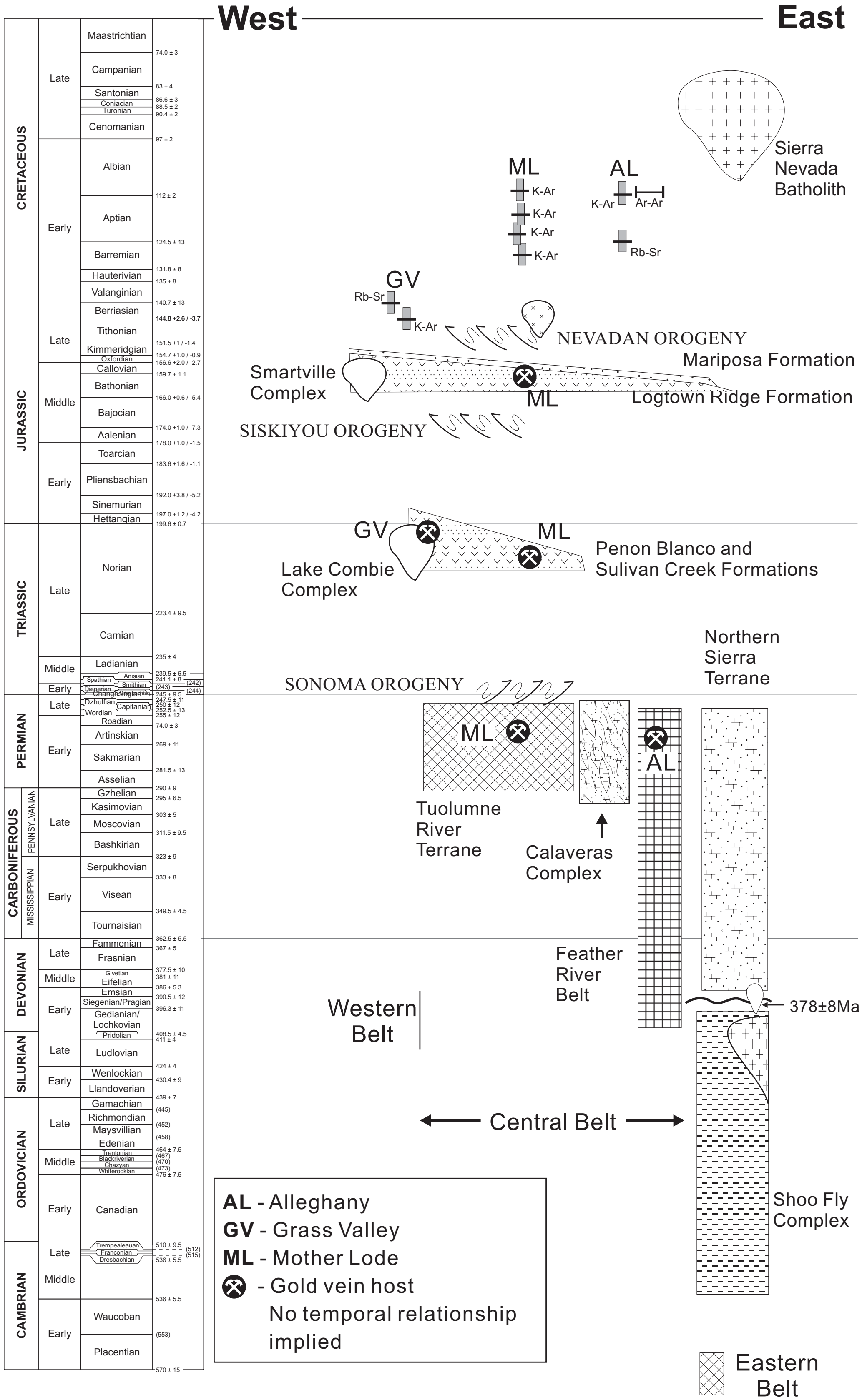


Figure 8.3. Relative age and tectonostratigraphic relationships for lithologies in the Western Sierra Nevada metamorphic belt. Age constraints for lithostratigraphic elements indicated are from Edelman and Sharp (1989), Edelman (1990) and Saleeby (1990, 1992). Isotopic age data for hydrothermal alteration are from Böhlke and Kistler (1986).

which intrude late Paleozoic ophiolitic basement rocks (Figure 8.3). These complexes are common in the Toulmune River belt and also act as basement for younger strata of the western belt. The bulk of the Grass Valley gold-quartz veins (Lake Combie complex), as well as some of those along the central and southern portions of the Mother Lode Belt in the Sullivan Creek and Penon Blanco Formations, are hosted by these tectono-stratigraphic elements.

(3) Middle-Late Jurassic (Callovian to Kimmeridgian) submarine mafic volcanic and slaty flysch sequences dominate the western margin of the belt (Western belt) where they are associated with coeval sheeted dike swarms and shallow-level intrusions, such as the Smartville ophiolite complex. Related sequences unconformably overly all older elements of the western Sierra and are interpreted to be depositionally linked, as a volcanic-sedimentary apron sequence and give the overall assemblage an ophiolitic character (Saleeby, 1990). Many of the significant producing lode gold deposits along the Mother lode belt are hosted by this tectono-stratigraphic element (*i.e*., Logtown Ridge and Mariposa Formations).

Early plate-tectonic interpretations of the origin of the Sierra belt postulate a number of discrete, exotic island-arcs which were accreted to the North American continental margin during the Late Jurassic Nevadian orogeny. These views have been supplanted (Edelman, 1990; Saleeby, 1990; 1992) by a scenario of tectonically disrupted, predominantly late Paleozoic ophiolitic rocks and chaotic chert-argillite deposits that formed an oceanic basement along the continental margin. This oceanic basement was disrupted by extensional fore-arc and possibly interarc basin development during the Late Triassic-Early Jurassic and again in the latest Middle Jurassic to early Late Jurassic. Both periods of constructional fore-arc basinal magmatism were followed by intervals of tectonism and related deformation during the Middle Jurassic Siskiyou orogeny, and again during the Latest Jurassic Nevadian orogeny. The main structural expression of the Nevadan orogeny was the eastward thrusting of the Smartville complex onto the Central belt, followed by high-angle reverse faulting, folding and cleavage development in the Mariposa flysch (Edelman and Sharp., 1989; Saleeby, 1982, 1990).

The post-Nevadian, Sierra Nevada batholith intrudes the Sierra Nevada metamorphic belt along its eastern margin. It is interpreted to be the roots of a Late Jurassic and Cretaceous magmatic arc related to eastward subduction of oceanic lithosphere, which generated the Franciscan subduction complex on the west. The timing of Sierran plutonism appears to have been episodic. An interval of post-Nevadan magmatism in the Late Jurassic, between 150 and 140 Ma, was followed by a lull in magmatic activity from 140 and 120 Ma, with renewed activity in the Cretaceous between 120 and 80 Ma. The earlier 150 to 140 Ma event is characterized by small intrusive bodies and high level dikes and sills throughout much of the Sierra Nevada Metamorphic belt. The younger intrusive activity produced the bulk of the batholith.

GRASS VALLEY

Grass Valley was the most prolific lode-mining district in California, producing close to 300 000 kilograms (10 million ounces) of gold from roughly 20 square kilometres (Figures 8.4 and 8.5). Gold was discovered in 1850 and apart from a shutdown during World War II, the district operated almost continuously until 1956, ending close to 106 years of mining (Clark, 1970).

Gold veins of the Grass Valley are hosted primarily within fissures cutting both the Lake Combie igneous complex and a younger (?) quartz monzodiorite to granodioritic intrusive body, the La Barr Meadows pluton (Tuminas, 1983). The Lake Combie complex is a fault-bounded, pseudostratigraphic sequence of serpentinized, foliated harzburgite, dunite and pyroxenite that is intruded and structurally overlain by a mafic igneous sequence of plutonic, hypabyssal and volcanic rocks (Tuminas, 1983; Day *et al*., 1985). Plutonic rocks range from gabbro to quartz diorite and grade upward through a sheeted zone into massive diabase. It is overlain in turn by a thick (>5km) sequence of mafic to intermediate volcanic rocks, followed by volcaniclastic and finally epiclastic sediments. The age of the complex has not been determined but a comparable pseudostratigraphic sequence with similar structural relationships occurs within the well dated latest Triassic to earliest Jurassic (210-200 Ma) Slate Creek complex to the north (Figure 8.1) and suggests a correlative age for the Lake Combie complex (Dilek *et al*., 1990; Edelman and Sharp, 1989; Edelman, 1990).

These volcano-plutonic igneous sequences are considered as suprasubduction zone ophiolite-transitional arc complexes developed during a period of incipient fore-arc rifting during the Late Triassic. This produced narrow oceanic basins in the Paleozoic basement rocks (Dilek *et al*., 1990; Saleeby, 1990). Subsequent Middle Jurassic orogenic activity (Siskiyou orogeny) resulted in west-vergent imbrication of these extensional fore-arc sequences and their ophiolitic mélange basement rocks. A 168 Ma pluton cuts the basal thrust fault of the Slate Creek complex and places an upper limit on the timing of tectonic emplacement of the igneous complex onto deformed Paleozoic oceanic basement (Saleeby, 1990).

The La Barr Meadows pluton (Tuminas, 1983) is a granodiorite to quartz monzodiorite intrusion, which underlies and extends south from the town of Grass Valley and also in part hosts many of the significant gold-quartz veins (Figures 8.4 and 8.5). This intrusion has been consistently interpreted to be a post-orogenic stock of the Sierra Nevada Batholith (Lingdren, 1896; Johnston, 1940; Clark, 1970; Boyle, 1979; Hutchinson and Albers, 1992).

Such an association in which post-orogenic intrusions are host to gold quartz veins is clearly inconsistent with the setting of gold veins in all other camps described previously. In all other cases the main plutonic rocks hosting gold-quartz veins are older accreted tectonic blocks or slivers of oceanic-transitional arc crust. Association of gold quartz veins with coeval, late syn-orogenic, high-level intrusions is not uncommon, but in such cases veins are proxi-

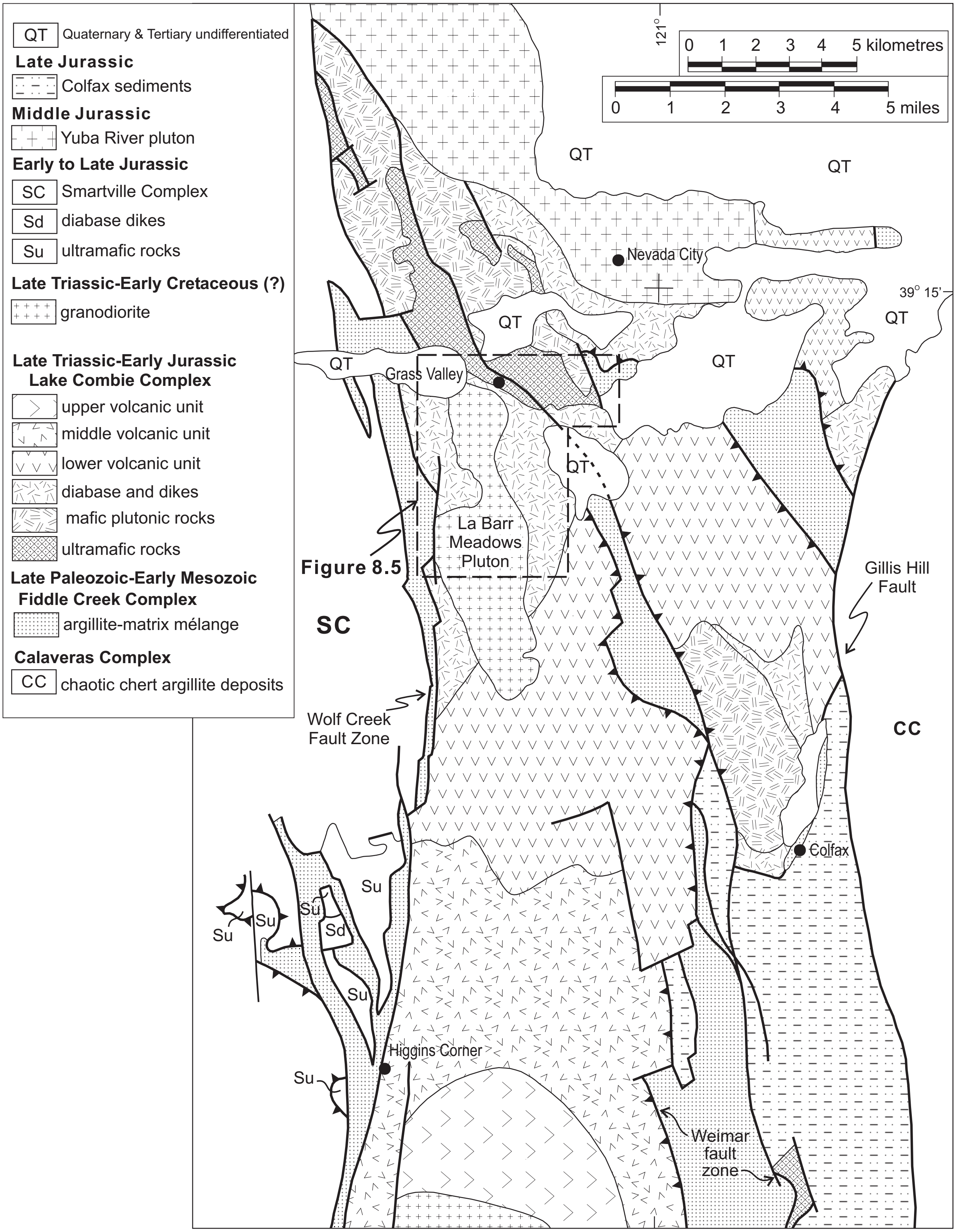


Figure 8.4 Geology of the Grass Valley - Colfax area depicting regional setting of the Grass Valley district (after Day *et al*., 1985 with updates to legend from Dilek *et al*., 1990 and Edelman, 1990).

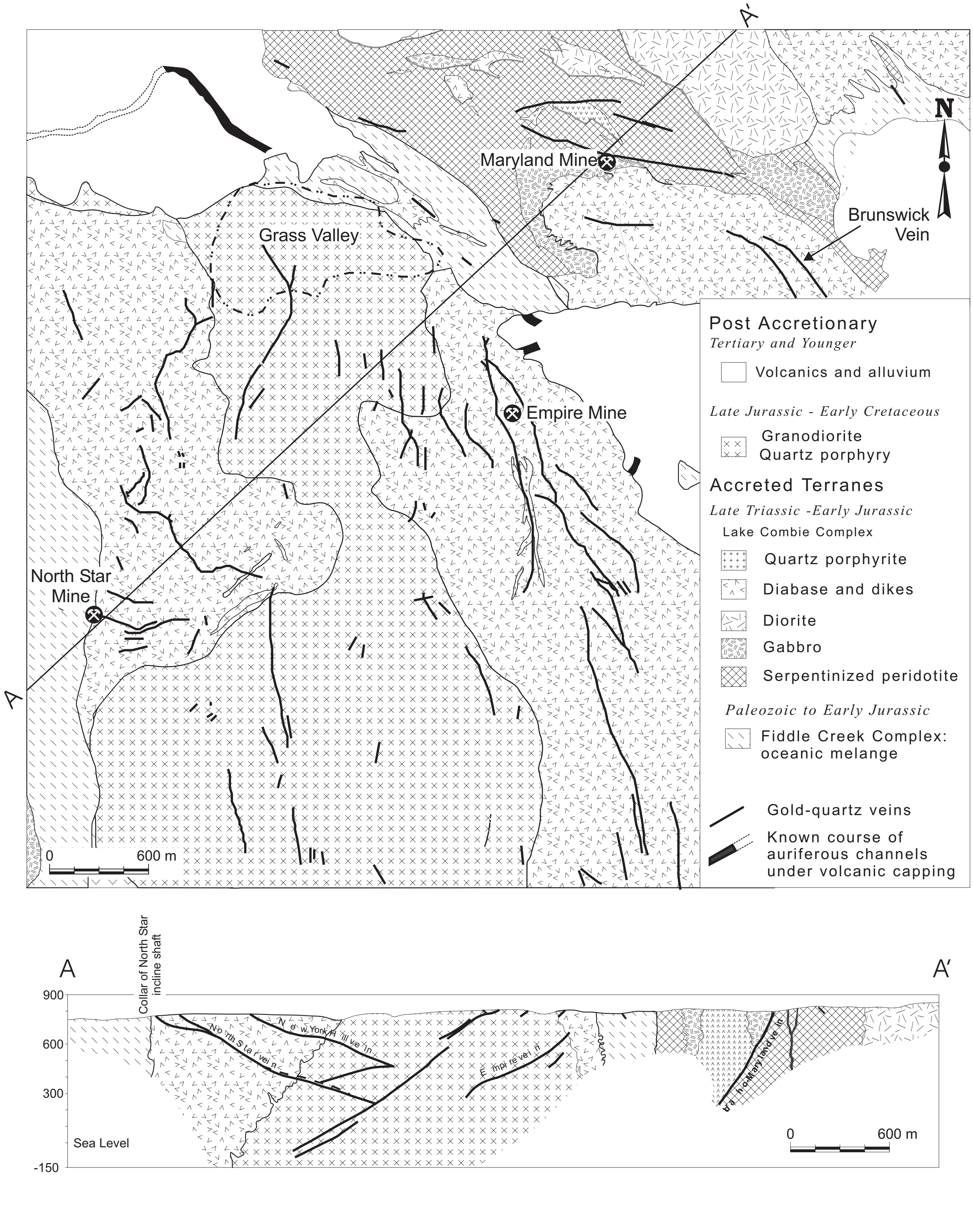


Figure 8.5. Geology of the Grass Valley district after Johnston (1940) with revised legend using data from Day *et al.* (1985), Edelman and Sharp (1989) and Edelman (1990).

mal to or co-structural with the intrusions and are not prominent host rocks.

Gold-quartz vein-bearing fissures cross-cut the intrusive contact of the La Barr Meadows Pluton with little, or no apparent offset (Johnston, 1940) suggesting that the mineralization is younger than the pluton.

The currently implied vein host rock relationship for Grass Valley implies that either the most productive gold quartz vein camp in the North American Cordillera is somehow lithotectonically distinct from all other similar deposit, or alternatively, as suggested following, the intrusion is not a post-orogenic stock of the Sierra Nevada Batholith.

The only existing isotopic age constraint for the La Barr Meadows pluton is a hornblende K-Ar date of 126.7±3 Ma on a sample collected from the Empire mine (Böhlke and Kistler,1986). Visual examination of a similar sample collected for U-Pb dating from the general area of the previously dated sample indicates that the rock is altered with both epidote and chlorite replacing plagioclase and hornblende respectively (J. Bohlke and J. Dilles, personal communication, 2000). This observation is consistent with that of Johnston (1940) who found that all samples of the pluton showed some degree of alteration of both the hornblende and plagioclase. The alteration affecting the dated sample suggests that the calculated K-Ar age might not reflect the magmatic cooling age of the pluton but may be more an artifact of subsequent thermal events.

If this is the case it eliminates the ambiguity of the isotopic K-Ar date of 143.7±4 Ma for hydrothermal mica (mariposite) from the Brunswick vein (Böhlke and Kistler, 1986), the only constraint for the timing of vein mineralization in the camp. This latest Jurassic apparent mineralization age is older than the previously inferred age of the pluton. Notably, the Brunswick vein is hosted entirely within diabase in the northeastern part of the Grass Valley camp roughly two kilometres from the pluton (Figure 8.3). The isotopic data suggests that either; a) there are two distinct ages of vein mineralization in the Grass Valley camp or, b) the interpreted age of 127 Ma for the La Barr Meadows pluton does not accurately reflect its cooling age. The general consistency of coeval ages of mineralization in the general region of mineralizarion for previously described camps argues against such a relationship.

Although an absolute age for the La Barr Meadows pluton is not available, detailed as well as regional geological considerations provide relative age constraints. Johnston (1940, page 15) identified detailed contact relationships between granodiorite and host hypabyssal rocks which suggested to him that the two were co-magmatic due to multiple intrusive relationship in which host diabase was seen to also intrude as dikes, the younger intrusion. He discounted this possibility in view of prevailing geological concepts at that time. In describing the contact relationship between the granodioritic rocks and the porphyritic diabase (his 'porphyrite') he states;

"The contact is remarkable for its sharpness and for lack of fine grained borders indicating chill or other contact phenomena. .... Dikes of intermediate composition cut the granodiorite, many of these dikes closely resemble the older diabase and porphyrites in texture and mineral composition."

He concludes (page 16);

" The similarity in mineral composition and texture between the porphyrite dikes that cut the granodiorite and the earlier pre-granodiorite porphyrite immediately suggests the existence of a single magmatic source for both rocks. It is very difficult, however, to postulate the independent existence of such a magmatic reservoir during the intrusion of the granodiorite."

Clearly his difficulty in accepting the observed relationships are a moot point in view of current plate tectonic concepts in which multiple intrusive contact relationships are a characteristic feature in the igneous genesis of volcano-plutonic arc/ophiolitic complexes.

From a regional geological standpoint there are several lines of evidence to support Johnston's (1940) initial contention that the intrusive-hypabyssal units are co-magmatic. The limits of the pluton are conspicuously constrained to within the Lake Combie complex and are for the most part within the massive diabasic portion (Day *et al*., 1985). Where not intrusive into the diabase or volcanic rocks of the Lake Combie complex, the pluton is cut by the bounding faults of the complex. This appears to be the case where in contact with Fiddle Creek Complex rocks (Dilek *et al*., 1990) along the northern edge of the Grass Valley town site (Johnston, 1940). It is also apparent along the western margin of the complex, where bordered by the Wolf Creek-Bear Mountain fault zone (Day *et al*., 1985). Further south this fault zone is cut by the by the Folsom-Aubrum dike swarm which is dated at 160 Ma (E.M. Moores, personal communication, 2000), suggesting significant movement along the fault was complete by that time. However, these dikes are foliated and have been affected by later deformation. This general relationship of bounding faults of the complex also cutting the pluton suggests both units were likely emplaced as a single tectonic entity onto the late Paleozoic basement.

It cannot be ruled out that the La Barr Meadows pluton could be coeval with the larger, north-trending Yuba Rivers pluton (158 ± 2 Ma; Saleeby *et al*., 1989) located several kilometres north of Grass Valley District (Figure 8.4).

It would seem that the most productive gold-quartz vein deposit in the North American Cordillera is worthy of modern day isotopic analysis to clarify existing age relationships between the plutonic host and mineralization. Such an exercise would be necessary to definitively compare this deposit to others discussed in this report.

MINERALIZATION

Gold from Grass Valley was obtained primarily from two vein systems, the Empire-Star and Idaho-Maryland groups (Figure 8.4 and 8.1). Gold-quartz veins at the Empire and North Star mines are hosted mainly by the La Barr Meadows pluton and its country rock, massive diabase. Most of the veins have a north to northwesterly strike with shallow to moderate dips (average 35^{o}); those on the west side of the pluton have prevailing dips to the east, while those on the east side have prominent dips to the west. Veins pass from diabase into granodiorite with little if any displacement at the contact. Most of these veins were observed to have remarkable persistence. The Empire vein, for example, extended over a strike length of 1.5 kilometres with a down dip extent of 2.1 kilometres and had an average gold content of 19.2 g/t (0.56 ounces/ton).

In contrast, the Eureka-Idaho-Maryland group of veins, northeast of the Grass Valley townsite, have a more easterly strike with steep southerly dips (average 70^o) although several veins dip at steep to moderate angles in the opposite direction. Veins in this group are better characterized as contact veins, as they occur primarily along highly ankerite altered faulted contacts that separate diabase and/or gabbro from serpentinite. The Idaho-Maryland vein contained one of the most famous ore shoots in which most of the gold was free and from which significant numbers of gold ore specimens were recovered (Johnston, 1940). The width of the ore shoot was on average 0.8 metres but in places was up to 2.5 metres wide. The ore shoot had a pitch length of 1.6 kilometres and a width of 150 to 300 metres with an average gold content of 34.3 g/t (1 ounce/ton).

MOTHER LODE GOLD BELT

The Mother Lode (from the Spanish 'veta madre') is a narrow, 1 to 1.5 kilometre wide, semi-continuous belt of gold deposits that extends over 190 kilometres from Georgetown in the north to Mariposa at its southern terminus (Knopf, 1929; Landefeld, 1988; Figure 8.2). Host rocks for gold-veins along the belt are varied. In the northern portion they are dominated by mafic volcanic rocks and black slate, whereas in the central portion they are predominantly greenschists and serpentinite, and in the southern segment are again dominated by mafic volcanic rocks and slate.

The majority of significant, producing gold-quartz vein deposits in the Mother Lode are in the north-central portion of the belt along a 16 kilometre stretch between Jackson and Plymouth (Figures 8.1, 8.2 and 8.6). Both the Central Eureka and Kennedy mines produced in excess of 46 500 kilograms (1.5 million ounces) gold with the Argonaut and Keystone each producing over a million ounces. Veins along this portion of the belt are hosted in a moderate to steeply east-dipping shear zone considered a splay of the Melones fault. The vein-hosting fissure zone cuts at an acute angle across a sequence of steep, easterly dipping, alternating 60 to 200 metre thick intervals of mafic volcanics and black slate. These units are part of relatively intact Callovian to Kimmeridgian (late-Middle and to middle-Late Jurassic) submarine mafic volcanic and slaty flysch sequences referred to as the Mother Lode Terrane by Graymer and Jones (1994). This Terrane consists of a lower stratigraphic succession with Callovian basaltic sandstone and argillites, overlain by Callovian to Oxfordian basaltic to andesitic clinopyroxene phyric breccias and tuffs of the Logtown Ridge Formation. These are overlain, in turn, by Oxfordian to Kimmeridgian slates and conglomerates of the Mariposa Formation. This Jurassic volcano-sedimentary succession was deposited on a composite basement of previously accreted and deformed late Paleozoic oceanic rocks and early Mesozoic fore-arc basinal sequences (Saleeby, 1990).

Gold-quartz veins within these various units occur most commonly at the stratigraphic and interfingering contact between the volcanic-dominated Logtown Ridge Formation and the overlying sediment dominated-Mariposa Formation.

The Carson Hill mine situated roughly 30 kilometres south of Jackson is the only other mine along the Mother Lode to produce in excess of one million ounces gold that is not along the gold rich portion of the belt between Jackson and Plymouth (Clark, 1970, Figure 8.1). The mine was noted for its high-grade pockets of gold ore and is hosted by highly disrupted late Paleozoic ophiolitic basement and younger basinal rocks. Carson Hill had a very rich, near surface deposit, which produced close to 4.5 tonnes (145 000 ounces; reported as $3 000 000), in its first two years of mining around 1850. In 1854 the mine produced the largest piece of gold ever found in California weighing 72.8 kilograms (2340 troy ounces, Knopf, 1929). High-grade gold ore was obtained largely from the steeply-dipping Bull vein where it intersected a number of flat-lying shear veins. The geology of Carson Hill is described as the most complex of the entire Mother Lode belt. Rock types include black phyllite, augite tuffs and breccias, chlorite and amphibolite schists, serpentinite (talc and mariposite schists) and gabbro. Vein hostrocks vary from massive ankerite rock to well-banded sericite-ankerite schist with mariposite-ankerite rock occurring in considerable quantity in the footwall schists of the Bull vein. Knopf (1929) reported that the combined underground workings of the Morgan and Melones mines on Carson Hill, which extended to a depth of nearly 1.5 kilometres, total more than 25 kilometres.

MINERALIZATION

Knopf (1929) characterized the ores of the Mother Lode belt as being of low to moderate grade with an average grade of 10.3g/t gold (0.3 ounces/ton; reported as $7.00 US). In addition to the typical quartz vein ore containing free gold (see Appendix III), a considerable amount of gold was recovered from disseminated sulphides in hydrothermally altered mafic igneous host rocks. Knopf (1929) applied the term 'grey ore' to the ankeritized greenstone with minor sericite and sulphides, which carried sufficient gold to warrant mining. This type of mineralization constituted the bulk of the gold resources in some of the more famous mines. 'Grey ore' was the mainstay at the Keystone mine, which is renowned for its longevity, operating almost continuously from 1852 to 1920. The prevalence of sulphide replacement ore along the Mother Lode belt, compared to most other gold vein deposits described from the Cordillera, may be due to enhanced permeability resulting from the primary brecciated character of the mafic volcanic host rocks.

Knopf (1929) described many of the `grey ore' shoots as large, valuable bodies. The largest at the Fredmont mine, for example, formed at the wedge end of a mass of greenstone that lay between two converging fissures. The orebody was 90 metres long by 5 to 20 metres wide (average 12 metres) and up to 100 metres down dip. The localization of such orebodies at the wedge end of greenstone between converging veins was noted as a common controlling feature. Grey ore contains from 3 to 6% sulphides consisting of

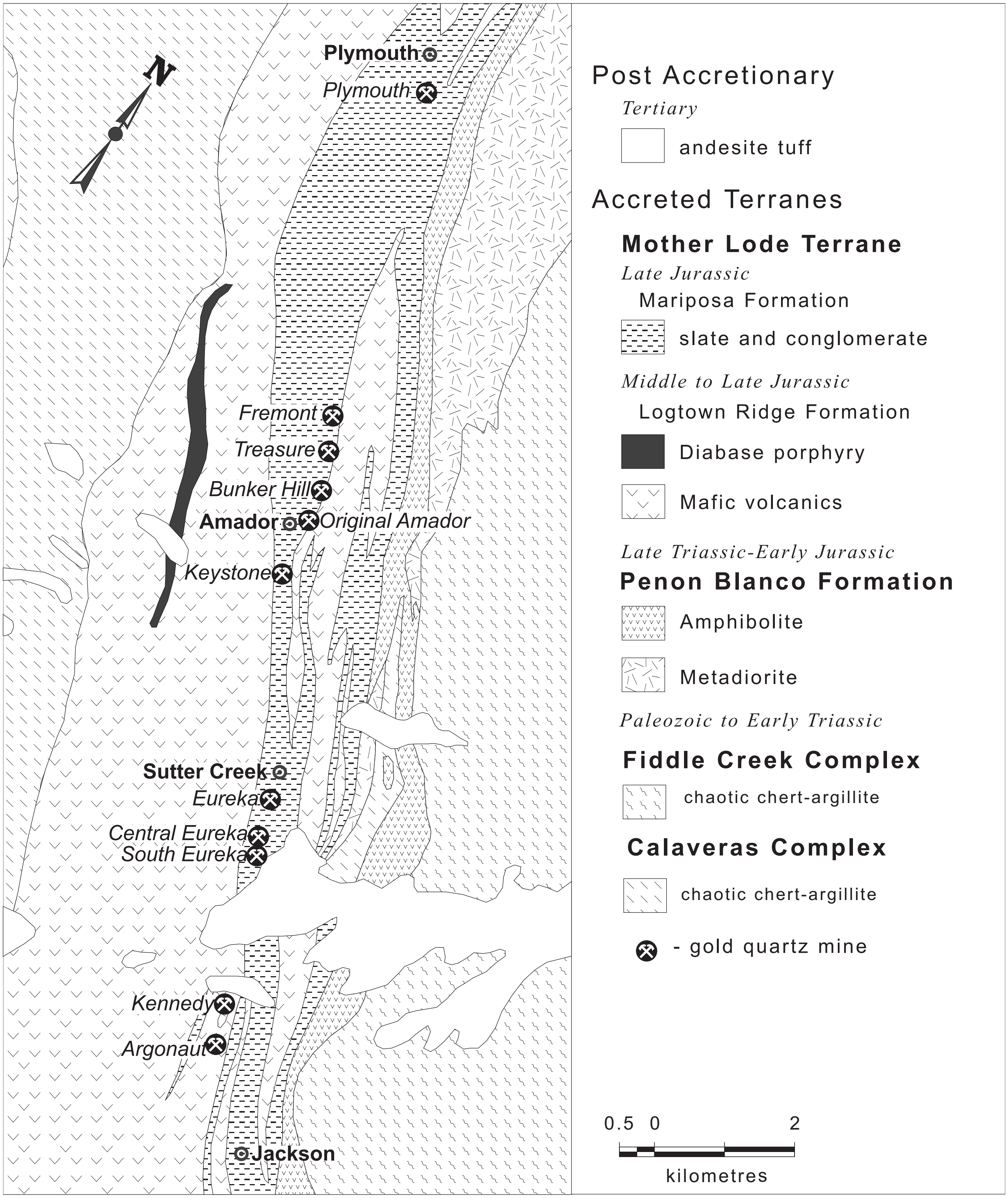


Figure 8.6. Geology of the Mother Lode belt between Jackson and Plymouth after Knopf (1929, Figure 3) with revised legend using data from Graymer and Jones (1994).

pyrite and arsenopyrite within carbonate and sericite-altered host rocks commonly traversed by veinlets of quartz containing ankerite and albite. The gold content of the grey ore is reported to be spotty but is as much 35 g/t, with some large bodies containing an average 10.3 to 13.7 g/t (0.3 to 0.4 ounces/ton) or more. The gold value of such ore could not be estimated on inspection, even by the most experienced miners. In some instances, quartz veins adjacent to the grey-ore were devoid of gold.

ALLEGHANY DISTRICT

The Alleghany camp in the northeastern Sierra Nevada (Figure 8.2 and 8.7) is the most famous gold-mining district of California. It differs from other gold vein districts in that nearly all production was from small shoots with very rich ore; little was obtained from lower grade ore characteristic of most other camps (Ferguson and Gannett, 1932). As a rule, the high-grade shoots carried from 3 kilograms per tonne (~100 oz/ton) in free gold and often exceeded many times that amount. The largest ore shoot in the Sixteen to One mine, for example yielded nearly 1370 kilograms (44 000 ounces) from an area less than 12 metres-square from 60 centimetres of quartz next to the hanging wall.

Lode mining started in 1852 but continuous production did not begin until 1904. The most productive vein system, the Sixteen to One (Figure 8.1 and 8.7) was mined for a total of 60 years prior to its closure in 1965 (Clark, 1970). This was the last lode mine to close that had been operated in the state of California on a sustained basis. Ironically it was in that same year that gold was designated as the official state mineral. Alleghany is recognized as the only town in California in which gold mining was the principal sector of the economy following World War II.

GEOLOGICAL SETTING

Gold-quartz veins of the Alleghany district occur west of the terrane-bounding Foothills suture within the ophiolitic Feather River Belt (Figure 8.2). This is a fault-bounded linear zone from 2 to 10 kilometres wide that extends southward for close to 150 kilometres from the northern end of the Sierra Nevada metamorphic belt (Saleeby, 1990). The Feather River belt contains harzburgite and lherzolite tectonite, dunite and pyroxenite, layered and massive gabbro and amphibolite that range from middle to late Paleozoic (Edelman and Sharp, 1989; Edelman, 1990; Saleeby *et al*., 1989; Saleeby, 1990; 1992). A relatively coherent Carboniferous ophiolite crustal sequence of massive gabbro, sheeted dikes, MORB pillow basalts and overlying metachert referred to as the Devils Gate ophiolite occurs along the west-central portion of the belt (Figure 8.2). The concurrence of mantle and crustal components suggests the remnants of a polygenetic ophiolite.

The geology of the Alleghany district comprises a number of panels of predominantly mafic igneous rocks separated by north-trending fault zones marked by tabular bodies or lenses of serpentinite (Ferguson and Gannett, 1932; Böhlke and McKee, 1984). The amphibolite and metagabbro protoliths consist mainly of a mafic to intermediate volcanic-plutonic protolith assemblage with minor interbedded clastic sedimentary rocks that underwent Devonian or earlier ages of amphibloite-facies metamorphism (Saleeby, 1990). Some significant veins occur in a distinctive chaotic assemblage of quartz mica schist, metaclastic and metavolcanic rocks with blueschist-facies metamorphic minerals. The unit is referred to collectively as the Red Ant schist and is considered to be a remnant of an early Mesozoic subduction complex (Edelman, 1990). The majority of veins in the Alleghany district are hosted by mafic igneous rocks but are notably absent from the larger adjoining serpentinite bodies. The most significant vein system at the Sixteen to One mine (including the Tightner, Sixteen to One, Twenty one mines and the Rainbow extension) are hosted by the amphibolite of the Red Ant schist. Other significant mines such as Plumbago, Oriental, and Kenton have veins contained largely within a metagabbro-amphibolite unit. The amphibolite schist, where unaltered, contains roughly equal proportions of hornblende and plagioclase with a major element composition similar to tholeiitic basalt and the associated ultramafic rocks consist of variably serpentinized harzburgite tectonite (Bohlke, 1989).

Ferguson and Gannett (1932) indicate that there are two principal vein orientations within the Alleghany camp. Both vein sets strike between north and west with the principal producing and generally thicker veins having shallow easterly dips, whereas less important veins dip steeply to the west. The width on average of the productive veins ranges from 1.5 to 1.8 metres with considerable local variation. Thicker portions of the veins occur where dips change, veins flatten or bow upward, or else there is a sharp change in strike direction.

Another well-documented characteristic feature of the Alleghany district is the occurence of higher gold grades as veins approach serpentinite (Ferguson and Gannett, 1932; Coveney, 1981; Wittkop, 1983; Weir and Kerrick, 1987; Böhlke 1989). Maximum concentration of free gold are found in veins at or near their intersection with altered ultramafic rocks. Most of this gold occurs within 30 metres of serpentinite as native gold in veinlets and as blebs in arsenopyrite. At the Oriental mine Coveney (1981) noted that coarse-grained arsenopyrite occurs only near serpentinite and, if present, it generally carries appreciable gold values. As an example of the size and grade of the ore shoots Coveney (1981) indicates that the Oriental mine contained small (from less than 5 to 10 metre-long) ore shoots with average gold contents of 3.4 kg/t (100 ounces/ton).

AGE OF MINERALIZATION

Most of the existing isotopic data for the California gold-quartz vein deposits described above include K-Ar ages mainly on mariposite, and Rb-Sr age determinations on quartz or carbonate. This data is summarized by Böhlke and Kistler (1986) and in Figure 8.3. A single K-Ar age of 143.7±4 Ma on mariposite with a corresponding Rb-Sr age of 140.9±3 Ma on quartz from the Brunswick Mine are the only constraints for hydrothermal activity related to gold vein mineralization at Grass Valley. Along the southern por-

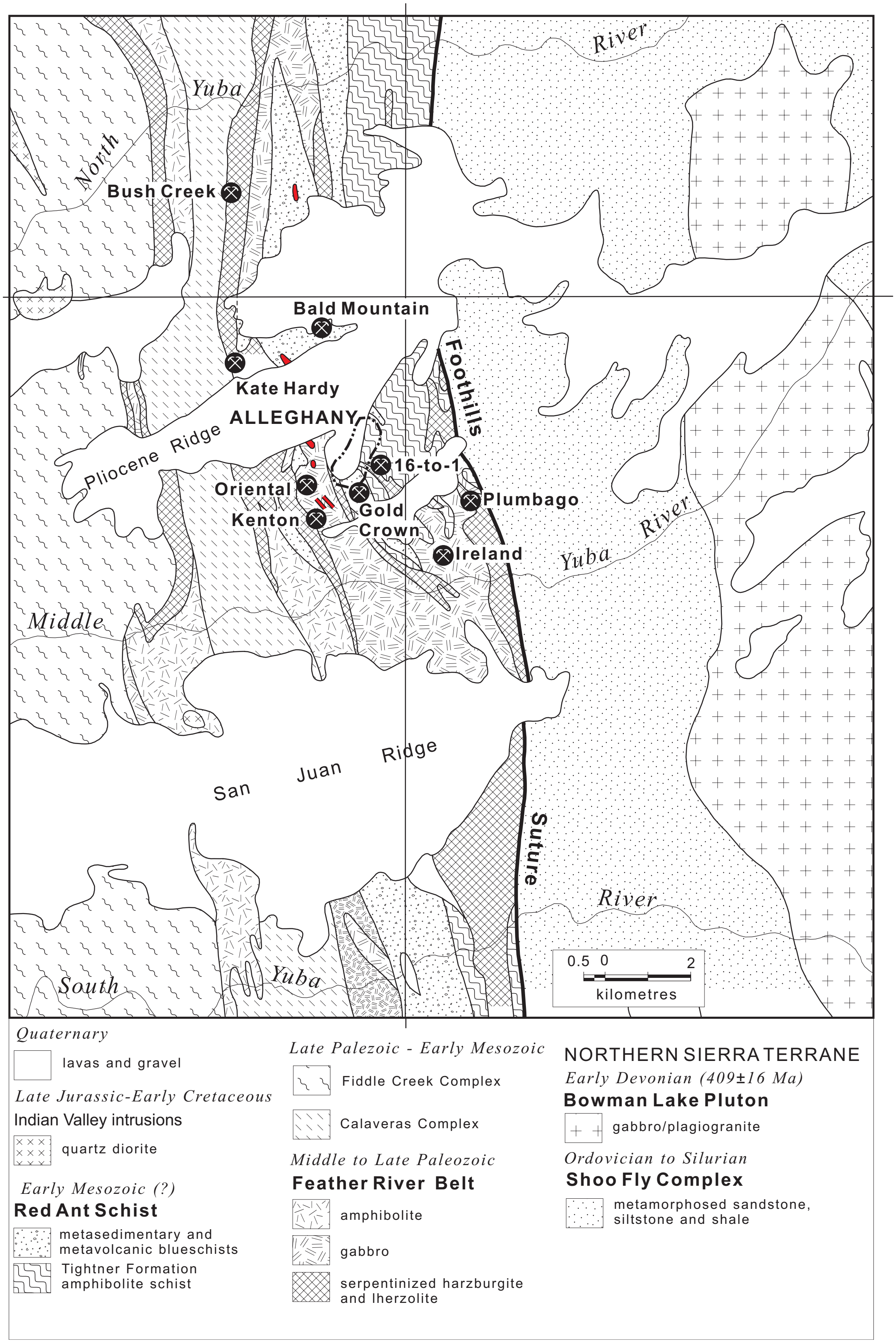


Figure 8.7. Geology of the Alleghany District after Ferguson and Gannett (1932) with revised legend using data from Böhlke and McKee (1984), Edelman and Sharp (1989) and Saleeby (1990).

tion of the Mother Lode, six K-Ar ages from hydrothermal vein micas reveal a near continuous range over 25 million years between 130 and 105. In the Alleghany camp K-Ar mica data from three different deposits including the Ireland (112.9±3 Ma), Plumbago (112.5±3 Ma) and Rainbow Extension (part of the 16 to 1 vein) (111.6±3 Ma) indicate a fairly restricted age range which is coeval with a more recent ^{40}Ar-^{39}Ar age of 111 Ma on mariposite from the Oriental vein (Böhlke, 1989). Rb-Sr ages from this camp show considerable variability, ranging from 109.6±3 to 124.5±3 Ma.

The overall variation in mineralization ages for California vein gold deposits has been interpreted in several ways. Böhlke and Kistler (1986) and Weir and Kerrick (1987) suggest the range of hydrothermal ages results from mineralizing fluids generated by deep magmatic activity in response to resumption of east-dipping subduction along the western margin of North America following the Nevadan orogeny. This implies that the mineralizing episode occurred over a protracted period of about 30 million years following orogenesis. Another interpretation, preferred here, was provided by Landefeld (1988) who proposed that the oldest ages (141-144 Ma) are closer to the true age of formation of the Mother Lode gold-quartz veins. She considers the spread of younger isotopic ages to be an effect of later thermal overprinting related to intrusion of the large, Cretaceous Sierra Nevada batholith (Figure 8.2). Notably, the oldest alteration ages are also most distant from the batholith. Support for Landefeld's (1988) interpretation that thermal resetting has taken place is provided by recent examination of mariposites from the Mother Lode belt (Y. Jia, personal communication, 2000) which indicate that they are altered to some degree to varieties of Cr-bearing clay minerals (illite, smectite, *etc*.).

Additional age data (Elder and Cashman, 1992) for gold veins from Quartz Hill in the Klamath Mountains, Northern California (inset map, Figure 8.2), add additional support for resetting as a cause for the span of younger ages. Deposits at Quartz Hill occur in a series of gold-quartz veins, in footwall basaltic greenstones along the Soap Creek Ridge fault zone. K-Ar data for two samples of hydrothermal vein micas give conventional K-Ar ages of 145.8±3.0 and 147±2.8 Ma and are considered the age of mineralization. This deposit is far removed from the influence of thermal overprinting related to Sierra Nevada magmatism. The data indicate a gold-mineralizing event within the latter stages of the Nevadan orogeny and is consistent with the age of Grass Valley mineralization.

RELATIONSHIP TO MAGMATISM

For the California deposits discussed there is a common spatial association with high level intrusive rocks. However, temporal relationships between the gold quartz veins and intrusions are not well constrained for most areas. In the Alleghany district, Ferguson and Gannett (1932) indicate that granite and aplite masses lie within a narrow zone that trends across the area in a northerly direction (Figure 8.5). The dikes in the host gabbro lack the penetrative fabric and postdate the regional greenschist metamorphism. Locally dikes are also hydrothermally altered with secondary carbonate-sericite-pyrite. Two distinct ages of granitic intrusion are known. In the western and southwest part of the camp (Figure 8.7) quartz dioritic intrusions of the Indian Valley suite are dated by K-Ar on hornblende at 143±5 Ma (Bohlke and McKee, 1984) consistent with a late syn-orogenic episode of magmatism following the Nevadan orogenic event. A peraluminous granitoid stock of Devonian age (Saleeby, 1990) intrudes the amphibolite/metagabbro in the Oriental Mine and forms the footwall to the Oriental vein (Coveney, 1981). This stock is coeval with the larger Bowman Lake pluton intruding Shoo Fly complex rocks to the east (Figure 8.6). Marginal to the vein, the Oriental Mine stock is pervasively albitized and contains fine gold in disseminated pyrite with an average grade of 7 g/t (0.2 ounces/ton).

Along the Mother Lode belt, Landefeld and Silberman (1987) indicate that late orogenic dikes intrude margins of the Melones fault zone and its adjacent rocks and that in the Coulterville region such dikes are hydrothermally altered. In a similar manner, south of Jackson along the central portion of the Mother Lode, Knopf (1929) described several localities of albitite porphyry dikes, which are in places auriferous. In the northern part of the belt, the Coloma pluton, an elongate 2 to 4 kilometre wide intrusion extending more than 16 kilometres north of Placerville, has been dated at 143 Ma by U-Pb (Graymer and Jones, 1994). It provides an example of late syn-orogenic plutonism that is coeval with the age of vein mineralization suggested for the Mother Lode belt (Landefeld, 1988), indicating a magmatic event which immediately postdates the Nevadan orogeny.

At Grass Valley, Johnston (1940) describes leucocratic aphanitic to quartz-albite porphyritic granitic dikes as a conspicuous feature throughout the mine workings. Relationships between vein mineralization and these high level intrusive rocks are not evident and there are no age constraints on the dike rocks.

SUMMARY

- Significant production from gold-quartz vein deposits in California was obtained from three main areas, the Grass Valley and Alleghany districts, and the Mother Lode belt which represent classic examples of gold-quartz vein deposits within accreted Phanerozoic terranes.
- There is a clear diversity of host rock associations for these gold-quartz vein deposits. Veins in the Alleghany are hosted by Paleozoic ophiolitic rocks, Early Paleozoic amphbolite and Devonian granite at Grass Valley, metamorphic ultramafic and mafic igneous rocks of the Late Triassic-Early Jurassic Lake Combie suprasubduction zone ophiolite/arc complex and a younger (?) enigmatic granodiorite-quartz monzodiorite intrusion, the La Barr Meadows pluton are host to veins. Along the Mother Lode belt veins are hosted primarily in a Late Jurassic sequence of alternating mafic volcanic breccia and slate but are also associated with Late Triassic volcanics and older Paleozoic ophiolitic rocks.

- The enigmatic La Barr Meadows pluton, which is host to significant gold quartz veins at Grass Valley is of unknown age and correlation. Traditional views that the pluton is a younger satellite stock of the Sierra Nevada Batholith have been considered but it is more likely an older and possibly a co-genetic with the Lake Combie complex for the following reasons:

(1) The limits of the pluton are conspicuously constrained to within the Lake Combie complex and mostly within the massive diabasic portion.
(2) Where not intrusive into the diabase or volcanic rocks of the Lake Combie complex, the pluton is cut by the bounding faults of the complex.
(3) Multiple intrusive contact relationships between the pluton and the host diabase suggest that the two are co-magmatic, i.e. dikes that are texturally and mineralogically similar to the host diabase also intrude the pluton.
(4) A reported Early Cretaceous hornblende K-Ar age for the pluton cannot be considered a reliable indication of the age of the intrusion as all primary hornblende appears to be, at least in part, altered to chlorite.

- California quartz-vein deposits discussed are some of the most significant gold producers in the North American Cordillera. They represent most of the better-documented deposits and occur in a region for which the geological setting is possibly best constrained. However, modern Ar-Ar dating to adequately constrain ages of mineralization (see discussion, chapter 9) combined with information for the age of host rocks, particularly for the Grass Valley district, are required to make definitive correlations with camps elsewhere in the Cordillera.

- Within the significant producing gold vein deposits of Western Sierra belt, high-grade, native gold is often found in close spatial association with carbonate-altered ultramafic rocks. This is entirely the case for the Alleghany camp, similarly for the Idaho-Maryland vein in the Grass Valley camp and is also characteristic of high grade gold for the central portion of the Mother Lode belt.

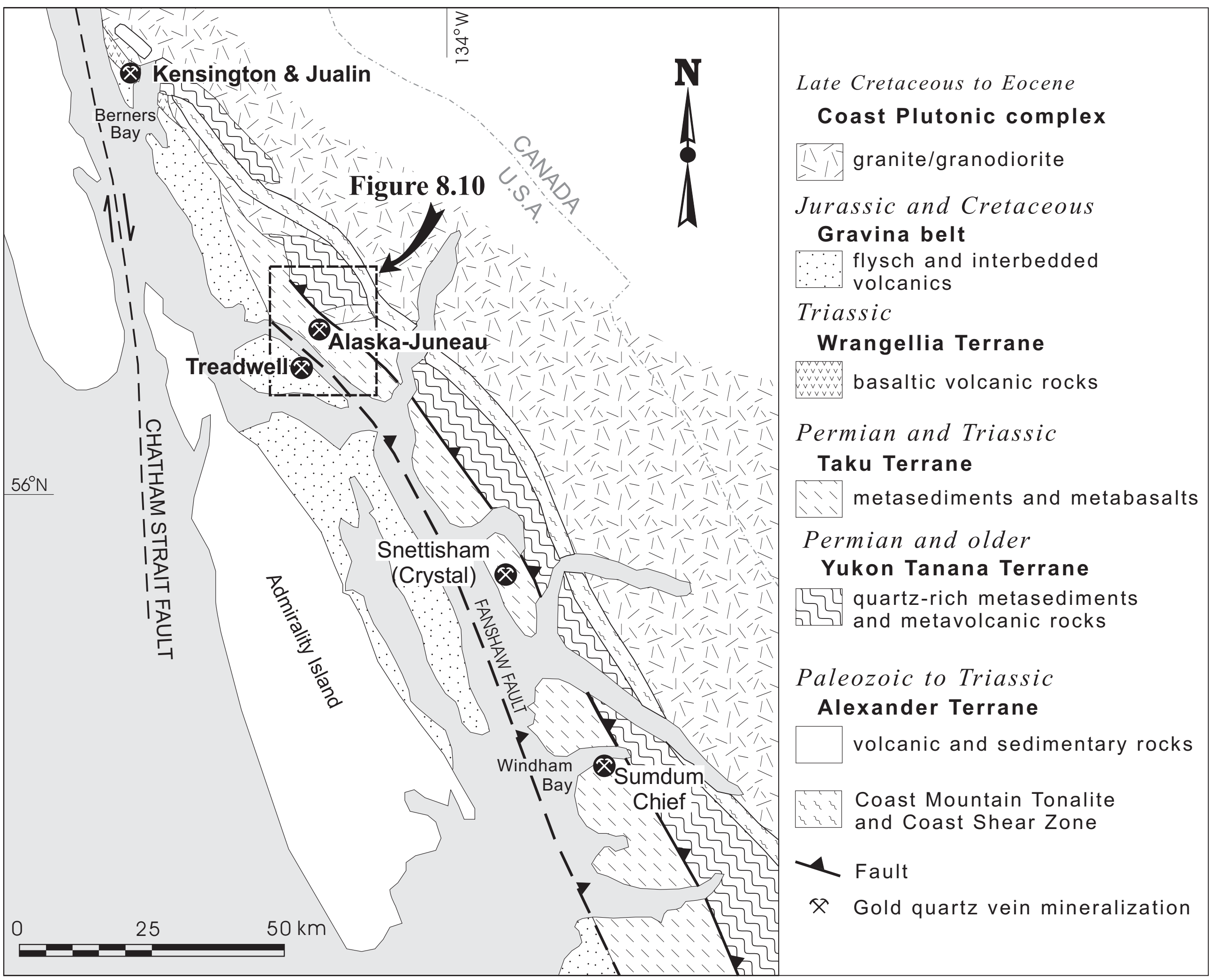


Figure 8.8. Regional geological setting of the Juneau Gold Belt, southeastern Alaska after Miller *et al.* (1995, Figure 1).

ALASKA-JUNEAU DEPOSIT

Alaska-Juneau is the largest among a number of gold quartz vein deposits in the Juneau Gold Belt of southeastern Alaska (Spencer, 1906; Figure 8.8). This belt contains a northwest-trending linear array of gold-quartz vein deposits that extend 200 kilometres from Windham Bay in the south, to Berners Bay in the north. Gold was discovered in 1880 by Joe Juneau and Richard Harris and the town of Juneau being named after the elder of the two discovers (Spencer, 1906). During its 40-year productive history from 1885 to 1944 close to 110 tonnes (3.5 million ounces) of gold were recovered from 90 million tonnes (99 million tons) of ore which makes it one of the largest and lowest grade underground operations in the world (Figure 8.1; Fredericksen and Miller, 1989).

PREVIOUS WORK

Geological mapping in the area was done first by Spencer (1906) and more recently by Brew and Ford (1985) and Gehrels (2000). Earliest descriptive works of the deposit include those of Spencer (1906) and Wernecke (1932). Recent work has focused on establishing the nature and age of mineralizing fluids (Leach *et al*., 1986; Goldfarb *et al*., 1988a, b; Goldfarb *et al*., 1991; Miller *et al*., 1995). Summary descriptions of the deposit have been published by Newberry and Brew (1987) and Fredericksen and Miller (1989).

GEOLOGICAL SETTING

The Juneau gold belt (Figure 8.8 and 8.9) consists of a number of northwest trending belts of oceanic rocks that comprise several distinct lithotectonic terranes (Miller *et al*., 1995; Gehrels, 2000). These consist largely of deformed and recrystallized marine clastic sediments and intermediate to mafic volcanics which are bordered to the east by the Eocene (54-48 Ma) granites and granodiorites of the Coast plutonic complex. Individual terranes are interpreted to be juxtaposed against one another along a series of southwest-verging, moderately to steeply northeast dipping, mid-Cretaceous thrust faults (Miller *et al*., 1995).

The oldest, most easterly belt of rocks, termed the 'schist band' by Spencer (1906) consists mainly of metamorphosed calcareous and argillaceous sandstone that occur as a garnet-mica-hornblende schist with intervals of quartzite and marble. These are currently correlated with the Yukon Tanana Terrane and are considered displaced near-shore remnants of the Early Paleozoic North American continental margin (Miller *et al*., 1995).

West of this belt, are intercalated slate- greenstone and greenstone schists, which are remnants of Permian and Middle to Late Triassic interbedded clastic sediments and mafic volcanic rocks, correlated with the Taku Terrane (Gehrels, 2000).

MINE GEOLOGY

Gold-quartz veins of the Alaska-Juneau deposit are hosted in the Taku Terrane, a sequence of deformed and metamorphosed Late Triassic intercalated black slates intruded by Mesozoic metagabbro (Figure 8.9). The slates are

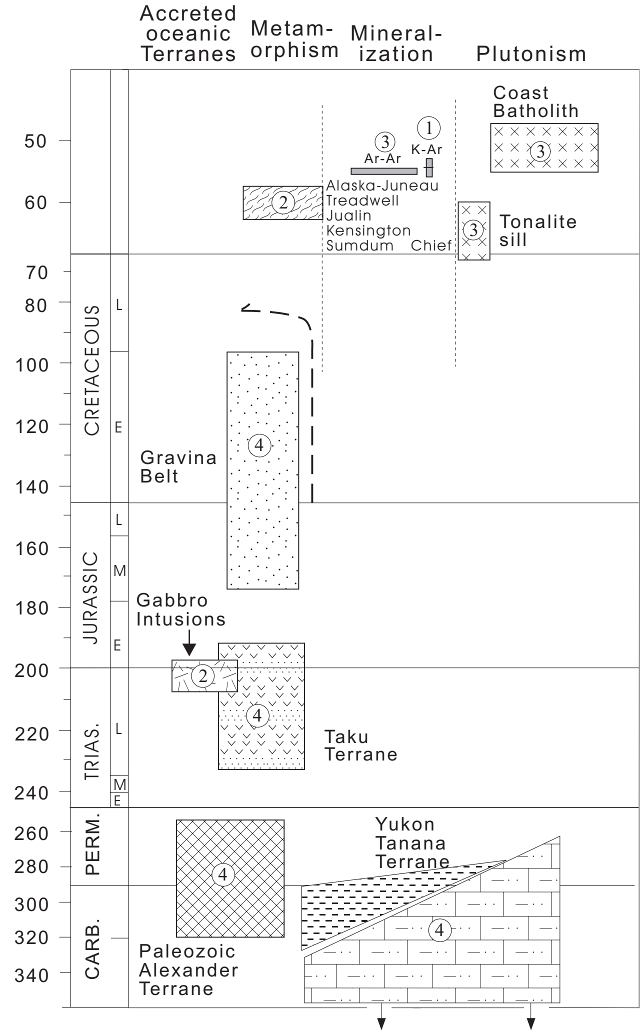


Figure 8.9. Relative age and tectonostratigraphic relationships for lithologies at the Alaska Juneau deposit. Data sources used to constrain age relationships for the elements depicted are: ① Miller, *et al*., 1995; ② Goldfarb *et al*., 1988a; ③ Goldfarb *et al*., 1988b and ④ Goldfarb *et al.*, 1991.

metamorphosed carbonaceous shales which are typically graphitic and contain occasional thin, dark limestone intervals.

Recrystallized gabbro and pyroxenite intrusions are prominent lithologies in the Juneau area (Spencer, 1906). They intrude all rock units in the mine region including the greenstone, greenstone schists and slate, from Gastineau Channel to the intrusive contact of the main Coast plutonic complex. The position of these dikes, however, is only shown on Figure 8.10 where they occur in the area of black slates hosting gold veins. A detailed geology map by Wernecke (1932) showing the distribution of ore bodies in the area of Gold Creek (North ore body), indicates that the gabbro bodies comprise nearly 50% of the slate belt in that area. These intrusions are from 3 to 60 metres in width and form irregular fingered laccolithic bodies or chonoliths and sills. They are dark-green to black in colour and commonly

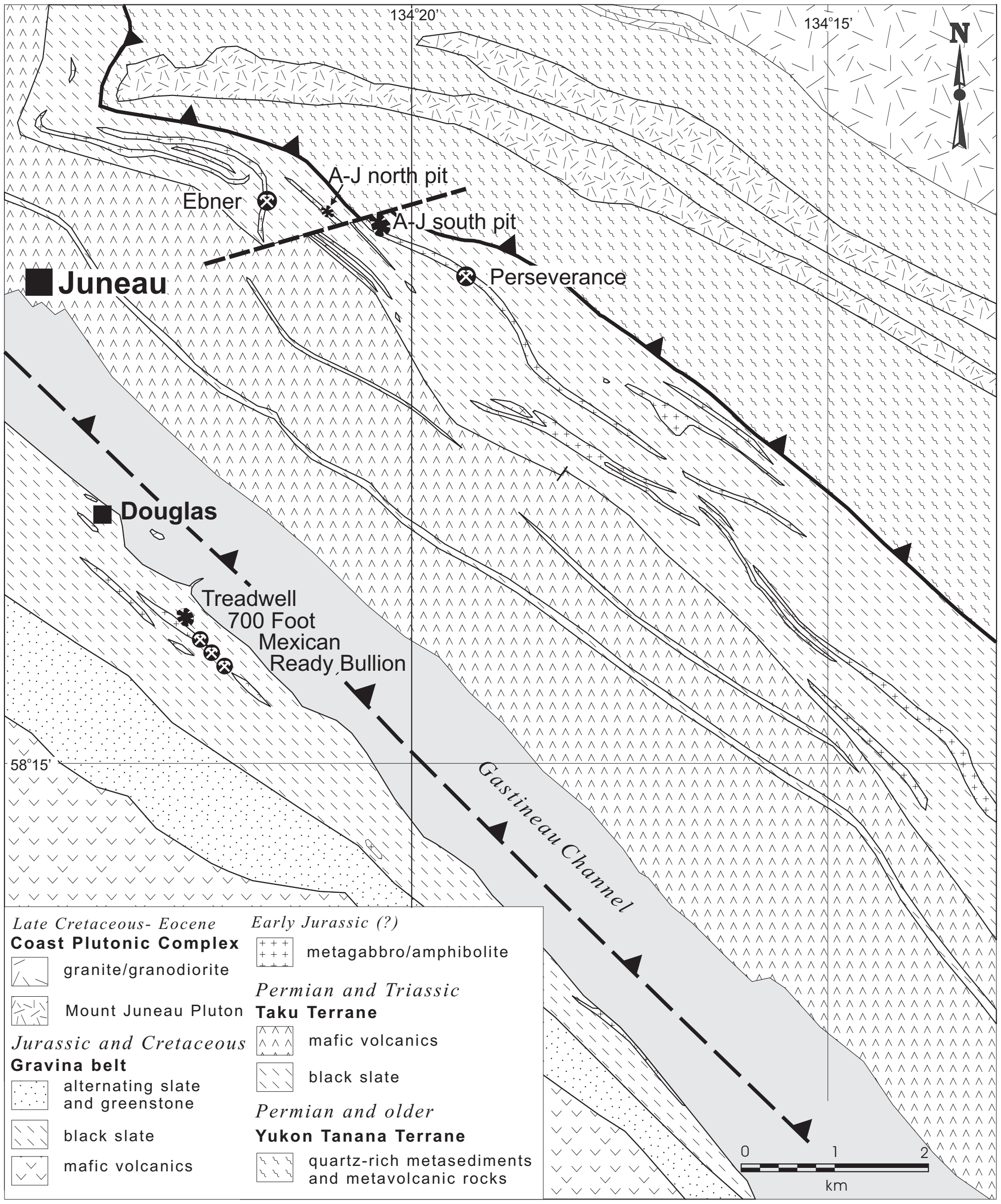


Figure 8.10. Geological setting of the Alaska-Juneau and Treadwell deposits, after Spencer (1906) with modified legend, using data from Miller *et al.* (1995).

schistose, but where less deformed, they display a moderately coarse-grained, granular texture. They are described as being hornblende-rich (secondary hornblende after pyroxene) but no quantities of the mineral are reported. Wernecke (1932) interpreted the gabbro, which intrudes the older tuffs and slates, to be sills and laccoliths feeding Early Jurassic mafic volcanic rocks. Recent interpretations (Newberry and Brew 1987, Goldfarb, *et al*., 1988a, 1990, 1991) are consistent with a Mesozoic age for these intrusions, although they are undated.

MINERALIZATION

Gold-quartz vein mineralization at the Alaska-Juneau deposit occurs in metagabbro and amphibolite bodies and in black slates immediately adjacent to metagabbro. Relatively continuous tabular quartz veins occur occasionally within the metagabbro. Many of the deposits, however, consist of broad irregular zones of numerous dispersed quartz stringers that fill irregular fractures in the slate.

Mine workings extend along the hillside over a strike length of almost half a kilometre and over a roughly 230 metre-wide zone. The ore occurs as irregular and discontinuous concentrations of quartz veins and veinlets that constitute typical ‘stringer leads’ (Spencer, 1906) or ‘stringer lodes’ (Wernecke, 1932). Although sparsely distributed along the zone these quartz veins are locally numerous and constitute ore where closely spaced, which in the early days permitted mining by open pit.

Bodies of quartz stringers in these broad mineralized zones occur in irregular, elliptical, isolated or discontinuous pipe-like groups along fracture ridges or tongues of carbonate-sericite-pyrite altered metagabbro (Wernecke, 1932). Vein filling is relatively uniform, consisting of either quartz or calcite, with negligible to several percent sulphide minerals that are locally abundant within some of the ore shoots. Where individual veins are well-developed they can be followed for several kilometres along strike. More commonly they are discontinuous and less than 100 metres in length.

Sulphide minerals include pyrite and arsenopyrite with lesser sphalerite, galena and chalcopyrite (Spencer, 1906; Wernecke, 1932). Pyrite is the most common sulphide mineral in the majority of the veins and is also common in altered mafic igneous wall rocks. Arsenopyrite occurs in many modes in the veins and in some it carries high gold values. Well-developed crystals and crystal aggregates are common. Sphalerite and galena occur in variable amounts, and only in the quartz veins. They are generally associated, with the former being more abundant. Chalcopyrite is minor but ubiquitous in the quartz veins.

Similar to the Mother Lode, gold was also recovered from replacement ore, which Spencer (1906) referred to as 'impregnated ore'. He reported that fracture fillings are well-developed at least locally in all rock types. Replacement is inconsequential in slate and is confined mainly to igneous rocks, in particular greenstone and diorite.

AGE OF MINERALIZATION AND RELATIONSHIP TO TECTONISM

Ar-Ar hydrothermal mica ages reported from five of the largest deposits developed along the 200 kilometre belt suggest that the veins were emplaced during a tightly bracketed time interval in the Early Eocene (*ca.* 53 to 56 Ma) (Figure 8.8.). This coincides with the late stages of orogenic deformation and is broadly coeval with intrusion of batholiths in the Coast Belt (Goldfarb, 1988a, b; Goldfarb *et al.*, 1991; Miller *et al.*, 1995). These data confirm the interpretations of Spencer (1906) and Wernecke (1932) that at least in part the 'Coast Plutonic Complex' is genetically related to gold vein mineralization at the Alaska Juneau deposits.

SUMMARY

- Alaska-Juneau is one of a number of gold-quartz vein deposits in the Juneau Gold Belt of southeastern Alaska. During its 40-year productive history close to 109 000 kilograms (3.5 million ounces) of gold were recovered from ores with a remarkably low average grade of 1.37 g/t (0.04 ounces/ton) gold.
- Gold-quartz veins of the Alaska-Juneau deposit are hosted entirely within a sequence of deformed and metamorphosed steeply-dipping intercalations of black slates and metagabbro, part of the Taku Terrane that lies immediately east of a terrane bounding suture, the Sumdum thrust fault.
- Gold-quartz vein mineralization within the Alaska-Juneau deposit occurs in metagabbro and amphibolite bodies and black slates immediately adjacent to the metagabbro bodies. Relatively continuous tabular quartz veins occur in the metagabbro bodies. However, many of the deposits consist of broad irregular zones with numerous quartz stringers filling irregular fractures in the slate. Bodies of quartz stringers are arranged in these broad mineralized zones as irregular, elliptical, isolated or discontinuous pipe-like groups along ridges or tongues of carbonate, sericite, pyrite altered metagabbro.

CHAPTER 9
SUMMARY AND CONCLUSIONS

INTRODUCTION

Aspects of gold-quartz vein deposits discussed in preceding chapters are first considered in terms of their host lithology and tectonic setting. Deposits are compared to highlight consistent features that characterize the mineralization, and to provide exploration criteria for identifying similar gold-quartz vein deposits elsewhere. Following this an attempt is made to characterize the paleo-tectonic environment of formation on the basis of relative age relationships between mineralization, magmatism and tectonism.

Determining the detailed geological character of host rocks for most of the significant gold producing deposits in California and Alaska required the use of older classic works for the individual camps (Figure 1.2). In addition to providing detailed lithological descriptions and contact relationships, these works also provided an overwhelming amount of data on the details of vein relationships. From these early descriptive works, some of the salient features are summarized in Appendix III.

HOST LITHOLOGY

On the basis of host lithologies, the major producing gold-quartz vein deposits in the North American Cordillera (Figure 8.1) can be subdivided into two main types (Figure 9.1). In the first type the veins are hosted almost exclusively by oceanic igneous crustal rocks, or 'ophiolitic-hosted gold veins'. In the second type veins occur in sequences of alternating mafic igneous rocks and slate, or 'mixed mafic igneous-sedimentary-hosted gold veins'.

OPHIOLITE-HOSTED GOLD VEINS

A simplified pseudo-stratigraphic oceanic crustal section illustrates the generalized character of host lithologies for the deposits (Figure 9.1). Figure 9.1a portrays host rock assemblages in their pre-accreted context to illustrate relative positions and the overall consistency of the plutonic, diabasic (hypabyssal) and volcanic units that are common to many of the host differentiated igneous suites. Undoubtedly the effect of tectonic dismemberment during accretion of the crust (*i.e.*, obduction), in addition disruption by subsequent faulting, will modify this primary pseudo-stratigraphy (Appendix 1).

Late Paleozoic, mainly Permian abyssal ocean crust is the predominant host rock for most of the ophiolitic deposits in the North American Cordillera. These include; Bralorne, Cassiar, I.X.L.-Midnight, Snowbird and Alleghany, as well as proposed gold source rocks for the Atlin, Barkerville and Klondike placers. Both Grass Valley and Rossland are hosted by Late Triassic-Early Jurassic extensional fore-arc igneous sequences with a likely transitional setting from suprasubduction regime to arc affinities.

Ophiolitic host rocks are all emplaced tectonically as competent, fault-bounded lenses or blocks that exhibit various levels of preservation. When gold production from individual deposits is examined in terms of host lithologies it is evident that the larger, better-preserved sections of competent igneous plutonic to hypabyssal crust are the most prolific hostrocks (Figure 8.1). This is a function of their relatively large size and structural competency that result in development of horizontally and vertically persistent vein-bearing fissures. The most productive lode gold camps in both British Columbia (Bralorne-Pioneer) and California (Grass Valley) demonstrate this (McCann, 1922b). Veins at Bralorne-Pioneer are hosted in the gabbro-trondhjemite-diabase portion of the late Paleozoic, abyssal Bralorne ophiolite (as defined in Chapter 4). Similarly, gold veins at Grass Valley are hosted in the gabbro-granodiorite-diabase section of the Lake Combie complex. The second largest lode gold producer in British Columbia, Rossland, is an additional example in which vein fissures are hosted by the plutonic to hypabyssal, Rossland monzonite and Rossland sill. In other areas where the igneous crustal portions are less complete, such as at Cassiar, I.X.L.-Midnight or Alleghany and the Klamath Mountains region of northern California (Elder and Cashman, 1992), the veins have comparatively limited continuity.

Ultramafic Rocks

Ultramafic rocks have been long recognized for their spatial association with gold occurrences (Lingdren, 1896, 1928). Such an association is common for all ophiolite-hosted deposits. Some igneous crustal blocks such as at Bralorne, Grass Valley and I.X.L.-Midnight are, in part, fault bounded against listwanite-altered ultramafic rocks. In other camps such as Cassiar and Alleghany, altered ultramafic rocks occur as attenuated lenses along imbricating shear zones.

The genetic association between ultramafic rocks and gold quartz vein deposits has been a topic of debate for some time. Ferguson and Gannett (1932, page 76) made a significant observation regarding ultramafic rocks as a gold source;

"Another objection to this hypothesis is the presence of a variety of sulphide minerals, such as tetrahedrite, chalcopyrite, jamesonite, sphalerite, and galena, which are also later than the quartz and whose introduction was about contemporaneous with that of the gold, although they are not everywhere closely associated with the gold and may be abundant where high-grade ore is absent. Such sulphides, being common to all veins of this type in the Sierra Nevada region, both in California and in Nevada, cannot be genetically connected with serpentinite, and therefore at about the time of the introduction of the gold there must have been an

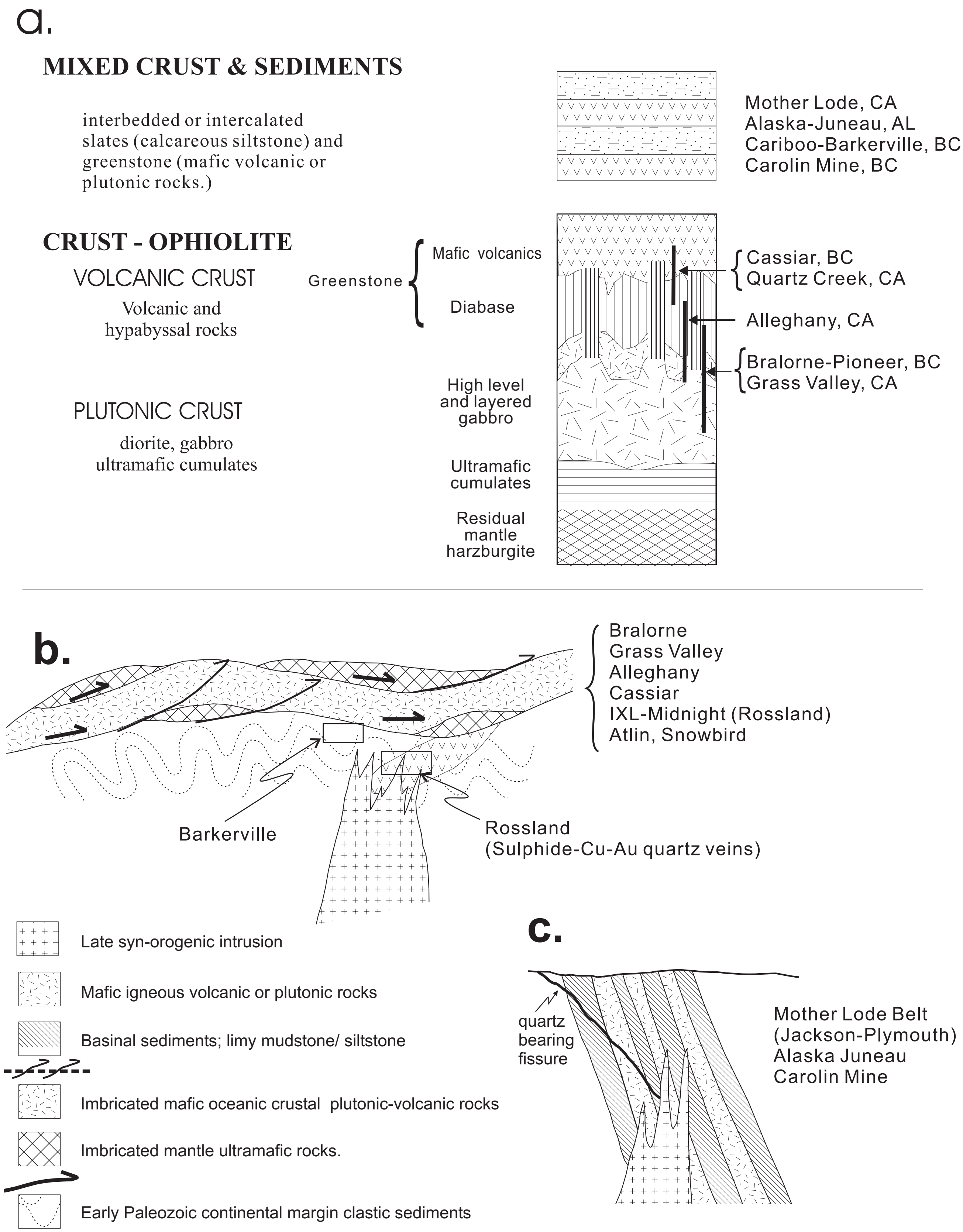


Figure 9.1. Schematic representation of host lithologies and tectonic setting of gold quartz vein deposits in the North American Cordillera. a. Pseudo-stratigraphic section of host lithologies in their pre-accreted setting. b. Structurally imbricated oceanic crustal lithologies in their post accreted setting. c. General lithological character of mixed mafic igneous-sedimentary hosted deposits.

association of minerals of hypogene origin from some source outside the serpentinite."

Ultramafic rock as a gold source has been suggested more recently (Buisson and Leblanc, 1985, 1986, 1987; Wittkopp, 1983). The significance as a CO_2-sink and a source of iron during fluid-rock reactions may also play some part in triggering gold deposition (Kerrich, 1983). Ferguson and Gannett (1932) were impressed with the physical effects of bending and increased fracturing of veins on approaching serpentinite bodies. Whether ultramafic rocks are a source of gold, or a favourable lithology for promoting its deposition, due to some combination of chemical reactions and structural preparation remains unresolved. There is, however, a well established relationship that the richest and most spectacular gold ore in Phanerozoic deposits is almost everywhere found in quartz veins associated with, or in close proximity to carbonatized ultramafic rocks. In British Columbia this relationship is well documented at Bralorne-Pioneer (Cairnes, 1937; Barr, 1980), Rossland (Fyles, 1984), Cassiar (Boronowski, 1988), Snowbird (Game and Sampson, 1987a), Atlin (Bloodgood *et al*., 1989a; Rees, 1989) and the Carolin Mine (Ray, 1990). A similar relationship is also well documented for California gold vein deposits; Alleghany (Ferguson and Gannett, 1932; Wittkopp, 1983; Böhlke and Kistler, 1986; Coveney, 1981; Böhlke, 1989); Grass Valley (Johnston, 1940) and in the central Mother Lode belt (Knopf, 1929).

Ophiolitic ultramafic rocks do however, offer significant tectonic constraints. As remnants of lower oceanic crust or upper mantle their exposure at surface along accreted margins delineate deep transcrustal fault zones. They therefore identify the first-order control for the development of such deposits, a major crustal break or terrane boundary (Ferguson and Gannett, 1932; Barr, 1980; Phillips and Groves, 1983; Roberts, 1987; Hoffman, 1990; Kerrich and Wyman, 1990). Where ultramafic rocks along these faults are converted to listwanite they further define deep crustal structures that have channeled large volumes of CO_2-rich hydrothermal fluids. In this respect listwanite-altered ultramafic rocks represent a first order exploration guide to this deposit type.

Ultramafic rocks are, in general not receptive to the development of gold-quartz veins (Cairns, 1937; Ferguson and Gannett, 1932; Stevenson, 1936). Veins with exceedingly rich gold ore are, however, commonly hosted by tectonic blocks of mafic igneous crustal rocks that are proximal to listwanite-altered ultramafic rocks. It is likely that excess effort has been directed over the past two decades in focusing exploration activity directly on occurrences of listwanite. A reassessment of host rocks with elevated gold values in the general area of listwanite-altered ultramafic rocks may prove more rewarding economically. Most notably this should be done where there is an association with "tectonic" fault bounded, mafic to felsic oceanic crustal rocks.

Importantly, significant gold-quartz vein deposits all tend to have associated listwanite, but there are also listwanites with no associated gold. Whether or not the fossilized hydrothermal fluid zone contained economic concentrations of metals, or that it was formed at crustal levels amenable to deposition of such metals is a question for detailed examination. Any examination should focus on quartz veins with associated hydrothermal micas and sulphides within broader carbonate alteration haloes.

MIXED MAFIC IGNEOUS-SEDIMENTARY SEQUENCES

Most of the significant producing veins of the Mother Lode belt and those at the Alaska-Juneau mine belong to this category of mixed mafic igneous-sedimentary sequences. The lithologic and tectonic setting of these two regions with productive gold-quartz vein deposits display remarkable similarities. Host lithologies at both include steeply-inclined, intercalated sequences of slate and mafic igneous lithologies (Figure 9.1a and 9.1c). Mother Lode deposits occur within Late Jurassic successions of alternating 60 to 200 metres wide intervals of greenstones (augite-phyric breccias and tuffs) and slates (Knopf, 1929). Mafic lithologies at the Alaska Juneau deposit consist of amphibolitized gabbroic dikes from several metres to several hundred metres thick with intervening screens of slate with a comparable range in thickness. In both areas quartz in the form of 'stringer lodes' (Knopf, 1929) or 'stringer leads' (Spencer, 1906) characterize veining in sediments. The sedimentary gold vein host rocks in both areas consist of Mesozoic basinal sedimentary sequences of siliceous limey mudstone or siltstone metamorphosed to slates and phyllites, which are often graphitic.

In the Mother Lode, 'grey ore' (Knopf, 1929) or 'impregnated ore' at Alaska-Juneau (Spencer, 1906) also contributed to gold production. In this style of mineralization gold is invisible and occurs with sulphides (4-8%) in pervasively carbonate-sericite±albite altered mafic igneous country rock, which is usually net-veined by quartz± carbonate±albite.

The best example of this catagory in British Columbia is along the Coquihalla gold belt in the southwestern portion of the province (Ray, 1990). Gold mineralization occurs mainly in sedimentary rocks of the Late Jurassic Ladner Group near its western contact with the late Paleozoic Coquihalla serpentinite belt along the East Hozameen fault. It also occurs in late Paleozoic, abyssal Spider Peak basalts, and several gold occurrences are associated with albite-rich felsic dikes that intrude Ladner Group sediments. Styles of mineralization vary from discrete quartz±carbonate veins to irregular quartz breccias and stringer zones to broad zones of pervasive alteration with invisible gold in sulphides.

Virtually all the gold production has been from deposits within 200 metres of the East Coquihalla serpentinite belt. Most of this gold was from the Carolin Mine (MINFILE No. 92HNW003 & 007), which from 1982 to 1984 produced 1354 kilograms of gold from 799 199 tonnes of ore, indicating an average recovered grade of 1.7 g/t. Ore zones at the mine are up to 30 metres thick within the more competent, coarse clastic Ladner Group sediments along the thickened hinge-regions of upright folds. Gold is not visible and occurs in association with pyrrhotite, pyrite and arsenopyrite, collectively comprising from 6 to 8 % of the pervasively albite-carbonate-sericite altered host and is best characterized as 'replacement ore' (G. Ray, personal communication, 2000). Significantly, the only native gold from the Coquihalla gold belt was found at the Aurium Mine in talcose shears along the East Hozameen fault immediately adjacent to the serpentinite belt.

Lode gold deposits of the Barkerville camp are also included in this category. Although having a different orientation and not interlayed as in the above examples, a similar lithologic association is evident, but on a relatively larger scale. Gold quartz veins are hosted in sediments below amphibolitized mafic igneous rocks. The limited vertical extent of the ore zone follows and also dissipates downward, away from the inferred low angle tectonic contact between Slide Mountain ophiolitic assemblage and North American margin sedimentary units. The distinctive characteristic of massive pyritic lenses at Barkerville may well reflect more the presence of limestone beds in this particular stratigraphic sequence of metasedimentary rocks.

On the basis of these consistent lithologic relationships one can conclude that where metamorphosed, variably calcareous, fine-grained siliclastic metasediments are associated with listwanite-altered mafic igneous rocks there is potential for gold-enriched quartz veins and vein marginal alteration zones. The best environment appears to be one in which hostrock successions are interlayered and steeply dipping (Figure 9.1c). Gold vein deposits in similar sedimentary rocks without a mafic igneous association are unknown in the North American Cordillera. Importantly, all productive deposits of this type are close to terrane boundary faults.

It is also apparent that these mixed mafic igneous-sediment-hosted vein deposits are of comparatively lower gold grade than deposits hosted by oceanic igneous crustal rocks. The average grade of the Alaska Juneau deposit at 1.34 g/t (0.04 ounces/ton) is only slightly lower than that of the Carolin Mine at 1.7 g/t. The grade of the sediment hosted deposits along the Mother Lode belt is difficult to establish directly due to the diversity of rocks along the belt, however, Knopf (1929) described the gold grade of the belt as a whole as being low to moderate, with an average grade of 10.6 g/t ($7.00/ton or 0.31 ounces/ton). In contrast gold-quartz vein mineralization hosted by oceanic igneous crustal rocks are dominated by more continuous vein fissures with gold grades averaging 17+ g/t (0.5 ounces/ton). Where igneous crustal rocks are closely associated with ultramafic rocks gold grades can be on the order of several thousand grams per tonne (100+oz/t).

It has been recently promoted (Goldfarb *et al.,* 1998; Bierlein and Crowe, 2000) that gold vein deposits of Phanerozoic age are hosted predominantly by oceanic sedimentary rocks. Such a characterization is misleading and in clear contradiction with the gold-quartz vein hostrock relationships described here. In many instances the deposits are either hosted predominantly by mafic igneous rocks and for the deposits where fine calcareous sediments are present as host lithologies, mafic igneous rocks are also present in roughly equal amounts.

It is compelling to point to a discussion by Knopf (1929) when describing the prominent host rocks for gold veins along the Mother Lode belt as;

"black slate with subordinate greywacke and conglomerate associated and interbedded with ***large*** *amounts of greenstone".*

He noted that the prominent mafic volcanic component of the Mariposa Formation had been largely disregarded in previous unit descriptions (Knopf, 1929, p.12);

"In the gold belt folios the Mariposa Formation is generally described as being composed of black slate, or "clay slate", with locally varying amounts of sandstone and conglomerate." The igneous rocks, although commonly predominating in volume, are not included, and this omission illustrates the cavalier treatment that the igneous rocks formerly received in stratigraphic geology".

Folios are map series that were produced for the gold fields of California throughout the late 1800's.

LITHOTECTONIC SETTING AND RELATIONSHIP TO PLACER GOLD DEPOSITS

Significant placer gold camps in the Canadian Cordillera such as Barkerville, Atlin and the Klondike are most often found within erosional windows through regionally extensive, flat-lying terrane-bounding suture zones. In all major Canadian Cordilleran placer camps, hangingwall lithologies are often dominated by ophiolitic assemblage rocks. Two of the largest placer camps (Barkerville and Klondike) reside immediately below, or in close proximity to terrane bounding sutures between Slide Mountain ophiolitic assemblage and North American metasedimentary rocks. The setting of both placer and related lode deposits of the Barkerville camp has been previously discussed (chapter 6). In the Klondike area Slide Mountain Terrane rocks consist mainly of serpentinite, carbonatized serpentinite and talc-carbonate schist with lesser gabbro and mafic volcanic rocks. These rocks are regionally distributed as isolated klippen that are dissected by the placer creeks Figure 9-3 (Mortensen, 1990). One can readily infer from the regional geology that an ophiolitic slab and basal suture zone originally occurred proximal to the productive placer creeks. Gold veins have not been identified within the ultramafic rocks, which is consistent with their characteristic lack of gold-vein development. One can reasonably infer from the typical setting of the richest gold veins residing in crustal igneous rocks adjacent to carbonate-altered ultramafic rocks that the most reasonable environment for the development of coarse, native gold would have been spatially associated with these listwanite-altered ultramafic rocks within pre-erosional ophiolitic crust.

Both placer camps are well known for coarse nugget gold, yet a compatible lode gold source has not been identified at either locality. Situated midway between these two camps, the Cassiar gold camp shares a comparable lithotectonic setting (Chapter 7). In this area the gold vein-bearing ophiolitic crustal component has not been completely removed by erosion and productive veins with occasional nugget gold are still present. But where it has been eroded, related placer gold is present.

In the Atlin camp, placers reside below an intensely carbonatized, flat-lying thrust fault that separates hanging wall ophiolitic assemblage rocks from disrupted footwall chert-argillite mélange (chapter 2). Known gold-quartz veins occur consistently within or marginal too this flat-lying carbonatized thrust fault and the placer gold is found below the projected trace of this fault where it has been removed by erosion.

Within all of these coarse, gold-rich placer camps there is a conspicuous absence of representative plutonic to hypabyssal oceanic crustal rocks. It may be readily inferred from the presence of mafic oceanic crustal volcanic and ultramafic rocks in these placer areas, that a plutonic hypabyssal component was also previously present. This relationship indirectly supports the significance of such rocks as prime gold vein hosts.

This regional lithotectonic relationship suggests that gold-rich lode deposits of this type will be found where ophiolitic crustal mafic to felsic igneous lithologies in tectonic contact with listwanite altered ultramafic rocks have not been removed by erosion. It is evident that exploration efforts for placer gold sources is better expended on the basis of an understanding of the litho-tectonic setting of the placer source. History has proven that the mere presence of gold-rich gravels probably has little relation to sources immediately beside or below them. The consistent vertical depth of these deposits below the sutures suggests that within this limited distance placers still remain near surface and thus have been identified. Below this level of crustal erosion such deposits become buried and dispersed.

Other areas in British Columbia with historically significant placer gold production include the Dease Lake (Holland, 1950; Gabrielse *et al*., 1979; Gabrielse, 1994) and Manson Creek camps (Holland, 1950; Ferri and Melville, 1994; Ferri, 1997). These placer areas are also associated with ophiolitic assemblage rocks at terrane boundaries. These placer camps have not been evaluated in this study and the relationship between the lithotectonic setting of the ophiolitic rocks and the placers is undefined.

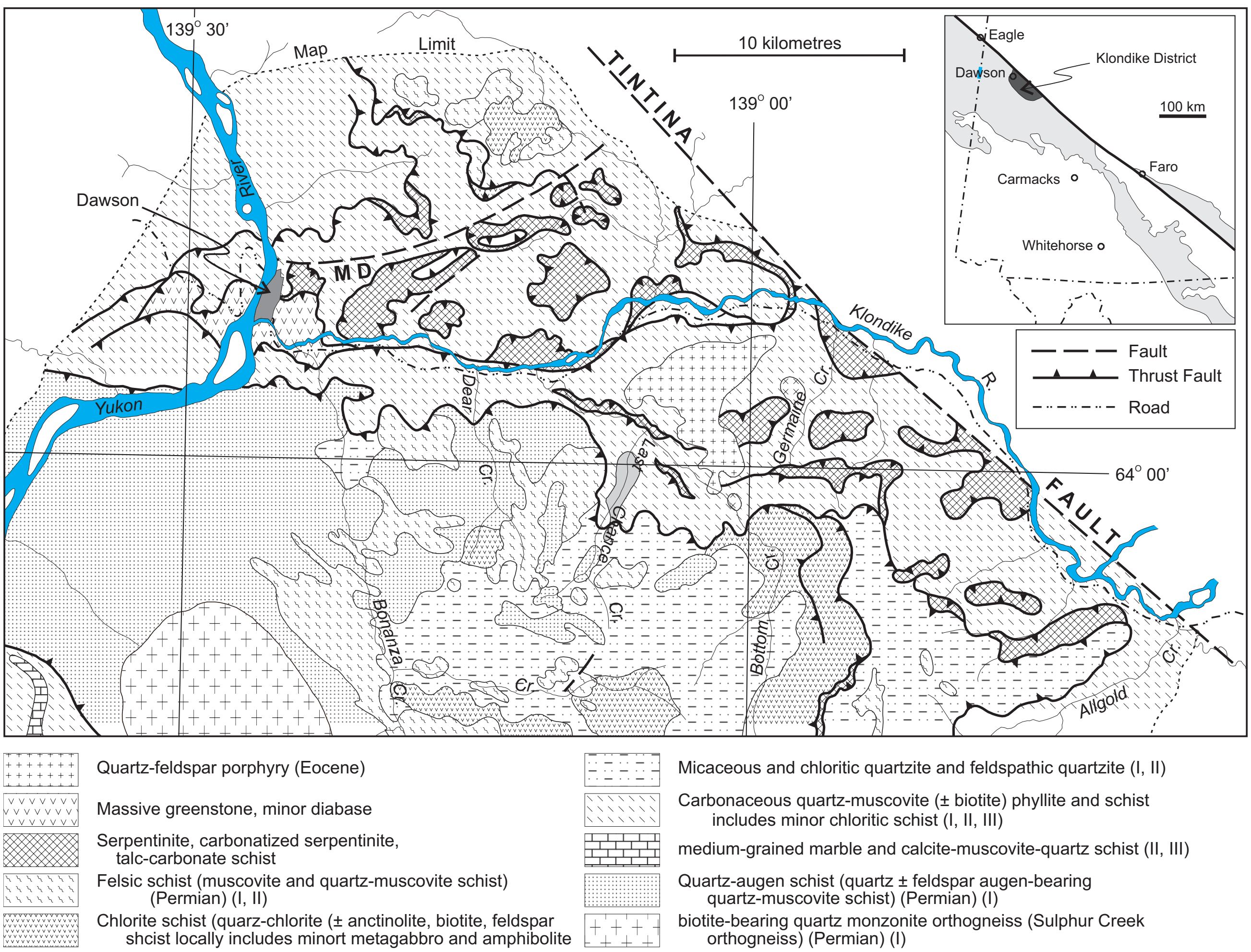


Figure 9.2. Geological setting of the northern part of Klondike District (after Mortensen, 1990).

PALEO-TECTONIC ENVIRONMENT OF FORMATION

Although there is general consistency in lithological associations, there are apparent major differences between the inferred tectonic environments of vein formation. When ages of mineralization, as constrained by isotopic age data for hydrothermal activity, are compared to the geological history of the host rocks (Figure 9.3 and 9.4), an apparent twofold subdivision is evident. One group, termed 'Late syn-orogenic', appear to have formed during restricted periods immediately following a major orogenic event and often display a close spatial and temporal association with high-level felsic intrusions. Another group, termed ' apparent anorogenic', in direct contrast appear to form during tectonically dormant periods, and tend to lack coeval high-level intrusions.

LATE SYN-OROGENIC GOLD-QUARTZ VEINS

Many of the gold-quartz vein deposits discussed fall into this category and include; Bralorne, Carolin, Snowbird, Atlin, Rossland, Alaska-Juneau and most likely those in California. Coincident formation subsequent to post orogenic activity in most instances is indicated by combined magmatic, metamorphic and stratigraphic relationships.

Three of the deposits, Atlin, Snowbird and Rossland are synchronous with regionally-extensive Middle Jurassic orogenic activity. California gold-quartz veins appear to have formed following the Late Jurassic Nevadan orogeny (Landefeld, 1988, Edelman and Sharp, 1989). Younger mid-Late Cretaceous orogenic activity coincides with the timing of vein development at Bralorne and possibly Carolin (G. Ray, personal communication, 2000), whereas those at Alaska-Juneau follow Early Eocene orogenic activity.

Most of these late syn-orogenic gold-quartz vein deposits share a close spatial and apparent coeval relationship with high-level felsic intrusions. These intrusive rocks are typically fine-grained to porphyritic, occurring as dikes and dike-like masses or small stocks. On the scale of individual camps the mineralogical composition of the dikes is relatively uniform, though textural variability is common. In some cases dikes appear to be finer-grained equivalents of larger coeval plutonic masses, such as at Atlin, Snowbird, Rossland. There can be considerable variability between the individual camps in mineralogical composition of intrusions ranging from quartz diorite and tonalite (Snowbird) to granodiorite (Atlin, Rossland) to granite. At Bralorne, Leitch (1990) describes vein-associated dikes as albitite and hornblende porphyries. Johnston (1940) referred to similar dikes at Grass Valley as leucocratic, aphanitic to quartz-albite porphyritic granite. They are described from the Mother Lode by Knopf (1929) as albitite porphyry dikes and by Lindgren (1928) as albite aplite dikes. Felsic dikes of this type commonly display the following features:

- They lack penetrative fabrics and postdate regional greenschist metamorphism, although they may be deformed or disrupted by subsequent deformation.
- They are hydrothermally altered and replaced to varying degrees by secondary carbonate, sericite and pyrite, often with elevated gold content.
- They often display some degree of structural control and dikes are commonly co-structural with and occupy the same vein-hosting fissure zones (Bralorne, Atlin).

APPARENT ANOROGENIC GOLD-QUARTZ VEINS

In contrast to these apparent 'late syn-orogenic' deposits, gold-quartz veins occurring along the central and northern Slide Mountain Terrane suggest an alternate tectonic regime of vein formation. Ages of hydrothermal vein micas from placer and lode camps along this belt, including Barkerville, Manson Creek (Ferri and Melville, 1994), Cassiar and Klondike (Hunt and Roddick, 1992; Rushton *et al*., 1993) all suggest Early Cretaceous (ca. 134-140 Ma) ages of gold vein mineralization (Figure 9.3 and 9.4). This timing corresponds to a period of relative tectonic quiescence in which no major metamorphic or magmatic activity is currently documented in rocks above the ancient North American margin. In most of these camps there is also a distinctive lack of late syn-orogenic, high-level felsic intrusive rocks. The hydrothermally altered Proserpine dike suite in the Barkerville camp may be analogous, but these are rare and have not been isotopically dated.

In Cassiar evidence for any spatial or temporal association between gold-quartz vein mineralization and high-level felsic intrusive rocks is lacking. Dikes of this type have not been reported to be associated with gold-quartz veins in the underground workings. A buried pluton at depth has been postulated by some previous workers (Nelson and Bradford, 1989; Nelson, 1990; Panteleyev, *et al*., 1996) but currently constrained ages of magmatic activity are all younger than the interpreted age of gold-quartz vein mineralization.

INTERPRETATION

Available age constraints for hydrothermal vein micas associated with Canadian Cordilleran gold-quartz vein deposits suggest that either:

- There are indeed two distinct tectonic regimes of gold-quartz vein formation in the Cordillera, one forming immediately following orogenic activity and the other during tectonically dormant stages,
- Alternatively all these vein deposits are late-synorogenic, but isotopic systematics of all 'apparent anorogenic' deposits have been reset by later thermal events.
- A third and preferred possibility is that all the deposits are late syn-orogenic but the observed differences simply result from the distinctive differences in regional lithotectonic setting of the two deposit groups.

To best convey these relationships, the concept of subdividing the Cordilleran margin into two major structural domains (Saleeby, 1999) is helpful. For the purposes of this discussion it is practical to subdivide the Canadian Cordillera into eastern and western structural domains. The eastern domain includes primarily the western limit of Late

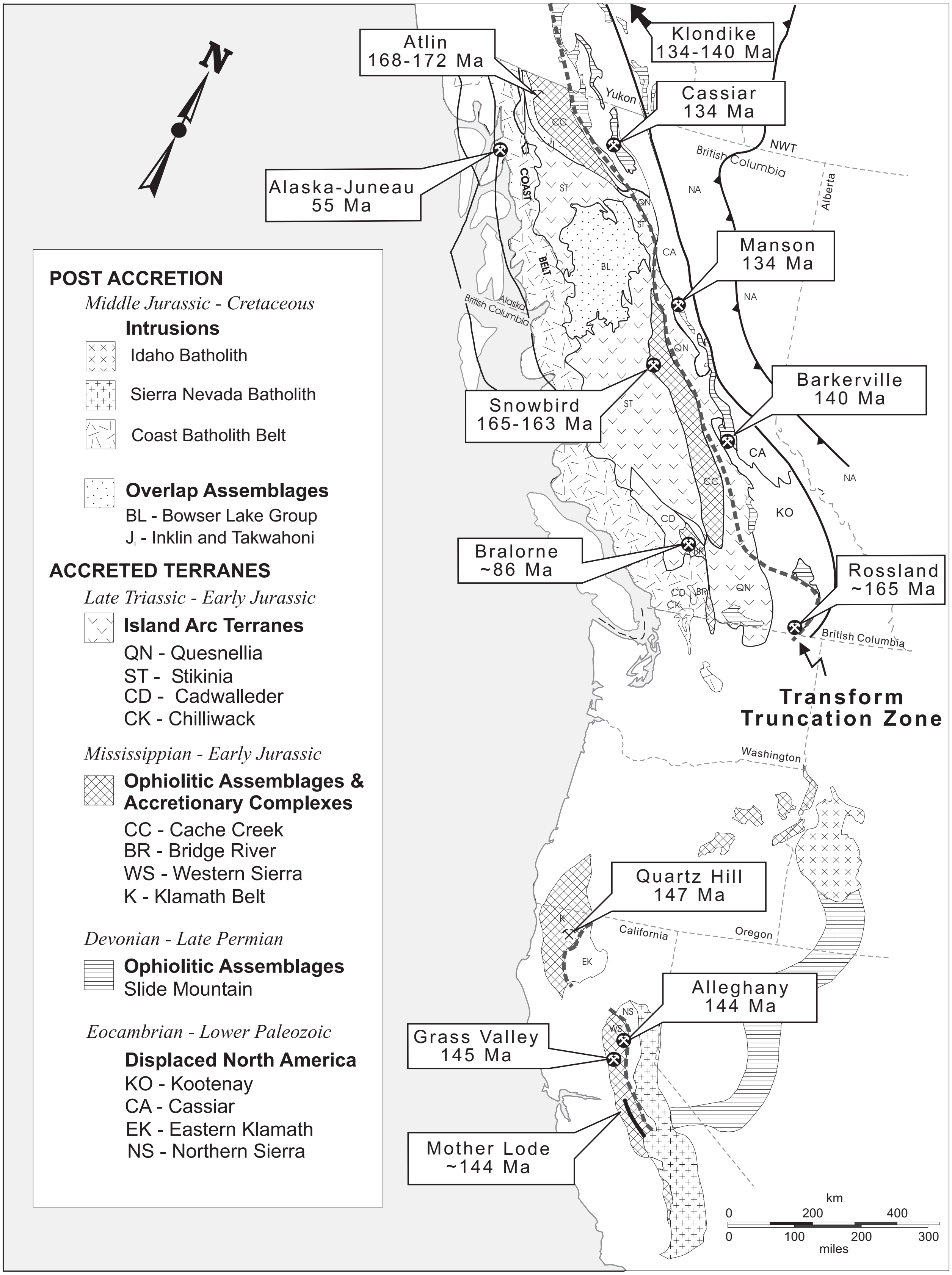


Figure 9.3. Distribution and age of hydrothermal micas from gold quartz vein mineralization throughout the Cordillera. Age for the Klondike is from two K-Ar dates on sericite from Hunt and Roddick (1992, page 236) and a single K-Ar age on mariposite for Manson Creek is from Ferri and Melville (1994). All other ages indicated are discussed in relevant chapters.

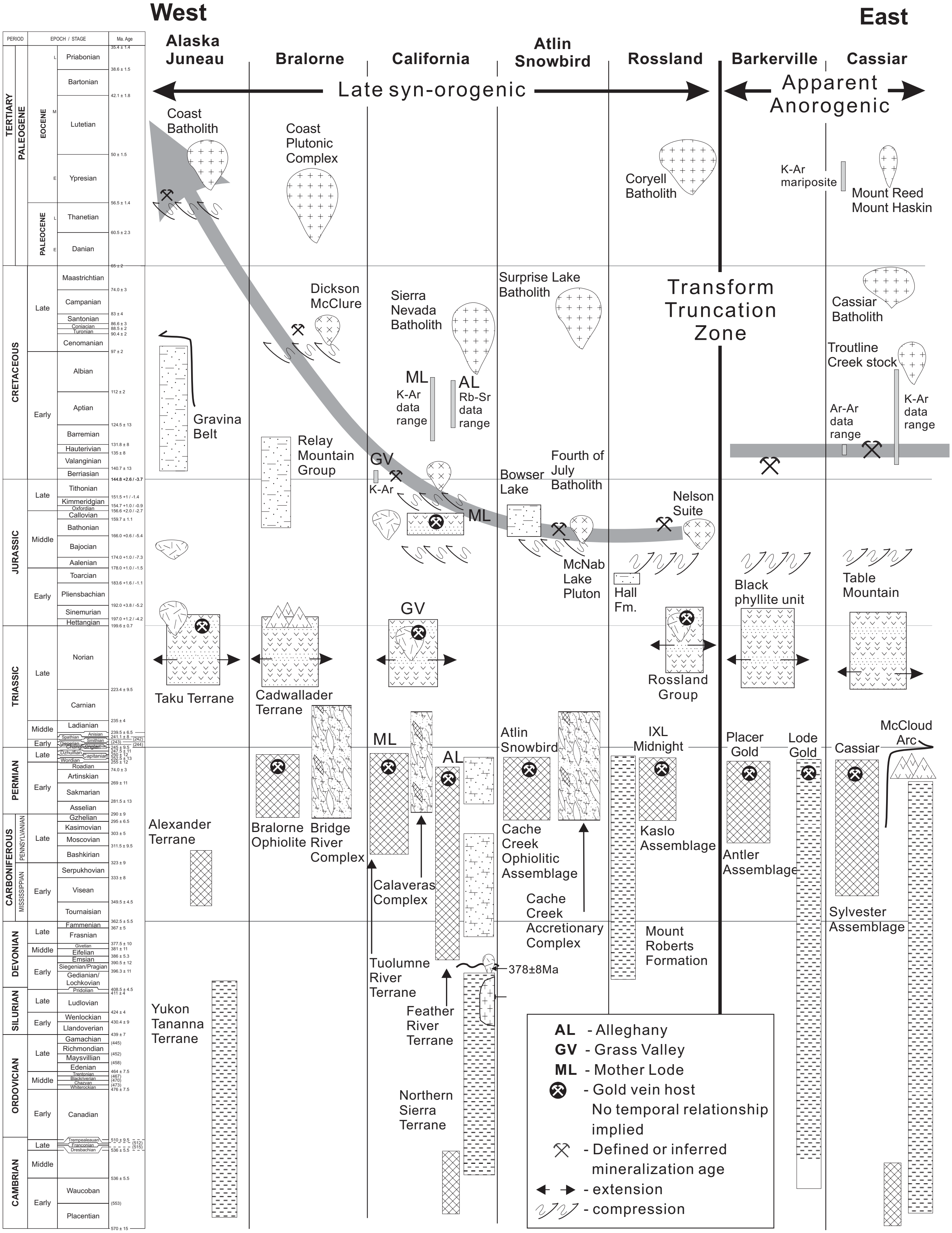


Figure 9.4. Summary of age relationships for host lithologies, mineralization, magmatism and tectonism for selected North American Cordillera gold-quartz vein deposits.

Proterozoic and Paleozoic North American miogeoclinal rocks and underlying crystalline basement. Importantly, it also includes obducted Slide Mountain terrane ophiolitic rocks. Bounding faults between individual assemblages in this domain are dominated by flat-lying imbriciating structures. The western structural domain consists of a much more diverse association of Early Paleozoic to Late Jurassic ensimatic assemblages. These were tectonically accreted to the continental plate edge through alternating episodes of subduction and transform plate-margin tectonics. Individual assemblages in this group are often separated by high-angle cryptic faults. The contact separating these two major structural domains occurs along the miogeoclinal plate edge and has been referred to as the 'transform truncation zone' (Saleeby, 1999).

All recognized late syn-orogenic deposits occur within the 'western transform domain' while all apparent anorogenic deposits are hosted by the 'eastern thrust-imbricated domain'. The obvious distinction between the two groups of deposits, characterized by the presence or absence of high-level, felsic intrusive rocks, is adequately explained by the contrasting differences in the dominant orientation of internal bounding faults within the two structural domains. The general high-angle, faulted character of the western transform belt provides an environment with enhanced potential for magma introduction. In contrast, the general sub-horizontal, tectonically-stacked structural character of the eastern belt would be much more impervious to vertical melt migration.

Based on this distinction it appears that altered felsic dikes could act as an additional guide for locating gold veins only in areas west of the 'transform truncation zone'. Even in these areas, high-level intrusions, although locally conspicuous in some mines, are not always present at the individual mine scale, and as a result should not be considered at that detail of investigation. It is reasonable to postulate that sericite-carbonate-pyrite altered high level felsic intrusions may indicate proximity to gold quartz veins where found in suitable lithotectonic settings. That is, in association with fault-bounded, tectonically emplaced, oceanic arc crust close to major tectonic breaks with evidence of pervasive carbonate alteration.

An examination of the relative rates of crustal exhumation or uplift between the two structural domains provides a possible explanation for the apparent contrasting tectonic environments of vein formation. Different rates of uplift between the two domains may result from several contributing factors. The high-angle structural style of the western domain would be much more conducive to vertical translation. In addition, this domain is also more directly impacted by crustal growth and uplift, that with time moves progressively away from the older Paleozoic continental margin. In contrast, the continental foreland or eastern domain is further removed from these influences, and would be presumably more rigid and also less predisposed to vertical fluctuations.

The change in the age-pattern of mineralization from west to east across the Cordillera (Figures 9.3 and 9.4) can indicate the relative differences in the rates of crustal uplift between the two structural domains. Late syn-orogenic deposits within the western transform domain become progressively older from west to east. The relative age and crustal position of the apparent anoroginic deposits is clearly not in sync with this otherwise uniform pattern of progressive aging of deposits west of the 'transform truncation zone'. The oldest and most eastern, 160 to 170 Ma mineralizing event within the western structural domain is 30 to 40 million years older than their neighbors to the east.

It is suggested that due to insufficient uplift and erosion, the Early Cretaceous plutonic and metamorphic roots of the system responsible for the ore bearing fluids of the apparent anorogenic deposits has not yet been exhumed. Therefore these differences are not considered to be the result of contrasting plate-tectonic processes, but merely a reflection of how similar vein forming processes are expressed in distinctly different lithotectonic environments.

This explanation for the apparent enigma of similar gold-quartz vein deposits forming in two distinct paleogeographic environments helps maintain a long held view. That view being, that the many similarities amongst these deposits irrespective of location or age strongly supports comparative processes of gold-quartz vein formation.

It is intriguing that the apparent anorogenic deposits are only slightly younger, and possibly overlap the age of Latest Jurassic Nevadan mineralization in California gold-quartz vein deposits. Why does the Nevadan orogeny appear to be a US specific event, and apparently unlike all previous orogenies which affected rocks of both the Canadian and US Cordilleras. A possible explanation is that the apparent anorogenic deposits reflect the northern extent of that event. It is also intriguing that most of the apparent anorogenic deposits of the Canadian Cordillera, like the California deposits, are regionally situated near the bounding structure between oceanic and continental margin rocks.

DISCUSSION

Research into gold-quartz vein deposits over the last two decades has focused primarily on determining the source of the gold-bearing fluids and their paleo-tectonic environment of formation. The initial stage of this research was successful in characterizing the physiochemical nature of the mineralizing fluids and found that there were remarkable similarities amongst gold quartz vein deposits globally, irrespective of their age (Groves and Phillips, 1987; Kerich and Wyman, 1990; Barley, *et al*., 1989; Kerrich and Wyman, 1990; NUNA conference volume, 1991; Kerrich, 1994). Deposits of both Archean and Phanerozoic ages are structurally controlled, have similar mineralogical and geochemical characteristics, display comparable fluid composition with broadly similar pressure and temperature conditions of formation with the relative timing of mineralization closely following post-peak metamorphism. Böhlke (1989) aptly summarized these findings when defining these deposits as part of a global class of:

"structurally discordant syn- to postmetamorphic gold-bearing quartz veins with low base metal contents, formed from through-flowing, high ^{18}O, low salinity,

CO_2-rich aqueous fluids at approximately 250° to 450°C and 0.5 to 3+ kilobars."

As a result of these defined similarities between the Archean and Mesozoic gold-quartz veins, deposit models that have evolved over the last decade have attempted to apply models of global applicability (Kerrich and Wyman, 1990; Kerrich and Cassidy, 1994; Poulsen, 1996; Groves *et al*., 1998 Poulsen *et al*., 2000) . This global model approach was also heightened by the growing realization that Archean greenstone terranes may have formed by processes of continental margin accretion analogous to those of the Cordilleran margin (Colvine, 1989; Hodgson and Hamilton, 1989; Barley *et al*., 1989; Hoffman, 1991; Corfu, 1993; Sutcliffe *et al*., 1993; Wang *et al*., 1993). An obvious draw-back to this approach is that geological features inherent to only one of the age groups become diluted or even lost when all information from the two are combined.

Irrespective of the likelihood that the origin of the two main age groups of gold-quartz veins may have formed through similar processes of continental margin accretion they display some distinct lithologic and tectonic characteristics in their present settings.

The major differences between the two age groups include structural setting and nature of the host lithologies. There are also some minor differences in vein mineralogy between them. Copper and zinc are common and locally conspicuous sulphide minerals in Mesozoic gold veins (Appendix III) but are rare in Archean deposits (Groves, 1993). Scheelite and tourmaline are common accessory minerals in Archean deposits (Robert and Poulsen, 1997) but are rarely identified in those of Phanerozoic age.

The most obvious distinction relates to the attitude of regional fault zones associated with the gold quartz vein mineralization. Mesozoic gold veins occur in moderate to shallow dipping collisional suture zones in continental margin mobile belts (i.e. accreted margins). Suture zones are characterized by dismembered ophiolitic lower crustal and upper mantle remnants, that mark major breaks and intercalations between diverse assemblages of arc rocks, subduction complexes and continental margin clastic wedges. In contrast, Archean gold quartz vein deposits are contained regionally in major, steep oblique slip fault systems within stable cratonic terranes.

The tendency to transfer the requirement of high-angle faults to Phanerozoic quartz vein deposits by proponents of the meteoric gold vein model serves as a relevant example of how lithotectonic characteristics of Archean aged deposits cannot be directly transferred to those hosted in Phanerozoic terranes. The meteoric model for gold quartz-vein mineralization is one that has been widely publicized for deposits in the Canadian Cordillera by Nesbitt and co-workers (Nesbitt *et al*., 1986, 1989; Nesbitt, 1988, 1992; Nesbitt and Muehlenbachs, 1989: Madu, *et al*., 1990). This model is based primarily on the bulk fluid inclusion isotopic composition of quartz and carbonate. It proposes that mineralizing fluid results from downward circulation of meteoric waters through the crust to the brittle-ductile transition zone to be focused upward along major transcurrent fault zones with various metals deposited at different depths. Contamination by secondary inclusion due to the bulk extraction method used to obtain the isotopic data (Pickthorn *et al*., 1987; Perring *et al*., 1987; Kerrich, 1989a), as well as problems with hydrostatic meteoric fluids being able to overcome lithostatic pressure (Kerrich, 1991) have been several points of concern with the meteoric model. As a result it has gained little acceptance for application to Archean (Perring *et al*., 1987; Franklin and Green, 1991) or Mesozoic gold-quartz vein deposits (Goldfarb *et al*., 1988; Böhlke, 1989; Leitch and Godwin, 1988; Leitch , 1990; Elder and Cashman, 1992).

A fundamental geological implication of the meteoric model is that gold-quartz vein deposition is genetically related to major, high-angle, transcurrent fault zones. The Pinchi Fault zone is typically promoted as a type example for such a structure related to gold vein mineralization in British Columbia. The Snowbird prospect, is suggested as the type example of gold-quartz vein inferred to be related to the Pinchi Fault. However this gold vein occurrence is situated roughly 25 kilometres from the Pinchi fault and is associated with a low-angle shear zone. In the Archean, gold deposits that are hosted by subsidiary brittle-ductile faults related to regional first-order transcurrent structures are typically constrained to within several kilometres of the primary fault zone (Eisenlohr *et al*., 1989).

An additional premise of the meteoric model is that the timing of gold mineralization at the Snowbird is synchronous with mercury mineralization at the Pinchi Lake mine. Mineralization at the Snowbird gold prospect (Chapter 3) is well constrained at Middle Jurassic (160 to 163 Ma). This predates the age of mercury mineralization at the Pinchi Lake mine, which is at the earliest, post-Cretaceous, as this mineralizing event effects sedimentary rock of that age (Patterson, 1977) and is likely younger, possibly Eocene (Ash, 1996). This age and spatial relationships suggests that mercury mineralization along the Pinchi Fault is unrelated to the much older gold vein mineralization at the Snowbird prospect, which is located a significant distance from it.

A number of other areas in the Cordillera for which inferred relationships of gold veins to high-angle transcurrent faults have been suggested to support the meteoric model include both the Mother Lode and Alaska Juneau deposits. Böhlke and Kistler (1986) are referenced by Nesbitt (1988) to support a transcurrent fault relationship for gold-vein deposits in the Mother Lode belt. However no evidence is presented by these authors to support such a relationship. On the contrary, Weir and Kerrich (1987) indicate that deep seismic reflection data suggests the Melones fault zone is a low angle structure, dipping 35° east for a depth of up to 40 km. The Coast Range lineament was the inferred meteoric gold-related transcurrent fault for the Alaska-Juneau deposit. More recently however, this linear topographic feature has been identified (Miller *et al.*, 1995) as a combination of separate and independent linear elements, and not a major crustal break as previously interpreted. The gold related regional structure is now considered more likely an easterly-dipping, terrane-bounding shear zone.

There appears to be little evidence to support a genetic relationship between gold-quartz vein mineralization and large transcurrent fault zones in the North American Cordillera. Where there is a regional association such as the Yalakom Fault northeast of the Bralorne-Pioneer mine, or the Pinchi Fault east of the Snowbird prospect, the transcurrent faults postdate the age of mineralization and in both cases the deposits are considerably removed from these mercury-rich structures which are characteristically devoid of gold.

Another fundamental difference between Phanerozoic and Archean gold-quartz vein deposits is the nature of host lithologies and their inferred tectonic significance. Ultramafic rocks associated with Phanerozoic deposits are exclusively remnants of lower oceanic crust or subcrustal mantle and therefore signify emplacement along a deep crustal fault. Ultramafic rocks associated with Archean lode-gold deposits are dominantly komatititic volcanics (Pike, 1976; Hodgson *et al.*, 1982) and therefore a similar tectonic interpretation is not valid. Arguments suggesting that there is no genetic link between host rocks, e.g., ultramafic rocks, and gold-quartz vein mineralization (Kerrich, 1991, 1993), have been the result of this global approach.

Ultimately a distinct lack of similar ultramafic ophiolitic rocks in Archean greenstone belts has contributed to their lack of recognition when comparisons have been made between the two age groups (Boyle, 1979; Hodgson, 1982; Poulsen *et al*., 1992, Poulsen, 1996; Robert, 1996; Groves *et al*., 1998). Ophiolites are a component of Cordilleran margins that in addition to being a common host for gold-quartz vein deposits, have also played a major roll in development of plate-tectonic, terrane accretion concepts. The absence of such rocks in the older greenstone belts would imply that conditions of crustal accretion must have been in some ways different. It would seem therefore that an explanation of these differences is required before direct paleo-tectonic comparisons between the two age groups can be made.

A pragmatic view of all gold-quartz deposits which addresses obvious lithotectonic differences suggests that the global approach may have detracted from providing any single viable exploration model, or models. It would appear that the pendulum of consensus may have swung too swiftly in trying to adopt a universal deposit model for gold-quartz veins based on their known similarities. A deposit model approach with an emphasis on the descriptive features of North American Cordillera deposits only, within a consistent plate-tectonic framework, indicate that a combination of distinctive geologically-definable characteristics can be used to focus exploration. The exact chemical or physical parameters that explain these persistent lithological relationships may not be fully realized, but clearly defining such relationships is a useful first step.

The geodynamic setting of gold mining camps discussed in this report appears to support an environment of vein formation where tectonically thickened crust is affected by metamorphism, partial melting and related magmatism in response to an orogenic event. Gold-quartz veins appear to form late in this process and are hosted within or proximal to structural zones developed by tectonic emplacement of oceanic lithosphere onto either continental margins (Slide Mountain) or are intercalated with both arc complexes and disrupted chert argillite deposits (Cache Creek and Bridge River). These fault zones appear to act as pathways and/or structural traps for mineralizing fluids. The relationship between the age of the host structure and that of mineralization is widely varied. The Nevadan aged fault zones along the Mother Lode belt are relatively close to the interpreted age of mineralization hosted within them. In Atlin, Snowbird and possibly Rossland the mineralization most likely formed shortly after Middle Jurassic crustal shortening. In other deposits, however, the age of mineralization is considerably younger than the age of initial development of the host structural zone. Terrane bounding structures associated with vein mineralization in Slide Mountain Terrane and spatially associated rocks are at least 25 to 30 (considering Middle Jurassic tectonism) and may be as much as 100 million years (considering Late Permian-Early Triassic tectonism) younger than the vein mineralization contained within them.

It would seem that refinement of any model that relates gold-quartz vein mineralization to geologic process, specifically tectonic environment of formation, will be gained from modern studies of gold-quartz vein deposits in accreted Phanerozoic terranes. Tectonic synthesis of Archean deposits is based in large part on secular variations in both the age and composition of greenstone magmatism, which is supported largely by empirical geochemical data (Kerrich, 1994). In contrast accreted Phanerozoic terranes maintain a tectonic integrity with a relatively intact record of collisional lithologic and tectonic relationships. These younger belts enable in general more precisely constrained isotopic age data for both hydrothermal and magmatic activity. Unlike the Archean settings, these younger belts are supplemented by biostratigraphic data to further constrain the relative timing of related tectonic activity. Kerrich (1994) indicates that gold mineralization in the Archean Superior province is related in space and time to accretionary tectonics over a 50 million year period (2720-2670). In contrast, within the North American Cordillera five distinct and temporally restrictive episodes of orogenic activity with associated gold vein mineralization are recognized (Figure 9.4). This is within a time interval that is only double the period of the singular Archean mineralizing event.

SUGGESTIONS FOR FUTURE STUDY

Several areas are worthy of consideration to further constrain relationships for the gold-quartz vein deposits described. In some areas there are still outstanding questions relating to the lithotectonic character and age of host rocks for certain deposits. Examples with difficiencies in this area include Rossland, Barkerville and the Grass Valley camps.

The relationship of gold veins to high-level felsic dike rocks is something that requires particular attention in most camps. Accurately constraining the magmatic, and where applicable hydrothermal alteration ages, as well as chemical composition of these dikes is necessary to constrain potential genetic relationships between the two.

For some deposits, more modern analytical techniques are required to make informative comparisons. In particular the nature and variations of metallic minerals associated with these vein systems requires updated evaluation to accurately compare the general deposit population. Few detailed microprobe analyses have been conducted on sulphide mineralogy from most of these Phanerozoic vein systems.

In the Rossland area characterization of the greenstone unit hosting the gold veins north of the I.X.L.-Midnight deposit would help to establish its paleo-tectonic character and possible genetic link to the ultramafic cumulate rocks with which they are spatially associated.

CONCLUSIONS

(1) On the basis of host lithologies, gold-quartz veins throughout the Canadian and US Cordillera can be divided into two main types; 'ophiolite-hosted' and 'mixed mafic igneous-sedimentary-hosted' deposits. Ophiolite-hosted gold veins that include Bralorne, Grass Valley, Alleghany, Atlin and Cassiar are contained in fault-bounded, internally imbricated blocks of oceanic igneous crust. The larger, more coherent blocks or lenses host the most significant gold producers mainly because veins within them are well-developed and continuous. Listwanite-altered ultramafic rocks are consistently associated with exceedingly rich, gold-quartz veins. The gold-quartz veins are rarely hosted by the altered ultramafic rocks but are generally contained in tectonic blocks of igneous oceanic crustal rocks (gabbro, diabase, mafic volcanics) in close proximity to them. Mixed mafic igneous-sedimentary hosted gold vein deposits include most of the significant deposits of the Mother Lode belt, Alaska Juneau and Carolin. Host rocks of these deposits consist of Mesozoic sequences of alternating mafic igneous rocks with slate and phyllite. These deposits are typically of lower grade and often associated with vein marginal replacement ore.

(2) Most large placer gold deposits in the North America Cordillera show a close spatial relationship to ophiolitic crustal rocks within, and marginal to, terrane-collisional boundaries. Placers with significant production in the Canadian Cordillera, *i.e.*, Barkerville, Atlin and Klondike, all have remarkably consistent lithotectonic relationships in which the gold often resides immediately below a flat-lying collisional suture zone, generally within 500 meters of the suture. Suture zones are often characterized by the presence of listwanite-altered ophiolitic rocks commonly forming isolated klippen above basement rocks. This consistent relationship with remnants of ophiolitic rocks in the hangingwalls of these suture zones combined with the fact that coarse native gold is found associated with such rocks is considered more than coincidence and offers a viable explanation for the source of coarse placer gold.

(3) Distinctive differences involving spatial associations with high-level felsic intrusive rocks and apparent differences relating to tectonic environment of formation enables subdivision of Canadian Cordilleran gold-quartz veins into two main types. 'Late syn-orogenic' gold veins which are often associated with coeval, structurally controlled high-level felsic intrusions, and appear to form during late stages of orogenic activity. In contrast, 'apparent anorogenic' deposits show no, or very limited associations with high-level felsic intrusive rocks, and appear to form during tectonically dormant stages of crustal activity. Differences do not result from mineralizing fluids being generated by different processes but from fluids generated by a similar process introduced into one of two major lithotectonic regimes. Differences in the regional structural fabric of the two major regimes accounts for the observed primary relationship with structurally controlled felsic intrusions. Differences in relative rates of crustal uplift between the two major lithotectonic regimes, subsequent to the mineralizing event, account for the apparent differences in paleo-tectonic environment of formation. All deposits are regarded as being late syn-orogenic.

(4)The vertical and lateral extent of the vein systems in the individual deposits appear to be influenced by the orientation of large-scale structures within the distinctive lithotectonic regimes. In deposits where fault zones bounding major lithologic units are relatively flat-lying, the vertical continuity of the vein systems is restricted (*e.g.*, Cassiar, Barkerville, Klondike). In contrast, where the related bounding faults are moderately to steeply-inclined the vein systems are well developed vertically (*e.g.,* Bralorne, Rossland, Grass Valley, Mother Lode and Alaska-Juneau).

(5) Very high-grade, coarse native lode gold in the North American Cordillera is characteristically found in quartz veins hosted by listwanite-altered, igneous ophiolitic crustal rocks in proximity to listwanite-altered ultramafic rocks. Igneous rocks comprise metagabbro, metadiorite and metadiabase (amphibolite and greenstone) that form competent fault- bounded tectonic blocks within the accreted ophiolitic assemblage. Ultramafic rocks consist of either variably serpentinzed harzburgite or cumulate dunite and wehrlite. These units form either large bodies in which listwanite alteration is localized to zones along faulted margins or may form thin discontinuous lenses along thrust fault zones.

(6) Visible free gold is found only in quartz veins and is usually concentrated along deformed vein margins or within brecciated and ribboned portions of veins, commonly in association with other sulphide minerals. Invisible gold ore can be locally developed in listwanite-altered igneous wall rocks in association with disseminated pyrite and arsenopyrite. Pyrite and arsenopyrite are the earliest sulphides, deposited mostly during early stages of quartz vein development. Other sulphides, including sphalerite, chalcopyrite, galena and sometimes tetrahedrite and bismuth minerals, are found only in the quartz veins and are generally associated with younger gold-quartz-carbonate veins cutting earlier-formed quartz.

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APPENDIX I

TERMINOLOGY

This Appendix deals with the terminology relating to both the gold-quartz vein host rocks and related alteration, i.e. ophiolite and listwanite. The terms, their usage and history are discussed in detail to provide a better background to understand the literature.

OPHIOLITE

The terms 'ophiolite' and 'ophiolite suite' are defined in the current Glossary of Geology (Bates and Jackson, 1987) as in preceding volumes (Gary *et al.*, 1972; Bates and Jackson, 1980):

Ophiolite - "*a group of mafic and ultramafic igneous rocks ranging from spilite and basalt to gabbro and peridotite, including rocks rich in serpentine, chlorite, epidote and albite derived from them by later metamorphism, whose origin is associated with an early phase of the development of a geosyncline. The term was originated by Steinman in 1905 (Miyashiro, 1968, p. 826)".*

Ophiolite suite - *"the association of ultramafic rocks with coarse-grained gabbro, coarse grained diabase, volcanic rock and red radiolarian chert in the Tethyan mountain system.*

These definitions are somewhat misleading as they apply terminology (*e.g.* geosyncline) which is out dated and evokes pre-plate tectonic views for the processes active along continental margins. No reference is made to the origin of an ophiolite as oceanic lithosphere, nor is there any recognition of the inherent tectonic emplacement history that must accompany any ophiolite. The definition given for 'ophiolite suite' suggests that the association is unique to the Tethyan Mountains, but ophiolite suites are described from major phanerozoic orogenic belts throughout the world.

The "ophiolite model" for oceanic lithosphere was defined at a Penrose Conference in 1972 (Coleman, 1977). Ophiolites were considered as crust generated at mid-ocean ridge spreading centers which then moves away toward continental margins to be subducted into the mantle. Under certain plate boundary conditions, slabs of oceanic crust detach and override (obduct) continental margins.

Since that time a wealth of data has been amassed from studies of both ophiolites and oceanic crust. These findings have been summarized in a recent Geoscience Canada series, 'The origin and evolution of oceanic lithosphere' (Malpas and Robinson, 1996, 1998, 2000; Robinson and Malpas, 1999).

The most significant advancement from this work is the realization that most ophiolites are characteristically not formed at mid-ocean ridges as earlier workers inferred. The majority have magma compositions suggesting that they were generated in a mantle slab above a subduction zone (supra-subduction zone environment). Most supra-subduction zone ophiolites are only slightly older than their time of obduction.

HISTORY

The early history and evolution in the understanding of the term 'ophiolite' has been described in some detail by Coleman (1977). As a geological term 'ophiolite' originated in Europe in the early 1800s where it was initially used to describe the rock serpentinite (Greek root "ophi" meaning snake or serpent). It was later elevated in status by Steinmann (1927), to characterize a genetically related assemblage of mafic and ultramafic rock types within alpine orogenic zones, 'the Steinmann trinity'. By the mid 1960s the view that ophiolites represented early outpourings of basaltic magma along rifts in eugeosynclines (Aubouin, 1965) was generally advocated by most European geologists. Following emplacement, the differentiated magma generated the apparent stratigraphic sequences from peridotite through to gabbros and finally basalts.

Pertinent to the current discussion is the divergence of historic scientific opinion regarding ophiolites, that existed between European and American geologists from the late 1920s to the advent of plate tectonics in the late 1960s. European geologists emphasized the close spatial and genetic relationship of peridotite, gabbro and pillow basalt and associated pelagic sediments (ophiolites) while American geologists considered peridotite separate from associated mafic rocks, thus not preceiving a common environment of origin.

North American geologists adopted the 'alpine peridotite' concept as proposed by Benson (1926) which suggested that peridotites and serpentinites were plutonic in origin and intruded folded geosynclinal sediments within orogenic belts. Subsequently, Hess (1938) proposed the existence of low temperature, hydrous, primary peridotite magma, largely to reconcile field relationships that lacked evidence of high temperature contact aureoles around peridotite. Bowen and Tuttle (1949) later showed experimentally that it was not possible for hydrous peridotite magma to exist under 1000^{o} C, thus eliminating the possibility of a low temperature ultramafic magma. Toward the late 1960s the prominent view of American geologists on the origin of ultramafic rocks as summarized by Wyllie (1967) was that they originated either as: (1) differentiation of basic liquids form an ultramafic "mush" which either formed a cumulate sequence or invaded as 'lubricated mush;" or (2) formation of a primary peridotite magma within the mantle which then intruded into the crust as mush or was emplaced as a solid by tectonic movement. The basic problem of plutonic (mantle-derived) peridotites exhibiting only embarrassingly slight or no contact metamorphism, remained unresolved at that time.

The current view of ophiolites is well rooted in the development of plate tectonic theory during the early 1970s. As pointed out by Coleman (1977),

"The long standing ophiolite controversy with its multiple theories was one of the first petrotectonic problems to yield new solutions within the framework of the plate tectonic theory."

He concluded that,

"The ophiolite concept of Steinmann, modified by plate tectonics and illuminated by modern petrology, remains intact and is essential to our understanding of continental margins, ancient seas, and major suture zones."

The application of plate tectonics to oceanic crust replaced previous concepts that ophiolites represented the earliest magmatic phases of an ensialic geosyncline, which required them to be autochthonous and interlayered with geosynclinal sediments (Aubouin, 1965). It resolved the paradoxical occurrence of high–temperature ultramafic and mafic rocks within sediments with no evidence of contact metamorphism.

OPHIOLITE SUITE

Where emplaced as relatively intact segments of oceanic lithosphere, ophiolites comprise a differentiated igneous crustal section of intrusive to extrusive rocks with overlying pelagic sediments and underlying metamorphic mantle (Figure A-1). A generalized model of constructive plate margin magmatic and deformational processes has developed (Gass, 1980; 1990).

MANTLE SECTION

The development of ocean crust at a spreading centre is considered to result from partial melting of upward convecting mantle (Figure A-1). As relatively fertile lherzolitic mantle moves upward it undergoes from 8 to 20 % partial melting to produce Mg-rich piritic melts. Progressive upward movement causes the volume of melt fraction to increase until eventually coalescing into discrete magma pockets in which olivine and chromite are precipitated. At sometime, most likely that of connective mantle overturn, melt is released into crustal magma chambers.

Metamorphic mantle rocks remaining after partial melting, commonly referred to as residual mantle, consist largely of highly refractory clinopyroxene-poor harzburgite tectonite. Harzburgite is an ultramafic rock consisting of olivine with lesser, though locally dominant, orthopyroxene and trace to minor chromite. Tectonite deformation structures and textures suggest development during solidus to hypersolidus conditions for plastic flow (1000-1200^{o}C) and are attributed to mantle convection are typical of most ophiolite mantle sections (Nicolas *et al*., 1980; Nicolas, 1986). Ophiolitic mantle rocks either forming the base of well persevered ophiolites or occurring as dismembered remnants are dominated by variably serpentinized residual harzburgite tectonite containing subordinate pods or lenses and dikes of dunite.

CRUSTAL SECTION

The petrological Moho separates oceanic crust from the uppermost mantle. It defines a change from metamorphic mantle peridotites to lower crustal cumulate peridotites. In contrast, the seismic Moho defines the change in rock type from peridotite to gabbro within the lower plutonic section of the crust (Figure A1A).

Oceanic crust is divisible into a lower plutonic section, an intermediate sheeted dike section and an upper extrusive lava sequence that is interbedded with and overlain by pelagic sediments.

The lower portion of the plutonic section comprises a differentiated sequence of ultramafic to mafic, layered to massive, cumulate rocks that range upward from dunites to wehrlites to gabbros. Higher in the section, cumulate gabbros give way to massive, isotropic to varitextured, high-level gabbros and plagiogranites. This plutonic crust forms in a dynamic environment in which magma chambers are periodically replenished by mantle melts only to be depleted by dike injection and extrusion of lava. Most crustal sections display a range of multiple intrusive relationships suggesting semi-continuous magma input and multiple magmatic events (Figure A1).

The transition from high-level gabbros into sheeted dikes occurs through an interval of up to several 100 metres of sheeted dikes with gabbro screens. A transition zone of similar thickness occurs at the top of the sheeted dike interval with screens consisting of lava.

TECTONIC SETTING

Although relatively coherent ophiolites with well preserved oceanic crustal sections are known, these are not typical of ophiolite suites in most orogenic belts. As stated in the original definition for ophiolites in 1972 (Coleman, 1977):

"Faulted contacts between mapable units are common. Whole sections may be missing. An ophiolite may be incomplete, dismembered or metamorphosed ophiolite".

Structural complexity and dismemberment of ophiolites into a number of more or less intact structural blocks is common and results from syn- and post-emplacement faulting and folding. Such rocks are truly allochthonous and typically record a complex polyphase deformational history.

Other regions of the world where ophiolites have been emplaced onto the continental foreland display features closely analogous to foreland fold and thrust belts (Lippard *et al*., 1986). Thrusting and nappe emplacement develops progressively from an external (outboard, oceanic) area towards an internal (inboard) continental region. As a result, the furthest-traveled nappe occurs highest in the sequence with the lowest thrust slices, the last to be detached and moved. Incorporation of successively lower thrust slices gives rise to the characteristic "piggy-back" style of thrusting. Differences from this generalized foreland fold and thrust tectonic style result from factors such as the lenticular nature of the thrust slices and probable irregular geometry of the surface over which the nappes are emplaced.

This generalized style of structural stacking gives rise to reversed ophiolite stratigraphy so that sedimentary units are beneath volcanics, which sit below plutonic rocks and ophiolitic basement with ultramafic mantle rocks com-

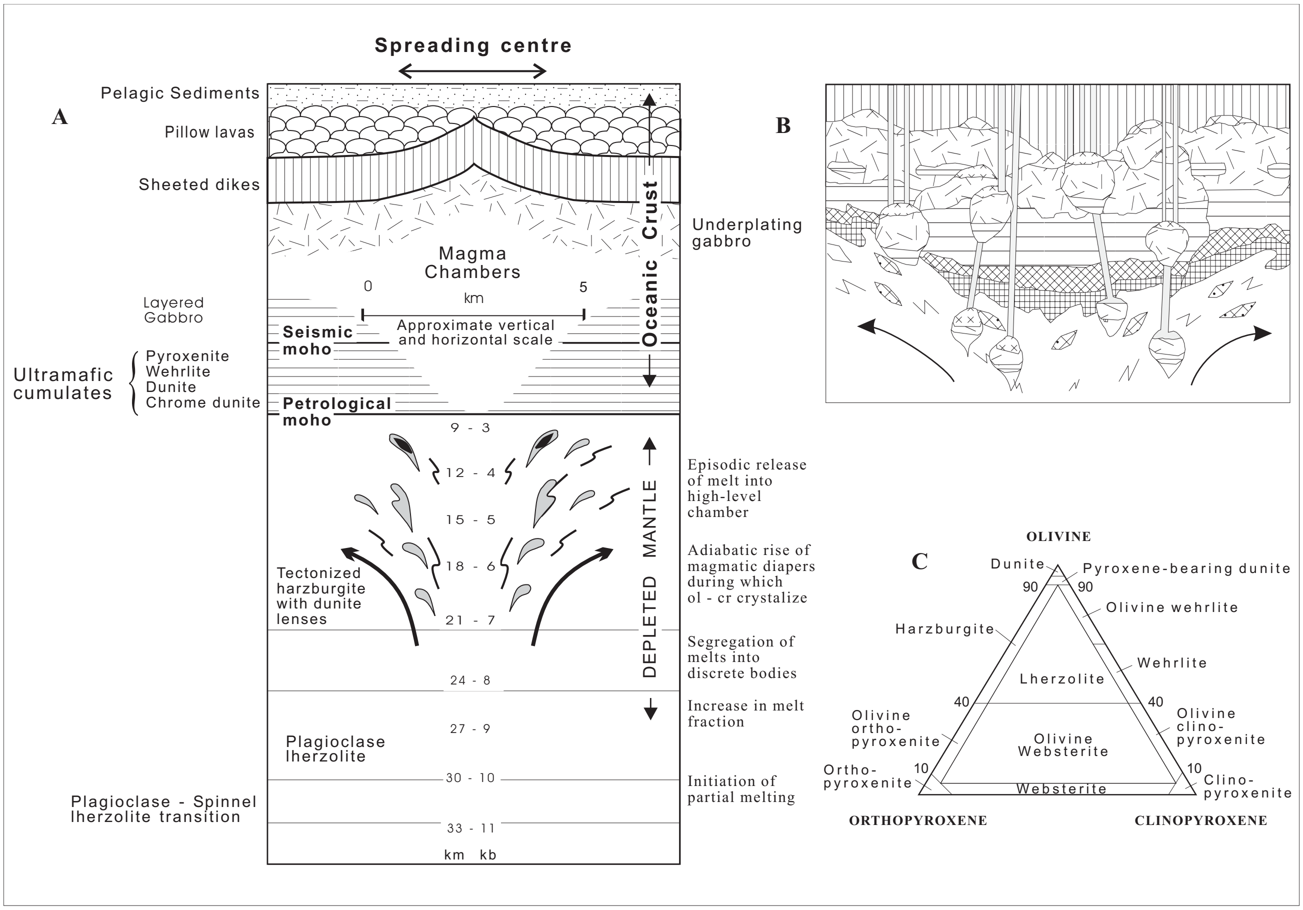

Figure A.1. Idealized oceanic crustal section illustrating the rock types and their relative position of formation within an idealized oceanic spreading centre, modified after Gass (1980), B. Multiple intrusive character of oceanic spreading centers after Ash (1990), C. Classification and nomenclature of ultramafic rocks in the olivine-orthopyroxene-clinopyroxene prism after Streckeisen (1975).

monly comprising the highest structural slices. Reversed ophiolite stratigraphies of this type are characteristic of most ophiolitic assemblages in British Columbia.

LISTWANITE

Listwanite (from the Russian "listvenity") is a term that until the last two decades has been used almost exclusively by Russian geologists to describe carbonate±sericite±pyrite altered ophiolitic mafic and ultramafic rocks that are veined by hydrothermal quartz±carbonate (Boyle, 1979). The term was coined by G. Rose in 1828 (Hall and Zhao, 1995) to describe the type locality at Beresovsk in the Ural Mountains of central Russia.

A review of limited translated Russian literature (Goncharenko, 1970; Buryak, 1972; Kuleshevich, 1984) and European publications applying Russian terminology (Capedri and Rossi, 1973; Pipino, 1980; Ivan, 1982; Aydal, 1990) indicates that there is an established classification scheme to describe different listwanite types. Reference by Goncharenko (1970) to a 149-page Russian textbook by Kashkai and Allakhverdiev (1965) devoted to the genesis and classification of listwanite supports this conclusion.

A sample of some of the terms encountered and their interpreted meanings include:

Ortholistwanite and **epilistwanite** (Goncharenko, 1970)

Ortholistwanite: carbonatized ultramafic rocks

Epilistwanite: rocks immediately associated with ortholistvenite that show similar alteration effects but differ in secondary mineralogy as a function of their differing primary mineralogies.

Allometamorphic and **autometamorphic** listwanites (Aydal, 1990).

Allometamorphic listwanites are those immediately associated with a granitic intrusion. They have a high potassium content, reflected in the presence of micas (muscovite, fuchsite) which are said to be introduced by hydrothermal fluids from the granitic intrusion.

Autometamorphic listwanites are potassium poor as reflected by a lack of secondary mica.

These examples are introduced simply to illustrate the complexity of usage of the term listwanite. More significant than the use of specific terms to characterize the different listwanite types is the way in which the rock types of the alteration suite are described. Listwanite described in the Russian and European literature is referred to in terms of the relative abundance of secondary mineral constituents, for example talc-carbonate listwanite or quartz-carbonate-mariposite listwanite.

The earliest, detailed account of the term 'listwanite' in North American literature was most likely that given by Boyle (1979, page 210).

"Basic and ultrabasic rocks, heavily carbonatized, sericitized and pyritized are called listwänite by Soviet geologists. The term listwäentinization is commonly used in the Ural goldfields and in other auriferous districts of the U.S.S.R. Kashki (1964) and Goncharenko (1970) have discussed the zoning and chemistry of listvenites in some detail. Briefly the metasomatic development of listvenite rocks follows the sequence: (1) initial formation of serpentinite-actinolite-chlorite rocks (with few carbonates) grading to serpentiite-chlorite-carbonate rock; (2) intermediate stage of formation of serpentinite-brucite-carbonate rocks containing hematite and quartz and grading to talc-chlorite-carbonate and talc-carbonate rocks; (3) listwänite stage of the mariposite listvenite.

The main characteristic of listwäentinization is the conversion of serpentinite into talc and/or carbonates. The chemical composition of listvenite is variable and is controlled by zonal factors and the composition of the host rocks. In general there is an introduction of K, Ca, Al, CO_2 and H_2O and an abstraction of SiO_2."

Additional insight into the application and characterization of the term is provided by Boyle's description of gold quartz vein occurrences in the Urals of Russia (page 105):

"Gold occurs at many places along the Ural chain, mainly on its eastern flank. Placers were formerly the main type of deposit, being derived mainly from a great variety of gold quartz veins and pyritized and silicified zones in highly folded and faulted gneisses, schists, phyllites, quartzites, listwänite (quartz-sericite-talc-calcite-dolomite rocks derived from the alteration of serpentinites and associated intrusives including serpentinites, gabbro, norite and diabase), granite, syenite, various types of porphyries and highly altered (sericitized and pyritized) fine-grained rocks called 'beresites.'…. In the northern and central parts of the Urals the gold deposits appear to show a close relationship to the acidic types of dikes and other intrusions."

Boyle's understanding of the Russian usage, translated from the pre-plate tectonic eugeosynclinal view, is significant in that listwanite denotes carbonate-quartz-sericite altered ophiolitic rocks *i.e.* "alteration of serpentinites and associated intrusives, including serpentinites, gabbro, norite and diabase", (underlined = ophiolite). Russian geologists using listwanite terminology viewed ultramafic-mafic rock associations as a related igneous complex, consistent with the European pre-plate tectonic view. The eastern slope of the Urals has been long regarded (Ivanov, *et al.*, 1979) to be a single great ophiolite belt with a length greater than 2000 km and a width up to 200 km or more.

Of particular interest in the application of alteration terminology used by Russian geologists is the way in which they have adopted distinct alteration names to distinguish between hydrothermally altered rocks of the ophiolite association 'listwanite', from alteration products of genetically unrelated post-accretionary felsic intrusive rocks referred to as 'beresites'. This distinction is a significant and useful concept as the spatial association of both these rock types is important to the development and identification of economically significant gold quartz veins.

Although the term listwanite existed in geological dictionaries and was described by Boyle (1979) when characterizing Russian gold deposits, prior to the mid 1980s the term was rarely used by North American geologists. Leaming (1978) was among the first to apply the term in British Columbia during a discussion of jade deposits in the province. Hopper (1984) used it to describe carbonate-altered rocks at the Cassiar gold camp.

Broader usage of the term is most likely attributed to several publications by Buisson and Leblanc (1985, 1986, 1987) and Leblanc (1986) describing listwanite (spelled listwaenite by these authors) alteration of ophiolite-hosted gold-quartz vein deposits in Northwest Africa, west central Saudi Arabia and Northern Italy. These authors were possibly the first to document the relationship between listwanite-associated gold-quartz vein mineralization and ophiolites. These publications have introduced the term into North American literature and have ultimately contributed to confusion in its usage. Listwanite was portrayed and often introduced as simply "carbonate-altered ultramafic rocks". The restriction of listwanite by these authors to carbonate altered ultramafic rocks, may be simply due to the fact that their studies focused entirely on ultramafic rocks. The likely unintended implication was that listwanite refers to only carbonate altered ultramafic rocks. This is clearly inconsistent with Russian usage that includes altered ultramafic and mafic rocks (Goncharenko, 1970; Buryak 1972; Boyle, 1979; Kuleshevich; 1984).

The variety of spellings that have appeared for the term in the geological literature, including listwaenite, listwanite, listvanite and listvenite, are attributed by Halls and Zhao (1995) to confusion in initial translation from Russian to German. They suggest that spelling of the word correctly translated to English should be 'listvenite'. Despite this suggestion, in order to be consistent with all previous spellings in North American geological dictionaries (Holmes, 1928, listwänite; Trush, 1968, listwanite; Gary *et al.*, 1972, listwänite; Bates and Jackson, 1987, listwanite) and publications providing detailed descriptions (Boyle, 1979, listwänite) the spelling 'listwanite' is maintained.

DICTIONARY DEFINITIONS

The term listwanite is currently defined in North America (Bates and Jackson, 1987; Jackson, 1997) as;

"a carbonatized and variably silicified serpentinite, occurring as dikes in ophiolite complexes in the Arabian shield"

Carbonate-quartz-sericite altered mafic and ultramafic rocks considered to be listwanites have been observed throughout both British Columbia and Newfoundland by the senior author. Similar rocks are described in the literature on gold occurrences in ophiolitic assemblage throughout the world (Boyle,1979) and in Russia (Goncharenko, 1970; Kuleshevich, 1984); Italy (Pipino, 1980); Turkey (Aydal, 1990); Morocco and Saudi Arabia (Buisson and Leblanc, 1985; Leblanc, 1986); Mali and Saudi Arabia (Buisson and Leblanc, 1986); Czechoslovakia (Ivan, 1982); Ireland (Halls and Zhao, 1995) and California (Knopf, 1929; Johnston, 1940; Böhlke and Kistler, 1986; Weir and Kerrick, 1987; Landefeld, 1988; Böhlke, 1989).

Nowhere is there any evidence to suggest that the altered serpentinized ultramafic rocks are, or ever were, dikes. Field observation and literature review indicate that in all cases the characteristically planar geometry of the altered mafic and ultramafic rock is considered to be controlled by a planar fracture or fault zone which has introduced a hydrothermal fluid, causing pervasive alteration of the mafic and ultramafic igneous or metamorphic hosts. The secondary mineral assemblages produced vary outwards from the vein fracture and reflect a decreasing alteration intensity away from the fluid pathway. The zoned variation in the intensity of alteration produces a characteristic alteration halo (Goncharenko, 1970). Listwanite is, therefore, a suite of rock types resulting from hydrothermal alteration of the original hostrock and is **not** a distinct rock type that has been intruded into the host rocks, as the current dictionary definition implies.

Prior to this most recent variation on the definitions of listwanite, earlier meanings given in North American geological dictionaries (Trush, 1968, listwanite; Gary *et al.*, 1972, listwänite) maintained the definition as given by Holmes (1928, listwänite). Notably, the term does not appear in the Glossary of Geology, Second Edition (Bates and Jackson, 1980):

Holmes (1928) listwänite, Rose. A schistose rock of yellowish green colour composed of various combinations of the minerals quartz, dolomite, magnesite, talc and limonite.(Beresowsk, Urals.)

Gary *et al.* (1972) "A schistose rock of yellowish green colour composed of various combinations of the minerals quartz, dolomite, magnesite, talc and limonite. (Holmes, 1928, p. 143) as is found in the Ural Mountains at Beresowsk",

Appropriately, this definition describes a specific rock type comprising a characteristic secondary mineral assemblage. The definition also relates the term to its origins in the Ural Mountains of central Russia. Interpreted as written, this definition does not include fuchsite/mariposite as an integral alteration phase of listwanite. Notably, as pointed out by Hall and Zhao (1995) when the description of listwanite was initially published by Rose in 1842 the term talc was applied in a more general sense than it is today. Then it included a much wider range of hydrous phyllosilicates that would have included micas. Evidently this confusion is compounded by the fact that talc, as it is currently defined (Bates and Jackson, 1987), is also a common but distinct alteration mineral associated with the development of listwanite.

An additional problem or point of confusion is the inclusion of quartz as a component of listwanite. If listwanite is regarded strictly to be a hydrothermal alteration product of mafic and ultramafic rocks, quartz would not be included. The absence of silica as an alteration component of these alteration systems was recognized during the initial studies of these deposits (Lindgren, 1896, p. 147):

"Replacement by silica is not among the processes here recognized. It should be borne in mind that a rock shattered and filled with quartz seams is not an evidence of metasomatic replacement by quartz, nor is such a rock a quartz vein in process of formation. In a mineral water containing carbon dioxide, sulphureted hydrogen, carbonates and silica, the former three compounds will vigorously attack, by chemical processes, the minerals of any ordinary rock and form new compounds, while the silica is inert and plays a passive role".

This feature was later reiterated by Johnston (1940, page 51) who confirmed, as earlier pointed out by Lindgren (1896), that hydrothermal solutions introduced three principal classes of minerals into the rocks – carbonate, sericite and sulphides.

"Quartz rarely replaces the wall rocks, although it commonly fills small fractures adjacent to veins, in many places of such great complexity as to suggest large-scale replacement when viewed in place or in hand specimens. Under the microscope, however, the quartz of the veinlets is in sharp contact with the carbonatized and sericitized country rock, and evidence of encroachment upon the rock minerals is wanting."

Therefore a listwanite is not entirely an altered rock but a combination of altered rock and fracture-filling vein quartz and carbonate.

Whether the term listwanite has expanded beyond its original meaning as a result of problems with translation of the term itself, or due to changes in meaning of specific mineral names (i.e. talc) the reality is that the term has evolved well beyond its original meaning. From the limited translated, Russian literature available on the topic, it is evident that the understanding and application of the term is one that has evolved in its country of origin to characterize the varied and related components of the alteration suite.

It would appear, therefore, the term 'listwanite' has been elevated in status from that of a rock type to that of an association of rock types. All these being genetically related to the same hydrothermal event but varying as a function of both alteration intensity and protolith composition.

From an exploration standpoint it would be practical to adopt 'listwanite suite' as a single descriptive term to characterize the full range of genetically related alteration assemblages. Under this scheme the traditional application of Russian geologists i.e., describing an alteration type based on mineralogy, such as: quartz-mariposite listwanite or quartz-carbonate listwanite would be used. This approach would rule out ambiguity by clearly indicating variation in alteration mineralogies within the different parts of the listwanite suite. An understanding of the relative distribution of the individual components of the alteration suite could then be applied as an exploration vector in localizing veins within these systems.

Within this framework 'true' listwanite (Hall and Zhao, 1995),consists of quartz, carbonate, mariposite/sericite and pyrite, also referred to as 'blue jay' by early miners in California, would be a component part of the listwanite alteration suite. From the perspective of gold mineralization it is this particular association of alteration minerals that is the most suggestive of its deposition and, therefore, the most economically significant component of that suite.

APPENDIX II

Ar-Ar DATING METHODS

All $^{40}Ar/^{39}Ar$ data reported here were obtained from the Department of Earth Sciences at Dalhousie University by the conventional step-heating method. For irradiation in the McMaster University nuclear reactor, separated mineral concentrates individually wrapped in aluminum foil were interspersed with 3 to 5 aliquots of the flux monitor, the hornblende standard MMhb-1 (assumed age = 520±2 Ma, Samson and Alexander, 1987). An internal tantalum resistance furnace of the double-vacuum type was used to carry out the step-heating, and all isotopic analyses were made in a VG 3600 mass spectrometer. Unless otherwise noted, errors throughout are quoted at the 2 level and include uncertainty in the parameter J but do not allow for error in the age of the standard.

TABLE A1
ISOTOPIC AGE DATA SAMPLE INFORMATION

			Mineral				UTM (NAD 27)		
Camp	Sample No.	Sample Type	Occurrance	MINFILE No.	NTS Map	Zone	Northing	Easting	Age
ATLIN	CAS89-14-2-3	Ar-Ar and K-Ar	Surprise	104N 076	104N 11W	8	6608000	588000	171±6Ma
Chapter 2		mariposite		104N 098			6599000	586000	170 Ma
	CAS91-90	Ar-Ar mariposite	Yellow Jacket	104N 043	104N/12E	8	6607000	582000	172 Ma
	CAS89-05-02	Ar-Ar and K-Ar	Aitken Gold	104N 019	104N/12E	8	6603355	573462	Ar-Ar 169 Ma
		mariposite							K-Ar 156±5Ma
	CAS89-01-01	K-Ar mariposite	Anna	104N 101	104N/12E	8	6601903	578203	169±6 Ma
	CAS89-08-03	Ar-Ar and K-Ar	Pictou	104N 044	104N/12E	8	6603701	535340	ca. 170 Ma
		mariposite							
SNOWBIRD	CAS89-40-1-2	Ar-Ar mariposite	Snowbird	93K036	93K/11	10	6034400	402250	165 Ma
Chapter 3									
	CAS91-83	Ar-Ar mariposite	Snowbird	93K 036	93K/11	10	6034400	402250	162 Ma
	CAS91-74	Ar-Ar mariposite	Snowbird	93K 036	93K/11	10	6034130	403500	162 Ma
	RMA92-16-1	sericite Ar-Ar			93K/11	10	6034420	403856	*ca*. 157-159 Ma
		Snowbird stock							
	RMA92-18-9	U-Pb zircon			93K/11	10	6030250	401000	165.7 +2/-1Ma
		McKnab Lake Pluton							
BRALORNE	CAS91-66	Ar-Ar mariposite	Pioneer Dump	92JNE 004	92J/15	10	5622750	515500	86 Ma
Chapter 4									
	BNC91-1-2	Ar-Ar Cr-illite	North Vein	92JNE 001	92/J15	10			*ca*. 74-76 Ma
	BNC91-1-3	Ar-Ar Cr-illite	Cosmopolitan	92JNE 164	92/J15	10			*ca*. 71-75 Ma
CASSIAR	CAS89-33-03	K-Ar mariposite			104P/5				
Chapter 7									
	80-AP-18	Ar-Ar sericite	Quartzrock		104P/5	10	6570675	460103	130 Ma
			Creek						

APPENDIX III

DETAILED DEPOSIT FEATURES

Determining the detailed geological character of host rocks for most of the significant gold producing deposits in California and Alaska required the use of older classic works for the individual camps (Figure 1.2). In addition to providing detailed lithological descriptions and contact relationships, these works also provided an overwhelming amount of data of the detailed vein relationships. From these early descriptive works, the salient features consistent throughout are summarized herein. Such an exercise is considered both necessary and timely. Necessary, as it is a wealth of descriptive data that is often not adequately considered in generating recent deposit models. And timely, as many of these dated classic works are becoming increasingly difficult to obtain and impossible to replicate.

Knopf (1929) used the term 'gold-quartz veins' because this deposit type contains economic concentrations of gold either in quartz veins or in bodies of mineralized country rock marginal to the quartz veins. He stated that;

"the only systematic relations that appear unmistakably with reference to gold mineralization in the MotherLode is that unless it is a substantial body of quartz there is no ore; and where the vein enters a stringer lode it becomes barren. Only in places adjacent to a quartz shoot does a stringer zone constitute ore".

The tenor of the vein material in these deposits is always dominated by quartz, with usually subordinate carbonate and less abundant albite. Sulphides are almost everywhere dominated by pyrite, usually with subordinate arsenopyrite, lesser sphalerite, tetahedrite and minor chalcopyrite and galena. Total sulphides vary from trace to several percent and may locally be dominant within the limited extent of ore shoots. A generalized summary for some of these vein features and terminology applied to them is illustrated in (Figure A.2)

These veins display remarkable similarities in gangue mineralogy and metal signature, irrespective of location, but the geometry or style of the veins and types of alteration associated with them shows considerable variation. These variations primarily reflect differences in both the composition and physical character, or competency, of the original host rocks.

Variations in alteration (Figure A.2) result from two factors. Primarily, differences in original host lithology result in the greatest variability and produce distinctly different alteration also decreasing intensity of hydrothermal alteration of the individual units away from mineralized fissures results in a lateral, gradational zoning. In general igneous units are susceptible to hydrothermal alteration, with the more mafic-rich lithologies being the more intensely carbonatized whereas metasediments such as phyllites and slates are much less altered. Altered metasedimentary rocks typically contain several percent euhedral, disseminated pyrite grains adjacent to quartz veins and in selvages along the veins.

It has been long recognized that the persistence of the vein bearing fissures is a function of the competency of the host rock. At the Alaska-Juneau deposit vein geometry varies from discrete tabular bodies of quartz, commonly hosted by competent metagabbro and diabase, to zones of pervasive micro-veining in the slates. There Spencer (1906, p.23) found it necessary to qualify his use of the term vein to account for this variability. He wrote;

"The word vein is here applied to mineral aggregates of whatever form or extent, deposited from solution in fractures in the rocks."

Even where hosted by competent bodies vein character has considerable variation. As pointed out by Lindgren (1896) the character of the fissure determines to a great extent the character of the vein. The zone of schistosity can vary from less than a metre up to 6 metres in width containing one or several quartz veins. Compound vein fissures with fractures formed over several feet, are usually separated by highly altered crushed and brecciated rock. Persistent veins are characterized by frequent pinches and swells along their length. Describing the character of the Empire vein at Grass Valley, Johnston (1940, page 88) wrote;

"The Empire fissure is not a simple break that can be followed continuously on the dip and strike; rather it is a zone of variable width and degree of shattering, within which the vein, as defined by the quartz filling, is confined"

VEIN EVOLUTION

Studies of vein paragenesis for most of the significant deposits *e.g.*, Grass Valley (Johnston, 1940), Bralorne (Cairns, 1937), Alleghany (Ferguson and Gannett, 1934; Coveney, 1981), Cassiar (Hopper, 1984) and Quartz Hill (Elder and Cashman, 1992), indicate that there are progressive stages of vein development and that gold deposition is consistently late in their development. All investigators define at least three and sometimes more stages of vein development. There is an older quartz-dominant stage, and a younger stage dominated by carbonate, with free gold associated with the latter. Some authors identify a very early stage which Ferguson and Gannett, (1932) referred to as the chlorite stage and related to initial development of the host shear zone or vein fissure.

The early quartz stage is the principle stage of vein formation, during which massive bull quartz is the primary gangue mineral. The earliest sulphides which include pyrite and arsenopyrite are deposited at this stage and are at least in part earlier than some of the early quartz.

A younger carbonate-bearing stage with associated gold mineralization is marked by the deposition of carbonates together with quartz and the associated sulphide minerals sphalerite, chalcopyrite, galena with or without

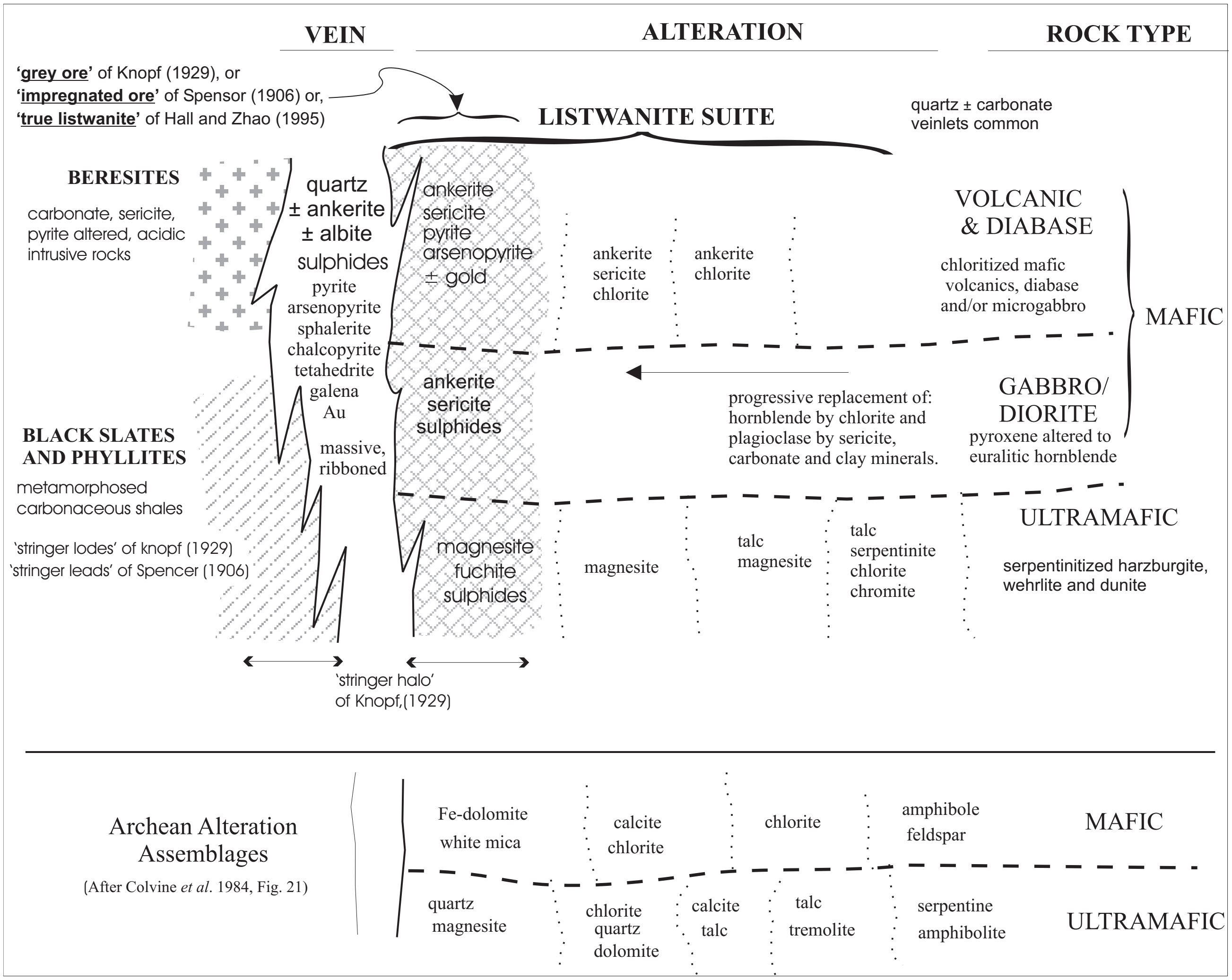

Figure A.2. Schematic representation of alteration products for different ophiolitic host rocks marginal to gold sulphide bearing quartz veins

tetahedrite. These sulphides, unlike the pyrite and arsenopyrite which also occur in the host rocks, are consistently only found within the quartz veins. Gold is the latest metallic phase to be deposited and is often associated with galena, which are both later than sphalerite and chalcopyrite. The timing of sericite formation within the sequence of vein-forming is interpreted to take place at various stages according to the individual authors.

A significant observation is that in all the deposits described gold deposition is late and is most often concentrated in deformed parts of veins. Following an investigation of Alaska Juneau deposit, Wernecke (1932, page 405) states:

"A remarkable fact is that in the quartz veins of the Alaska Juneau, Bendigo, the Mother Lode of California, and Nova Scotia the gold is younger than the quartz, and is deposited on the outside of the quartz or in fractures in the veins, associated with muscovite ankerite and some pyrite. Like effects should have like causes, even though different eminent geologists have formulated different theories for the different deposits."

Studies of gold-quartz vein deposits in France by Bonnemaison and Marcoux (1990) suggest that successive stages of vein evolution result in the progressive concentration of gold. These authors define three major evolutionary stages: an early stage with invisible gold, an intermediate stage of fine-grained gold and a late stage accompanied by coarse nugget gold. Their early stage, synonymous with the early chlorite stage of Ferguson and Gannett (1932) relates to the development of the host structure in which the rock is converted to schists and mylonites along restricted zones. This provides the fluid conduit and sites of subsequent dilation and vein development. In these early formed structures invisible gold is broadly disseminated in pyrrhotite and within the structure concentrated in pyrite. The second stage involves the deposition of quartz as lenses and veins in dilational zones with fine gold deposited in both quartz and altered hostrocks. The third stage is characterized by brittle deformation of quartz with associated deposition of coarse gold in fractures.

These observations on the paragenesis of gold-quartz vein deposits suggests that they develop in a dynamic environment in which fluid source regions change over time.

SULPHIDE MINERALS

North American Cordillera gold-quartz vein deposits display a relatively limited, though consistent ore mineralogy. Although there is a range in overall abundance of sulphides between individual deposits, they all display a similar paragenesis. Sulphide assemblages typically include a combination of pyrite, arsenopyrite, sphalerite, chalcopyrite and galena with or without tetahedrite and pyrrhotite.

The data are in large part constrained by visual observation. In limited instances where modern day analytical techniques have been applied like scanning electron microprobe (SEM) analysis, it shows that an extended range of sulphides is present. Veined quartz in listwanite-altered ultramafic rocks examined at both Alleghany (Wittkopp, 1983) and Atlin (Chapter 2) reveals that the nickel arsenide gersdorffite (NiAsS) is common where associated with ultramafic rocks. Bonnemaison and Marcoux (1990) found that both ullmannite (NiSbS) and gersdorffite (NiAsS) are present in all listwanites studied from France, China and Arabia with millerite (NiS) being common but less consistent.

Pyrite is the most abundant sulphide mineral in all vein deposits. It is everywhere the most abundant sulphide in altered and mineralized wallrocks and is the most abundant mineral recovered by gravity on concentrating tables during the milling of ores. The bulk of its deposition is earlier than, or contemporaneous with the earliest vein quartz in association with **arsenopyrite**.

Arsenopyrite paragenesis throughout the deposits is similar to that of pyrite but its relative abundance is highly varied. The bulk of the mineral is formed early during the initial quartz stage and is characterized by well-developed pyramidal crystals and crystal aggregates. At many of deposits such as Bralorne-Pioneer (Carirnes, 1937), Alleghany (Ferguson and Gannett, 1932), Alaska-Juneau (Spencer, 1906) and in the central Mother Lode (Knopf, 1929), coarse arsenopyrite consistently coincides with extraordinarily high gold content. This was the general nature of most gold ore at Alleghany, which is renowned for this style of gold-rich pockets with coarse arsenopyrite. Though generally less abundant, arsenopyrite is also found as a minute acicular crystals in late veins. In contrast to most other deposits it is rarely reported at Grass Valley (Lindgren, 1896; Johnston, 1940).

Sphalerite is more abundant than **galena** and the two generally occur together. They are present in variable amounts and can locally be abundant. In most cases galena and to a lesser degree sphalerite are contemporaneous with gold. At Grass Valley sphalerite is abundant and widely distributed and occurs in quartz within almost every vein. Throughout California **galena** has been consistently considered as the most favorable indicator of gold (Lindgren, 1896; Ferguson and Gannett, 1932; Johnston, 1940). Knopf (1929) indicated that among all the sulphide minerals galena is the only reliable indicator of gold mineralization.

Chalcopyrite is comparatively rare, but generally is widely distributed in small quantities throughout most veins but in some mines it can be locally conspicuous. Johnston (1940) suggested that it belongs to the same age group as the sphalerite and galena, being later than the pyrite. At Cassiar, however, Hopper (1984) found that chalcopyrite forms isolated blebs and rims on sphalerite and tetrahedrite, indicating that it is at least in part later, likely formed by exsolution.

Tetrahedrite is one of the most varied in abundance of the sulphide minerals between these deposits. In a number of camps it is relatively common sulphide, for example Grass Valley and Cassiar. At most other deposits it was either not recognized or extremely rare.

Bismuth sulphides have been described from the Barkerville deposits, where they are associated with native gold in the quartz veins (Skerl, 1948; Sutherland Brown, 1957). Scanning electron microprobe investigation of sulphide grains in quartz veins from the Atlin camp (Chapter 2) reveal that both bismuthinite and tetradymite are present at several gold occurrences.

Stibnite has been rarely described from these gold deposits in any of the significant gold-producing mines. In the underground workings of one of the mines at the southern end of the Mother Lode stibnite occurs along a distinct fracture zone that was clearly later than the gold-quartz veins (Knopf, 1929). At the Snowbird deposit, a past producer of the mineral in central British Columbia (Chapter 3) it is the predominant sulphide mineral. The paragenetic relationship between the gold and stibnite at this deposit has not been determined.

Gold is invariably late in the history of vein paragenesis and it is generally present in the deformed, sheared and ribboned parts of the early-formed quartz veins. Free, native gold is found only in the quartz veins, and is contained within or closely associated with sulphide minerals, often filling fractures or as inclusions in association with galena. In hydrothermally altered wall rock gold is microscopic and usually within pyrite and less often arsenopyrite.

The association between gold and sulphide minerals is a consistent one, increased sulphide content reflect increased gold values. Knopf (1929) referred to this relationship as being:

"the only visible feature that distinguishes some but not all ore shoots from the remainder of the vein."

Significantly, this consistent increase is not a dramatic one, with amounts of sulphide minerals increasing from trace to a few percent (1-4%).

DISTRIBUTION OF GOLD ORE

An early-recognized and often reiterated feature of these vein systems is that the distribution of gold ore within them is extremely erratic. Economic concentrations are referred to as 'ore shoots' or 'pay shoots' with smaller areas of limited extent (roughly a metre or less) and irregular form termed pockets. As a rule, pay shoots are long-drawn bodies with maximum extension in the direction of dip (Lindgren, 1896). Ore shoots with a regular long-drawn form were referred too as 'chimneys'.

In the Mother Lode, Knopf (1929, p. 27) described ore shoots as short, generally a small fraction of the vein with shoots up to 300 metres in length being exceptional and 60 to 90 meters being closer to the average stope length. Ore shoots generally occur where there are abrupt bulges in the vein and commonly fray out into stringer lodes that eventually become unproductive. Knopf (1929) uses the Empire shoot at the Plymouth Mine as an example from which over 300,000 ounces of gold was recovered from a shoot that was only 140 meters of the greater than two kilometre strike length of the vein. An important feature of the Mother Lode belt is that most of the ore shoots did not crop out on surface. Gold ore on the Central Eureka vein, for example, was not encountered until a depth below surface of 335 metres.

Consistent relationships documented for all the developed mines regarding the localization of pay shoots within these vein systems can provide camp-scale exploration guidelines. These features relate specifically to the late stages of gold deposition within the brittle and deformed parts of the veins and are related to localized structural conditions that promote brittle fracture. The most prevalent observation relates to the localization of many shoots to the intersection or junction of veins. Knopf (1929, page 29) stated:

"The earliest generalization that has stood the test of time is that point and junction and intersection of veins are favorable to the occurrence of ore."

Ferguson and Gannett (1932) studied the peculiar concentration of gold in high-grade shoots of the Allegheny district. They found that areas in which physical conditions favored the fracture of the vein prior to the introduction of the gold were seen as most promising. Such fracturing is largely dependent on changes in strike or dip of the vein with such changes commonly found when domains are near serpentinite and at junctions of veins, or where veins have been faulted prior to the introduction of gold.

Although for most deposits ribbon quartz is a good indicator of ore, ribbon quartz is not always mineralized. In the same manner, vein intersections, although common loci for gold ore shoots, do not always contain gold.

EXPLORATION CRITERIA

Deep crustal faults with extensive carbonate alteration are clearly indicated by the presence of listwanite-altered ultramafic rocks. Although gold-quartz veins are not generally hosted by listwanite, the richest gold veins are almost always found in shoots close to the ultramafic rocks, usually within competent tectonic blocks of plutonic to hypabyssal crust that are in faulted contact with the listwanite-altered ultramafic rocks. A definitive spatial and temporal relationship to high-level felsic intrusive rocks is either defined (Bralorne, Atlin, Snowbird, Alaska-Juneau) or suggested (Alleghany, Grass Valley).

Undoubtedly it appears that ultramafic rocks, particularly where carbonatized, are important as indicators and perhaps vectors to gold-quartz vein mineralization. Ultramafic rocks in British Columbia have received considerable attention for potential economic concentrations of asbestos, jade, magnesite, chromite and talc. Occurrences of these commodities have been summarized, notably: jade (Leaming, 1978), chromite (Hancock, 1990), magnesite (Grant, 1987), talc (MacLean, 1988) and asbestos (Harvey-Kelly, 1995). These works provide information about the distribution of such rocks throughout the province. The report on magnesite (Grant, 1987) is particularly relevant for isolating specific occurrences of carbonate-altered ultramafic rocks.

Significant gold-quartz vein deposits are characterized by silicification, sulphidation and potassic metasomatism in alteration envelopes within broader carbonate-alteration haloes. Systematic surface mapping that focuses on the distribution and intensity of the listwanite alteration suite is critical in identifying potential fracture-controlled veins. This alteration zonation can therefore be used to provide a vector for locating the zones of dilation and fluid flow, now marked by quartz veining.

Alteration envelopes surrounding productive gold-quartz veins in ophiolitic mafic to intermediate plutonic rocks (gabbros, diorites and trondjemites) are typically more subdued than those associated with mafic volcanic or ultramafic rocks. Altered wallrock margins are relatively narrower (<1 to 3 metres) and the lower primary Mg-Fe content of these mafic plutonic rocks compared to that of associated more mafic rocks results in much less visibly conspicuous weathered exposures. Both these features suggest that gold-quartz veins and their related alteration envelopes in the most prospective host rocks will be more elusive than the commonly associated listwanite-altered ultramafic rocks, particularly in areas of significant overburden.

Collisional suture zones containing relatively coherent blocks of oceanic plutonic crust that are intruded by late syn-orogenic plutonic rocks are prime targets. Detailed exploration of a prospective fault zone should focus on segments with alteration characteristics indicative of carbonate, potassium and sulfur metasomatism.

APPENDIX IV

MAJOR ELEMENT CHEMISTRY OF THE MCKNAB LAKE PLUTON

Sample No.	UTM (Zone 10)		NTS												
	East	North	Map	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
CAS92-027	373250	6044500	93K/10	57.54	0.77	18.04	6.69	0.11	3.51	6.63	4.09	1.48	0.26	0.80	99.92
CAS92-040A	390600	6052200	93K/10	63.83	0.45	16.57	3.68	0.08	2.13	3.21	5.12	1.20	0.18	3.44	99.89
CAS92-040B	390600	6052200	93K/10	63.73	0.44	16.51	3.63	0.06	2.03	3.92	5.53	0.88	0.16	2.88	99.77
CAS92-041	390150	6052300	93K/10	63.30	0.42	16.70	3.41	0.08	1.98	3.46	5.08	1.34	0.16	4.09	100.02
CAS92-061	396700	6030700	93K/7	60.93	0.68	16.29	5.96	0.12	3.18	5.92	3.75	1.89	0.20	0.74	99.66
CAS92-083	372450	6061950	93K/10	63.56	0.51	16.39	3.44	0.08	1.44	4.38	4.41	1.02	0.17	4.32	99.72
CAS92-102T	359550	6060700	93K/11	50.72	0.80	14.70	5.77	0.10	7.00	7.19	3.68	0.56	0.19	9.20	99.91
CAS92-156	352640	6063950	93K/11	69.00	0.38	15.13	3.17	0.11	1.00	3.19	3.77	3.14	0.17	0.45	99.51
CAS92-158	364450	6065150	93K/11	73.51	0.25	14.26	1.94	0.08	0.44	2.11	4.90	0.86	0.11	0.91	99.37
CAS92-160	363050	6066250	93K/11	58.30	0.90	17.52	6.47	0.13	3.17	6.33	4.19	1.31	0.28	1.04	99.64
RMA92-3.7	375850	6044350	93K/10	59.97	0.69	17.04	6.22	0.13	3.02	5.90	3.77	2.22	0.21	0.67	99.84
RMA92-14.15	367200	6053200	93K/11	59.00	0.74	16.96	6.60	0.13	3.38	6.56	3.75	1.48	0.21	0.80	99.61
RMA-16.7	366550	6063300	93K/11	64.01	0.56	17.66	4.28	0.10	1.70	5.08	4.57	0.95	0.17	0.97	100.05
CAS92-102A	359550	6060700	93K/11	47.41	1.29	17.45	11.37	0.17	7.83	5.88	4.24	0.44	0.14	3.62	99.84
CAS92-102B	359550	6060700	93K/11	47.72	0.95	18.18	10.81	0.18	5.05	8.30	4.15	0.90	0.10	3.56	99.90
CAS92-107	364950	6056650	93K/11	48.07	1.91	14.44	13.35	0.22	6.49	8.35	3.39	0.42	0.21	3.06	99.91
CAS92-128	373600	6057900	93K/11	48.72	1.73	14.59	12.35	0.21	6.21	10.4	3.04	0.32	0.18	1.98	99.73
RMA92-13.1	367250	6055450	93K/11	83.67	0.27	5.73	3.02	0.63	1.24	0.90	1.38	0.54	0.02	2.03	99.43
RMA92-13.11	373000	6057550	93K/11	58.08	0.58	16.03	6.75	0.12	5.38	4.73	5.48	0.38	0.11	2.03	99.67
RMA92-15.3	354300	6062350	93K/11	48.49	2.71	15.20	11.26	0.22	6.88	5.46	3.91	1.26	0.43	3.48	99.30