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TECTONIC CONTROLS ON MUDROCK GEOCHEMISRY, MESOZOIC ROCKS OF EASTERN OREGON AND WESTERN IDAHO, U.S.A.: IMPLICATIONS FOR CORDILLERAN TECTONICS

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ABSTRACT: **Tectonic models for the Mesozoic evolution of accreted island arcs and subduction complexes in the Blue Mountain Province (BMP) of eastern Oregon and western Idaho vary widely. The BMP is situated between coeval accreted terranes of southern British Columbia and the western U.S., and is critical for interpreting Mesozoic paleogeography of the U.S. Cordillera. In this study, we interpret the Triassic–Jurassic evolution of the BMP using geochemistry as a tool to evaluate the provenance of mudrocks in fine-grained turbidites. Temporal and spatial variations in mudrock geochemistry indicate that during Late Triassic to Early Jurassic time the Wallowa terrane was an intra-oceanic island arc and the Olds Ferry terrane was a pericratonic (continental-fringing) island arc. Subsequently, a regionally extensive Middle to Late Jurassic marine basin received input from continental sources and sediment may also have been derived from coeval terranes to the south. Comparison of provenance data from the BMP with similar data from accreted terranes to the north and south suggests that Triassic–Jurassic basins of the western U.S. share a long-term provenance history within a complex system of continent-fringing and intra-oceanic island arcs. In contrast, it appears that the Quesnel terrane of southern British Columbia had a distinct provenance with a more direct link to Laurentia during Triassic time. Early to Middle Jurassic sedimentary rocks from southern British Columbia and the western U.S. show a high degree of geochemical provenance similarity. This may indicate reorganization of formerly discrete tectonic regions into a nascent, integrated western Laurentian margin prior to complete development of a Cretaceous Andean-type margin. The results of this study demonstrate the utility of mudrock geochemistry in tectonic analyses and show that major- and trace-element geochemistry of mudrocks is useful for developing a comprehensive understanding of regional tectonic evolution.**

INTRODUCTION

The original composition of weathered source rocks is a dominant control on the makeup of terrigenous sediments, therefore geographic and stratigraphic variations in provenance can provide important constraints on the tectonic evolution of a region (e.g., Dickinson and Suczek 1979; Dorsey 1988; Ingersoll 1988; Frost and Coombs 1989; Clift and Dixon 1994; Clift et al. 2000; McLennan et al. 2003; many others). In particular, fine-grained clastic rocks (i.e., mudrocks) represent the average crustal composition of a source area and are reliable provenance indicators (e.g., McLennan et al. 2003). The fine-grained fraction of turbidite systems reflects short-term sedimentation processes including mass wasting in subaerial source areas and submarine-fan systems, longshore sediment reworking and redistribution, and longer-term processes that control the evolution of drainage systems. As a result of sediment mixing, the sedimentary record of turbidite systems reflects longer-term (i.e., 5 to 10 s of millions of years) variability associated with lithospheric-scale processes such as the evolution of magmatic and plate-tectonic systems (Clift and Dixon 1994; Clift et al. 2000).

In this study, we use temporal and spatial variations in the provenance of mudrocks from fine-grained marine turbidites to evaluate the Triassic–Jurassic evolution of tectono-magmatic terranes in the Blue Mountains Province (BMP) of Oregon and Idaho (Fig. 1). Significant controversy exists regarding tectonic models for terrane origins, genetic relationships between terranes, and timing and styles of arc amalgamation and accretion in the BMP (Fig. 1; e.g., Brooks and Vallier 1978; Dickinson and Thayer 1978; Dickinson 1979; Avé Lallemant 1995; Vallier 1995; Gray and Oldow 2005; Dorsey and LaMaskin 2007; Mann and Vallier 2007). According to most existing models for the BMP, sedimentary rocks of the Izee terrane accumulated in a long-lived, Triassic–Jurassic forearc basin between a non-collisional, east-dipping subduction zone in the west and a west-facing magmatic arc in the east (Dickinson and Thayer 1978; Dickinson 1979, 2004; Brooks and Vallier 1978; Vallier 1995). Alternatively, Dorsey and LaMaskin (2007) suggested a two-stage evolution of the region. Stage 1 includes Late Triassic collision between facing accretionary prisms and forearc regions of the Wallowa and Olds Ferry arcs. According to this model, arc–arc collision produced a large, doubly vergent thrust belt in the Baker terrane which shed sediment into flanking syntectonic basins formed on forearc crust of the outboard Wallowa and inboard Olds Ferry terranes. During stage 2, a large, Jurassic marine basin formed and subsided on top of the previously amalgamated arc terranes in response to crustal thickening and loading in the former back-arc region.

Numerous studies have attempted to interpret the tectonic setting and geodynamic evolution of the BMP based on whole-rock geochemistry of igneous rocks, structural and stratigraphic analysis, and paleontologic evidence (e.g., Vallier 1995; Brooks and Vallier 1978; Dickinson and

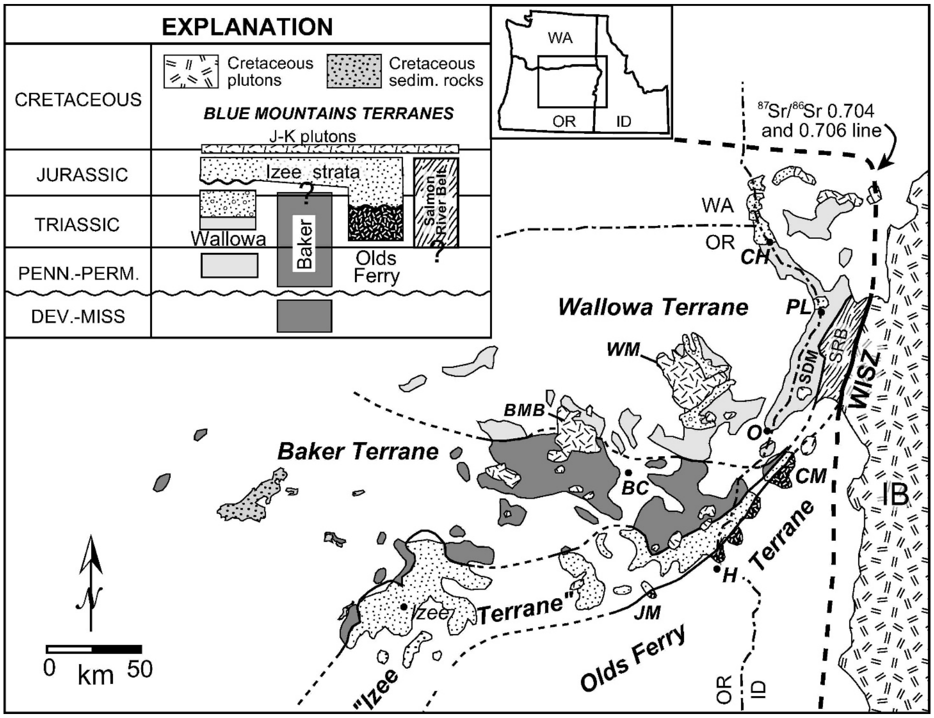

FIG. 1.—Generalized terrane map of the Blue Mountains Province (BMP), modified from Dickinson (1979), Follo (1992), Vallier (1995), Gray and Oldow (2005), Dorsey and LaMaskin (2007), and Mann and Vallier (2007). BC, Baker City; BMB, Bald Mountain batholith; H, Huntington; IB, Idaho Batholith; JM, Juniper Mountain; O, Oxbow; PL, Pittsburg Landing; CM, Cuddy Mountains; CH, Coon Hollow; SDM, Seven Devils Mountains; SRB, Salmon River Belt; WM, Wallowa Mountains and Wallowa batholith; WISZ, Western Idaho Shear Zone.

Thayer 1978; Dickinson 1979; Avé Lallemant et al. 1985; Pessagno and Blome 1986; Follo 1992; Avé Lallemant 1995; Bishop 1995a, 1995b; Walker 1995; Kays et al. 2006; Mann and Vallier 2007). This study represents the first systematic investigation of sedimentary provenance across the different terranes of the BMP. Our objectives are to (1) characterize the tectonic settings of sediment source areas in different depocenters through time, (2) constrain the timing of terrane accretion by assessing the onset of continental influence on sedimentation, and (3) compare sediment provenance in the BMP with coeval arc terranes in the western North American Cordillera to assess paleogeographic models.

The results of this study advance understanding of source areas for Blue Mountains Province sediments by discriminating between intra-oceanic, fringing-arc, and continental sources. The data reveal provenance patterns that can be interpreted in a geodynamic context, and address first-order problems concerning the timing of terrane accretion to the North American craton. These results increase our understanding of the complex Mesozoic history of western North America by constraining relationships between coeval arc terranes to the south in California and Nevada and to the north in southern British Columbia. In addition, the results of this study highlight the value of mudrock geochemistry in tectonic analysis. Despite some suggestions that trace-element plots cannot be relied upon for tectonic discrimination (i.e., Floyd et al. 1991; Ryan and Williams 2007), our analysis indicates that trace elements are indeed useful for revealing distinctive provenance characteristics of samples. Integration of mudrock geochemical provenance data with sandstone petrography advances our understanding of source areas and provides important constraints on the coupled tectonic evolution of arc terranes and cratonal margins.

GEOLOGIC FRAMEWORK

Regional Geology

Rocks of the Blue Mountains Province (BMP) trend east and northeast across northeast Oregon into western Idaho (Fig. 1) and occupy a critical position between contemporaneous arc terranes along strike to the south in California and Nevada and to the north in northern Washington and the Canadian Cordillera. The Wallowa terrane lies outboard of other rocks in the BMP and has been correlated to either the Wrangellia terrane (Wernicke and Klepacki 1988; Dickinson 2004) or the Stikine terrane (Mortimer 1986; Oldow et al. 1989) in British Columbia. The Wallowa terrane consists of upper Paleozoic, arc-related plutonic basement rocks overlain by Permian through Upper Triassic stratified volcanic and volcaniclastic rocks and by a widespread Upper Triassic shallow-marine limestone unit (Fig. 2; Vallier 1977, 1995). Carbonate sedimentation was followed by deposition of fine-grained clastic marine sediment in Late Triassic through Early Jurassic time. The Olds Ferry terrane includes Middle Triassic to Lower Jurassic plutonic, volcanic, and marine volcaniclastic and epiclastic rocks that formed in an island-arc setting (Brooks and Vallier 1978; Brooks 1979; Vallier 1995; Tumpane et al. 2008) and has been correlated with the Quesnel terrane in British Columbia (Dickinson 2004) and the Black Rock terrane in Nevada (Wyld and Wright 2001). Upper Triassic to Lower Jurassic rocks in the Izee–Suplee area (Fig. 1; Vester Fm. and Aldrich Mtns. Group) are distal marine forearc-basin deposits (Dickinson and Thayer 1978; Dickinson 1979) that are temporally correlative with Upper Triassic to Lower Jurassic, arc-proximal volcanic and volcaniclastic rocks of the Olds Ferry terrane in eastern Oregon and western Idaho (LaMaskin 2008; Tumpane et al. 2008). Thus, the Olds Ferry terrane is interpreted to include both Middle Triassic–Lower Jurassic rocks of eastern Oregon and Western Idaho (i.e., Huntington Fm.) and Upper Triassic–Lower Jurassic deposits of the Izee–Suplee area (Vester Fm. and Aldrich Mtns. Group; Dorsey and LaMaskin 2007).

Some workers have inferred that the Wallowa and Olds Ferry arcs were built on the same crust that underwent a reversal in arc polarity (e.g., Vallier 1995). Alternatively, tectonic juxtaposition of the two arcs may have occurred in Late Triassic time followed by deposition of a Jurassic overlap assemblage (Dorsey and LaMaskin 2007), or collision of the two arcs may be entirely post-depositional and recorded only in Upper Jurassic thrust faults, folds, and structural fabrics (Dickinson and Thayer 1978; Dickinson 1979; 2004; Gray and Oldow 2005).

The Wallowa and Olds Ferry island-arc terranes are separated by the Baker terrane (Fig. 1), a large belt of deformed argillite, limestone,

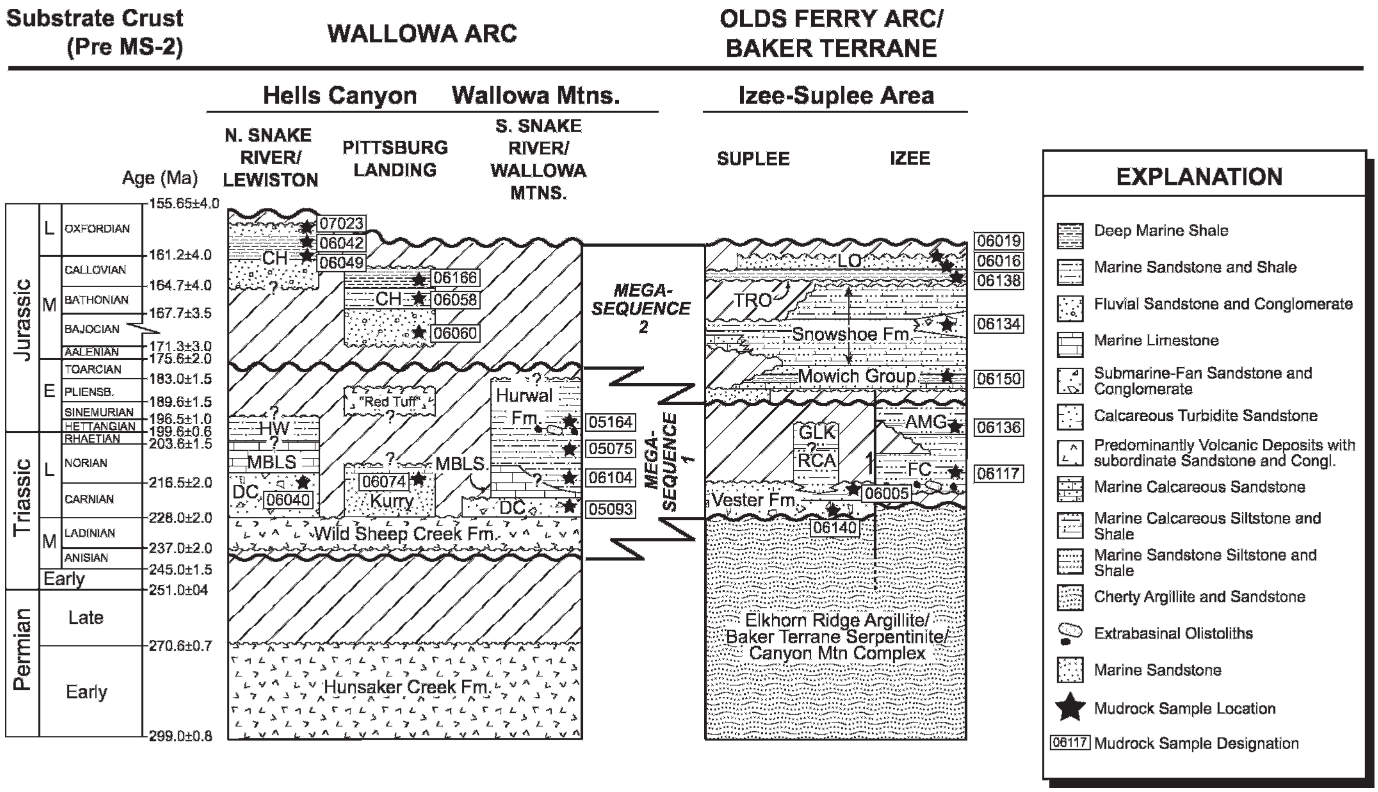

FIG. 2.—Sample locations (stars) plotted on a chronostratigraphic correlation chart for sedimentary and volcanic rocks in the Blue Mountains. Modified from Dorsey and LaMaskin (2007). Abbreviations are as follows: CH = Coon Hollow Fm., HW = Hurwal Fm., DC = Doyle Creek Fm., MBLS = Martin Bridge Limestone, LO = Lonesome Fm., TRO = Trowbridge Fm., AMG = Aldrich Mountains Group, FC = Fields Creek Fm., GLK = Graylock Fm., RCA = Rail Cabin Argillite. See Dorsey and LaMaskin (2007) for data sources.

serpentinized forearc and oceanic crustal fragments, arc-related igneous rocks, and locally developed blueschist-facies assemblages (Carpenter and Walker 1992; Hotz et al. 1977; Bishop 1995a, 1995b; Ferns and Brooks 1995; Vallier 1995; Schwartz et al. 2006; Schwartz and Snoke 2007). These rocks were deformed in a long-lived subduction and accretionary complex. The Baker terrane is widely considered to be correlative to similar rocks of the Cache Creek terrane in British Columbia and the Stuart Fork terrane and Central Metamorphic Belt in the Klamath Mountains (Saleeby 1983; Oldow et al. 1989; Hacker and Goodge 1990; Burchfiel et al. 1992; Kays et al. 2006).

Rocks of the Wallowa, Olds Ferry, and Baker terranes are unconformably overlain by Lower through Upper Jurassic clastic deposits (Fig. 2; Dickinson and Vigrass 1965; Dickinson and Thayer 1978; Dickinson 1979; Follo 1992 1994; White and Vallier 1994; White 1994; Goldstrand 1994; White et al. 1992; Dorsey and LaMaskin 2007). This overlap assemblage includes the Mowich Group and overlying deposits in the Izee–Suplee area of central Oregon, and the Weatherby and Coon Hollow formations of eastern Oregon and western Idaho.

To the northeast, the BMP merges with metamorphic rocks of the Salmon River Belt (SRB, *sensu* Gray and Oldow 2005; Fig. 1). This zone contains highly deformed tectonites that appear to be the metamorphosed equivalents of supracrustal rocks in the BMP, although protolith ages and terrane affinities remain poorly understood (Lund and Snee 1988; Selverstone et al. 1992; Manduca et al. 1993; Gray and Oldow 2005).

Regional Stratigraphy

Izee–Suplee Area.—In the Izee–Suplee area, the oldest deposits of the Triassic basinal succession are marine argillite, turbidites, chert-rich and volcaniclastic sandstone and conglomerate, and large chaotic slide breccias and olistostromes of the Upper Triassic to Lower Jurassic Vester Formation and Aldrich Mountains Group (Fig. 2; Dickinson and Vigrass 1965; Dickinson and Thayer 1978; Brown and Thayer 1977; Dickinson 1979). These deposits record slope instability and mass-flow deposition in fault-bounded marine subbasins of the distal Olds Ferry forearc. These basins were progressively deformed during thrusting, uplift, and erosion of the adjacent Baker terrane (Dickinson and Vigrass 1965; Dickinson 1979; Dickinson and Thayer 1978; Brown and Thayer 1977), which represents the accretionary prism and possible exhumed forearc crust of the Olds Ferry arc (Bishop 1995a, 1995b; Leeman et al. 1995).

Deformed Triassic deposits are unconformably overlain by ~ 2,500 meters of Lower and Middle Jurassic volcaniclastic deposits of the Mowich Group and Snowshoe Formation. These deposits record regional transgression from Pleinsbachian through Callovian time (~ 190 to 161 Ma), culminating in widespread deposition of black shales (Trowbridge Formation). During the Callovian, the starved basin was succeeded by deposition of an ~ 3000 m-thick regressive sequence of sandy turbidites with an increase in metamorphic and sedimentary lithic fragments (Lonesome Formation; Dickinson 1979; Dickinson et al. 1979). Dickinson et al. (1979) interpreted these provenance data in the Izee–Suplee area to record (1) Late Triassic uplift and emergence of the Baker terrane accretionary prism, (2) Early to Middle Jurassic volcanic activity of the Olds Ferry arc, and (3) late Middle Jurassic dissection of the metamorphic and plutonic roots of the Olds Ferry arc.

Wallowa Terrane.—In the Wallowa terrane, Middle to Upper(?) Triassic volcanic rocks of the Wild Sheep Creek Formation interfinger with, and are overlain by, Upper Triassic volcaniclastic deposits of the Doyle Creek Formation (Vallier 1977 1995), which record deposition in a forearc and/or intra-arc basin contemporaneous with magmatism in the Wallowa arc. These volcanic and volcaniclastic deposits are conformably overlain by widespread shallow-platform carbonates and deep-marine calcareous shales of the Upper Triassic Martin Bridge Limestone and correlative units. This carbonate unit is conformably overlain along a regionally diachronous, upward-deepening transition by the Hurwal Formation (Upper Triassic to Lower Jurassic). The Hurwal Formation consists of marine turbidites and calcareous shale with locally abundant carbonate- and chert-clast conglomerate (Excelsior Gulch unit; Follo 1992, 1994). These deposits record slope failures, synbasinal faulting, and input of detritus eroded from the Baker terrane (Follo 1992).

The Coon Hollow Formation is a Middle to Upper Jurassic marine succession that overlies older deposits in the Wallowa terrane along a regional angular unconformity. This succession records regional late Middle to early Late Jurassic transgression and widespread deposition of black shale and volcaniclastic sandstone (Lower Flysch and Marine/Turbidite units of the Coon Hollow Fm. of Goldstrand 1994, and White and Vallier 1994). This deep-marine shale is overlain by an Upper Jurassic regressive succession of sandstone and conglomerate that contains abundant chert and sedimentary lithic fragments (Upper Flysch Unit; Goldstrand 1994). Goldstrand (1994) interpreted petrographic data from the Coon Hollow Formation as representing a change from (1) erosion of the underlying Wallowa arc (volcaniclastic petrofacies) to (2) uplift and erosion of the Baker terrane (chert and sedimentary lithic petrofacies).

Stratigraphic Architecture.—Dorsey and LaMaskin (2007) divided the regional stratigraphy of the BMP into megasequences (hundreds of meters thick; tens of millions of years) that are defined by regional-scale bounding unconformities and unique deformation histories (Fig. 2). The large temporal and spatial scale of megasequences indicates their formation is controlled by regional tectonics.

Megasequence 1a deposits include the Wild Sheep Creek and Doyle Creek formations of the Wallowa arc and record deposition in a forearc and/or intra-arc basin. Megasequence 1b records sedimentation in a marine basin that was influenced by growth of an uplifted accretionary prism (Baker terrane) and exhumed forearc crust (Dickinson and Thayer 1978; Dickinson 1979; Follo 1992, 1994; Dorsey and LaMaskin 2007), providing an important provenance link between terranes of the BMP in Late Triassic time. Megasequence 1b in the Wallowa arc includes the Hurwal Formation and Kurry Creek Unit of the Doyle Creek Formation. Megasequence 1b in the Izee–Suplee region includes the Vester Formation and overlying Aldrich Mountains Group.

Megasequence 2 in the Izee–Suplee region includes the Mowich Group and the Snowshoe, Trowbridge, and Lonesome formations. In Hells Canyon, megasequence-2 deposits are represented by the Coon Hollow Formation. Megasequence 2 is a regional overlap assemblage that overlies older rocks and structures along a major angular unconformity and records ~ 20–40 My of deep subsidence in a large marine basin.

SAMPLE COLLECTION AND ANALYTICAL PROCEDURES

Twenty-one samples of mudrock were collected from biostratigraphically dated horizons ranging in age from Late Triassic to early Late Jurassic across the Blue Mountains Province (BMP; Fig. 2; Table 1). Sampled units include megasequence 1 in the Wallowa and Olds Ferry arcs and megasequence 2 in the Izee–Suplee region, in the southern Wallowa Mountains, and in Hells Canyon. Samples were carefully selected to avoid visible alteration and crosscutting mineral veins.

Mudrock samples were ground to $< 30\ \mu m$ powder for determination of major- and trace-element concentrations by ICP-MS and XRF at Washington State University (WSU), following procedures described by Knaack et al. (1994) and Johnson et al. (1999) (Table 2).

GEOCHEMICAL PROVENANCE: RESULTS AND INTERPRETATIONS

Major Elements

Results.—Chemical weathering can influence the major-element geochemistry of sedimentary rocks, with the most significant changes resulting from alteration of feldspars and volcanic glass (Nesbitt and Young 1982; Taylor and McLennan 1985). The degree of chemical weathering of a source area can be expressed using the chemical index of alteration (CIA; Nesbitt and Young 1982), which is calculated using mole proportions as

$$CIA = Al_2O_3/(Al_2O_3 + K_2O + Na_2O + CaO^*) \times 100. \qquad (1)$$

CaO* values were calculated using the method of McLennan (1993), where CaO was corrected for apatite using P_2O_5. In general, CIA values are typically less than ~ 50 for unweathered igneous and metamorphic rocks, 70 to 75 for shales, and 100 for pure aluminosilicate weathering products (i.e., kaolinite; Taylor and McLennan 1985; McLennan et al. 1993). CIA values for mudrocks of the BMP range from 59 to 81 with a mean value of 68 ($n = 21$; Table 2, Fig. 3A). On a ternary $Al_2O_3 - CaO^* + Na_2O - K_2O$ plot, BMP deposits lie along a diffuse trend from basalt–andesite toward shale and illite (Fig. 3A). It is noteworthy that samples from Olds Ferry megasequence 1 and from megasequence 2 in the Izee–Suplee region show an increased enrichment in K_2O (Fig. 3A).

The relationship between degree of weathering (i.e., CIA) and original source composition can be assessed by combining CIA with the index of compositional variability (ICV; Fig. 3B; Cox et al. 1995; Potter et al. 2005). The ICV can be used to discriminate source rock types based on major-element geochemistry of mudstones, where

$$ICV = (CaO + K_2O + Na_2O + Fe_2O_3 + MgO + MnO + TiO_2)/Al_2O_3. \qquad (2)$$

In this equation, CaO includes all sources of Ca including detrital carbonate. A high ICV value indicates compositionally immature source rocks rich in non-clay silicate minerals whereas low values represent compositionally mature source rocks. As weathering progresses, ICV values decrease due to conversion of feldspars to Al-bearing clays. Thus, variability in ICV values may be due to variations in source-rock composition or to differences in weathering (Cox et al. 1995; Potter et al. 2005) (Fig. 3B).

The ICV values for BMP deposits range from 0.6 to 2.8 (Table 2). Samples from megasequence 1 plot along andesite and basalt weathering trends, indicating variable mineralogy and degree of weathering, whereas samples from megasequence 2 plot along a well-defined weathering trend originating from an andesitic composition. Note that sample 06150 (Nicely Fm.), from the basal transgressive unit of megasequence 2 in the Izee–Suplee region, is locally associated with carbonate biostromes and diagenetic nodules. The higher ICV value is likely due to elevated CaO from associated carbonate.

Most major elements are susceptible to post-depositional mobility and are of limited value for provenance analysis (Taylor and McLennan 1985; Clift et al. 2000; Armstrong-Altrin and Verma 2005). Ti and Al, however, may be relatively immobile up to greenschist-grade metamorphic conditions (MacLean 1990; Pearce and Cann 1973; Jenner 1996). Accordingly, plots of TiO_2 (wt %) and Al_2O_3/SiO_2 versus $Fe_2O_3 + MgO$ are considered good indicators of sedimentary provenance due to variations in the mineralogy of mafic versus felsic source rocks (Bhatia and Crook 1986; Peterson et al. 2004; Ryan and Williams 2007). As shown on Figure 4A and B, mudrock compositions from megasequence 1

TABLE 1.—*Sample Location Information.*

Sample No.	Stratigraphic Association	Formation, Location	Easting[1]	Northing	Age
06140	MS-1	Vester Fm., Begg Mbr., Izee–Suplee area	0289898	4883972	Middle Triassic(?) to Carnian: 225 Ma (Dickinson and Vigrass 1965; Dickinson and Thayer 1978; Brown and Thayer 1977)
06005	MS-1	Vester Fm., Brisbois Mbr., Izee–Suplee area	0305333	4890634	Late Carnian: 220 Ma (Dickinson and Vigrass 1965; Dickinson and Thayer 1978; Blome 1984)
06117	MS-1	Fields Creek Fm., Izee–Suplee area	0317144	4912041	Norian: 210 Ma (Dickinson and Thayer 1978; Yeh 1989)
06136	MS-1	Keller Creek Shale, Izee–Suplee area	0352220	4897386	Early Sinemurian: 193 Ma (Dickinson and Thayer 1978; Brown and Thayer 1977; Imlay 1986 and references therein)
05093	MS-1a	Doyle Creek Fm., Southern Wallowa Mtns.	0475915	4979181	Late Carnian: 220 Ma (McRoberts 1993)
06040	MS-1a	Doyle Creek Fm., Grande Rhonde River	0604319	5101366	Early Norian: 215 Ma (Conodont age from base MBLS; identified by E. Katvala, pers. comm. 2007)
06074	MS-1b	Doyle Creek Fm., Pittsburg Ldg. Kurry Creek Unit	0540940	5054771	Early Norian: 215 Ma (*Halobia* cf. *H. beyrichi* identified by C. McRoberts, pers. comm. 2007)
06104	MS-1b	Hurwal Fm., Southern Wallowa Mtns.	0465650	4983712	Late Carnian–early Norian: 215 Ma (Ammonites identified by D. Taylor, pers. comm. 2006 and the Halobiid Bivlave *Halobia* cf. *H. radiata* identified by C. McRoberts, pers. comm. 2007)
05075	MS-1b	Hurwal Fm., Southern Wallowa Mtns.	0466219	4983562	Middle Norian: 208 Ma (*Halobia fallax* identified by C. McRoberts, pers. comm. 2007)
05164	MS-1b	Hurwal Fm., Southern Wallowa Mtns.	0467595	4983034	Sinemurian: 193 Ma (Based on youngest zircon grains in an associated detrital-zircon sample)
06060	MS-2	Coon Hollow, Fm., Hells Canyon, Pittsburg Ldg., Fluvial Unit	0541936	5056170	Bajocian: 171 Ma (Stratigraphic position below sample 06058)
06058	MS-2	Coon Hollow, Fm., Hells Canyon, Pittsburg Ldg., Marine Unit	0542012	5057080	Bajocian: 170 Ma (Stanley and Beauvias 1990; White et al. 1992: White and Vallier 1994)
06166	MS-2	Coon Hollow, Fm., Hells Canyon, Pittsburg Ldg., Turbidite Unit	0540905	5052242	Early Callovian: 164 Ma (Imlay 1986; White and Vallier 1994)
06049	MS-2	Coon Hollow, Fm., Hells Canyon, Cougar Bar, Base of Flysch Unit	0509046	5090575	early Early Oxfordian: 161 Ma (Morrison 1963; Imlay 1986 and references therein; Goldstrand 1994)
06042	MS-2	Coon Hollow, Fm., Hells Canyon, Little Cougar Creek, Middle of Flysch Unit	0508985	5090819	~ Oxfordian: 160 Ma (Stratigraphic position above sample 06049)
07023	MS-2	Coon Hollow, Fm., Hells Canyon, Little Cougar Creek, Top of Flysch Unit	0509275	5091205	~ Oxfordian: 159 Ma (Stratigraphic position above sample 06049 and 06042)
06150	MS-2	Nicely Fm., Izee–Suplee area	0314753	4889182	Late Pleinsbachian: 185 Ma (Imlay 1986 and references therein)
06134	MS-2	Snowshoe Fm., Izee–Suplee area	0321824	4894722	Bajocian: 170 Ma (Dickinson and Vigrass 1965; Dickinson and Thayer 1978; Imlay 1986)
06138	MS-2	Trowbridge Fm., Izee–Suplee area	0315693	4884503	Early Callovian: 164 Ma (Imlay 1986 and references therein)
06016	MS-2	Lonesome Fm., Izee–Suplee area	0310937	4881051	late Early to middle Callovian: 162 Ma (Imlay 1986 and references therein)
06019	MS-2	Lonesome Fm., Izee–Suplee area	0311902	4878318	late Early to middle Callovian: 162 Ma (Imlay 1986 and references therein)

Notes: 1-UTM Datum NAD 27 CONUS, UTM zone 11

TABLE 2.—*Major- and Trace-Element Concentrations.*

Sample No.	05075	05093	05164	06005	06019	06040	06049	06058	06060	06074	06104	06117	06134	06136	06138	06140	06150	06166	06016	06042	07023
Major Elements in wt%																					
SiO_2	56.88	53.72	57.29	59.21	62.50	55.66	64.42	60.83	51.94	49.23	56.65	69.09	60.04	70.63	64.37	62.22	50.93	65.21	63.75	65.03	60.40
TiO_2	0.72	1.07	0.71	0.96	0.69	0.73	0.70	0.77	0.87	0.51	1.06	0.58	0.69	0.60	0.48	0.91	0.73	0.68	0.669	0.714	0.856
Al_2O_3	12.02	17.33	16.89	14.45	14.95	17.43	14.33	16.41	20.25	9.01	16.52	11.83	14.59	11.95	13.74	13.32	13.26	13.76	14.00	14.47	18.74
FeO	4.77	9.95	6.43	8.30	4.70	7.69	6.58	6.28	8.22	4.36	6.32	4.54	6.08	4.26	3.92	6.49	4.88	4.40	5.03	5.87	6.22
MnO	0.017	0.211	0.062	0.080	0.015	0.124	0.091	0.027	0.055	0.093	0.031	0.030	0.049	0.035	0.039	0.030	0.060	0.032	0.030	0.086	0.039
MgO	2.99	4.68	4.01	3.41	2.43	5.69	2.30	2.59	1.67	2.30	8.72	2.51	2.77	2.14	2.08	3.04	2.25	1.43	2.28	2.68	1.09
CaO	7.21	5.66	4.57	1.57	0.83	3.85	2.29	1.06	2.46	16.52	0.49	0.68	1.23	2.19	2.03	0.95	9.67	2.38	1.29	1.67	1.03
Na_2O	2.19	3.36	3.08	2.54	0.61	1.46	2.09	1.98	0.71	0.68	2.01	1.59	1.20	1.66	0.96	1.19	1.32	1.42	1.14	1.36	0.84
K_2O	1.06	0.37	1.82	1.36	3.66	1.78	1.86	2.41	2.80	1.06	1.27	2.65	3.93	2.22	3.87	2.87	2.16	1.44	3.17	2.79	1.58
P_2O_5	0.233	0.215	0.146	0.120	0.193	0.111	0.114	0.133	0.115	0.148	0.233	0.092	0.263	0.101	0.131	0.114	0.218	0.124	0.294	0.123	0.033
LOI (%)	8.48	3.80	5.72	6.40	7.66	5.50	4.67	5.36	8.96	15.90	6.75	5.22	7.79	3.75	6.15	7.10	13.20	7.63	7.23	4.06	7.79
Total	96.56	100.36	100.72	98.40	98.24	100.03	99.44	97.84	98.04	99.81	100.04	98.81	98.63	99.54	97.78	98.24	98.67	98.51	98.89	98.86	98.60
Trace Elements in ppm																					
La	6.28	8.27	7.52	12.25	25.78	4.63	11.56	12.68	13.91	6.17	6.74	12.38	19.14	10.27	21.96	16.68	13.98	8.29	26.52	9.75	15.10
Ce	8.67	19.95	13.28	23.86	49.24	11.61	24.32	25.76	29.36	12.58	12.69	22.52	33.15	21.63	43.32	26.49	24.79	15.79	51.22	20.73	33.06
Pr	1.74	2.84	1.97	3.53	6.26	1.62	3.44	3.74	4.19	1.88	2.18	3.70	4.95	3.27	5.52	4.35	3.89	2.93	6.45	2.94	4.27
Nd	8.36	14.24	9.20	14.48	24.71	7.72	14.80	15.87	18.52	8.80	10.02	15.14	19.82	13.67	21.62	17.30	16.75	13.30	25.91	12.62	18.48
Sm	2.43	4.43	2.73	3.70	5.38	2.40	3.88	4.29	4.99	2.43	2.76	3.60	4.59	3.50	4.91	4.11	4.05	3.62	5.75	3.31	4.64
Eu	0.48	1.54	0.92	1.11	1.27	0.82	1.14	1.03	1.55	0.74	0.76	0.83	1.17	0.90	1.02	1.10	0.96	1.04	1.43	1.07	0.89
Gd	2.73	5.19	2.93	3.88	4.98	2.88	3.97	4.48	5.19	2.69	3.00	3.57	4.40	3.35	4.71	4.01	4.08	3.89	5.66	3.53	4.65
Tb	0.48	0.91	0.50	0.70	0.81	0.51	0.70	0.77	0.85	0.46	0.52	0.62	0.72	0.58	0.78	0.67	0.68	0.67	0.91	0.63	0.84
Dy	3.13	5.90	3.20	4.37	4.95	3.39	4.41	4.86	5.32	2.90	3.34	4.01	4.58	3.47	4.97	4.32	4.18	4.23	5.61	4.06	5.31
Ho	0.67	1.27	0.66	0.94	1.02	0.73	0.91	1.03	1.08	0.63	0.72	0.85	0.94	0.71	1.07	0.90	0.88	0.87	1.16	0.85	1.09
Er	1.83	3.49	1.82	2.57	2.77	1.99	2.51	2.85	2.96	1.72	2.13	2.36	2.60	1.99	3.03	2.54	2.44	2.41	3.17	2.42	2.98
Tm	0.27	0.51	0.26	0.39	0.41	0.30	0.39	0.42	0.43	0.25	0.32	0.36	0.39	0.29	0.46	0.38	0.36	0.35	0.45	0.37	0.44
Yb	1.63	3.22	1.64	2.50	2.63	1.86	2.50	2.76	2.69	1.59	2.09	2.38	2.53	1.86	3.00	2.40	2.23	2.27	2.86	2.37	2.80
Lu	0.26	0.51	0.26	0.40	0.43	0.30	0.40	0.44	0.43	0.25	0.34	0.38	0.40	0.29	0.50	0.38	0.35	0.35	0.45	0.39	0.43
Ba	359	116	581	451	751	473	579	250	668	118	238	1357	549	762	903	1545	558	519	1034	602	674
Cr#	137	48	96	185	96	118	77	61	42	50	78	82	115	58	44	165	82	37	95	69	49
Cs	1.60	0.60	1.52	1.83	9.02	0.82	2.46	2.50	5.11	1.24	1.27	4.33	12.45	6.86	8.05	5.36	3.66	2.84	8.17	2.60	2.79
Cu#	90	22	87	77	82	2	71	74	110	33	55	122	84	78	45	90	75	36	79	67	54
Ga#	14	21	18	18	17	17	16	19	19	13	17	16	17	14	15	16	15	14	17	17	20
Hf	1.83	3.18	1.90	3.05	3.43	1.87	2.92	3.19	2.98	1.38	2.53	2.79	3.33	3.14	5.17	3.23	3.18	2.95	3.59	3.03	4.10
Nb	1.98	2.51	2.27	7.31	9.09	1.84	4.16	4.12	3.41	1.67	2.19	5.06	7.14	5.14	9.66	9.46	4.76	2.95	9.12	4.29	4.97
Ni#	48	29	39	94	57	54	32	30	24	25	39	63	89	26	39	76	96	14	56	31	25
Pb	5.03	3.79	2.92	4.25	9.43	3.95	7.41	6.39	6.87	1.16	2.02	11.44	12.35	9.14	13.11	5.16	7.00	5.75	21.47	8.61	2.78
Rb	25.2	6.6	39.7	43.7	128.2	26.5	53.6	58.8	60.3	23.2	27.0	76.6	155.5	68.1	127.0	91.2	64.4	36.1	111.8	64.2	42.8
Sc	26.4	31.2	26.4	29.2	21.4	29.3	25.1	26.8	28.0	17.5	36.3	21.5	21.3	18.9	14.2	24.5	18.4	25.0	18.3	25.1	25.2
Sr	1054	636	798	89	103	438	428	114	95	163	275	105	156	317	116	91	182	147	163	208	388
Ta	0.13	0.18	0.16	0.49	0.65	0.13	0.29	0.28	0.23	0.11	0.15	0.36	0.51	0.38	0.70	0.65	0.35	0.19	0.64	0.30	0.33
Th	0.78	1.02	0.98	3.17	7.66	0.74	3.00	3.21	2.54	0.79	0.88	4.22	5.87	4.71	9.56	4.66	4.94	2.35	7.26	3.04	3.31
U	3.78	0.76	0.68	1.18	2.25	0.45	1.32	1.51	1.66	1.46	6.13	1.62	3.61	1.69	3.92	1.68	7.47	1.61	2.36	1.40	1.81
V#	245	208	194	202	200	140	221	233	234	199	564	160	380	136	115	185	439	231	181	221	206
Y	19.22	34.82	18.37	22.20	25.92	18.23	21.52	24.30	26.59	17.82	19.01	20.73	25.46	17.29	28.29	22.55	24.59	22.85	31.83	21.70	27.09
Zn#	131	108	81	124	122	86	157	176	144	65	265	88	727	127	130	135	220	132	100	154	157
Zr	61	114	61	105	116	58	96	104	98	45	80	100	114	107	180	113	110	94	126	101	143

TABLE 2.—*Continued.*

Sample No.	05075	05093	05164	06005	06019	06040	06049	06058	06060	06074	06104	06117	06134	06136	06138	06140	06150	06166	06016	06042	07023
Calculated Parameters																					
CIA	61	61	59	63	72	74	62	68	80	73	75	64	64	61	65	66	67	69	66	67	81
ICV	1.58	1.46	1.22	1.26	0.87	1.22	1.11	0.92	0.83	2.83	1.20	1.06	1.09	1.10	0.97	1.16	1.59	0.86	0.94	1.00	0.60
Eu/Eu*^	0.57	0.98	1.00	0.89	0.75	0.96	0.88	0.72	0.93	0.88	0.80	0.71	0.79	0.81	0.65	0.83	0.72	0.84	0.76	0.95	0.59
La_N/Sm_N	1.63	1.17	1.73	2.08	3.02	1.21	1.88	1.86	1.76	1.60	1.54	2.16	2.62	1.85	2.81	2.56	2.17	1.44	2.90	1.85	2.05
Gd_N/Yb_N	1.36	1.31	1.45	1.26	1.53	1.25	1.29	1.32	1.56	1.37	1.16	1.21	1.41	1.46	1.27	1.36	1.48	1.39	1.60	1.21	1.35
La_N/Yb_N	2.60	1.73	3.09	3.32	6.63	1.68	3.13	3.11	3.49	2.62	2.18	3.51	5.12	3.73	4.94	4.70	4.23	2.47	6.26	2.78	3.65
ΣREE	128.05	239.01	146.41	222.30	339.69	134.59	221.45	240.48	269.06	133.71	153.05	212.80	276.01	189.05	313.42	246.81	228.94	190.28	362.03	196.82	266.33

Notes:
Major-element analysis by XRF. Trace-element analysis by ICP-MS except where denoted by # analyzed by XRF.
^ = Eu/Eu* = $Eu_N/(Sm_N \times Gd_N)^{1/2}$
Subscript N = concentrations in ppm normalized by chondrite values of Taylor and Mclennan (1985).
CIA = Chemical Alteration Index after Nesbitt and Young (1982). Calculated from mole fractions as $100(Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O))$. CaO* calculated based on McLennan (1993).
ICV = Index of Chemical Variation after Cox et al. (1995). Calculated as $(CaO + K_2O + Na_2O + Fe_2O_3 + MgO + MnO + TiO_2)/Al_2O_3$

are widely scattered, whereas compositions from megasequence 2 are more clustered.

Interpretation.—CIA values of Blue Mountains Province mudrocks (Table 2, Fig. 3A) indicate low to moderate degrees of weathering in source areas. The broad trend from basalt–andesite toward shale and illite indicates that weathering was dominated by the conversion of plagioclase to clay (Fig 3A). Deviation from the predicted weathering trend towards the K_2O apex can be interpreted as either provenance mixing with a more continental signature (e.g., Cox et al. 1995) or K-enrichment during diagenesis (e.g., Fedo et al. 1995).

Trends in CIA vs ICV values (Fig. 3B) suggest evolution of the sediment source areas from basalt–andesite sources during megasequence-1 deposition in the forearc regions of the Wallowa and Olds Ferry systems to a more uniform, andesitic source area during megasequence-2 deposition. Plots of TiO_2 and Al_2O_3/SiO_2 versus Fe_2O_3 + MgO also suggest progressive homogenization of the sediment source area towards a more evolved provenance and support the model of a regionally integrated megasequence 2 basin.

Trace Elements

Trace elements in clastic deposits provide useful information about sedimentary provenance and composition of crustal source regions (e.g., Bhatia and Crook 1986; McLennan et al. 1990; Floyd et al. 1991; Garver and Scott 1995; Unterschutz et al. 2002; Petersen et al. 2004; many others). Trace elements including large-ion lithophile elements (LILEs), high-field-strength elements, and rare earth elements (REEs) are efficiently transferred into sedimentary rocks, are strongly excluded from seawater, and have low potential for post-depositional mobility (Taylor and McLennan 1985; McLennan et al. 1993). Normalized multi-element (spider) and REE diagrams (Fig. 5) as well as multiple trace-element plots (Fig. 6) are used to assess temporal and spatial variations in the composition of Triassic and Jurassic deposits in the BMP.

Multi-Element Patterns: Results.—Trace-element concentrations of mudrock samples are normalized to N-MORB (values of Sun and McDonough 1989) to characterize source-area patterns (Pearce 1983; Wilson 1989). Multi-element plots for mudrock samples reveal remarkably similar patterns in the different terranes, as well as through time (Fig. 5). All samples are enriched in fluid-mobile LILE elements to varying degrees and have prominent negative Ta and Nb anomalies. All samples are also characterized by incompatible-element enrichment and have concentrations of least-incompatible elements that are similar, or slightly depleted, relative to N-MORB.

Multi-Element Patterns: Interpretation.—Multi-element patterns (Fig. 5) are consistent with a subduction-zone, arc origin for the source rocks of all BMP deposits. In arc settings, fluid flux of the mantle wedge generates enrichment in water-mobile LILEs and negative anomalies in Ta and Nb (Pearce 1983; Kelemen et al. 2003). Resultant arc rocks and clastic deposits derived from erosion of the arc edifice carry this subduction signature. Post-depositional fluid flow is not likely to be responsible for the observed enrichment in LILEs because the magnitude of enrichment is remarkably consistent across the BMP despite regionally variable metamorphic grade and is similar to modern arc lavas (Kelemen et al. 2003; Clift et al. 2005). The LILE enrichment and negative Ta-Nb anomalies indicate a common, arc origin for source rocks.

Rare-Earth-Element Patterns: Results.—Deposits of the BMP have REE patterns (Table 2) that vary systematically with terrane association and stratigraphic position. Samples from Wallowa megasequence 1a (Doyle Creek Formation) have relatively flat REE patterns with

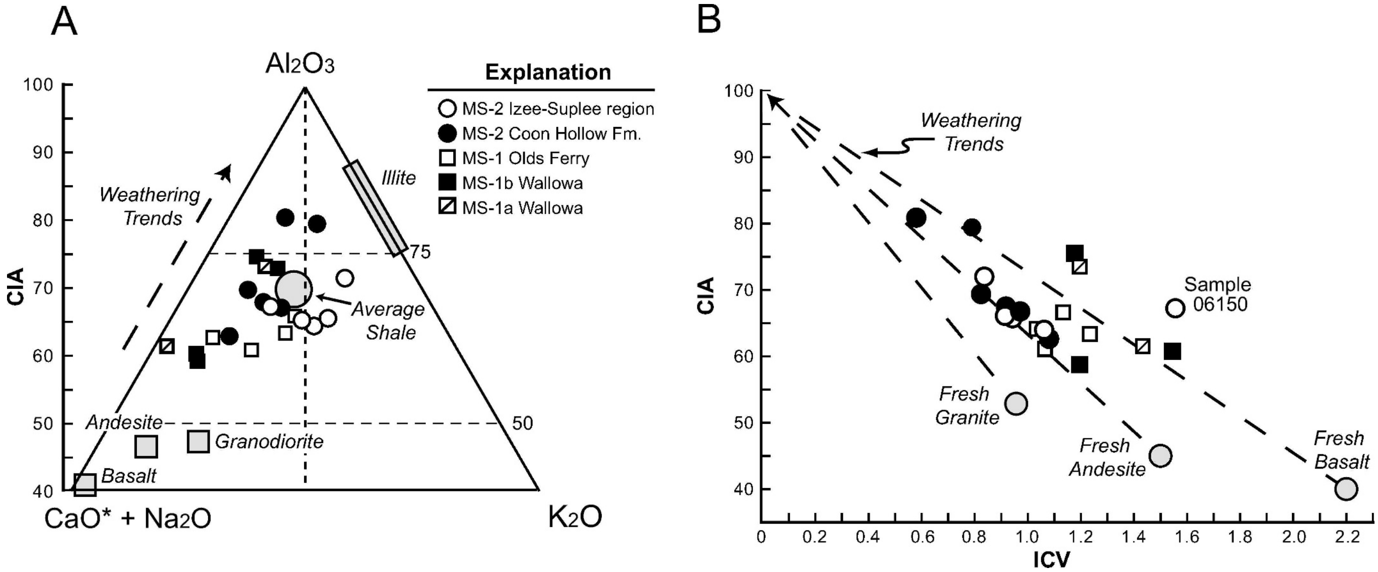

FIG. 3.—**A)** Ternary plot of chemical index of alteration (CIA) and Al_2O_3 − (CaO^* + Na_2O) − K_2O, after Nesbit and Young (1982) showing degree of source-area weathering. Note that the lower part of the plot (< 40) is not shown. Values for basalt, andesite, granodiorite, and average shale are from McLennan et al. (1993). Key to symbol locations is illustrated in the explanation. **B)** Plot of CIA vs. index of chemical variability (ICV), after Potter et al. (2005), showing relationship of degree of source-area weathering and original detrital mineralogy. ICV values for basalt and granite are from Li (2000) and for andesite from Ewart (1982). Sample 06074 (Kurry Creek unit of Doyle Creek Formation) is not plotted due to elevated carbonate content.

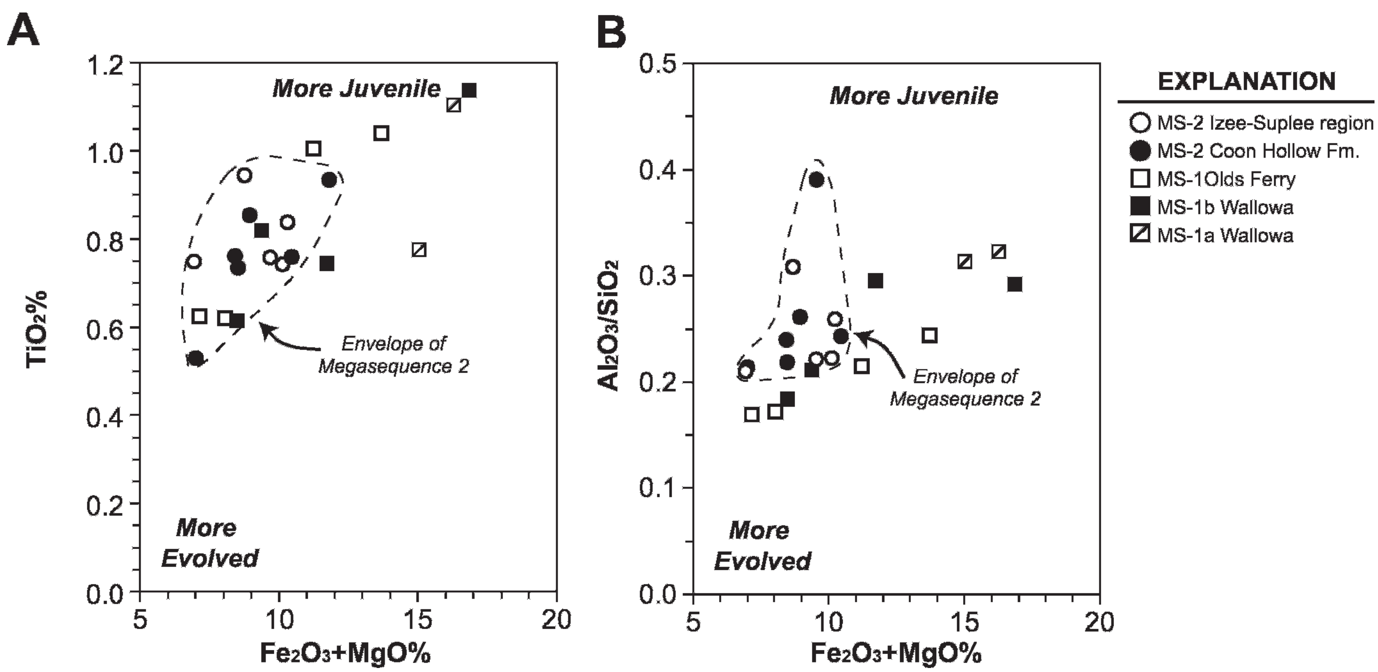

FIG. 4.—Major-element sedimentary provenance discrimination diagrams. Key to symbol locations is illustrated in the explanation. **A)** Plot of TiO_2 vs. Fe_2O_3 + MgO after Bhatia and Crook (1986) showing scatter of megasequence-1 deposits and clustering of megasequence-2 deposits. **B)** Plot of Al_2O_3/SiO_2 vs. Fe_2O_3 + MgO after Bhatia and Crook (1986), also showing scatter of megasequence-1 deposits and clustering of megasequence-2 deposits.

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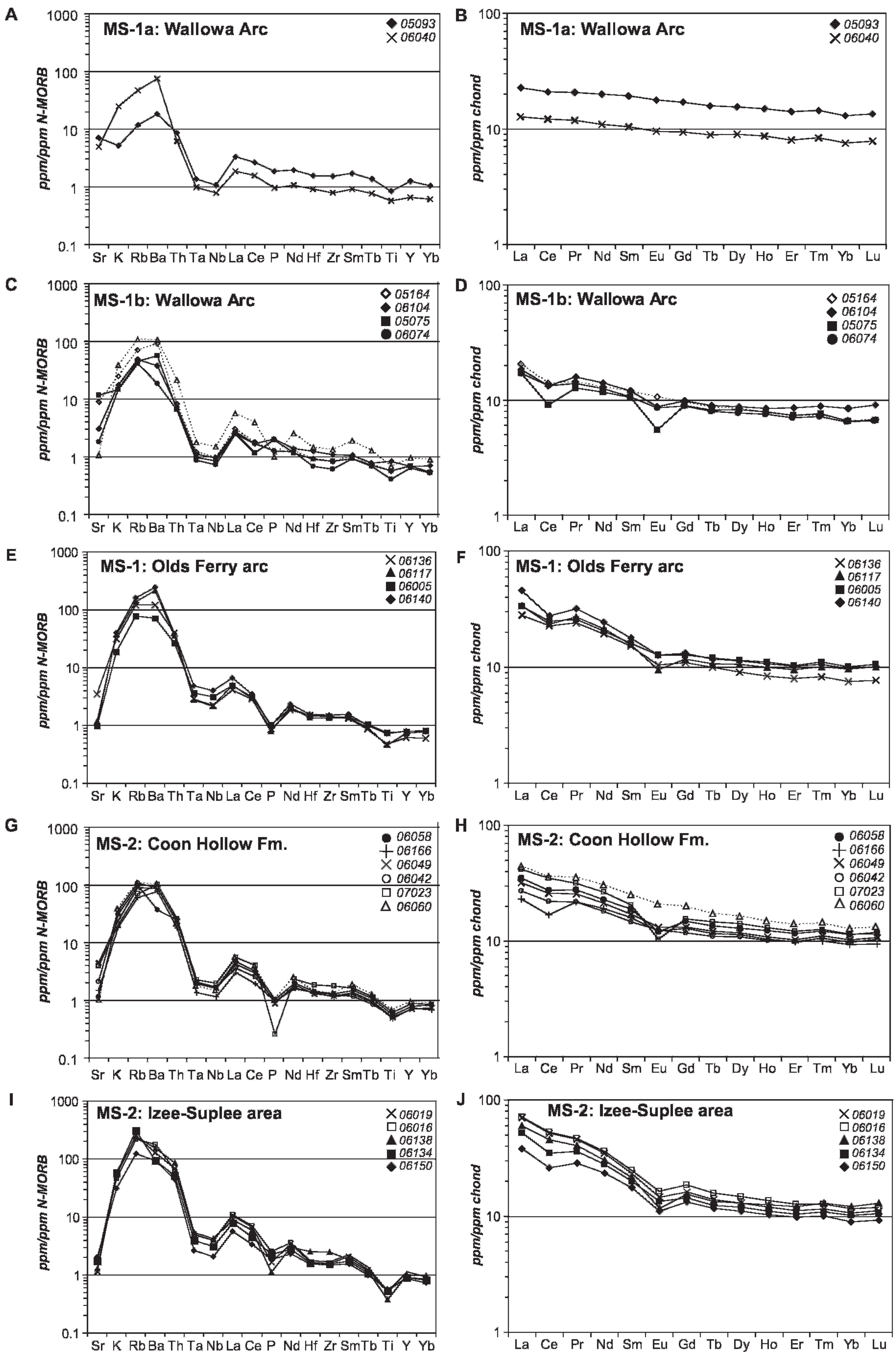
FIG. 5.—Multi-element spider diagrams (normalized to N-MORB values of Sun and McDonough 1989) and chondrite-normalized (values of Taylor and McLennan 1985) REE diagrams for BMP deposits. **A**, **B)** Megasequence 1a from the Wallowa terrane showing arc signature in trace elements and flat REE patterns lacking Eu anomalies. **C**, **D)** Megasequence 1b from the Wallowa terrane showing arc signature in trace elements and moderate LREE enrichment with variable Eu anomalies. **E**, **F)** Megasequence 1 from the Olds Ferry arc (Izee–Suplee area) showing arc signature in trace elements and moderate LREE enrichment with variable Eu anomalies. **G**, **H)** Megasequence 2 from the Coon Hollow Formation showing arc signature in trace elements and moderate LREE enrichment with variable Eu anomalies. **I**, **J)** Megasequence 2 from the Izee–Suplee area showing arc signature in trace elements and strong LREE enrichment with consistent negative Eu anomalies.


A
MS-1a: Wallowa Arc
05093
06040
ppm/ppm N-MORB
1000
100
10
1
0.1
Sr K Rb Ba Th Ta Nb La Ce P Nd Hf Zr Sm Tb Ti Y Yb
B
MS-1a: Wallowa Arc
05093
06040
ppm/ppm chond
100
10
1
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
C
MS-1b: Wallowa Arc
05164
06104
05075
06074
ppm/ppm N-MORB
D
MS-1b: Wallowa Arc
05164
06104
05075
06074
ppm/ppm chond
E
MS-1: Olds Ferry arc
06136
06117
06005
06140
ppm/ppm N-MORB
F
MS-1: Olds Ferry arc
06136
06117
06005
06140
ppm/ppm chond
G
MS-2: Coon Hollow Fm.
06058
06166
06049
06042
07023
06060
ppm/ppm N-MORB
H
MS-2: Coon Hollow Fm.
06058
06166
06049
06042
07023
06060
ppm/ppm chond
I
MS-2: Izee-Suplee area
06019
06016
06138
06134
06150
ppm/ppm N-MORB
J
MS-2: Izee-Suplee area
06019
06016
06138
06134
06150
ppm/ppm chond

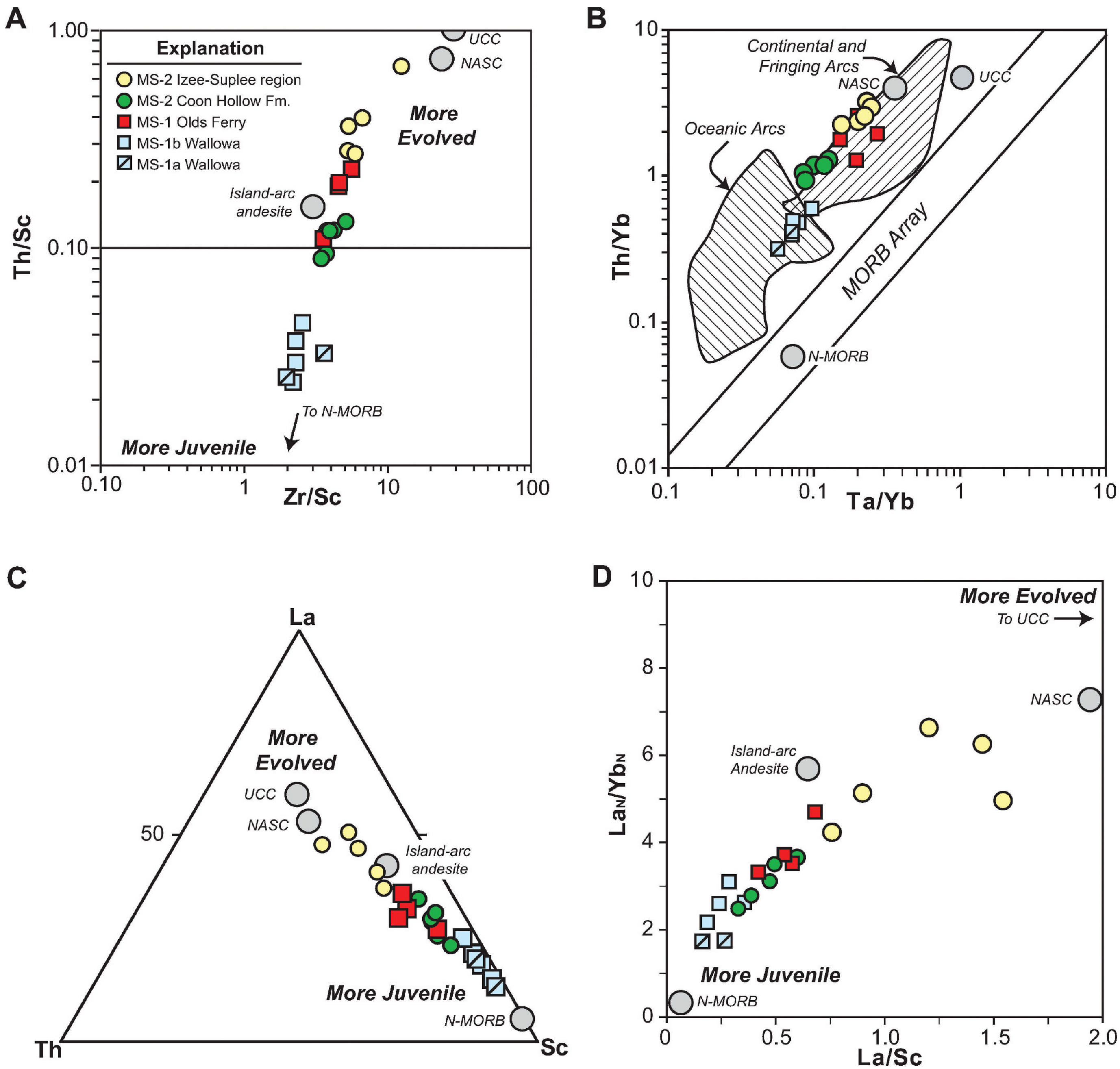


FIG. 6.—Representative trace-element plots from BMP mudrocks. UCC = Upper Continental Crust (Taylor and McLennan 1985), NASC = North American Shale Composite (Gromet et al. 1984), N-MORB = Normal Mid-Ocean Ridge Basalt (Sun and McDonough 1989.) **A)** Th/Sc vs. Zr/Sc. Both ratios increase with increasing differentiation. Th/Sc gives an indication of bulk crustal composition (McLennan et al. 1990). Th/Sc and Zr/Sc of ~ 1.0 and ~ 10, respectively, are representative of upper continental crust (UCC in Part A), whereas Th/Sc and Zr/Sc of ~ 0.1–0.2 and 2–3, respectively, represent andesitic arc sources (Taylor and McLennan 1985; McLennan et al. 1993; McLennan et al. 2003). MORB and Island-arc andesite values are from McLennan et al. (2003). **B)** Th/Yb vs. Ta/Yb diagram modified after Pearce (1983) is useful for assessing Th/Ta fractionation that occurs in the subduction-zone environment and distinguishes between oceanic and continental source areas. Samples that plot above the MORB array represent subduction enrichment of clastic sources and the degree of source area enrichment increases with positive slope. **C)** Ternary plot of La-Th-Sc where mudrock samples typically lie along a mixing line between a juvenile, MORB-type end member (N-MORB in Part C) and a more evolved (La and Th enriched) component representing the upper continental crust or average shale (McLennan et al. 1990). Values of potential source rocks are from Taylor and McLennan (1985) and McLennan et al. (2003). **D)** La/Yb (normalized to chondrite values of Taylor and McLennan 1985) vs. La/Sc showing values of potential source rocks. La_N/Yb_N is used as a proxy for enrichment of LREEs whereas La/Sc is a good discriminant between juvenile oceanic crust and evolved continental crust. Higher La_N/Yb_N and La/Sc are indicative of continental crustal inputs to the sediments.

negligible Eu anomalies (Eu/Eu* = 0.96–0.98; Table 2, Fig. 5B). Samples from Wallowa megasequence 1b (Hurwal Formation and Kurry Creek Unit of the Doyle Creek Formation) have greater LREE enrichment than megasequence-1a samples from the Doyle Creek Formation (Table 2, Fig. 5D), with variable and mostly negative Eu anomalies (Eu/Eu* = 1.00 − 0.57). Megasequence-1 samples from the Izee–Suplee area (Olds Ferry terrane) have consistent REE patterns (Fig. 5F) characterized by moderate LREE enrichment (La_N/Yb_N = 3.32–4.70) and negative Eu anomalies (Eu/Eu* = 0.71–0.89).

Mudrocks from megasequence 2 in the Wallowa region (Table 2, Fig. 5H; Coon Hollow Fm.) have moderate LREE enrichments (La_N/Yb_N average 3.10) and Eu anomalies (Eu/Eu* average 0.82). Megasequence-2 samples from the Izee–Suplee area (Fig. 5J; Mowich Group, Snowshoe, Trowbridge, and Lonesome formations) have the largest LREE enrichments (La_N/Yb_N = 4.23–6.63) and negative Eu anomalies (Eu/Eu* = 0.65–0.79).

Rare-Earth-Element Patterns: Interpretation.—REE patterns of Wallowa megasequence-1a samples (Doyle Creek Formation; Fig. 5B) are indicative of first-cycle volcaniclastic deposits of a forearc basin, consistent with patterns from modern intra-oceanic forearc basins (Taylor and McLennan 1985; McLennan et al. 1990; McLennan et al. 1993). The trend toward steeper REE patterns from megasequence 1a to 1b, and variable Eu anomalies in megasequence-1b deposits (Fig. 5D), suggests a change in sediment provenance and sediment dispersal. Based on regional stratigraphic architecture and the results of Follo (1992 1994), Dorsey and LaMaskin (2007) suggested that the Hurwal Formation was derived from the Baker terrane. Recent work by Schwartz et al. (2006) and Schwartz and Snoke (2007) has shown that chert-argillite in the Baker terrane has isotopically evolved signatures and is structurally interleaved with lesser amounts of juvenile plutonic rocks that likely represent imbricated thrust sheets of Wallowa forearc crust. We interpret the observed change in REE geochemistry from Wallowa megasequence 1a to 1b to reflect a change in sediment provenance and sediment dispersal from (1) Wallowa-arc dominated in megasequence-1a samples (Doyle Creek Fm.; Fig. 5B) to (2) Baker-terrane dominated in megasequence-1b samples (Fig. 5D). Moderate LREE enrichment and the presence of Eu anomalies in Olds Ferry deposits (megasequence 1; Fig. 5F) are consistent with derivation from a moderately evolved arc setting similar to the Japan forearc and other continental-margin arc settings (McLennan et al. 1990; McLennan et al. 1993).

Moderate to strong LREE enrichment and the presence of negative Eu anomalies in megasequence-2 deposits (Fig. 5H, J) are consistent with either derivation from a differentiated magmatic-arc setting or mixing between arc and continental sources (e.g., McLennen et al. 1993). Megasequence-2 samples from the Coon Hollow Formation (Fig. 5H) are similar to samples of the young differentiated arc province in the Aleutians (McLennan et al. 1990; McLennan et al. 1993). The more enriched samples from the Izee–Suplee area (Fig. 5J) resemble modern marine sediments that receive a component of continental input such as the Japan and Aleutian arcs, as well as continental arcs and continental collisional basins (McLennan et al. 1990; McLennan et al. 1993; Kelemen et al. 2003). Megasequence-2 samples are more enriched in LREEs than most samples from modern forearc settings (cf. McLennan et al. 1990; McLennan et al. 1993; Clift and Lee 1998; Kelemen et al. 2003).

Trace Element Plots: Results.—Mudrocks of the BMP plot along well-defined trends between more juvenile and more evolved compositions in trace-element plots (Fig. 6A–D). Samples from megasequence 1 in the Wallowa terrane have the most juvenile compositions of all BMP deposits, with slight enrichment over MORB-type values on all four plots and also low ratios of Th/Sc (Fig. 6A), Th/Yb (Fig 6B), and La/Sc (Fig. 6C, D).

Megasequence 2 in the Wallowa region (i.e., Coon Hollow Formation) and megasequence 1 in the Izee–Suplee area (Olds Ferry terrane) plot near typical island-arc andesite composition and between island-arc andesite and upper continental crust compositions (Fig. 6A–D). Megasequence-2 samples from the Izee–Suplee area consistently have the most evolved compositions (in particular, high Th/Sc and La/Sc, Fig. 6A, C, D). Regionally, both Wallowa and Olds Ferry samples have lower ratios of incompatible/compatible elements in megasequence 1 and higher ratios in megasequence 2.

Trace-Element Plots: Interpretations.—Trace-element plots reveal systematic compositional variations that distinguish the samples according to terrane association and stratigraphic position. Low Th/Sc (Fig. 6A), Th/Yb (Fig. 6B), and La/Sc (Fig. 6C, D) of Wallowa megasequence-1 samples are indicative of a juvenile, intra-oceanic arc setting (i.e., young undifferentiated arc province of McLennan et al. 1993; McLennan et al. 2003). This interpretation is supported by a consistent lack of Precambrian detrital zircons in associated sandstone samples (LaMaskin et al. 2007; unpublished data). Intermediate compositions of megasequence 2 samples from the Wallowa region and megasequence 1 in the Izee–Suplee area (Olds Ferry terrane; Fig. 6A–D) likely represent mixing of arc-derived and continent-derived material (cf. McLennan et al. 1990). This interpretation is supported by the presence of Precambrian detrital zircons in associated sandstone samples (LaMaskin et al. 2007; unpublished data). Greatly enriched La/Sc and Th/Sc in megasequence-2 samples from the Izee–Suplee region (Fig. 6A–D) indicate larger input from more evolved continental sources.

Trace-element plots reveal geochemical similarities between megasequence 1 in the Izee–Suplee area (Olds Ferry terrane) and megasequence 2 of the Coon Hollow Formation (Fig. 6A–D), indicating either derivation from similar sources or a similar degree of mixing between arc and continental sources. The regional trend toward higher incompatible/compatible element ratios suggests a trend toward more evolved compositions through time across the entire BMP.

DISCUSSION

The results of this study demonstrate the utility of mudrock geochemistry in tectonic analyses. Work by Floyd et al. (1991) and Ryan and Williams (2007) suggests that trace-element plots cannot be relied upon for specific tectonic discrimination (i.e., using the fields of Bhatia and Crook 1986). However, this analysis indicates that trace-element systematics typically used for tectonic discrimination can be useful for showing fine-scale provenance distinctions and for highlighting differences between samples (cf. Ryan and Williams 2007). Although caution should be exercised when discriminating tectonic origin from mudrock geochemistry, major- and trace-element data for mudrocks can be important for revealing otherwise ambiguous provenance differences between distinct sample populations. Moreover, trace-element analysis is shown here to be a useful discriminator between arc and continental sources. This study has shown that mudrock geochemistry can provide important constraints on regional models for volcanic-arc and craton-margin tectonic evolution. Integration of mudrock geochemistry with sandstone petrography and igneous geochemistry leads to a more complete assessment of tectonic setting and a more comprehensive understanding of regional tectonic evolution.

Megasequence 1 (Late Triassic–Early Jurassic)

Spatial and temporal variations in major- and trace-element compositions in the Blue Mountains Province support previous suggestions that during Triassic time the Wallowa terrane was an intra-oceanic arc system and the Olds Ferry terrane was a pericratonic or fringing-arc system. In

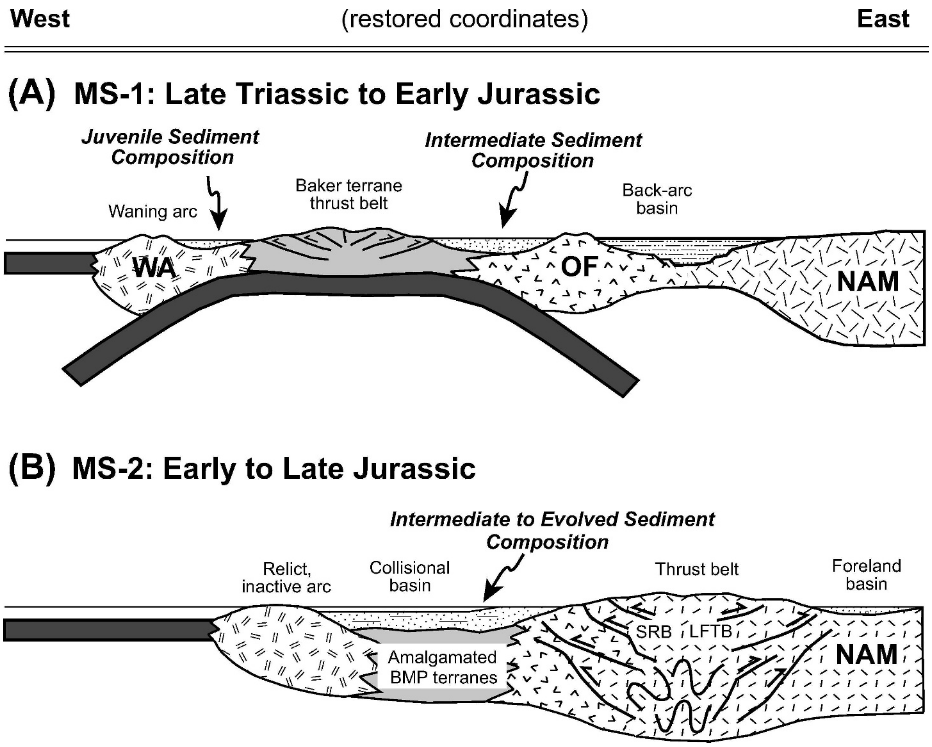


FIG. 7.— Cartoon diagrams depicting sediment sources for BMP strata. **A)** Late Triassic through Early Jurassic time. Juvenile provenance geochemistry indicates that the Wallowa arc (WA) was an intra-oceanic arc receiving no sediment input from continental sources. Intermediate provenance geochemistry suggests a fringing-arc setting for the Olds Ferry arc (OF). NAM = North America. **B)** Early through Late Jurassic time. Intermediate and evolved provenance geochemistry indicates input from a mixture of arc- and continent-derived detritus.

addition, the data provide evidence for significant changes in provenance through time, with a trend toward more evolved compositions in mudrocks of the BMP.

Wallowa Arc.—Previous studies have shown that (1) Triassic and older plutonic and volcanic rocks of the Wallowa terrane have an island-arc affinity with juvenile geochemical and isotopic compositions (Vallier and Batiza 1978; Phelps and Avé Lallemant 1980; Ferns and Brooks 1995; Vallier 1995; Schwartz et al. 2006; Kays et al. 2006; and Kurz et al. 2007), and (2) Upper Triassic sedimentary rocks of the Wallowa terrane have a volcanic-arc provenance (Follo 1992). These characteristics indicate that the Wallowa arc was built on oceanic lithosphere, although the distance to the Laurentian craton remains uncertain (Vallier 1995; Avé Lallemant 1995). Data presented above show that, as predicted from previous studies, Triassic sedimentary basins associated with the Wallowa arc did not receive sediment input from continental sources (Fig. 7A). Distinctive trace-element signatures (including REE) and a lack of Precambrian detrital zircons (LaMaskin et al. 2007; unpublished data) confirm that during Triassic and Early Jurassic time the Wallowa arc formed in an intra-oceanic setting and was not linked to Laurentia. Stratigraphic and petrologic evidence suggests that the Wallowa terrane evolved from a Middle Triassic intra-oceanic arc to a marine basin influenced by arc-arc collision in Late Triassic to Early Jurassic time (Dorsey and LaMaskin 2007). Thus, existing data from both igneous and sedimentary rocks of the Wallowa arc are consistent with a young undifferentiated arc province (cf. McLennan et al. 1993) similar to the modern Mariana or Tonga arc systems.

Olds Ferry Arc.—Vallier (1995) concluded that rocks in the Olds Ferry terrane represent an intra-oceanic island arc on the basis of geochemical analysis of arc-proximal volcanic rocks of the Huntington Formation and plutonic bodies inferred to represent the roots of the Middle Triassic to Lower Jurassic Olds Ferry arc. Upper Triassic to Lower Jurassic (megasequence 1) mudrock samples from the Olds Ferry arc overlap with the composition of igneous samples reported by Vallier (1995) (Fig. 8) but are generally more LREE enriched and have steeper REE patterns overall. The difference between the igneous and sedimentary trace-element compositions suggests that the Olds Ferry arc was built on oceanic lithosphere, as recorded in arc-related igneous rocks, but was a continent-fringing arc that received sediment from the craton, as recorded in sedimentary deposits (Fig. 7A). This is consistent with the concept that sedimentary systems preserve a more reliable indication of continental input than contemporaneous igneous rocks (e.g., Samson et al. 1991; Patchett and Gehrels 1998; Frost et al. 2006), and further suggests that data from *both* igneous and sedimentary rocks are necessary to adequately characterize the tectonic setting of ancient arc terranes. Presence of Precambrian detrital zircons in the oldest Olds Ferry sediments in the Izee–Suplee area (Upper Triassic Vester Fm.; LaMaskin et al. 2007, unpublished data), provides further evidence for a fringing arc

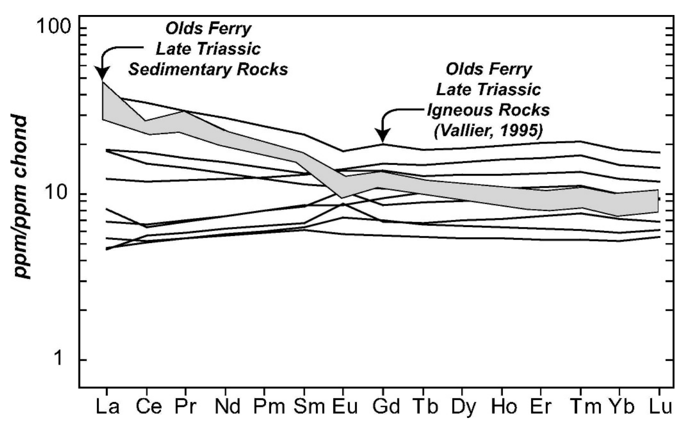


FIG. 8.— Chondrite-normalized (values of Taylor and McLennan 1985) REE diagram showing values for Olds Ferry volcanic and plutonic rocks (solid black lines; data from Vallier 1995) vs. megasequence-1 deposits of the Izee–Suplee area (gray box; Late Triassic and Early Jurassic). REE concentrations overlap, but LREE enrichment is more pronounced in sedimentary deposits.

setting similar to the modern eastern Aleutian or Japan arc (McLennan et al. 1993).

Megasequence 2 (Jurassic)

Trace-element plots of mudrocks indicate a change throughout the BMP from less-evolved source areas during deposition of megasequence 1 toward more-evolved source areas representing a mixture of arc and continent-derived detritus for megasequence 2 (Fig. 7B). This shift in geochemical provenance is consistent with sandstone petrofacies data that record a change from dominantly volcanic sources in megasequence 1 to mixed-composition sources in megasequence 2 (Dickinson et al. 1979; Follo 1992; Goldstrand 1994). Our results also suggest that the mixed provenance in megasequence 2 included a continental component and was not limited to dissected volcanic-arc and subduction-complex sources (cf. Dickinson et al. 1979; Goldstrand 1994).

The regional shift toward a more-evolved source is consistent with three possible interpretations for megasequence 2: (1) it could record uninterrupted input from an evolving, more fractionated Jurassic Olds Ferry arc; (2) sediments may have been derived from more continent-proximal arc systems to the south, which were active during Early to Middle Jurassic time; or (3) it may reflect increased influx of continental material into a regional collisional basin following closure of the continent-fringing back-arc region and associated crustal thickening in the Salmon River belt and Luning Fencemaker thrust belt (Wyld 2002; Gray and Oldow 2005; Dorsey and LaMaskin 2007) (Fig. 7B). The presence of sediment compositions that are more enriched than typical arc andesite argues against a more evolved Olds Ferry arc as the source for megasequence-2 deposits (i.e., interpretation 1). Moreover, no arc rocks of the appropriate age (i.e., Middle–Late Jurassic) are known in eastern Oregon or western Idaho. Discrimination between interpretations 2 and 3 above remains ambiguous, and the interpretations are not mutually exclusive. The shift to more-evolved compositions in Middle Jurassic deposits of the Izee–Suplee area is consistent with other evidence for a Jurassic collisional basin formed on the previously amalgamated BMP terranes (Dorsey and LaMaskin 2007). In this scenario, contemporaneous Early and Middle Jurassic arc activity in the south could have influenced transport of detritus northward into the subsiding collisional basin in the BMP.

Implications for Cordilleran Tectonics

The data presented above are consistent with prevailing models for the western U.S. Cordillera that suggest an along-strike transition in the Mesozoic arc system, from a continental arc in the south to an arc constructed on oceanic lithosphere in the north, with the transition located approximately at the latitude of the northern Sierra Nevada (Sharp 1988; Wright and Fahan 1988; Oldow et al. 1989; Burchfiel et al. 1992; Cowan and Bruhn 1992; Wyld and Wright 2001; Gray and Oldow 2005). The Olds Ferry arc is likely a northward continuation of fringing arc systems of the northernmost Sierra Nevada and Klamath Mountains terranes. Differences between the igneous and sedimentary trace-element reservoirs suggests that the Olds Ferry arc system was built on oceanic crust but was close enough to North America to receive input of sediment from the continent.

The Blue Mountains Province occupies a critical position between coeval arc terranes to the north and south, yet a clear understanding of how these crustal provinces are related remains elusive. Below, the long-term sedimentary provenance record of these major crustal provinces is compared to better constrain regional arc affinities.

Southern British Columbia.—Based on geochemical provenance studies of sedimentary rocks, Unterschutz et al. (2002) and Petersen et al. (2004) concluded that Upper Triassic and Lower to Middle Jurassic strata of the Quesnel terrane record deposition in a fringing-arc setting in which arc- and continent-derived material were mixed. Highly enriched LREE and incompatible element compositions in sedimentary rocks of the Nicola, Slocan, and Ymir groups indicate that southern Quesnelia formed on or near the Laurentian margin and received sediment from the continent in Late Triassic time (Unterschutz et al. 2002) (Fig. 9A, B). In contrast, Petersen et al. (2004) showed that Lower Jurassic (Sinemurian–Pleinsbachian) sedimentary rocks of Quesnelia are geochemically and isotopically less evolved than underlying Triassic deposits. They suggested that the shift from Triassic to Jurassic compositions resulted from increased input of sediment from the less evolved Quesnel arc during Jurassic time.

The apparent change to less evolved compositions in sedimentary rocks of the Quesnel terrane from Triassic to Jurassic time is in marked contrast to BMP deposits, which show a systematic trend toward a more evolved composition across the region during this time period (Figs. 6A–E, 9B, 10). This intriguing disparity suggests that the continent-fringing Quesnel terrane of southern British Columbia may not share a long-term provenance history with the continent-fringing Olds Ferry arc terrane to the south, and that the western Laurentian Triassic fringing-arc system may have been partitioned into discrete tectonic complexes. Geochemical provenance data (this study) suggest that, during Triassic time, the Olds Ferry fringing arc was less directly linked to western Laurentia than the Quesnel fringing arc (Unterschutz et al. 2002). Data from arc-proximal locations within the Olds Ferry system of the BMP (i.e., Huntington Fm.) are needed to further test and evaluate this possibility.

Petersen et al. (2004) also noted that overlying Jurassic sedimentary rocks of Quesnelia show a trend toward more evolved compositions from Early to Middle Jurassic time (Figs. 9B, 10) and suggested that the Jurassic compositional trend records renewed influx of continental detritus. This influx of continent-derived material appears to be coincident with accretion of the southern Quesnel arc complex to North America (Petersen et al. 2004; Umhoefer and Blakey 2006; and references therein), similar to the collision-accretion setting proposed for the BMP basin during Jurassic time (Dorsey and LaMaskin 2007 2008).

The results of this study show that the deposits of megasequence 2 in the BMP record an Early to Middle Jurassic increase in influx of material from continental North America. As shown on Figures 9A and B, trace-element characteristics of megasequence-2 rocks in the Blue Mountains overlap those of Lower and Middle Jurassic rocks in the Quesnel terrane. Thus, rocks of both the Quesnel and Blue Mountains terranes record increasing input of continental detritus during Early to Middle Jurassic time, apparently during accretion of the arc complexes to North America (i.e., accretion timing of Dorsey and LaMaskin 2007, 2008). The similarities between sediment provenance and timing of accretion may record Early to Middle Jurassic along-strike integration of southern British Columbia with the Blue Mountains Province via back-arc closure.

Western U.S.—A complete review of the Mesozoic history of the Klamath Mountains, Sierra Nevada, and western Nevada terranes is beyond the scope of this paper. To a first order, however, Triassic igneous and associated sedimentary rocks within the Klamath–Sierran arc system exhibit relatively juvenile (i.e., MORB-OIB, intra-oceanic arc) compositions, and the compositions of Jurassic rocks reflect more evolved arc complexes (e.g., Hacker 1993; Wright and Wyld 1994; Frost et al. 2006; Snow and Scherer 2006; Ernst et al. 2008; many others). Lithologically and temporally correlative Lower to Middle(?) Jurassic volcanic-arc and volcaniclastic rocks are present in both the Northern Sierra and Eastern Klamath terranes, as well as in western Nevada (Renne and Scott 1988; Harwood 1992; Hacker et al. 1995; Hanson et al. 1996; Quinn et al. 1997; Hanson et al. 2000; Lewis and Girty 2001; Snow and Scherer 2006; Scherer and Ernst 2008). Based on REE patterns, Lewis and Girty (2001) concluded

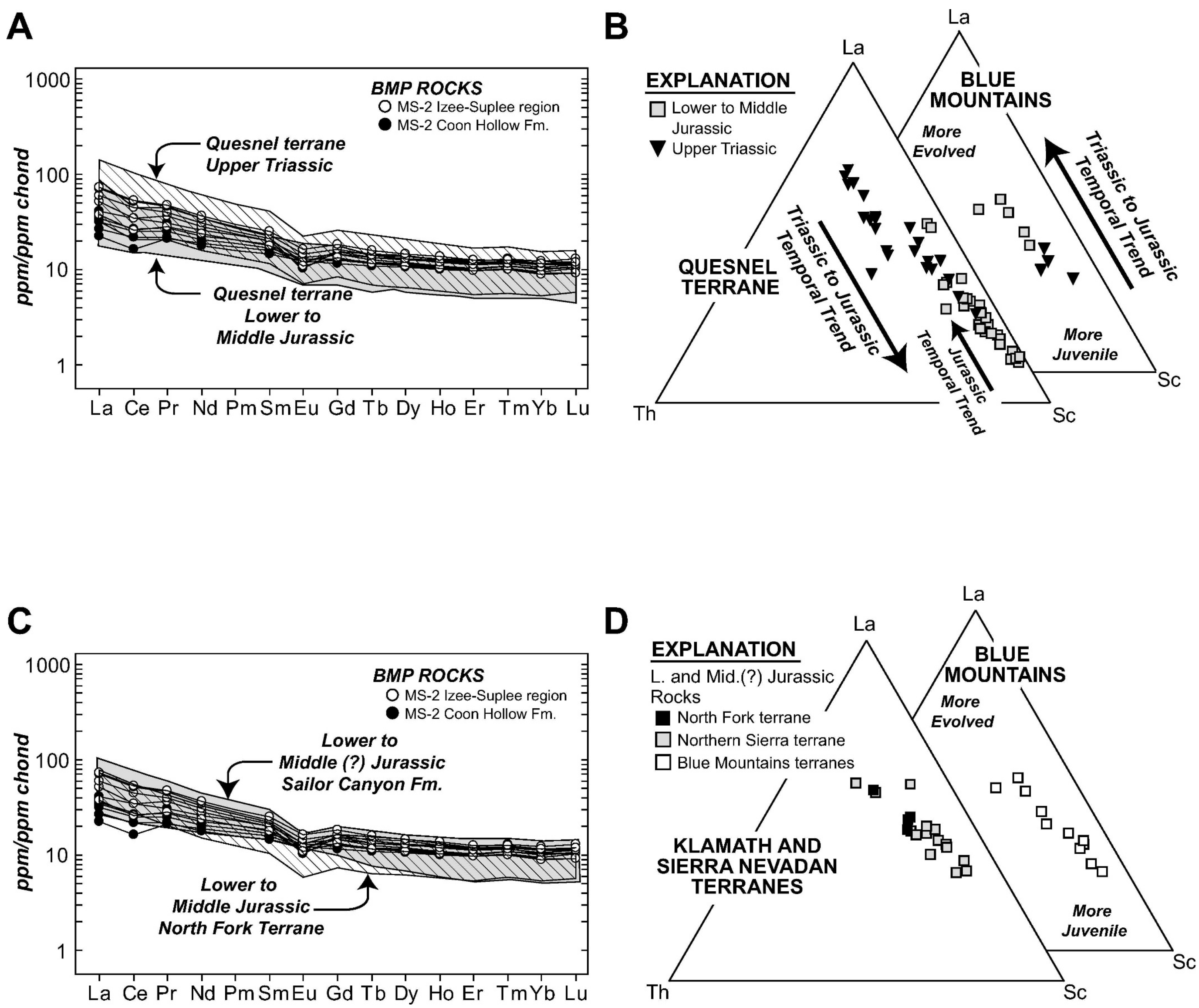


FIG. 9.— Comparison of regional Triassic and Jurassic provenance geochemistry. **A)** Comparison of REE data from Quesnel-affinity strata in southern British Columbia with data from the BMP. Data were compiled from Petersen et al. (2004) for Upper Triassic samples and from Unterschutz et al. (2002) for Lower to Middle Jurassic samples. Triassic sediments from southern British Columbia are more LREE enriched than overlying Jurassic deposits. Jurassic sediments from the BMP overlap Jurassic sediments from Quesnel-affinity strata. **B)** Comparison of La-Th-Sc plots from Quesnel-affinity strata in southern British Columbia with data from the Izee–Suplee region of the Olds Ferry terrane (data sources are the same as for Part A). Quesnel-terrane sediments show a trend from more evolved to more juvenile compositions from Triassic to Jurassic time, whereas BMP deposits trend from more juvenile to more evolved with time. **C)** Comparison of REE data from Lower to Middle(?) Jurassic rocks of the North Fork terrane, (Klamath Mountains; data from Scherer and Ernst 2008) and the Northern Sierra terrane (Sailor Canyon Formation; data from Lewis and Girty 2001) with similar-age rocks of the BMP. Jurassic sediments from all three regions show a strong degree of overlap. **D)** La-Th-Sc plots of Lower to Middle(?) Jurassic rocks of the North Fork terrane and the Northern Sierra terrane (data sources are the same as for Part C). Jurassic rocks of all three regions plot in close proximity suggesting similar trace-element characteristics.

that Lower and Middle(?) Jurassic volcaniclastic deposits in the Northern Sierra terrane were derived from contemporaneous volcanic centers in western Nevada (i.e., Happy Creek Complex; Quinn et al. 1997). In contrast, Scherer and Ernst (2008) concluded that Lower and Middle(?) Jurassic, deep-water metasedimentary deposits of the North Fork terrane in the central Klamath Mountains were derived from contemporaneous volcanic rocks now exposed in the Eastern Klamath terrane. Dickinson (2000) recognized similarities in rock types and timing of deposition between the Jurassic volcaniclastic deposits in the northern Sierra Nevada and the Izee–Suplee area of central Oregon (i.e., megasequence 2). We suggest that Lower and Middle(?) Jurassic volcanic and volcaniclastic rocks in the central and eastern Klamath and northern Sierra Nevada mountains, northwestern Nevada, and the BMP in northwestern Oregon may represent dismembered fragments of the same complex arc-forearc system.

Figure 9C provides a comparison of REE patterns for Lower and Middle(?) Jurassic deposits from (1) the North Fork terrane (central Klamath Mountains; data from Scherer and Ernst 2008), (2) the Northern Sierra terrane (data from Lewis and Girty 2001), and (3) megasequence-2 deposits of the BMP. This comparison shows that normalized REE concentrations are remarkably consistent in all three regions. In addition, a plot of La-Th-Sc (Fig. 9D) for the BMP, Klamath Mountains, and Northern Sierra Nevada shows consistent compositional overlap. These

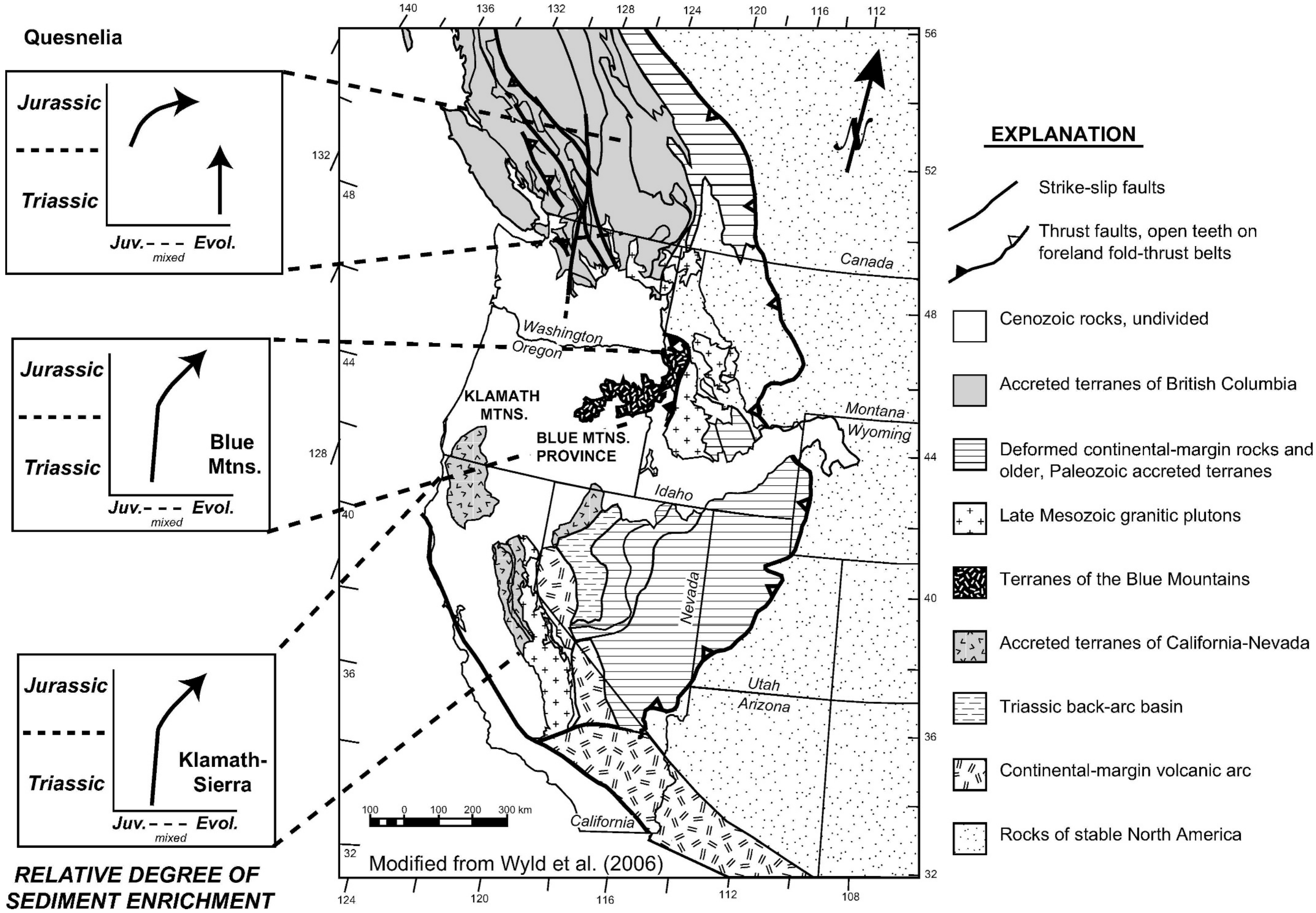


FIG. 10.— Regional comparison of sediment enrichment in accreted-arc terranes. Sedimentary rocks of the Klamath–Sierra Nevada and Blue Mountains share an overall trend from relatively juvenile to relatively evolved compositions from Late Triassic to Middle Jurassic time, whereas rocks of the Quesnel terrane in southern British Columbia are more evolved in Late Triassic time and relatively juvenile during the Lower and Middle Jurassic.

similarities suggest a common source for Lower and Middle(?) Jurassic deposits of each region and support paleogeographic reconstructions and tectonic models that juxtapose rocks of the BMP, Klamath Mountains, Northern Sierra Nevada Mountains, and western Nevada during Jurassic time (e.g., Wyld and Wright 2001; Wyld et al. 2006; Dorsey and LaMaskin 2007). However, tectonic models for late Middle and Late Jurassic (i.e., post ~ 170 Ma) time in these regions are substantially different. These models include intra-arc extension and transtension in the Klamath Mountains (Harper 1984; Harper et al. 1985; Frost et al. 2006), extension and transtension *or* compression and transpression in the Northern Sierra Nevada mountains (Proffett and Dilles 1984; Fisher 1990; Schweickert 1996), and compression and transpression in western Nevada terranes (Oldow 1983; Oldow et al. 1989; Wyld 2002) and the BMP (Gray and Oldow 2005; Dorsey and LaMaskin 2007). These apparent disparities in histories suggest a late Middle–Late Jurassic reorganization of regional plate-boundary conditions prior to onset of Andean-type subduction along the length of the Cordilleran margin.

Comparison of data from the BMP with similar data from accreted terrane complexes to the north and south (Fig. 10) suggests that the terranes of the western U.S. share a long-term provenance history and may have formed a complex system of continent-fringing and intra-oceanic island arcs and related basins. In contrast, these data also show that the Quesnel terrane in southern British Columbia had a Triassic–Jurassic provenance history different from that of terranes to the south. Specifically, highly evolved Late Triassic sediment compositions suggest that Triassic Quesnellia may represent a distinct island-arc complex with more direct ties to western Laurentia. Importantly, REE patterns and trace-element ratio plots of Lower and Middle Jurassic rocks from southern British Columbia and the western U.S. show a high degree of similarity (Figs. 9A–D, 10). This suggests reorganization of formerly discrete tectonic regions into a Lower to Middle Jurassic nascent, integrated western Laurentian margin. Subsequent late Middle to Late Jurassic variation in the tectonic setting of the western U.S. suggests incompletely understood tectonic complexities along the western margin of Laurentia prior to development of an Andean-type margin in Early Cretaceous time. Detailed basin analysis and provenance investigation of Jurassic sedimentary rocks from the Stikine terrane and Bowser Basin of British Columbia, as well as the Klamath and Sierra Nevada regions, are needed to assess when and how western Laurentia first showed signs of becoming an integrated, Andean-type margin. Future analysis of Sm-Nd isotopes and detrital-zircon age distributions from the Blue Mountains Province will aid in understanding the controls on systematic variations in mudrock geochemistry in the region and across western Laurentia.

CONCLUSIONS

The results of this study demonstrate that major- and trace-element geochemistry of mudrocks are useful for developing a comprehensive understanding of regional tectonics. Integration of mudrock geochemistry with sandstone petrography and igneous geochemistry leads to a more complete assessment of tectonic setting and can provide important constraints on regional models for volcanic-arc and craton-margin tectonic evolution.

Analysis of mudrock geochemistry in the Blue Mountains Province reveals systematic compositional variations that reliably discriminate Triassic–Jurassic samples according to their terrane affinity and stratigraphic position. These compositional variations record systematic changes in sediment source areas through time and are consistent with division of BMP deposits into two tectono-stratigraphic megasequences (Dorsey and LaMaskin 2007). Major-element data records progressive homogenization of sediment sources toward a more-evolved provenance through time. Consistent overlap in the trace-element character of Olds Ferry megasequence-1 deposits and Wallowa-area megasequence-2 deposits suggests either a common provenance component or similar degrees of mixing between arc and continental sources.

Major- and trace-element geochemistry supports previous suggestions that the Triassic Wallowa arc was an undifferentiated intra-oceanic arc system similar to the modern Tonga or Mariana arcs, and that the Olds Ferry arc was a more evolved, moderately differentiated pericratonic or continent-fringing arc system similar to portions of the eastern Aleutian or Japan arcs. Trace-element plots record a change from less-evolved (megasequence 1) toward more-evolved source areas (megasequence 2) throughout the BMP. This compositional shift is consistent with other evidence for growth of a Jurassic collisional basin that formed on the previously amalgamated BMP terranes (Dorsey and LaMaskin 2007). An Early to Middle Jurassic magmatic arc in the Klamath and northern Sierra mountains could have supplied detritus northward into the collisional basin. This conclusion is somewhat speculative and requires further testing.

Comparison of data from the BMP with similar data from the Klamath and northern Sierra Nevada mountains suggests that the terranes of the western U.S. share a long-term provenance history and are likely part of a complex, integrated system of continent-fringing and intra-oceanic island arcs. In contrast, it appears that the Quesnel terrane of southern British Columbia had a distinct provenance with a more direct link to Laurentia during Triassic time, and later (during the Jurassic) may have become partially integrated with the BMP and Klamath basins to the south. Data from arc-proximal locations within the Olds Ferry system of the BMP are needed to further substantiate this possibility. Overlap of REE patterns and trace-element ratio plots of Lower to Middle Jurassic rocks from southern British Columbia and the western U.S. may indicate a phase of along-strike integration of the Western Laurentian margin.

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