Trace elements in shale as indicators of crustal provenance and terrane accretion in the southern Canadian Cordillera

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ABSTRACT

In this study, the trace-element geochemistry of shale is used to infer the nature of adjacent crustal blocks during terrane amalgamation and accretion in southern British Columbia. The geochemistry of about fifty shale samples from one of the best-dated stratigraphic sections in the North America Cordillera is used to (1) infer proximity to source regions characterized by juvenile ocean arcs, continental arcs, and ophiolites and (2) address a controversy concerning the timing of terrane amalgamation and accretion. This study includes analyses of shale from the entire Mesozoic stratigraphic section of the Cadwallader terrane and overlying Tyaughton basin, as well as argillites from the structurally adjacent Bridge River Complex.

The mid-Cretaceous (Albian) strata of the upper Taylor Creek Group, show light rare earth (LREE) enrichment (La_N/Sm_N of ~3.0) and anomalously high Cr and Ni. Older units (Upper Triassic–Lower Cretaceous) that stratigraphically underlie the upper Taylor Creek Group have less LREE enrichment, high Ba_N/La_N ratios, and no Cr or Ni anomaly. The mid-Cretaceous strata were probably derived from a continental arc during a period of uplift and erosion of ultramafic rocks (probably ophiolites) and the co-extensive nature of these sediments suggests accretion of many basement terranes to the edge of a continent. The trace-element geochemistry of the older strata is similar to that of sediment derived from an oceanic arc; however, Lower Cretaceous strata of the Relay Mountain Group may record the incipient collision and progressive closure of this ocean basin.

The Bridge River Complex, which is dominated by oceanic rocks and is interpreted to be an accretionary complex, contains two suites of argillites, one of which shows significant LREE enrichment, and isotopic data suggest a Jurassic-Cretaceous age for these argillites that compose the matrix in this complex (Leitch et al., 1991). We suggest that the Bridge River Complex was a Jurassic-Cretaceous accretionary complex that formed outboard of the Methow section of rocks and was not juxtaposed with the Cadwallader terrane and Tyaughton basin until the Albian when these terranes were accreted to North America. Paleomagnetic data from these rocks (Maxson et al., 1993) indicate that accretion took place at the latitude of central Mexico and that subsequent strike-slip faulting brought these terranes to their present position by Eocene time.

INTRODUCTION

The movement, amalgamation, and accretion of terranes together are recognized as a fundamental process by which continents grow through time (Coney et al., 1980; Samson et al., 1989). The history of an individual terrane, which by definition is distinct from neighboring crustal fragments, is generally marked by a point at which a link can be made to adjacent terranes. Various methods are used to establish the timing of amalgamation between terranes, but by far the most important are studies of stratigraphic overlap assemblages and provenance links. Stratigraphic overlap assemblages are strata that rest unconformably on two different terranes. Less reliable, but also common in terrane analysis, is establishing terrane amalgamation by a provenance link. In this case, detritus deposited on a terrane may be traced to a distinct rock type in adjacent terranes. One problem with this approach is that it is commonly difficult to find a unique rock type characteristic of only one terrane. In this paper we use a new approach of using sediment geochemistry to help solve problems associated with terrane amalgamation, accretion, and postaccretion dispersion. Volcanic arcs built on continental crust, juvenile volcanic arcs, and ocean crust (ophiolites) are three common petrotectonic assemblages that yield sediment with a fairly distinct geochemistry. This paper uses trace-element geochemistry of sediment derived from these distinct petrotectonic assemblages to address a controversy concerning the timing of terrane movement in the southern Canadian Cordillera.

The timing of amalgamation and accretion of outboard terranes of the Canadian Cordillera is controversial because many of the relations among different terranes have been obscured by subsequent deformation and plutonism. Following Jones et al. (1983), we use the term *amalgamation* to signify the joining of terranes but not necessarily at the edge of a continent, and we use the term *accretion* to represent the collision and welding of a terrane to the craton. The Insular superterrane was accreted to the edge of the North American continent in mid-Cretaceous time (ca. 100 Ma) (Monger et al., 1982). Sedimentologic and structural relationships document significant contraction between the Insular terrane and the Cretaceous margin during this time (Misch, 1966; Kleinspehn, 1985; Brandon et al., 1988; McGroder, 1989, 1991; Rubin et al., 1990; Garver, 1992; Monger and Journeay, 1992). In the southern Canadian Cordillera, volcanic arc sequences are preserved to the east on the Intermontane terrane (Thorkelson and Smith, 1989), as well as to the west on the Insular terrane (Monger and Journeay, 1992), possibly indicating subduction of ocean crust under both crustal blocks

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Data Repository item 9505 contains additional material related to this article.

GSA Bulletin; April 1995; v. 107; no. 4; p. 440–453; 6 figures; 3 tables.

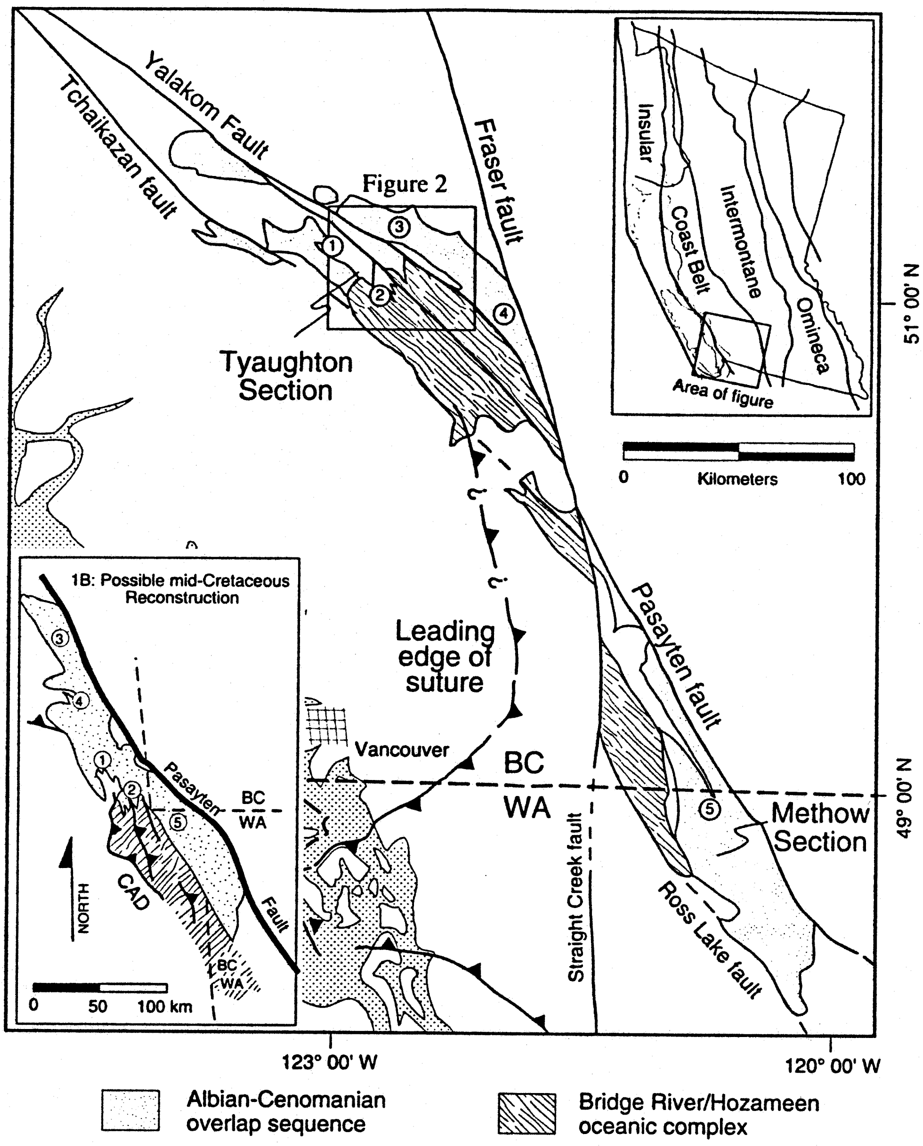

Figure 1. Simplified geologic map of the southern Coast Mountains of British Columbia and adjacent Washington State. The Bridge River area, labeled as Figure 2, contains rocks of the Cadwallader terrane, the Bridge River Complex, and the overlying strata of the Tyaughton basin of which only the thick Albian overlap sequence is shown. Correlative mid-Cretaceous strata in the Methow basin to the east and south are interpreted to have been deposited in the same tectonic setting. Together, mid-Cretaceous rocks of the Methow and Tyaughton areas are interpreted to represent an overlap assemblage that ties various underlying terranes together in the mid-Cretaceous (Albian-Cenomanian). Inset at top right shows the principal tectonic subdivisions of British Columbia. Note that the study area lies mainly in the Coast Belt, which lies between the Insular superterrane to the west and the Intermontane superterrane to the east.

Figure 1B shows a possible basin reconstruction with the effects of Late Cretaceous and Tertiary strike-slip faults removed (after Garver and Brandon, 1994). Principal stratigraphic sections on main figure (1–5) are shown in their restored positions. BR = Bridge River Complex and correlative Hozameen complex; CAD = the Cadwallader terrane. North-south dashed line is the future trace of the Fraser–Straight Creek fault (note offset of the WA/BC border). Position of the northern extension of the Pasayten fault (northeast of localities 3 and 4) is speculative.

prior to the mid-Cretaceous orogenic event. However, inferred mid-Jurassic amalgamation of some of the miniterranes in the southern Coast Ranges (Rusmore et al., 1988; Rusmore and Woodsworth, 1990) has been used to infer a Middle Jurassic accretion of the Insular terrane to North America (McClelland et al., 1992; van der Hyden, 1992). Also controversial is the latitude of accretion, because the interpretation of paleomagnetic data from this area, which indicate accretion at a latitude of central Mexico, is presently disputed (see Ague and Brandon, 1992; Cowan, 1994).

The Bridge River area is well situated to test these relations because it is underlain by various well-dated miniterranes that are located between the Insular terrane to the west and the Intermontane terrane to the east (Fig. 1). The nature of stratigraphic overlap assemblages and provenance links among different miniterranes is controversial, but the provenance of clastic sediment, especially in conjunction with sediment dispersal patterns, provides the best, if not the only, means at present to document links among different terranes modified by young deformation.

Trace-element geochemistry of fine-grained clastic sediments has been used in many studies to determine provenance. The rare earth elements (REE)—lanthanum–lutetium in this discussion—have been shown to reliably indicate crustal provenance because of their near quantitative transfer in the sedimentary system, low natural abundance in seawater, and relative immobility during diagenesis and metamorphism (Taylor and McLennan, 1985; McLennan, 1989, and references therein). In general, mud derived from continental crust (with or without a superimposed volcanic arc) is LREE enriched (high La/Sm) and has high ΣREE when compared to mud deposited adjacent to juvenile arcs (McLennan et al., 1990). Geochemically distinct rock types such as ultramafic rocks, which have very high concentrations of Cr and Ni, can produce elevated concentrations of some trace elements in sediment derived from a source region that contains these geochemically unique markers. Therefore, assuming that the provenance of mud is a reliable indicator of the average crustal composition in a source region, we explore how sediment geochemistry may shed light on the composition of adjacent crustal blocks adjacent to the stratigraphic section in the Bridge River area, and we then use this information to

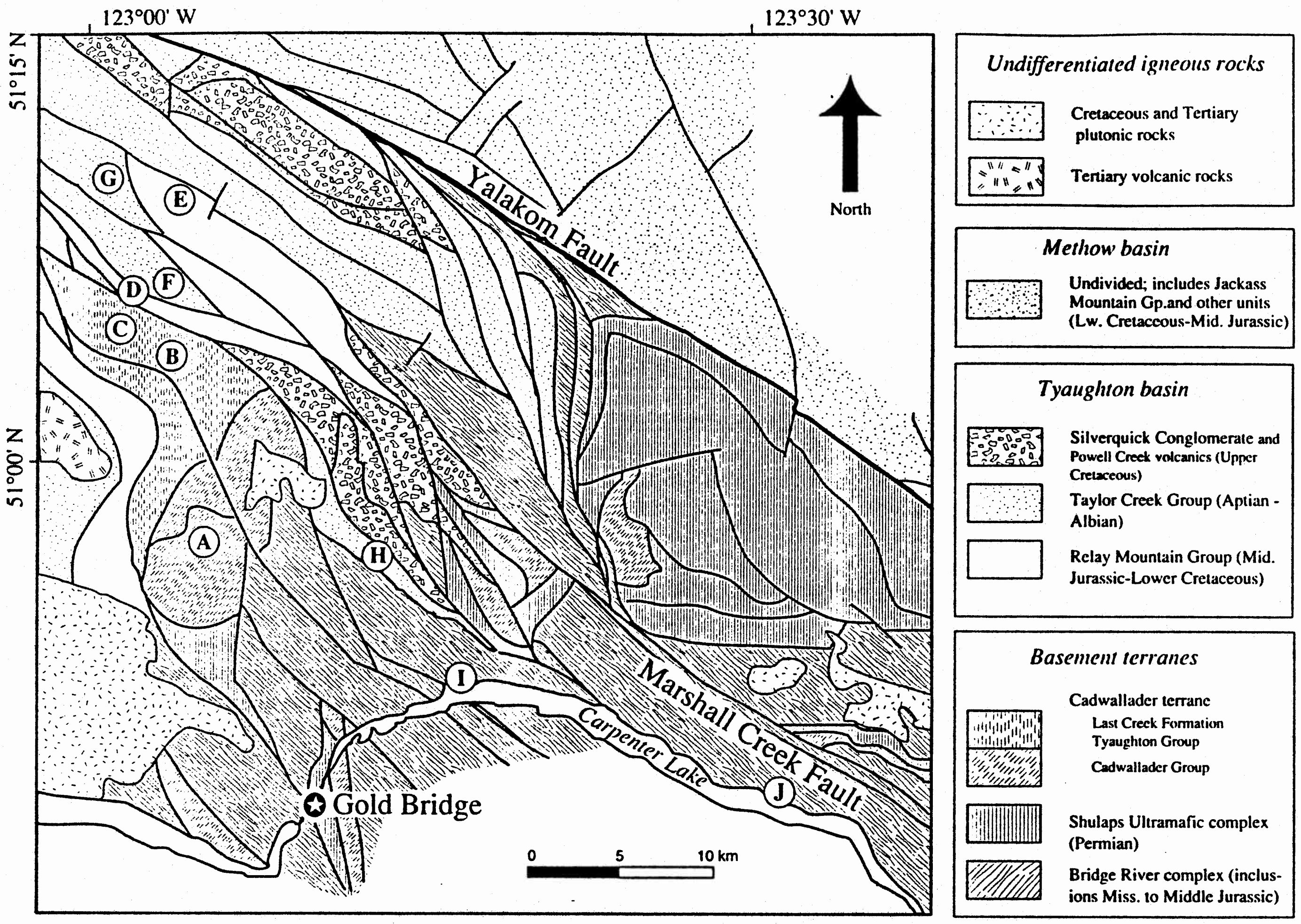

Figure 2. Geologic map of the study area (after Garver, 1991). Note that the geology of the area is dominated by northwest-trending strike-slip faults (e.g., Yalakom and parallel strands) that cut a mid-Cretaceous fold and thrust system. Sample locations shown as circled letters (see Fig. 3): (A) Cadwallader Group (Hurley Formation), Eldorado basin; (B) Tyaughton Group, west of Castle Peak; (C) Last Creek Formation, west of Castle Peak; (D) Lower Relay Mountain Group, Relay Pass; (E) upper Relay Mountain Group, type section north of Relay Mountain; (F) lower Taylor Creek Group (Paradise formation—informal type section), southern Relay Mountain; (G) upper Taylor Creek Group (Dash conglomerate and Lizard formation—informal type sections), Red Hill; (H) upper Taylor Creek Group—type section (Dash conglomerate and Lizard formation)—and the Silverquick conglomerate (type section), Cinnabar Creek area; (I through J) more-or-less evenly spaced sample localities of shale of the Bridge River Complex. See Appendix A (Data Repository) for precise sample localities.

infer the history of terrane amalgamation and accretion.

GEOLOGIC SETTING OF THE BRIDGE RIVER AREA

Over the past decade, numerous studies have been aimed at understanding the Mesozoic history of basement terranes and subsequent deformation of rocks in the Bridge River area (Figs. 1 and 2; see Potter, 1986; Rusmore, 1985; Garver, 1992; Umhoefer, 1990; Schiarizza et al., 1990, and references therein). Controversy exists concerning the timing of amalgamation of the basement terranes, with the discussion centering on the existence of an overlapping sequence that links the Bridge River Complex, the Shulaps ultramafic complex, and the Cadwallader terrane (Table 1). The oldest proposed overlap, which signifies the amalgamation of these terranes and possibly accretion to the continent, is either a mid-Cretaceous unit (Albian; Garver, 1992) or an upper Middle Jurassic unit (Callovian; Rusmore et al., 1988). Unfortunately, several phases of Cretaceous to Tertiary faulting have modified virtually all of the contacts among these different terranes, so deciphering older events and stratigraphic relationships has been difficult. The nature of these terranes and basin strata is summarized in Table 1 and is only briefly discussed below.

Basement Terranes

The geochemistry of volcanic rocks, which are predominantly island-arc tholeiites, sandstone petrography, and conglomerate composition, indicates that the Cadwallader terrane formed adjacent to an oceanic arc complex (Fig. 3; Rusmore, 1987; Umhoefer, 1989; Leitch et al., 1991; Cordey and Schiarizza, 1993). The Shulaps ultramafic

TABLE 1. PRINCIPAL BASEMENT TERRANES AND OVERLAP SEQUENCES ASSOCIATED WITH THE ROCKS IN THE BRIDGE RIVER AREA

Terrane	Predominant stratigraphic units	*Basement terranes* Age range	Lithology	Tectonic setting
Cadwallader terrane	Cadwallader Group (16, 17)[†] Tyaughton Group (20, 21) Last Creek Formation (20, 21)	Upper Triassic to lower Middle Jurassic	Island arc tholeiites, volcaniclastic sedimentary rocks	Arc proximal sedimentary rocks and volcanics (1, 2)
Shulaps ultramafic complex*	Shulaps ultramafic complex, and Bralorne–East Liza complex (1, 3, 10, 18)	Permian (1)	Harzburgite, dunite, serpentinite melange	Ophiolite (4, 18)
Bridge River Complex*	No internal stratigraphy; informal Carpenter Lake assemblage and Bridge River schist (5, 6, 14, 18)	Mississippian to upper mid-Jurassic known (10), possibly as young as Cretaceous	Chert, greenstone, argillite, sandstone, conglomerate, limestone, serpentinite, gabbro, blueschist	Disrupted arc-proximal setting (17, 14) or accretionary complex (8, 13, 6)
Methow terrane	Spider Peak basalt	Triassic (15)	Mid-ocean-ridge basalt	Ocean floor (15)

Sequence	Predominant stratigraphic units	*Basin overlap sequences* Age range	Lithology	Basement terrane
Tyaughton sequence	(a) Powell creek volcanics (8) (b) Silverquick conglomerate (7, 8) (c) Taylor Creek Group (7, 8)	(a) Cenomanian-Santonian(?) (b) upper Albian–Cenomanian (c) Aptian–upper Albian	Marine sedimentary rocks, passing upward into nonmarine conglomerates and volcanics	Bridge River Cadwallader Provenance link to Shulaps and Methow sequence (7, 8)
Older units	Relay Mountain Group (20)	Callovian-Barremian		
Methow sequence	(a) Pasayten Group (11, 12) (b) upper Jackass Mountain Group and Harts Pass Group (2, 4, 9)	(a) upper Albian–Cenomanian to Santonian	Marine sedimentary rocks, passing upward into nonmarine sandstones, conglomerates, and volcanics	Methow terrane Provenance link to Bridge River (19, 8)
Older units	Lower Jackass Mountain Group, Dewdney Creek Group, Lillooet Group, Thunder Lake Formation, and others (2, 4, 9)	Callovian to Aptian		

*Unlike previous usage of the term *Bridge River terrane* (e.g., Rusmore et al., 1988, and references therein), we treat both the Shulaps ultramafic complex and the Bridge River Complex as separate terranes because recent mapping suggests that there is no pre-Cretaceous tie between these different units.

[†] References as follows: (1) Archibald and others, 1991; (2) Barksdale, 1975; (3) Calon and others, 1990; (4) Coates, 1974; (5) Coleman and Parrish, 1991; (6) Cordey and Schiarizza, 1993; (7) Garver and Brandon, 1994; (8) Garver, 1992; (9) Kleinspehn, 1985; (10) Leech, 1953; (11) McGroder, 1988; (12) McGroder, 1989; (13) Monger and others, 1982; (14) Potter, 1986; (15) Ray, 1986; (16) Rusmore and others, 1988; (17) Rusmore, 1985; (18) Schiarizza and others, 1990; (19) Trexler, 1984; (20) Umhoefer, 1989; (21) Umhoefer, 1990.

complex, which comprises variably serpentinized harzburgite and dunite, and a distinct serpentinite melange, is interpreted to be a dismembered ophiolite sequence of Permian age (Calon et al., 1990; Schiarizza et al., 1990; Archibald et al., 1991). The Shulaps thrust, with inferred mid-Jurassic movement (Potter, 1986), is now mapped as a Tertiary low-angle normal fault (Coleman and Parrish, 1991; Schiarizza et al., 1990), so the older relationship between the Shulaps ultramafic complex and the Bridge River Complex is questionable, and initial amalgamation of these two terranes may have been mid-Cretaceous or younger (Cordey and Schiarizza, 1993). Considering this possibility, we subdivide the original Bridge River terrane (see Potter, 1986) into two separate terranes, the Bridge River Complex and the Shulaps ultramafic complex, with an uncertain history with respect to one another.

The Bridge River Complex lacks internal stratigraphy and is a structural complex composed of oceanic rocks such as chert, greenstone, argillite, sandstone, conglomerate, limestone, serpentinite, gabbro, and Permo-Triassic blueschist (Roddick and Hutchison, 1973; Potter, 1986; Schiarizza et al., 1990; Garver et al., 1989a). Radiolarians and conodonts from chert and limestone indicate that the age range of these rocks includes Mississippian through late Middle Jurassic (Cordey and Schiarizza, 1993), but the age of lithologic mixing is unknown and may be as young as Cretaceous. Although the interpretation of the tectonic setting of the Bridge River Complex is controversial, we use the interpretation of an accretionary complex in this paper. The Bridge River Complex is a key element in understanding the tectonic evolution of the Methow and Tyaughton sequences, because Cretaceous strata in both sequences contain detritus derived from this terrane.

Coextensive Overlap Sequences

Strata in the Tyaughton Creek area and the Methow Valley in Washington State (Fig. 1) are considered to be part of a single coextensive basin that has subsequently been cut by Late Cretaceous and Tertiary strike-slip faults (Fig. 1B). This correlation has focused on the thick (>3 km) Albian-Cenomanian strata common to both areas, but stratigraphic correlation among older units (pre-Albian) is controversial (Garver and Brandon, 1994). To separate stratigraphy from inferred basin geometry, we use the terms *Tyaughton sequence* to refer to the stratigraphic section in the Tyaughton Creek area (Fig. 3, and see 1 and 2 in Fig. 1); *Methow sequence* for the stratigraphic section in the Methow Valley, Manning Park, and Camelsfoot Ranges (see 3, 4, and 5 in Fig. 1); and *Methow-Tyaughton basin* for the coextensive Albian-Cenomanian basin that is interpreted to have been more-or-less continuous during this time (Garver, 1992; Garver and Brandon, 1994) but subsequently displaced by strike-slip faults (Fig. 1B). Lack of a compelling correlation between older units in the Tyaughton sequence and the Methow sequence indicates to us that the older strata and the underlying terranes may not have been in close proximity before the Albian. This very important point suggests that prior to the Albian, the Methow sequence and the Tyaughton sequence may have been completely unrelated and separated by an unknown distance of water.

In the Tyaughton sequence, the Relay Mountain Group includes ~3000 m of sediment with a magmatic arc provenance, much of which was deposited in a shallow marine setting (Umhoefer, 1989). Westward thickening, facies changes, and sandstone provenance suggest that in the Early Cretaceous, the source of these sediments may have been volcanic and plutonic rocks to the west that are interpreted to have been built on the Insular terrane (see discussion in Umhoefer, 1989). In the Bridge River area, the Relay Mountain Group is interpreted to have been deposited unconformably on the Cadwallader terrane, although the contact is not exposed (Jeletzky and Tipper, 1968; Tipper, 1978; Umhoefer, 1989). The Taylor Creek Group and overlying Silverquick conglomerate consist of 3000–5000 m of Aptian-Albian to Cenomanian coarse clastic strata with three distinct petrofacies that are interpreted to have been derived from a volcanic terrain to the west, an uplifted oceanic complex to the east, and quartzofeldspathic sediment that was also derived from the east but transported longitudinally north-south along the basin axis (Garver, 1989). Recent work suggests that these clastic strata provide a provenance link across the Yalakom fault (Fig. 1) between this unit and age correlative strata in the Methow basin (Garver, 1992; Garver and Brandon, 1994).

Controversy Surrounding Amalgamation of Basement Terranes

The original relationship between the Bridge River Complex, Cadwallader terrane, Shulaps ultramafic complex, and overlying strata of the Tyaughton basin is controversial because the present distribution of the units has been severely affected by mid-Cretaceous through Tertiary deformation (e.g., see Fig. 2). A critical aspect of this controversy which we are trying to address using geochemistry is the oldest evidence for terrane juxtaposition.

Because we regard the Shulaps ultramafic complex and the Bridge River Complex as separate terranes, it is reasonable to consider the timing of their initial juxtaposition. Presently, the Shulaps ultramafic complex is separated from the Bridge River Complex by a Tertiary low-angle fault (Schiarizza et al., 1990; Coleman and Parrish, 1991). The presence of detrital chromite in Aalenian (lower Middle Jurassic) sandstones along the Yalakom fault (see Leech, 1953) has been used as evidence of erosion and presumably thrusting of the Shulaps ultramafic complex during this time (Potter, 1986; Rusmore et al., 1988). This interpretation is controversial because the stratigraphic affiliation of this chromite-bearing sandstone is unknown and because it occurs as a sliver in the fault zone. Garver (1992) noted the abundance of detrital chromite in heavy mineral assemblages of sandstones of the Taylor Creek Group and suggested that the Shulaps ultramafic complex supplied this detritus when it was thrust over the Bridge River Complex. By examining the geochemistry of shale from strata of known stratigraphic affinity, we hope to elucidate the timing of amalgamation of the Shulaps with adjacent terranes, because ultramafic rocks contain such a high concentration of chromium and nickel and detritus shed from them is geochemically distinct.

The relation between the Cadwallader terrane and the Bridge River Complex is also controversial, with the point of contention centering around the age of the oldest strata that are a common overlap on both units. The mid-Cretaceous Taylor Creek Group is a thick synorogenic clastic wedge that contains detritus derived from the Cadwallader terrane, Bridge River Complex, and the Shulaps ultramafic complex (Garver, 1989, 1992), and it is likely that these basement terranes were amalgamated at the time of deposition. Additionally, only in the Albian strata can a depositional contact with the underlying strata of the Cadwallader terrane and the Bridge River Complex be demonstrated (Jeletzky and Tipper, 1968; Umhoefer et al., 1988; Garver, 1991). This relationship, which provides a solid link between the Bridge River Complex and the Cadwallader, and possibly the Shulaps ultramafic complex, is generally not disputed; it is the pre-Cretaceous relationship between the two terranes that is controversial.

Rusmore et al. (1988) argued that the upper Middle Jurassic to Lower Cretaceous Relay Mountain Group is an overlap sequence that links the Bridge River Complex and the Cadwallader terrane. There is little question that the Relay Mountain Group rests on strata of the Cadwallader terrane (Jeletzky and Tipper, 1968; Umhoefer, 1989), but nowhere can a depositional contact be demonstrated between the Relay Mountain Group and the Bridge River Complex (Schiarizza et al., in press).

Workers who favor a Middle Jurassic terrane amalgamation between the Bridge River Complex and the Cadwallader terrane note that the two units have similar volcanic-rich clastic strata that may serve as a link between these two terranes (Potter, 1986; Rusmore et al., 1988). This contention has not been rigorously scrutinized and is difficult to substantiate because the clastic strata in the Bridge River Complex are highly deformed and lack age control, and volcanic activity was common along the length of the Cordillera during the entire Mesozoic (Cowan and Bruhn, 1992).

In sum, Albian strata of the Taylor Creek Group serve as an important link between different terranes (see discussion in Garver, 1992; Garver and Brandon, 1994), and the controversy surrounds the possibility of a Middle Jurassic amalgamation between the Cadwallader terrane, the Bridge River Complex, and the Shulaps ultramafic complex. One of the ways to resolve this controversy is to document provenance links among the stratigraphic sequences through the use of sediment geochemistry, which can be used to identify certain rock types in source terranes.

RARE EARTH ELEMENTS IN SHALE AND CRUSTAL PROVENANCE

The REE (lanthanum–lutetium) are commonly used indicators of igneous processes. The REE have a similar charge (3^+), but a slight decrease in ionic radii from the light REE (LREE) to the heavy REE (HREE), known as the *lanthanide contraction*, results in LREE enrichment through igneous processes of crustal differentiation. Although these processes are complicated in detail, the general trend is for LREE enrichment, an increasingly pronounced Eu anomaly, and an increasing total REE content (ΣREE) with progressive crustal differentiation (Taylor and McLennan, 1985).

As a result of the geochemical behavior of the REE, the concentration of the REE in shale has become a widely used indicator of crustal provenance because of the near-quantitative transfer of these elements in sedimentary systems (Taylor and McLennan, 1985; McLennan, 1989, and references therein) and their relative immobility during diagenesis and metamorphism (Chaudhuri and Cullers, 1979; Taylor and McLennan, 1985; McLennan, 1989); however, a few studies have documented some mobility of the REE during diagenesis (e.g., Milodowski and Żalasiewicz, 1991). We suspect that the REE in strata analyzed for our study have been relatively immobile because the sandstone of these units have not experienced significant metamorphism (as described in Rusmore, 1985; Garver, 1989; Umhoefer, 1989) and these basin strata have not experienced high water/rock ratios known to mobilize the REE (e.g., Seifert et al., 1985). Even in extreme cases where rocks have been affected by high water/rock ratios (such as hydrothermal alteration of basalt at mid-ocean ridges), the absolute

REE concentrations are affected, but most of the REE are affected together so that the La/Sm ratio, which is the measure of LREE enrichment that we use in this paper, remains about the same (see data in Seifert et al., 1985). Because the transfer of the REE from a source region to a site of deposition is nearly quantitative, terrigenous sediments should reflect the average composition of a source region. One advantage of using shale is that fine-grained clastic sediment homogenizes the geochemical characteristics of the source terrane. In this regard, studies using shale are generally aimed at understanding the overall composition of the rocks in a source region.

A number of studies have used REE to determine or infer derivation of sediment from different plate tectonic settings in modern and ancient sequences (Dypvik and Brunfelt, 1976; Nathan, 1976; Bhatia and Crook, 1986; McLennan et al., 1990; McLennan and Taylor, 1991; Centeno-Garcia et al., 1993; Girty et al., 1993). In general, these studies show that sediment derived from mature continental crust and volcanic arcs built on continental crust is characterized by LREE enrichment (indicated by high La/Sm) and high total rare earth elements (ΣREE). On the other hand, sediment derived from young, undifferentiated oceanic arcs has lower La/Sm than either continental arc or old continental crust, has lower ΣREE, and can lack a europium anomaly. In a general sense, therefore, the REE pattern of sediment derived from either a continental arc or old continental crust can be differentiated from that derived from an undifferentiated oceanic arc.

Cr AND Ni AS PROVENANCE INDICATORS OF ULTRAMAFIC ROCKS

Many studies have noted anomalous concentrations of Cr and Ni in shale and have inferred the presence of ultramafic rocks in the source region. Much of this work has focused on Archean rocks (e.g., Danchin, 1967; McLennan et al., 1983; Taylor et al., 1986; Wronkiewicz and Condie, 1987) when the composition of crustal material and surface processes were different than in the Phanerozoic. Several studies have used Cr and Ni concentrations in Phanerozoic shale as a provenance indicator for ultramafic rocks, and therefore presumably for ophiolites, in tectonic highlands (e.g., see Papavassiliou and Cosgrove, 1982; Yucesoy and Ergin, 1992; Thiébault and Clément, 1992; Garver and Royce, 1993; Garver et al., 1994). Most of these studies indicate that the high correlation coefficient between Cr and Ni is a result of their presence on clay minerals and, ultimately, their derivation from ultramafic rocks. Garver and Royce (1993) suggest that where Cr and Ni concentrations are anomalously high, a Cr/Ni ratio of about 1.2 to 1.6 should be expected if these elements were derived from a source with ultramafic rocks; higher ratios are probably indicative of derivation of these elements from mafic volcanic rocks. Therefore, anomalous concentrations of Cr and Ni can be used to determine if ultramafic rocks were in a source region, and then inferences as to the tectonic implications of this information can be explored.

SAMPLE COLLECTION AND LABORATORY PROCEDURES

We collected and analyzed 49 samples of shale from the entire Mesozoic section in the Bridge River area, including the Cadwallader Group, Tyaughton Group, Last Creek formation, Relay Mountain Group, Taylor Creek Group, Silverquick conglomerate, and clastic rocks of the Bridge River Complex (Fig. 2; see Appendices[1] for sample locations and data). Shale samples were ground and pulverized in an agate mortar and pestle ignited at 950 °C for one hour, and duplicates were dissolved in concentrated HF and HNO_3. Cr, Ni, V, Co, Cu, Nb, Ba, La, and the lanthanides were analyzed using a VG Inductively Coupled Plasma Mass Spectrometer (model PQ2+) at Union College. Aliquots of Sc, Ga, In, Cs, and Re were used as internal standards, and NBS 688 and NBS 278 were used as rock standards at the beginning and end of each run. The data (Appendix B) were reduced using an in-house correction routine (K. Hollocher, unpub. data), and the reported concentrations represent the average of duplicates. The average relative deviation of the mean values of duplicates is 3%–5% for the REE and 2%–4% for Cr, Ni, V, Co, Cu, Nb, and Ba (see Jarvis, 1988, for I.C.P.M.S. technique).

DATA

The individual units can be distinguished mainly on the basis of their LREE enrichment (shown by chondrite-normalized La/Sm or La_N/Sm_N), ΣREE, Cr and Ni anomalies, Cr/Ni ratios, Ba_N/La_N, and lithologic association (Tables 2 and 3; Figs. 3, 4, and 5). From the stratified sequence, all of the pre–middle Albian units, including the Cadwallader Group, Tyaughton Group, Last Creek formation, Relay Mountain Group, and the lower Taylor Creek Group (Aptian to lower Albian Paradise formation) show relatively low ΣREE, low La_N/Sm_N, background concentrations of Cr and Ni, variable Cr/Ni ratios, relatively high V/Ni and V/Cr ratios, and high Ba_N/La_N (Fig. 3). The Lizard formation and Dash conglomerates of the upper Taylor Creek Group show LREE enrichment (average La_N/Sm_N ratios of ~2.4 to 3.0 with some samples as high as 4.2), and high ΣREE (~120 ppm and higher; Table 2; Fig. 3). In fact, excluding two samples of uncertain stratigraphic affiliation (92JS-74 and -76, which could be from the Silverquick), the Lizard formation has a La/Sm range of 2.9 to 4.2 with a mean of 3.2—unquestionably the most LREE enriched of all units in the stratigraphic sequence. The nonmarine Silverquick has lower La_N/Sm_N (2.4) but very high concentrations of Cr and Ni.

Chromium and nickel values are generally low (Cr, ~20–70 ppm; Ni, ~7–30 ppm) throughout the entire Mesozoic section with the notable exceptions of the Dash conglomerate, the Lizard formation, and the Silverquick conglomerate, all of Albian-Cenomanian age, which have anomalously high values of both Cr and Ni (Cr, ~117–360 ppm; Ni, ~72–294 ppm; see Fig. 3). Although lower in absolute concentrations, cobalt is also higher in this group of samples, and V/Cr and V/Ni ratios are also low.

Samples of the Bridge River Complex can be subdivided into two geochemically distinct suites based mainly on La_N/Sm_N and Cr and Ni concentrations. Suite A (Table 2) contains samples with significant LREE enrichment (La_N/Sm_N of ~3.5), and anomalously high concentrations of Cr and Ni (Table 2). Suite B is characterized by only moderate LREE enrichment (La_N/Sm_N of ~2) and high Ba_N/La_N ratios.

INTERPRETATION

The LREE enrichment in Albian strata probably reflects continental proximity and

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[1] GSA Data Repository item 9505, Appendices A, B, and C, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

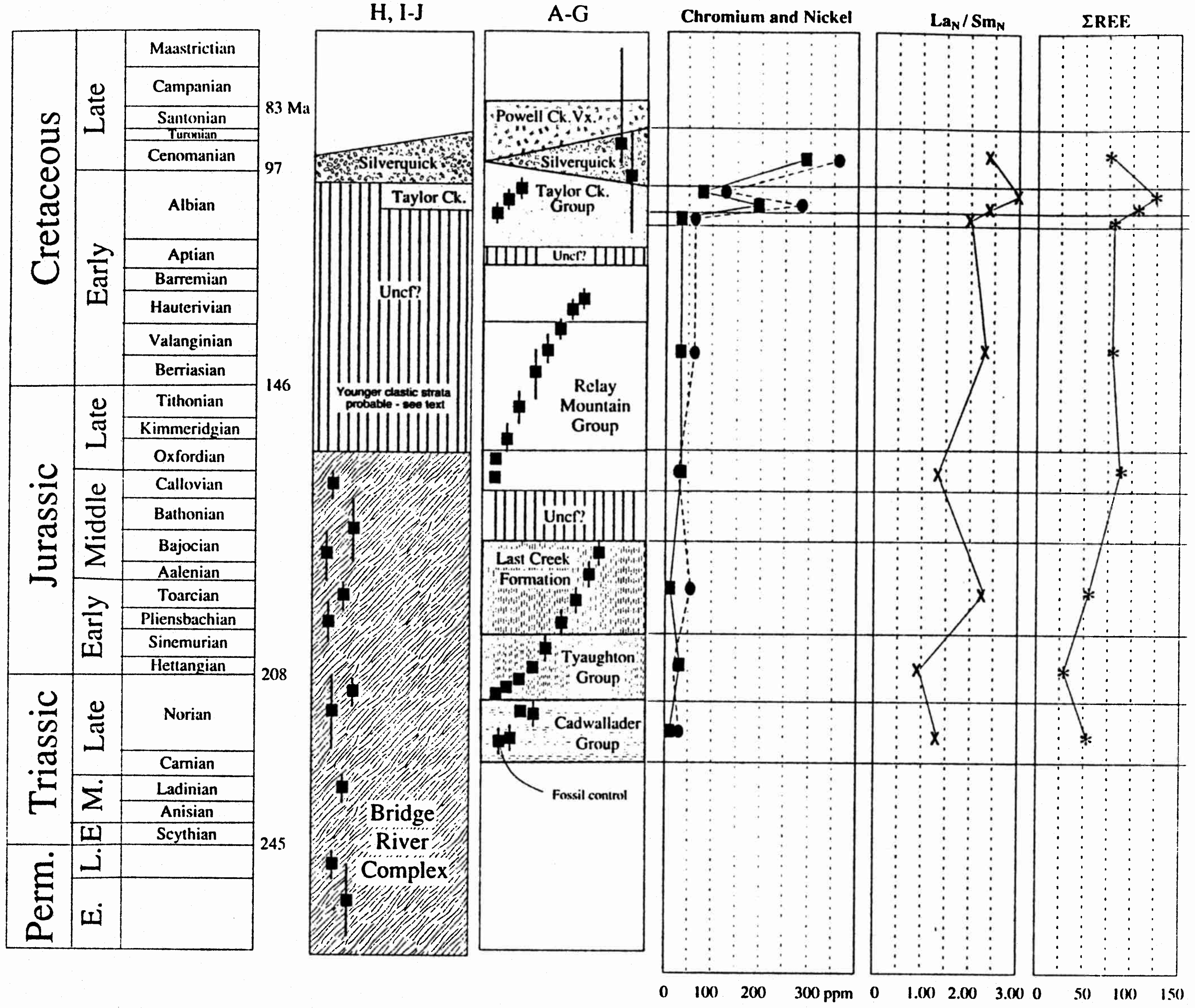

Figure 3. General stratigraphy of the Bridge River area (after Garver et al., 1989a). Shown is the stratigraphic relationship in the central part of the area on the left (samples H, and I–J; see Fig. 2) and stratigraphic relations in the northwestern part of the area (samples A–G; see Fig. 2). It is important to note that rocks of the Taylor Creek Group depositionally overlie rocks of the Cadwallader terrane and rocks of the Bridge River Complex. Squares on the stratigraphic sections represent faunal control and the associated error on the fossil calls (see Garver et al., 1989, and Cordey and Schiarizza, 1993). Uncf? represents the probable range of the unconformity in this section of rocks; in all cases the exact bounds of unconformity are imprecisely known. To the right are summaries of some of the geochemical data from this study. The first column shows the average Cr (solid circles) and Ni (solid squares) for all units; elevated concentrations in the Dash Conglomerate, Lizard formation (both upper Taylor Creek Group), and the overlying Silverquick conglomerate are interpreted to represent ultramafic detritus. The second column shows the average La$_N$/Sm$_N$ ratios (concentrations normalized to chondrite before calculation) which are a measure of light rare earth element (LREE) enrichment. Note that the unit showing the highest LREE enrichment is the Lizard formation of the upper Taylor Creek Group which has La$_N$/Sm$_N$ as high as 4.2. The trend in total REE (ΣREE) is shown in the third column. Time scale of Harland et al. (1990).

therefore terrane accretion to the edge of a continent with contemporaneous uplift and erosion of ophiolites. Older strata reflect proximity to an oceanic arc, but the relative position of that arc terrane with respect to a continental margin is unknown. These findings support previous interpretations that these Albian strata serve as an overlap sequence that ties underlying terranes to the edge of a continent (Garver and Brandon, 1994). The Bridge River Complex contains two geochemically distinct suites of argillites, which we discuss separately. In the following section, we first interpret the results from the stratified sequence, and we then discuss the results from the Bridge River Complex.

TABLE 2. AVERAGE VALUES AND ELEMENT RATIOS FOR INDIVIDUAL UNITS

Formation	V	Cr	Co	Ni	Cu	Nb	Ba	Ba/Nb	Cr/Ni	V/Cr	V/Ni	ΣREE	La/Yb	La/Sm	Ce/Ce*	Eu/Eu*
Bridge River Complex–Jurassic-Cretaceous(?) accretionary prism(?)																
[J] Bridge River Complex Suite B	207	103	15	59	106	8	1040	135	2.0	2.7	5.7	96	3.2	2.0	0.95	0.88
[I] Bridge River Complex Suite A	209	428	21	241	86	26	354	20	1.8	1.3	2.3	135	8.2	3.5	0.93	0.81
Mid-Cretaceous continental overlap																
[H] Silverquick	222	360	36	294	85	12	1648	140	1.2	0.6	0.8	75	5.9	2.4	0.79	0.82
[G] Lizard	247	117	20	73	79	10	829	85	1.6	2.1	3.4	122	8.1	3.0	1.00	0.83
[F] Dash	245	282	28	195	76	15	464	31	1.4	0.9	1.3	109	6.4	2.4	0.98	0.84
Average	238	253	28	187	80	12	980	85	1.4	1.2	1.2	102	6.8	2.6	0.90	0.83
Triassic to mid-Cretaceous oceanic-arc sedimentary sequences																
[E] Paradise	222	63	17	30	66	6	646	105	2.1	3.5	7.5	82	5.8	2.0	1.04	0.92
[D] Upper Relay Mountain	217	69	12	29	55	6	783	130	2.4	3.2	7.4	79	6.3	2.3	0.93	0.91
[C] Lower Relay Mountain	175	26	21	25	50	5	638	135	1.0	6.7	6.9	89	3.7	1.3	0.80	0.80
[B] Last Creek	189	54	9	9	55	4	1034	284	6.5	5.8	23.0	59	2.6	2.3	0.75	1.15
Tyaughton	54	20	11	23	22	2	65	39	0.9	2.7	2.3	27	2.9	0.9	0.96	0.69
[A] Cadwallader	173	30	18	18	69	2	851	362	1.7	5.7	9.4	57	3.1	1.3	0.80	0.89
Average	178	45	14	22	54	4	707	175	2.8	4.2	10.6	66	4.2	1.7	0.88	0.90

Note: ΣREE were calculated from concentrations of each element analyzed in ppm. La/Yb and La/Sm ratios were calculated from chondrite-normalized values. Ce/Ce* and Eu/Eu* represent the cerium and europium anomalies as calculated from chondritic-normalized values (Ce and Eu) and their interpolated values (Ce* and Eu*) according to the method of McLennan, 1989, p. 176.

Oceanic-Arc-Proximal Sediments

The older sequences, represented by the Cadwallader terrane (Cadwallader Group, Tyaughton Group, and Last Creek formation), the overlying Relay Mountain Group, and the Paradise formation (lower Taylor Creek Group), do not show significant LREE enrichment, and their overall rare-earth-element patterns are similar to mud derived from modern oceanic arcs (McLennan et al., 1990). Additionally, these units have a high Ba_N/La_N ratio, which may be a discriminator of volcanic arc signatures (e.g., Gill, 1981), but these numbers must be regarded with caution because the formation of authigenic barite results in unusually high Ba concentrations (Fig. 3). The interpretation that these units have been derived from an oceanic arc is consistent with previous work that suggests the clastic sediments of the Cadwallader terrane and lower part of the Tyaughton basin were derived from a juvenile and/or dissected volcanic terrane (Rusmore, 1987; Umhoefer, 1985; Garver, 1989). The carbonate-rich shale of the Tyaughton Group has very low ΣREE (Table 3) presumably due to carbonate dilution.

None of these units shows anomalous concentrations of Cr, Ni, or Co, so it is unlikely that much, if any, of the source region was composed of ultramafic rocks (see Garver et al., 1994). Although the average Cr/Ni ratio is 2.8 for this group, there is variation among the values, especially when concentrations of these elements are low. Note that for those units with higher concentrations (Paradise formation, upper Relay Mountain Group, and Last Creek formation; see Table 2), the average Cr/Ni ratio is 4.1, and shale of the upper Relay and the Paradise have a ratio of 2.4 and 2.1, respectively. In these cases, Cr is more highly correlated with V and Ti than are other elements. We suspect that these sediments reflect a volcanic provenance, an interpretation that is supported by high V/Cr and V/Ni ratios and sediment composition.

Mid-Cretaceous Continental Overlap

The REE pattern of the Albian (ca. 110 Ma) Lizard formation and the Dash conglomerate, both of the upper Taylor Creek Group, shows the most significant LREE enrichment (La_N/Sm_N of up to 4.2 for sam-

TABLE 3. CHONDRITE-NORMALIZED RARE EARTH ELEMENTS FOR ALL UNITS STUDIED

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	La/Sm	Ba_N/La_N	Ce/Ce*	Eu/Eu*
Bridge River Complex–Jurassic-Cretaceous(?) accretionary prism(?)																		
Suite A	89.7	64.1	53.2	43.2	26.2	18.2	19.0	16.1	14.0	12.8	12.2	11.5	11.4	11.6	3.5	0.58	0.93	0.81
Suite B	48.6	38.9	35.0	31.5	24.9	18.9	18.4	17.8	16.6	15.8	15.4	15.3	15.5	15.8	2.0	3.45	0.95	0.88
Mid-Cretaceous continental overlap																		
Silverquick conglomerate	46.0	29.3	29.7	25.5	18.7	12.9	13.2	11.5	11.4	10.7	10.9	11.0	11.7	11.6	2.4	5.25	0.77	0.81
Lizard formation	73.9	58.3	45.7	38.2	25.2	17.5	17.7	15.4	13.9	13.3	13.1	13.2	13.6	13.7	3.0	1.88	1.01	0.82
Dash conglomerate	60.8	48.8	40.8	35.1	25.0	18.2	18.8	17.2	15.6	14.9	14.3	14.1	14.1	14.3	2.4	1.22	0.97	0.83
Triassic to mid-Cretaceous oceanic arc sedimentary sequences																		
Paradise formation	40.9	36.8	30.7	27.7	20.2	15.6	14.1	12.9	11.2	10.8	11.0	10.1	10.4	10.3	2.0	2.40	1.03	0.93
Upper Relay Mountain	44.1	34.5	31.2	27.0	19.2	14.7	13.6	12.2	10.9	10.4	10.3	10.2	10.4	10.6	2.3	2.73	0.93	0.91
Lower Relay Mountain	38.0	29.0	34.4	34.5	29.6	20.9	23.2	21.4	18.8	16.6	15.8	14.9	15.3	15.0	1.3	2.68	0.81	0.80
Last Creek formation	33.6	19.9	20.9	19.3	15.1	16.5	11.8	11.5	11.5	11.4	11.6	11.8	12.6	14.3	2.3	7.91	0.75	1.15
Tyaughton Group	10.4	9.9	10.4	9.3	8.6	5.1	6.3	7.1	5.8	6.8	5.9	5.7	5.1	5.6	1.4	1.38	0.96	0.70
Cadwallader	24.2	17.9	20.8	21.1	18.8	14.9	14.8	14.2	13.0	12.1	11.9	11.1	11.6	11.2	1.3	5.50	0.80	0.88

Note: Excluded from this list is TY89-6 from the Tyaughton Group, which is dominated by carbonate and has very low REE concentrations (~0.3 × chondrite). Rare earth elements normalized using the chondrite values of Boyton (1984). Ba_N/La_N are normalized using the chondrite values of Wheatly and Rock (1988), and Ce/Ce* and Eu/Eu* are a measure of cerium and europium anomalies, respectively, and are calculated using the formula of McLennan (1989, p. 176).

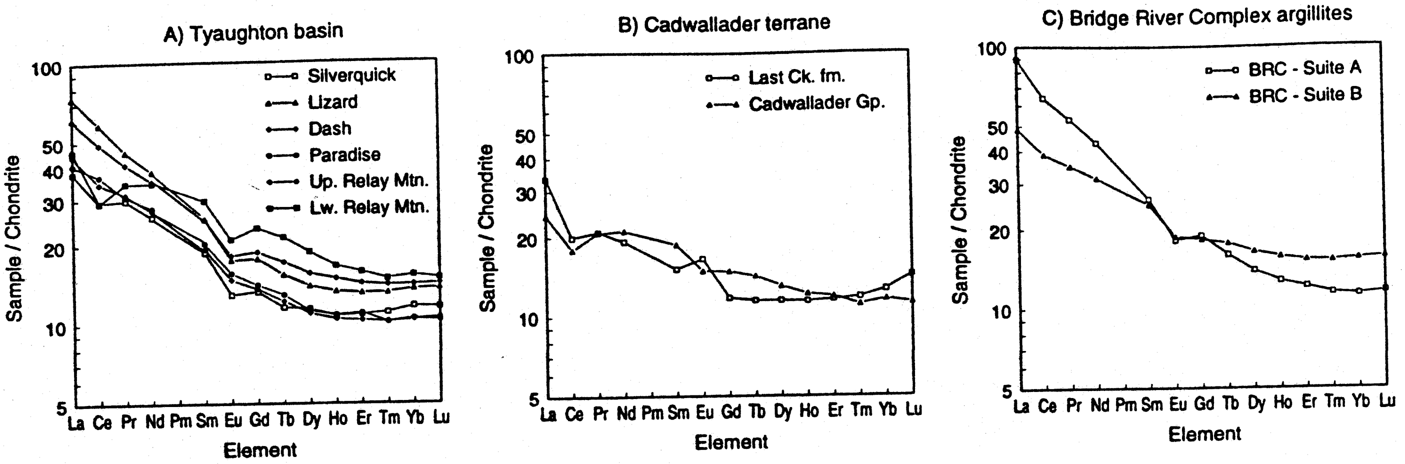

Figure 4. Chondrite-normalized REE data for shale from the stratigraphic units of the (A) Tyaughton basin strata, (B) Cadwallader terrane, and (C) the Bridge River Complex. Units displayed are the averages for the following units (see Fig. 2 for locations of lettered units): (A) Cadwallader Group (Upper Triassic–Norian) from the Hurley formation in the Eldorado area; (B) Last Creek formation (Lower Jurassic; Hettangian-Toarcian) from the Castle Peak area; (C) lower Relay Mountain Group (Middle to Upper Jurassic; Callovian-Oxfordian) from south of Relay Mountain; (D) upper Relay Mountain Group (Upper Jurassic to Lower Cretaceous; Tithonian-Barremian) from north of Relay Mountain; (E) lower Taylor Creek Group (Paradise formation; mid-Cretaceous; ?Aptian-Albian); (F) upper Taylor Creek Group (Dash conglomerate of mid-Cretaceous age—upper lower Albian to middle-upper Albian); (G) upper Taylor Creek Group (Lizard formation of mid-Cretaceous age—upper lower Albian to middle-upper Albian); (H) Silverquick conglomerate (Albian-Cenomanian); (I) Bridge River Complex, Suite A; and (J) Bridge River Complex, Suite B. See Appendix A and B (Data Repository) for precise sample locations and REE values. Chondrite-normalizing values of Boynton (1984) were used.

ples of the Lizard formation) of any of the stratified sequences in this study, and the REE concentrations compare closely to the REE concentrations of sediment derived from modern continental arcs (McLennan et al., 1990). Shale samples from the overlying Silverquick conglomerate (Fig. 3) do not have as high La_N/Sm_N, which can be ascribed to their provenance because sediments of this unit were derived from a source region dominated by rocks of the underlying terranes with newly superimposed arc-volcanic rocks, neither of which would have significant LREE enrichment (Garver, 1992). As discussed below, our data suggest that a significant part of the source to the Silverquick conglomerate was composed of ultramafic rocks and chert that have almost no REE. Therefore, like the upper Taylor Creek Group, these strata are synorogenic, but the continental influence has presumably been diluted or excluded by a source of exhumed LREE-poor oceanic rocks and superimposed volcanic rocks. Likewise, coarse clastic sediments of the Dash conglomerate are dominated by REE-poor rocks of the Bridge River Complex (Garver, 1992), so it is significant that even with this dilution, the average La_N/Sm_N is 2.4.

The Taylor Creek Group preserves critical relationships with respect to adjacent crustal blocks and sediment sources (Garver, 1992). Sediment composition, paleocurrents, and stratigraphic trends indicate that in the Albian strata, arc-derived sediments derived from the west (e.g., Paradise formation) interfinger with sediments derived from uplifted oceanic rocks of the Bridge River Complex (e.g., Dash and Silverquick conglomerates) and a continental landmass to the east (e.g., Lizard formation and correlative arkosic rocks in the Methow sequence). An important aspect of this interpretation is that in the Albian, the Cadwallader terrane and its overlying sedimentary sequences (including the Relay Mountain Group) received, for the first time, detritus clearly derived from a continental landmass.

As discussed in detail below, it is possible that the REE data from the upper Relay Mountain Group ($La_N/Sm_N = 2.3$) indicate proximity to a continent, but the geochemical signal from the continent has been diluted by oceanic-arc-derived material; the same effect of sediment mixing is clearly seen in the Dash and Silverquick conglomerates as discussed above (Fig. 3). In this sense, the strata of the upper Relay Mountain Group may record the progressive closure of the ocean basin and the dual source may only be recognized in strata that record conditions when the oceanographic environment was conducive to sediment mixing. Note that this possibility is different from interpretations that suggest the entire Relay Mountain Group is a postamalgamation overlap sequence in which terrane juxtaposition occurred prior to deposition in the Middle Jurassic (e.g., Rusmore et al., 1988). Geochemically, there is little reason to suspect that the Middle Jurassic was a time of terrane amalgamation or accretion.

The distinct Cr and Ni anomaly present in shale of the upper Taylor Creek Group and shale of the overlying Silverquick conglomerate is interpreted to represent a significant component of uplifted ultramafic rocks in the source area. In these sediments, Ni, Cr, and Co are all highly correlated (correlation coefficient > 0.73), and none of these elements are strongly correlated to Ti or V as is the case in the stratigraphically underlying units as discussed above. As pointed out by Garver (1989, 1992), the coarse clastic sediments of the Taylor Creek Group and the Silverquick conglomerate have abundant detrital chromite and serpentinite clasts probably derived from erosion of the Shulaps ultramafic complex, which was thrust over the Bridge River Complex during this time (Schiarizza et al., 1990).

Ultramafic rocks have Cr and Ni concentrations of ~2400 and ~1500 ppm, respectively (Goles, 1967; Coleman, 1977)—a Cr to Ni ratio of about 1.6. In this study, shales containing elevated Cr and Ni have a similar to slightly lower ratio (1.2 to 1.6; see Table 2). Higher ratios are probably characteristic of detritus derived from a source with a dominant component of volcanic rocks (Garver et al., 1994). Assuming a near quantitative transfer of Cr and Ni from the source to the site of deposition, we estimate that in the source region, ultramafic rocks composed 12%–13% for the Dash conglomerate, ~5% for the Lizard formation, and 15%–20% for the Silverquick conglomerate. These fluctuations of Cr and Ni through time (Fig. 3) may be related to the episodic thrusting and subsequent erosion of the Shulaps ultramafic complex (Garver, 1989; Schiarizza et al., 1990).

In light of the Cr and Ni anomalies, the LREE enrichment, and the demonstrable stratigraphic overlap, we suggest that the Albian-Cenomanian strata record terrane amalgamation and accretion to the edge of a continent. As discussed above, it is unfortunate that our data cannot confirm or rule out an earlier progressive closure of an ocean basin that may be recorded in strata of the upper Relay Mountain Group. In addition, we see no geochemical evidence for terrane amalgamation in the Middle Jurassic.

Bridge River Complex: A Jurassic-Cretaceous Accretionary Complex?

The origin of the Bridge River Complex has been the subject of considerable controversy. In the Bridge River area (adjacent to Carpenter Lake, Fig. 2), the Bridge River Complex includes pebble- to kilometer-scale inclusions of chert, greenstone, sandstone, conglomerate, limestone, serpentinite, and gabbro that are enveloped in an argillaceous matrix. Although we know the age range of many inclusions in the Bridge River Complex, the age of structural imbrication and mixing is unknown. A traditional view holds that the Bridge River Complex was active during the span of the age range of chert (mainly Triassic), which suggests contemporaneity with the Cadwallader arc. Our view holds that an important phase of imbrication and deformation in the Bridge River Complex is Jurassic and Cretaceous in age, and the older tectonic inclusions were brought in on oceanic plates or reworked from adjacent terranes.

Argillites of the Bridge River Complex (Suite A) are notable for their LREE enrichment ($La_N/Sm_N = 3.5$) and high (but variable) concentrations of Cr and Ni. A striking observation of both Suite A and Suite B samples is that they are geochemically distinct from any unit of the Cadwallader terrane but similar to strata of the upper part of the Tyaughton basin. The LREE enrichment of the samples from Suite A is similar to mud from modern continental arcs (McLennan et al., 1990). Geochemically, the average trace-element characteristics of these sediments are similar to the shale of the upper Taylor Creek Group, and the obvious question is whether clastic sediments of the Bridge River Complex are not simply imbricated and structurally interleaved synorogenic sediments of the upper Taylor Creek Group.

The stratigraphic setting of these clastic rocks provides some clue as to their origin, because six of the seven samples of the Bridge River Complex are from a disrupted argillite-sandstone-chert association. This unusual chert/clastic association is very different from any rocks of the Tyaughton sequence, and it is unlikely these rocks were deposited under the same basin conditions. Regionally, however, this chert/clastic association is common in rocks of the Jurassic-Cretaceous Constitution Formation, the Jurassic-Cretaceous Pacific Rim complex in the San Juan Islands and western Vancouver Island, and in parts of the Franciscan Complex of California (Brandon et al., 1988, and references therein).

Although there are no fossils from the coarse clastic rocks in the Bridge River Complex, recently published isotopic data from clastic rocks of the Bridge River Complex pertain to their age and provenance. Using Rb-Sr to investigate the origin and age of whole-rock samples of argillaceous rocks of the Bridge River Complex, Leitch et al. (1991) noted that their data for the Bridge River Complex plot in a band (0.002 wide) in $^{87}Sr/^{86}Sr$ with an initial ratio of about 0.7050 and a 152 Ma slope. They point out that this envelope is similar to units in the Pacific Northwest and other Mesozoic subduction-accretion assemblages of the western Cordillera (e.g., Franciscan Complex of California). The two groups of samples, which experienced low-grade metamorphism, have a calculated age of 154 ± 27 and 142 ± 20 Ma. Although Leitch et al. (1991) suggested that these ages must represent a reset age because they are younger than the fossil ages, this fossil range is only for bedded chert and limestone, and therefore we see no reason to suspect that these ages are reset. These Jurassic-Cretaceous ages are consistent with the known paleontologic age ranges of the Constitution Formation and Pacific Rim Complex, which we suggest are correlatives to the south along the leading edge of the thrust system (Brandon et al., 1988).

In light of the Rb-Sr data (Leitch et al., 1991) and our REE data from the Bridge River Complex, we suggest that the clastic sediment represents two distinct Upper Jurassic to Lower Cretaceous clastic units that were imbricated and thoroughly mixed with oceanic rocks of the Bridge River Complex. One of these units is represented by arc-like detritus that may be similar to the Relay Mountain Group, and the other is continentally derived and may be similar to chert and clastic rocks of the Constitution Formation and Pacific Rim Complex to the southeast, which are also inferred to have a continental source (Brandon et al., 1988). This suggestion implies that if the Bridge River Complex is interpreted as an accretionary complex (Garver, 1992; Cordey and Schiarizza, 1993), then it received and imbricated sediment in the Upper Jurassic and Lower Cretaceous. Regionally, therefore, it is part of a sequence of rocks inferred to be along the leading edge of the mid-Cretaceous thrust system (Fig. 1; see Brandon et al., 1988; Garver and Brandon, 1994).

Clastic strata of Suite A of the Bridge River Complex have a Cr/Ni ratio of 1.8 and a near perfect correlation between Cr and Ni. We entertain two possibilities for the Cr and Ni anomalies which, like the Taylor Creek Group and the Silverquick conglomerate, presumably reflect ultramafic rocks in the source region. First, these strata may be Taylor Creek equivalents, and the Cr and Ni anomalies correspond to the thrusting, uplift, and erosion of the Shulaps ophiolite. However, Ba, Nb, and V concentrations of the three Bridge River Complex samples with elevated Cr and Ni fall outside the range determined for the Taylor Creek Group, and, more important, the lithologic association is different. Second, it is possible that these Cr and Ni anomalies represent simple cannibalism of the Bridge River Complex during imbrication and accumulation of oceanic strata as an accretionary complex. This scenario would involve having the Bridge River Complex partially uplifted during steady-state accretion, and the Cr and Ni anomaly resulted from the uplift and erosion of some of the many ultramafic slivers in the Bridge River Complex (Schiarizza et al., 1990).

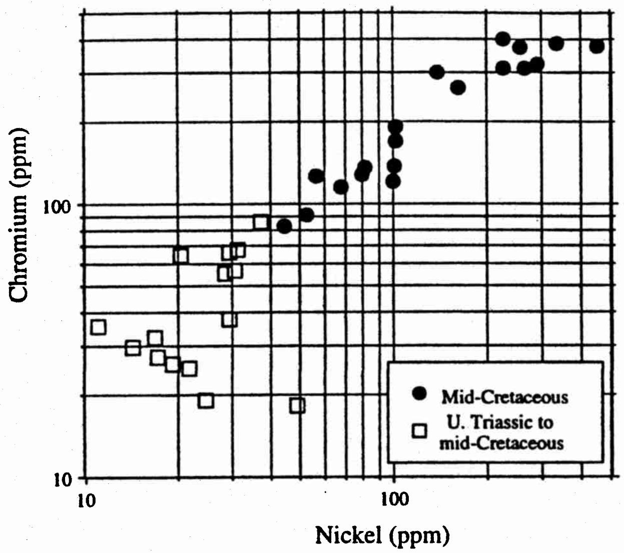

Figure 5. Graph showing the relationship between chromium and nickel in shale of the (1) Cadwallader Group, Tyaughton Group, Relay Mountain Group, and lower Taylor Creek Group (Paradise formation) (shown as open squares) and (2) the upper Taylor Creek Group (Dash conglomerate and the Lizard formation) and Silverquick conglomerate (shown as solid circles). For clarity, values <10 ppm were excluded from the data set (see Appendix B in the Data Repository for data). Elevated values of Cr and Ni with a Cr/Ni ratio of ~1.4 are interpreted to represent detritus from ultramafic rocks in the source region.

TIMING OF ACCRETION

A fundamental conclusion that can be drawn from our data is that the geochemistry of shale from the Cadwallader terrane and the overlying stratigraphy of the Tyaughton basin supports a scenario of deposition adjacent to an oceanic arc until the mid-Cretaceous when the area received the first sediment clearly derived from a continent. This event was also characterized by the uplift and erosion of ultramafic rocks in the source area, and a case based on sediment geochemistry cannot be made for erosion of ultramafic rocks earlier than this. Although we cannot rule out the possibility that rocks of the Cadwallader terrane were close to a continent prior to this time, there is no geochemical evidence for this hypothesis. Our data, combined with abundant sedimentological and structural evidence, suggest that the mid-Cretaceous was a time of terrane amalgamation and accretion in a contractional setting, with concurrent basin formation adjacent to a continent (Fig. 6; Cole, 1973; Davis et al., 1978; Monger et al., 1982; Garver, 1992; McGroder, 1989, 1991; Garver and Brandon, 1994). Prior to this time, sedimentation in the Methow section and in the Tyaughton section occurred in different places, perhaps in the same ocean basin, but separated by an unknown distance of water (Fig. 6a).

The La_N/Sm_N of 2.3 in the Relay Mountain Group and 2.0 in the overlying Paradise formation may signal a change in sediment provenance, and a comparison to data from modern mud is instructive. Although there are very few data on modern settings, La_N/Sm_N ratios of mud from along the edge of continents (continental arcs and trailing margins) are between 2.1 and 5.2, and those of oceanic arcs (fore arc and back arc) are between 1.3 and 3.8 (see data in McLennan et al., 1990). Therefore a value of 2.3 for the upper Relay Mountain Group is difficult to interpret, especially in the context of the overlying unit, which has a slightly lower ratio of 2.0. In this regard, a La_N/Sm_N ratio of 2.3 in shale of the upper Relay Mountain Group could represent (1) sediment from a geochemically evolved oceanic arc or (2) sediment from a juvenile oceanic arc that mixed with sediment from an evolved continental source.

In the context of our study, this first option requires that the mud from the upper Relay Mountain Group was entirely derived from an arc to the west. In this case, the mud reflects the more-evolved nature of the volcanic arc that was built on the Insular terrane. This scenario is supported by stratigraphic thickening of the unit to the west into a contemporaneous volcanic belt (see discussion in Umhoefer, 1989). Farther to the north, in southeast Alaska, coeval rocks of the Gravina belt were likely deposited in such a setting (Cohen and Lundberg, 1993). Provenance analysis suggests that these possible northern correlatives were entirely derived from the contemporaneous Gravina arc and the underlying Insular terrane (Cohen and Lundberg, 1993). On the other hand, it is possible, and even likely, that to some extent the mud from the upper Relay Mountain Group was derived from both an arc to the west (with La_N/Sm_N of ~2) and a continent to the east (with La_N/Sm_N of ~3 or greater), resulting in an intermediate La_N/Sm_N ratio. In this second option, one would predict that a detailed look at provenance changes upsection and laterally may reveal increasing continentality which would culminate in the Albian Lizard Formation. Unfortunately, however, with our present data set, there is no way to distinguish between these two options.

Therefore, although the final closure of this ocean basin is clearly recorded in Albian-Cenomanian strata of the Taylor Creek Group and correlative Virginian Ridge Formation in the Methow (Fig. 6B), it is probable that the incipient stages of closure are recorded in Lower Cretaceous strata of the (1) Relay Mountain Group; (2) strata of the Cayoosh assemblage, which is known to rest on the Bridge River Complex (Mahoney and Journeay, 1993); and (3) Jackass Mountain Group and other strata of the Methow sequence that rest on the Methow terrane (Fig. 6A). In this regard, it is important that future studies more closely scrutinize the relations among these different units that may record the progressive closure of this basin. Even so, however, one must bear in mind that lack of continental detritus prior to the Albian does not prohibit an early amalgamation of these terranes if sediment from a nearby continent was unable to reach this site of deposition. Nonetheless, important information about the precollisional terrane configuration will result from future geochemical and isotopic studies aimed at determining the similarities or differences among these units and if two distinct source terranes existed during this time.

Notably, Cr and Ni anomalies do not exist in the older strata. Recall that other workers have suggested that thrusting of the Shulaps ultramafic complex occurred during the Middle Jurassic (Potter, 1986; Rusmore et al., 1988). Likewise, those favoring a Mid-

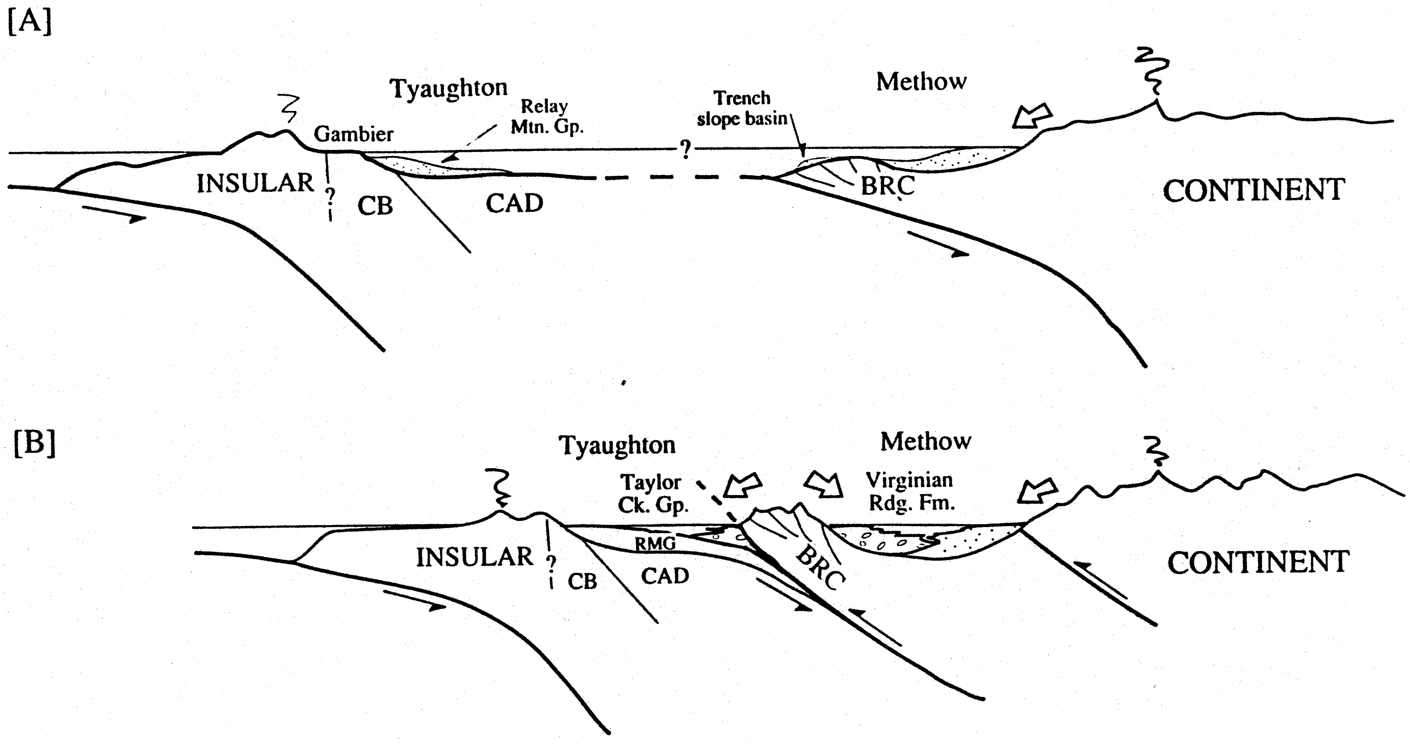

Figure 6. Tectonic cartoon showing the inferred development of the Tyaughton sequence, Methow sequence, Coast Belt (CB), Cadwallader terrane (CAD), and the Bridge River Complex (BRC). A, Upper Jurassic to Lower Cretaceous; B, mid-Cretaceous (Albian-Cenomanian). We envision that the Bridge River Complex formed along the edge of a continent, perhaps as the partial basement to the Methow basin. The Cayoosh Assemblage, which rests on the Bridge River Complex (Mahoney and Journeay, 1993), may represent trench-slope deposits with nearby correlatives in the Methow Basin. The Cadwallader terrane and overlying strata of the Tyaughton basin (Relay Mountain Group, RMG) are envisioned to have formed and accumulated in an oceanic-arc-proximal setting. Mid-Cretaceous convergence brought these sequences, and probably the Insular terrane, against a continental margin. We do not imply a genetic relationship between the Cadwallader terrane and the Insular terrane; workers have proven that they have formed in different settings in the Triassic (Rusmore, 1987). Our data suggest, but do not demand, that the first time the Cadwallader terrane and strata of the Tyaughton basin came into contact with the edge of a continent was in the mid-Cretaceous (Albian; ca. 110 Ma). The zone of tectonic juxtaposition, therefore, is located between the Bridge River Complex and the Cadwallader terrane and is marked by thick synorogenic deposits and contractional structures, both of which have been modified by later deformation. Cross section corresponds to an east-west profile through the basin strata and basement terranes at 2 in Figure 1B.

dle Jurassic amalgamation of the Insular terrane to the Intermontane suggest that perhaps ophiolites were uplifted and completely eroded during this time (van der Hyden, 1992). Our data indicate that no Cr and Ni anomaly exists in the strata of the Cadwallader terrane and the overlying Jurassic strata of the Tyaughton basin. By itself, this observation only proves that if amalgamation did occur during the Middle Jurassic, ultramafic rocks (i.e., ophiolites) were not uplifted and exposed in this area.

Finally, our data support the interpretation that the Bridge River Complex served as an accretionary complex against a continental margin, possibly in the Jurassic to the mid-Cretaceous. For this reason, and because the Methow basement (Table 1) is similar to basalts of the Bridge River Complex, we suspect that the Bridge River Complex was partial basement to the Methow sequence (Fig. 6), but a test of this hypothesis awaits future studies. In this case, the Bridge River Complex served as an accretionary prism that accumulated outboard of the Methow strata, which was a fore-arc basin (west facing) prior to terrane accretion.

Nature and Location of the Adjacent Continental Landmass

Our data suggest that the Cadwallader terrane and Tyaughton sequence show proximity to a continental landmass by the mid-Cretaceous, but not necessarily at the present latitude of British Columbia or Washington. Paleomagnetic data from 100 Ma plutonic rocks of the North Cascades and southern Coast Plutonic complex, and sediments of the Silverquick conglomerate indicate that a large part of western British Columbia may have experienced ~2900 km of coast-parallel northward transport prior to Eocene time (Beck et al., 1985; Irving et al., 1985; Umhoefer, 1987; Maxson et al., 1993). A probable restoration places rocks of the Bridge River area and other outboard rocks (collectively referred to as "Baja BC") to a latitude around central Mexico. Such a restoration of Baja BC has been questioned because the same result can be produced by systematic tilting (Butler et al., 1989). However, Ague and Brandon (1992) have directly measured tilt using geobarometry, and their results indicate that even once the tilting is resolved, ~2900 km of latitudinal displacement is implied.

Paleomagnetic results from rocks west of the Pasayten fault are different from those obtained from coeval rocks east of the Pasayten fault (Fig. 1), which show only ~1200 km of displacement (Marquis and Globerman, 1988; Irving and Thorkelson, 1990)—approximately the calculated displacement on known strike-slip faults to the east (Gabrielse, 1985). In light of paleomagnetic data and geologic evidence, Cowan (1993, 1994) proposed that the Pasayten fault and other faults to the north represent the boundary between far-traveled, southern-derived terranes to the west and rocks that have experienced significantly less movement to the east. The controversy surrounding Baja BC leaves us with two options for the source of the continentally derived sediment in the Albian strata of the Methow-Tyaughton basin and Bridge River Complex. In an *in situ* scenario, which rejects the paleomagnetic data, the sediment was derived from old crustal material of eastern British Columbia and Washington State. In a *far-traveled* scenario, LREE-enriched sediment must have been derived from less-evolved crustal material far to the south.

Garver and Brandon (1994) used fission-track data from detrital zircon to infer that the eastern source terrane was represented by an active volcanic arc built on a plutonic and metamorphic basement; these basement rocks experienced cooling in the Early Cretaceous and in the Early Triassic. Isotopic findings from similar strata of the Methow section (Barfod and Nelson, 1992) shed additional light on this eastern source terrane because these sediments have high ε_{Nd} values (+2.8 to +3.1), which suggests, but does not prove, lack of Proterozoic or older basement in the source region.

If large-scale displacement did not occur, the source of the fine-grained sediment in the Lizard formation would have been dominated by sediment from the evolved crustal rocks in the Omineca belt and its southern continuation as discussed in Garver and Brandon (1994) (Fig. 1). This belt contains numerous plutons and volcanic rocks that have intruded a basement of Proterozoic and Paleozoic continental margin sediments and, locally, Archean crust (Armstrong, 1988). This crustal signature contrasts sharply with the probable source in the southern option. A restoration of Baja BC using paleomagnetic data suggests that a likely source for the east-derived arkosic sediments in the Methow-Tyaughton basin was the Peninsular Ranges batholith, which also originated at the latitude of central Mexico (Garver and Brandon, 1994). The majority of the Peninsular Ranges batholith intrudes relatively young crust (Cowan and Bruhn, 1992) and therefore it has probably not experienced the crustal differentiation of rocks in the Omineca belt. The LREE enrichment in the Albian strata (e.g., Lizard formation) indicates differentiated crust, but we would expect even greater LREE enrichment from sediments derived from the Omineca belt. Unfortunately, our trace-element data cannot be used to determine the age of crustal material in the source terrane—perhaps one of the few ways to support or refute the Baja BC hypothesis. Future isotopic work on the sediments deposited during collision and during coast-parallel transport will provide an important test of the Baja BC hypothesis, because the age and extent of cratonal material varies from north to south along its proposed route.

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