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Analysis of the Wallowa-Baker terrane boundary: Implications for tectonic accretion in the Blue Mountains province, northeastern Oregon

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ABSTRACT

The Baker terrane, exposed in the Blue Mountains province of northeastern Oregon, is a long-lived, ancient (late Paleozoic–early Mesozoic) accretionary complex with an associated forearc. This composite terrane lies between the partially coeval Wallowa and Olds Ferry island-arc terranes. The northern margin of the Baker terrane is a broad zone (>25 km wide) of fault-bounded, imbricated slabs and slices of metaigneous and metasedimentary rocks faulted into chert-argillite mélange of the Elkhorn Ridge Argillite. Metaplutonic rocks within tectonic units in this zone crystallized between 231 and 226 Ma and have low initial $^{87}Sr/^{86}Sr$ ratios (0.7033–0.7034) and positive initial ε_{Nd} values (+7.7 to +8.5). In contrast, siliceous argillites from the chert-argillite mélange have initial $^{87}Sr/^{86}Sr$ values ranging from 0.7073 to 0.7094 and initial ε_{Nd} values between –4.7 and –7.8. We interpret this broad, imbricate fault zone as a fundamental tectonic boundary that separates the distal, Wallowa island-arc terrane from the Baker accretionary-complex terrane. We propose that this terrane boundary is an example of a broad zone of imbrication made up of slabs and slices of arc crust tectonically mixed within an accretionary complex, providing an on-land, ancient analog to the actualistic arc-arc collisional zone developed along the margins of the Molucca Sea of the central equatorial Indo-Pacific region.

INTRODUCTION

Subduction-related accretionary complexes are fundamental lithotectonic units in orogenic belts and are considered to be a hallmark of Phanerozoic-type, plate-tectonic processes (Hamilton, 1998a, 1998b; McCall, 2003; Cawood et al., 2006; Shervais 2006). Active accretionary wedges can reflect a long-lived history that may span 50 Ma or more (e.g., Barbados Ridge complex; Westbrook, 1982; Westbrook et al., 1988; Torrini and Speed, 1989), whereas ancient accretionary complexes can reflect an even longer history (Cordey and Schiarizza, 1993) that may involve collisional deformation events as well as subduction-accretion processes such as offscraping, subduction erosion, and tectonic underplating (Byrne, 1984; Sample and Fisher, 1986; Scholl and von Huene, 2007). Hence, accretionary complexes commonly include a mixture of rock types that could not have formed in a single tectonic setting (e.g., oceanic components are intermixed with arc components; Shervais, 2006).

The architecture of active subduction-related accretionary wedges has been studied by marine geophysical surveys (e.g., Hamilton, 1979; Snyder et al., 1996; Bader et al., 1999; Pubellier et al., 1999) that have yielded complex structural histories involving imbrication of oceanic lithosphere (ophiolitic suites), forearc extension and/or contraction, delineation of suprasubduction thrust belts and/or broad zones of mélange, and tectonic wedging. Despite the significance of these marine geophysical studies in developing a broad understanding of the development of accretionary wedges in a variety of tectonic settings (e.g., arc-continent collision, arc-arc collision, transpressional/transtensional regime), many aspects of the deformational history of long-lived accretionary complexes remain poorly understood. For example, how is strain partitioned in upper- to middle-crustal levels during arc-arc collision? What metamorphic conditions accompany deformation in an evolving orogenic wedge? Direct examination of exposed, on-land, ancient accretionary complexes can provide insights into these accretionary processes, which are largely inaccessible by conventional marine geophysical techniques.

The Baker terrane of northeastern Oregon (Fig. 1) is a well-exposed example of a long-lived accretionary complex that has broad similarities to other subduction-related terranes of the western North American Cordillera (Cowan, 1985; Dickinson, 2004, 2008; Snoke, 2005). In this paper, we examine the structural, geochemical, and isotopic nature of a slab mélange (i.e., fault-bounded slabs or slices of metaigneous and metasedimentary rocks in argillite-matrix mélange) in the Baker terrane and its significance in the deformational history of this long-lived accretionary complex. In particular, we focus on the northern margin of the Baker terrane and propose that slabs/slices of metaigneous rocks in the Bourne subterrane record the imbrication of the southern Wallowa arc terrane during a collisional orogeny in the Blue Mountains province (Fig. 1). This zone of tectonic imbrication is not significantly overprinted by younger deformation and thus provides an important opportunity to study primary structural features related to subduction and upper-crustal strain localization in an orogenic wedge during a long-lived accretionary history and a progressive arc-arc collision.

GEOLOGIC FRAMEWORK OF THE BLUE MOUNTAINS PROVINCE

The Blue Mountains province of northeastern Oregon and western Idaho (Fig. 1) consists of a group of large-scale, erosional inliers of Middle Devonian–Late Jurassic oceanic-affinity rocks intruded by Late Jurassic–Early Cretaceous plutonic complexes exposed beneath a widespread cover of chiefly Cenozoic rocks (Walker, 1977; Orr et al., 1992). Within the Blue Mountains, many previous authors have recognized four or five tectonostratigraphic terranes (Fig. 1; Brooks and Vallier, 1978; Dickinson and Thayer, 1978; Dickinson, 1979; Silberling et al., 1987):

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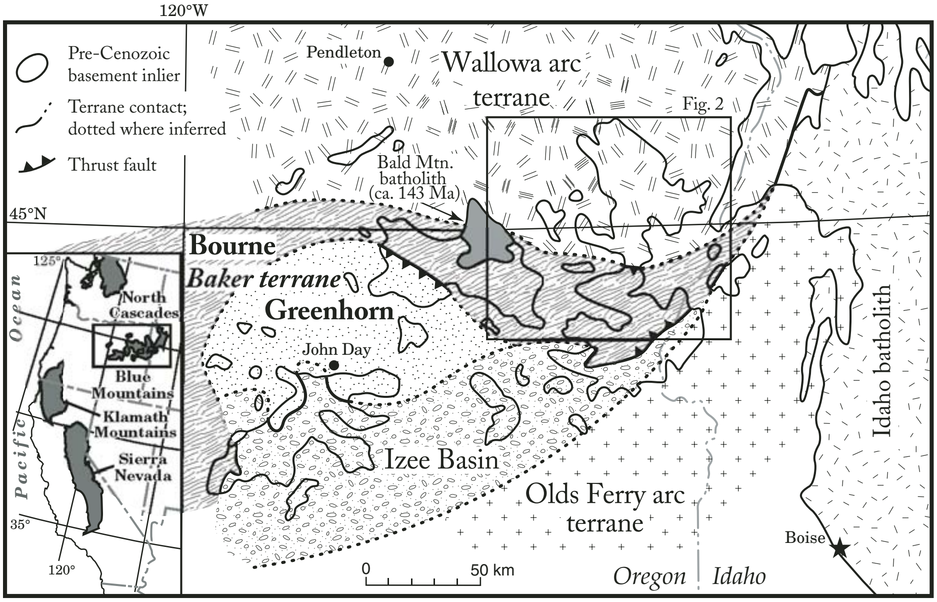

Figure 1. Regional map of the Blue Mountains province, northeastern Oregon and western Idaho, showing the locations of the various terranes and subterranes. Inset map shows location of the Blue Mountains province with respect to other Paleozoic–Mesozoic accreted terranes of the North American Cordillera. The Baker terrane lies between the Olds Ferry and Wallowa island-arc terranes and contains two subterranes: the Bourne and Greenhorn subterranes. The Bourne subterrane and its relationship to the Wallowa terrane is the focus of this study. The Upper Triassic–Upper Jurassic Izee Basin is interpreted to be an overlap sequence.

Wallowa and Olds Ferry oceanic-island arcs, Baker oceanic mélange terrane (includes Grindstone terrane of Blome and Nestell, 1991), and Izee Basin terrane. Although the Late Triassic–Late Jurassic Izee Basin terrane is commonly considered to be a distinct tectonostratigraphic terrane (Dickinson and Thayer, 1978; Silberling et al., 1987), it unconformably overlies the Baker terrane and is here considered an overlap sequence (cf. Walker [1986]; also see Dorsey and LaMaskin [2007] for a recent synthesis of the stratigraphy of the Izee Basin). Consequently, in the following discussion, we only consider the Wallowa, Olds Ferry, and Baker terranes and their relationship to each other in late Paleozoic to early Mesozoic time.

Wallowa Island-Arc Terrane

The Wallowa terrane is a composite island-arc system consisting of a Permian island-arc sequence overlain by extensive Triassic volcanic and volcaniclastic rocks (e.g., Vallier, 1977, 1995; Vallier and Batiza, 1978; Vallier et al., 1977; Kays et al., 2006). Discordant U-Pb zircon ages suggest that parts of the Wallowa arc may be as old as Pennsylvanian (Walker, 1986); however, most plutonic rocks range in age from ca. 264 to 225 Ma (Walker, 1986, 1995). Upper Triassic massive and thin-bedded limestone (i.e., Martin Bridge Limestone) and an Upper Triassic to Lower Jurassic clastic sequence (Hurwal Formation) unconformably overlie the Permian–Triassic volcanogenic rocks, and these rocks are in turn unconformably overlain by Middle to Upper Jurassic flysch-like sedimentary rocks (i.e., Coon Hollow Formation) (Brooks and Vallier, 1978; LaMaskin and Dorsey, 2006). The Wallowa terrane is intruded by Late Jurassic–Early Cretaceous plutonic rocks of the Bald Mountain (Taubeneck, 1957, 1995; Taubeneck and Poldervaart, 1960) and Wallowa Batholiths (e.g., Taubeneck, 1964, 1967, 1995; Armstrong et al., 1977; Walker, 1989; Johnson et al., 1997), as well as by smaller Jurassic–Cretaceous plutons (White, 1973).

Olds Ferry Island-Arc Terrane

The Olds Ferry terrane is a less extensively exposed arc assemblage consisting chiefly of Middle to Late Triassic weakly metamorphosed, volcanic and volcaniclastic rocks with intercalated sedimentary rocks (Brooks and Vallier, 1978). The volcanogenic rocks are dominantly andesitic in composition, but they can range from basalt to rhyolite. The underlying basement is not exposed. Walker (1986) reported an age of ca. 235 Ma from a tonalite stock that intruded rocks of the Olds Ferry terrane; however, U-Pb geochronological studies from the Huntington Formation (part of the Olds Ferry terrane) indicate that volcanism may have lasted into Early Jurassic time (Tumpane et al., 2008). Geologic mapping and structural studies near Huntington, Oregon (Avé Lallemant, 1983) indicate that the arc-affinity rocks of the Olds Ferry terrane (i.e., Huntington Formation) are structurally overlain by a penetratively deformed Jurassic flysch sequence (i.e., Lower to Middle Jurassic Weatherby Formation) with southerly vergent folds. The Jurassic flysch sequence (part of the Izee Basin "terrane" according to Dickinson [1979]) is bounded on the northwest by the reverse-sense, northeast-striking, northwest-dipping Connor Creek fault (Brooks and Vallier, 1978), which emplaced rocks of the Baker terrane onto the younger footwall rocks. The Lookout Mountain stock, dated at ca. 124 Ma by U-Pb zircon techniques, intruded both the footwall and hanging-wall blocks of the Connor Creek fault and thereby provides a minimum age on displacement associated with this important tectonic boundary (Walker, 1986, 1989).

Baker Terrane

The Baker terrane lies between the Wallowa arc terrane to the north and the Olds Ferry arc terrane to the southeast (Fig. 1). It is the oldest and most structurally complex terrane in the Blue Mountains province, containing extensively disrupted fragments of ocean-floor (non-arc) and island-arc volcanic, plutonic, and sedimentary rocks ranging in age from Middle Devonian to Early Jurassic(?) (Nestell, 1983; Coward, 1983; Walker, 1986, 1995; Blome and Nestell, 1991; Carpenter and Walker, 1992; Nestell et al., 1995; Nestell and Nestell, 1998; Nestell and Orchard, 2000). The Baker terrane contains at least two subterranes (the Bourne and Greenhorn subterranes; Fig. 1), which preserve a complex history of deposition, magmatism, metamorphism, and structural processes marginal to the Wallowa and Olds Ferry arc terranes (Ferns and Brooks, 1995).

Greenhorn Subterrane

The Greenhorn subterrane is dominated by serpentinite-matrix mélange containing large blocks of metaplutonic, metavolcanic (locally pillowed), metavolcaniclastic rocks, and chert-argillite breccia. Moderate- to high-pressure metamorphic rocks (5–6 kbar, or 0.5–0.6 GPa) have been found within mélange of the Greenhorn subterrane (Bishop, 1995). Permian–

Triassic conglomerate/grit, sandstone, argillite, and limestone of the Badger Creek metasedimentary unit apparently overlie the serpentinite-matrix mélange (Wheeler, 1976; Mullen, 1978; Ferns and Brooks, 1995). Polymict conglomerate in the Badger Creek unit records erosion of nearby subjacent metamorphosed and lineated gabbro, greenstone, chert, and serpentinite- and talc-matrix rocks (Ferns and Ramp, 1988) during deposition. The presence of altered ultramafic rocks indicates that deposition of the Badger Creek unit continued after serpentinization, which is imprecisely dated between Late Permian and Late Triassic time (Carpenter and Walker, 1992; Ferns and Brooks, 1995). Fusulinids in the Greenhorn subterrane are of McCloud affinity (Mullen, 1978). Jones et al. (1976) reported a well-preserved radiolarian fauna of Early and Middle Jurassic age from a block of black chert in serpentinite about 14.5 km south-southwest of John Day, Oregon (this serpentinite-matrix mélange [Miller Mountain mélange] is inferred to be part of the Greenhorn subterrane, west of the Canyon Mountain complex).

The relationship of the Canyon Mountain complex to the Greenhorn subterrane or Olds Ferry terrane is an unresolved issue in the Blue Mountains province. Some workers have suggested that the Canyon Mountain complex is a large tectonic slab within serpentinite-matrix mélange (e.g., Brooks and Vallier, 1978; Dickinson and Thayer, 1978; Dickinson, 1979; Mullen, 1983, 1985; Walker, 1995). In contrast, Avé Lallemant (1995) suggested that the Canyon Mountain complex represents the Permian part of the Olds Ferry volcanic island-arc terrane. U-Pb zircon ages from hornblende tonalite and metatrondhjemite from the Canyon Mountain complex have yielded Permian ages that range from 276 to 268 Ma (Walker, 1995, his Table 6.2). However, a sample of metacumulate from the eastern part of the gabbroic zone (zone 2 of Avé Lallemant, 1976) yielded a minimum age of ca. 278 Ma and older components that suggested a protolith age older than ca. 314 Ma (Walker, 1995, p. 259). Major-, minor-, and trace-element studies on various rocks from the Canyon Mountain complex (Gerlach et al., 1981a, 1981b; Leeman et al., 1995) also indicate a multiphase petrogenesis, although the abundance of silicic igneous rocks (plagiogranite and keratophyre) and the relative depletions of Nb and Ta in basaltic rocks of the mixed volcanic and sill unit of the complex indicate subduction-related magmatism in proximity to a volcanic arc. If the Canyon Mountain complex is truly a part of the Greenhorn subterrane, the published geochronological and geochemical data are compatible with a phase of Permian magmatism in an island-arc setting (Mullen, 1983, 1985) during rifting, as proposed in the tectonic models presented in Hawkins et al. (1984, see their Figures 10–12) for the progressive rifting of an intra-oceanic island arc during seaward rollback of the subducting oceanic lithospheric slab.

Bourne Subterrane

The Bourne subterrane of the Baker terrane is characterized by extensive exposures of stratally disrupted chert and argillite (chert-argillite mélange) of the Elkhorn Ridge Argillite (Pardee and Hewett, 1914; Gilluly, 1937; Coward, 1983). Meter-scale blocks of coherent, bedded argillite and ribbon chert also occur within the Elkhorn Ridge Argillite, and they are commonly isoclinally folded and cut by a penetrative spaced-cleavage, faults, and/or zones of cataclasite. Limestone blocks (olistoliths or tectonic blocks) are enclosed within the Elkhorn Ridge Argillite and contain fusulinids, conodonts, corals, and crinoids of Middle Devonian to Late Triassic age (Vallier et al., 1977; Wardlaw et al., 1982; Nestell, 1983; Nestell et al., 1995; Nestell and Nestell, 1998; Nestell and Orchard, 2000). Radiolarian-bearing cherts from the Elkhorn Ridge Argillite are Permian to Early Jurassic(?) in age (Coward, 1983; Blome et al., 1986; Ferns et al., 1987; F. Cordey, 2006–2009, personal commun.), indicating that deep-sea deposition possibly continued into Jurassic time. Both Tethyan and McCloud fusulinids are reported from the Bourne subterrane (Bostwick and Koch, 1962; Bostwick and Nestell, 1965; Nestell, 1983). The presence of McCloud-type fauna in rocks of the Bourne and Greenhorn subterranes implies a paleogeographic tie to an inferred oceanic arc that fringed the continental margin of western North America in Permian time (Miller, 1987).

The Bourne subterrane also contains fault-bounded slabs or slices of arc-related plutonic/hypabyssal, volcaniclastic, and sedimentary rocks—all metamorphosed under lower greenschist-facies conditions—within the Elkhorn Ridge Argillite (see Jurassic to Pennsylvanian metasedimentary rocks in Fig. 2) (Stimson, 1980; Brooks et al., 1982a, 1982b; Evans, 1986, 1989, 1995; Ferns et al., 1987; Bishop, 1995; Ferns and Brooks, 1995; Schwartz et al., 2005, 2006). These slabs/slices generally are separated from adjacent overlying and underlying Elkhorn Ridge Argillite by moderate- to low-angle, southward-dipping, reverse-sense faults (Ferns and Brooks, 1995). U-Pb zircon ages for these metaplutonic rocks range from ca. 230 to 245 Ma (Walker, 1995) and include metaigneous, fault-bounded slices

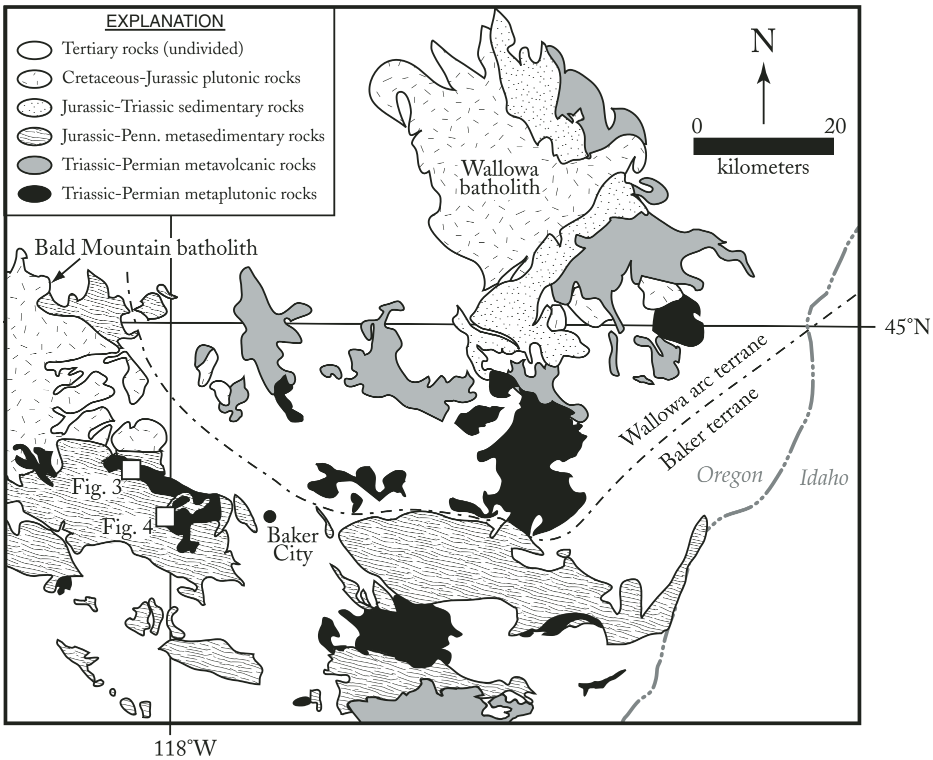

Figure 2. Geologic map of the Baker-Wallowa terrane boundary highlighting the occurrence of metaigneous slices in the Bourne subterrane. The locations of Figures 3 and 4 are shown west of Baker City, Oregon.

in the Burnt River Schist (interpreted as a higher-grade equivalent of the Elkhorn Ridge Argillite; Ashley, 1967, 1995). Trace-element discrimination diagrams imply that these metavolcanic and metaplutonic rocks were generated in a suprasubduction-zone setting, suggesting an intra-oceanic island-arc setting for their formation (Mullen, 1985; Ferns and Brooks, 1995). Based on petrologic, geochemical, and age similarities, Ferns and Brooks (1995) suggested that these slabs of metaigneous and metasedimentary rocks represent imbricated fragments of the nearby Wallowa island-arc terrane, which became tectonically intercalated into the Baker terrane in post–Late Triassic time. These slabs and their tectonic significance are the primary focus of this study.

In addition to arc-derived metaigneous fault-bounded slabs, fragments of nonarc metavolcanic rocks are also present within the Bourne subterrane (Olive Creek unit of Ferns and Brooks, 1995), and they typically occur as fault-bounded slices near the tectonic boundary between the Bourne and Greenhorn subterranes (Ferns and Brooks, 1995). These rocks consist of alkalic pillow basalts and related volcaniclastic rocks with geochemical characteristics similar to ocean-island basalts (within-plate alkali basalts of Mullen, 1985). They are also geochemically distinct from the arc-related, metaigneous rocks distributed along the Wallowa-Baker terrane margin, and they have been interpreted to represent fragments of non-arc oceanic crust faulted into the Bourne subterrane during a period of collision between the Wallowa and Olds Ferry terranes (Ferns and Brooks, 1995).

Relationship between Island-Arc Terranes and the Baker Terrane

The relationship between the Wallowa and Olds Ferry island-arc terranes is poorly understood, but it is critically important in paleotectonic reconstructions of the Blue Mountains province, as well as the North American Cordillera. Some authors argue that the Wallowa and Olds Ferry arc terranes represent a single, complex island-arc system (e.g., Pessagno and Blome, 1986; Vallier, 1995), whereas other authors suggest that the Olds Ferry terrane was a fringing, continental-margin, island arc (e.g., Miller, 1987; Avé Lallemant, 1995) analogous to the Quesnellia arc (Mortimer, 1987) of the Canadian Cordillera, and the Wallowa terrane was an exotic, far-traveled island arc (e.g., Sarewitz, 1983; Ferns and Brooks, 1995; Moores et al., 2002). Follo (1994, p. 26) argued that the Wallowa terrane developed at low northerly paleolatitudes as part of an east-facing oceanic-arc system that was separated from the North American continental margin by a narrow ocean basin.

The relationship between the Baker terrane and Wallowa and Olds Ferry arc terranes is also controversial, stemming in part from the presence of both Tethyan and McCloud fauna in the Baker terrane. In some models (e.g., White et al., 1992; Vallier, 1995), the Baker terrane is a far-traveled, exotic terrane with closer affinities to the Wallowa arc than the North American continental margin, whereas in other models (Oldow et al., 1989; Burchfiel et al., 1992; Avé Lallemant, 1995), the Baker terrane is genetically linked to the Olds Ferry terrane and the North American margin. Each of these contrasting models makes specific predictions about the crustal structure and location of lithospheric suture zones in the Blue Mountains province. In the "far-traveled terrane" model, the Baker–Olds Ferry terrane boundary is a lithospheric suture. In the "pericratonic-terrane" model, this lithospheric suture lies instead between the Baker and Wallowa terranes. The location and nature of these potential suture zones not only represent first-order tectonic problems in the Blue Mountains province, but they also have implications for the interpretation of Mesozoic–Cenozoic magmatism and postulated lithospheric displacements during the Cretaceous (e.g., Leeman et al., 1992). However, both interpretations are permissive in terms of the present faunal data.

By the Late Jurassic–Early Cretaceous, the three major terranes (Olds Ferry, Baker, and Wallowa) of the Blue Mountains province had been amalgamated and intruded by post-tectonic batholiths and plutons (Armstrong et al., 1977; Vallier and Brooks, 1986; Walker 1986, 1989; Snee et al., 1995; Vallier, 1995). The Bald Mountain Batholith intrudes the Bourne subterrane and Wallowa terranes and constrains amalgamation to prior to ca. 143 Ma (Walker, 1989). The oldest pluton in the Wallowa Batholith yielded a U-Pb zircon age of ca. 137 Ma, and the youngest post-tectonic arc pluton in the Blue Mountains province is ca. 120 Ma (Walker, 1989).

Cenozoic rotation of the whole Blue Mountains province is based on the paleomagnetic data reported in Wilson and Cox (1980) for Cretaceous–Jurassic intrusions in the Blue Mountains and the early Tertiary Clarno Formation. These authors demonstrated ~60° of clockwise vertical-axis, tectonic rotation of the Blue Mountains province prior to the Eocene. Restoration of that clockwise rotation brings the Blue Mountains into a more north-south orientation and provides a prerotational framework to attempt potential terrane correlations to either the north or south. Interestingly, Wilson and Cox (1980) also speculated that the clockwise rotation of the Blue Mountains was related to Late Cretaceous right-lateral strike-slip faulting—a hypothesis that has recently been explored in detail by Wyld and Wright (2001), Wyld (2005), Giorgis et al. (2005), and Housen and Dorsey (2005).

METHODS

Detailed geologic-structural mapping was conducted in the Cougar Basin (Fig. 3) and Marble Point areas (Fig. 4). All rocks from the Cougar Basin and Marble Point areas are affected by varying degrees of greenschist-facies alteration associated with fluid transport. Samples for major- and trace-element, and Rb-Sr and Sm-Nd isotope geochemistry were selected to represent the major rocks types of the Bourne subterrane and were collected from the least-altered and least-deformed rocks to minimize effects of greenschist-facies alteration. Rock chips were handpicked at the University of Wyoming, and weathered and greenschist-facies veins were discarded. Despite these precautions, some rock analyses indicate element mobility (e.g., elevated Na_2O concentrations) suggestive of Na metasomatism.

Geochemical sampling consists of nine samples of Elkhorn Ridge Argillite, three samples of Burnt River Schist (a possible higher-grade equivalent of the Elkhorn Ridge Argillite), four samples of metaplutonic rocks, and six samples of metasedimentary rocks associated with the metaplutonic rocks (informally referred to as the "Cougar Basin metasedimentary sequence"). Samples for isotopic analyses were selected from a subset of these analyzed samples. Samples collected for U-Pb geochronology consist of a metatonalite from the Marble Point area (EHP-04–3) and a metadiorite from the Cougar Basin area (EHP1–05–3). Sample locations are shown on

Figure 3. Geologic map of the Cougar Basin area (Elkhorn Peak 7.5 min quadrangle) in the Bourne subterrane of the Baker terrane showing fault-bounded slices of arc-related rocks intercalated within (meta)sedimentary rocks of the accretionary complex. Locations of geochemical samples are shown by stars, and the geochronologic sample is depicted as a gray circle. Geology is modified from Ferns et al. (1987).

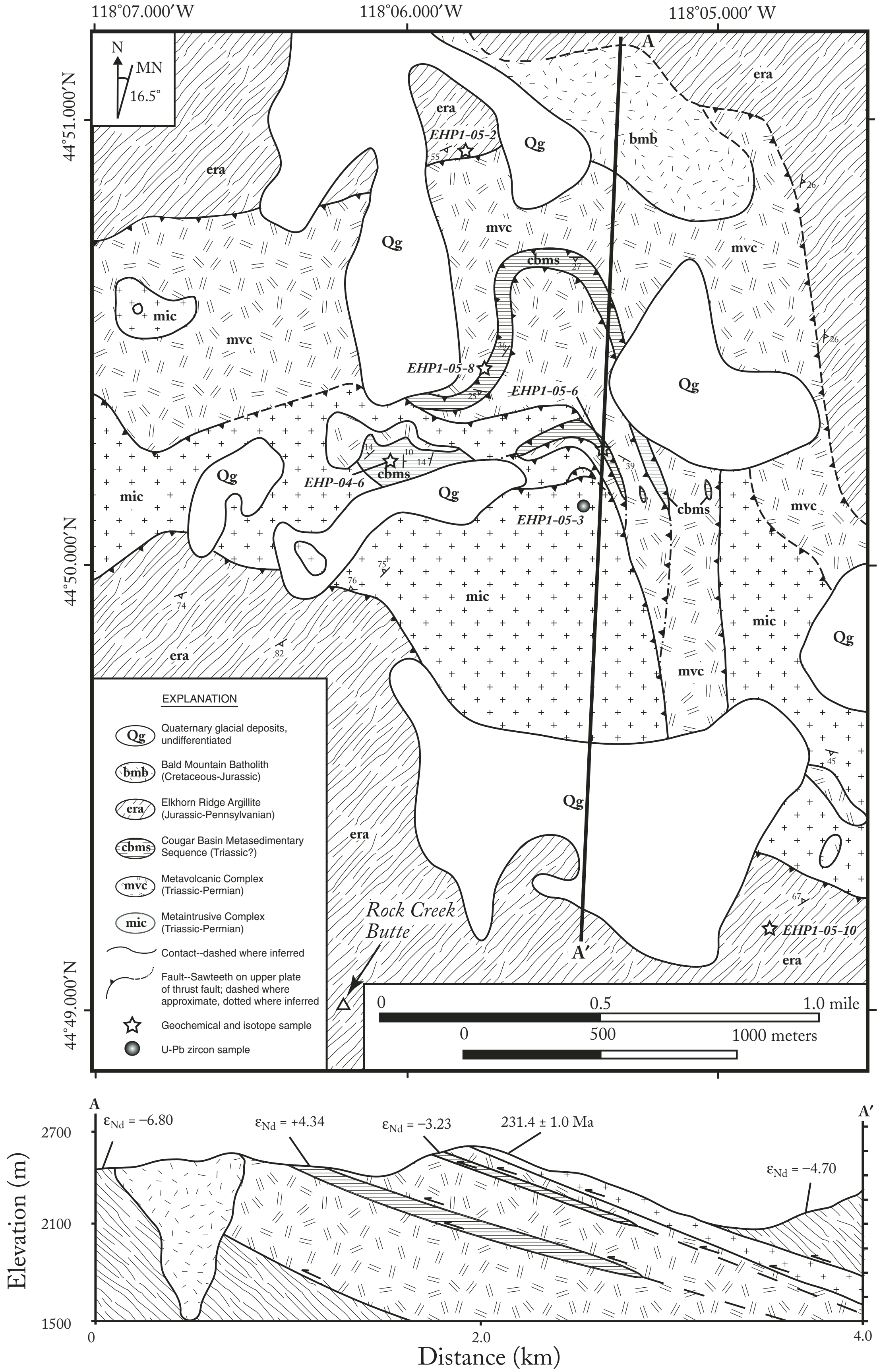
118°07.000′W
118°06.000′W
118°05.000′ W
44°51.000′N
44°50.000′N
44°49.000′N
N
MN
16.5°
A
A′
era
bmb
Qg
mvc
cbms
mic
EHP1-05-2
EHP1-05-8
EHP1-05-6
EHP-04-6
EHP1-05-3
EHP1-05-10
Rock Creek Butte
0
0.5
1.0 mile
0
500
1000 meters
EXPLANATION
Qg Quaternary glacial deposits, undifferentiated
bmb Bald Mountain Batholith (Cretaceous-Jurassic)
era Elkhorn Ridge Argillite (Jurassic-Pennsylvanian)
cbms Cougar Basin Metasedimentary Sequence (Triassic?)
mvc Metavolcanic Complex (Triassic-Permian)
mic Metaintrusive Complex (Triassic-Permian)
Contact--dashed where inferred
Fault--Sawteeth on upper plate of thrust fault; dashed where approximate, dotted where inferred
Geochemical and isotope sample
U-Pb zircon sample
εNd = −6.80
εNd = +4.34
εNd = −3.23
231.4 ± 1.0 Ma
εNd = −4.70
Elevation (m)
2700
2100
1500
0
2.0
4.0
Distance (km)

Figure 3.

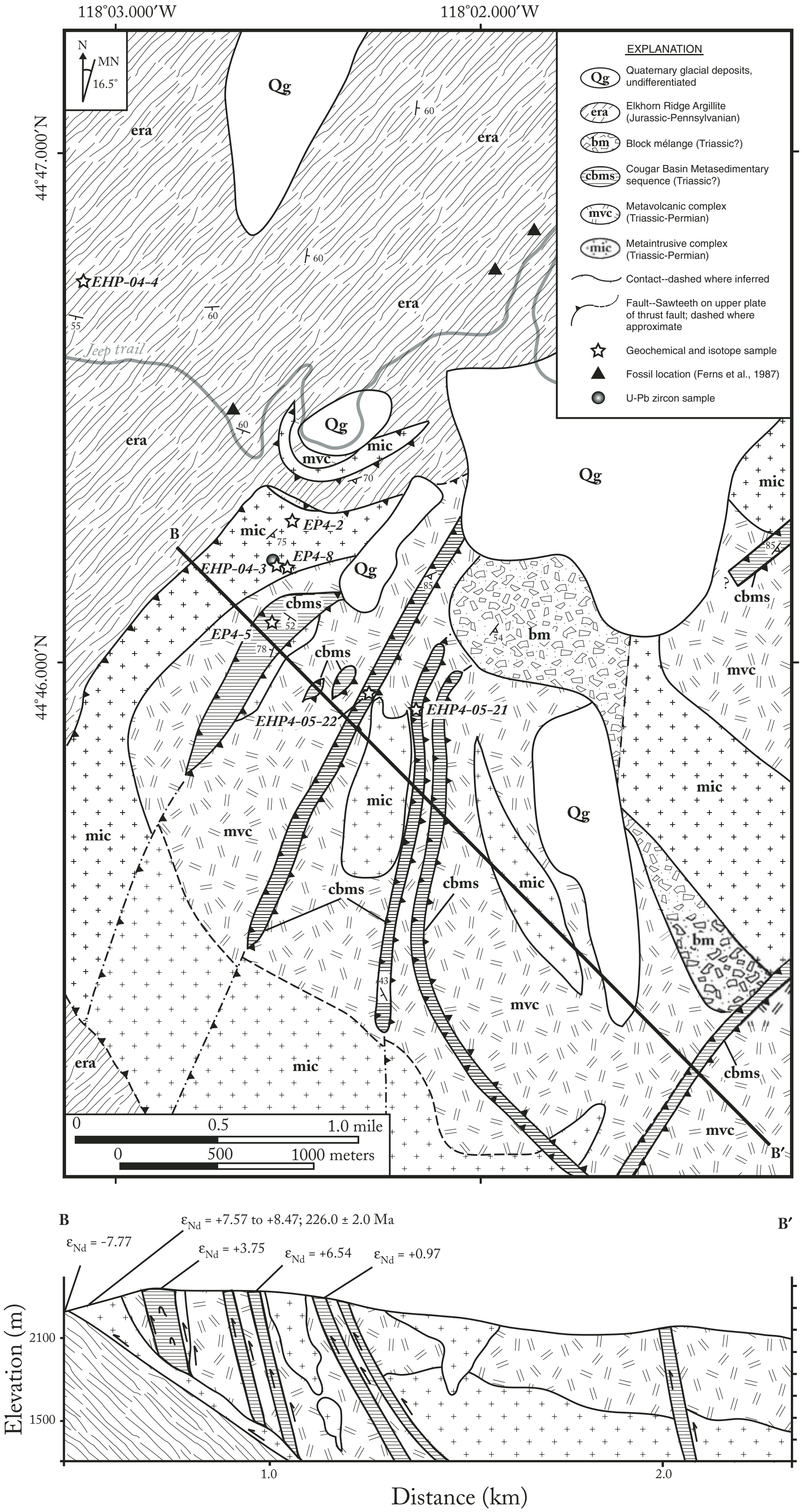

Figure 4. Geologic map of the Marble Point area (Elkhorn Peak 7.5 min quadrangle) in the Bourne subterrane of the Baker terrane showing fault-bounded slices of arc-related rocks intercalated within (meta)sedimentary rocks of the accretionary complex. Locations of geochemical samples are shown by stars, and the geochronologic sample is depicted as a gray circle. Geology is modified from Ferns et al. (1987).

Figures 3 and 4, and UTM locations are given in GSA Data Repository Table DR1.[1] Data for these samples are presented in Tables 1–3.

Whole-rock geochemical analyses were performed at Texas Tech University by inductively coupled plasma–atomic emission spectrometry (ICP-AES) for major elements, plus Sr, Zr, Y, V, Nb, Ba, Be, Sc, Cu, Cr, and Zn. Nd and Sr isotopic compositions were determined at the University of Wyoming by thermal ionization mass spectrometry (TIMS). Sm, Nd, Rb, and Sr concentrations were determined by isotope dilution (ID) on aliquots of the same sample dissolved for isotope ratio measurements. Further analytical details are given in footnotes to Tables 1 and 2.

Zircons were separated from whole-rock samples following standard crushing methods involving density (Wilfley table and heavy liquids) and magnetic (Frantz isodynamic separator) separation techniques. Nonmagnetic zircons (at 1.5 A) were handpicked at Brown University to obtain optically clear, colorless grains free or largely free of mineral and fluid inclusions. Analytical methods followed those of Krogh (1973, 1982). Initial Pb corrections were made using an age-appropriate Pb isotopic composition (Stacey and Kramers, 1975). All U-Pb ages were calculated using PBDAT (Ludwig, 1984) and are reported at 95% confidence limits. Except as noted, crystallization ages were calculated from the weighted average of the $^{206}Pb/^{238}U$ age.

RESULTS

Field Observations and Petrography of Bourne Subterrane

Elkhorn Ridge Argillite

Elkhorn Ridge Argillite is the most abundant rock type in the Bourne subterrane (Fig. 5A). Fine-grained argillaceous rocks of the Elkhorn Ridge Argillite contain mineral assemblages of quartz + plagioclase + carbonate ± chlorite ± white mica. Grain sizes for these rocks are typically less than 5 µm, and the grains are generally angular to subangular. Poorly preserved recrystallized radiolarian tests were commonly observed.

Metaigneous Fault-Bounded Slabs/Slices

Slabs/slices of metaplutonic, metavolcaniclastic, and associated metasedimentary rocks are ubiquitous in the Bourne subterrane (Figs. 5B–5D) (Stimson, 1980; Brooks et al., 1982a, 1982b; Evans, 1986, 1988, 1995; Ferns et al., 1987; Bishop, 1995; Ferns and Brooks, 1995; Schwartz et al., 2005, 2006). They range in width from meter- to kilometer-scale (Fig. 2) and strike approximately east-west, roughly parallel to the penetrative cleavage and associated hinge lines developed in the Elkhorn Ridge Argillite. Metaplutonic rocks occur as isolated bodies of hornblende gabbro to quartz diorite, which locally grade into fine-grained diorite. On Marble Point, fine-grained diorite appears to intrude lithic-clast volcaniclastic breccia that contains fragments of metaplutonic, metavolcanic, and metasedimentary rocks, including diorite, andesite, limestone marble, argillite, and siliceous argillite. Greenschist-facies cataclastic veins are characteristic features of both metaplutonic and metavolcaniclastic rocks (e.g., Fig. 5C). In the metavolcaniclastic rocks, cataclastic veins cut across both clasts and matrix, implying that deformation occurred after deposition. Although greenschist-facies cataclastic veins are widely distributed in the metaigneous rocks, they are most densely distributed near fault contacts.

Metaplutonic rocks in the Marble Point and Cougar Basin areas chiefly range from diorite to quartz diorite but also include minor gabbro. Magmatic mineral assemblages include plagioclase + green hornblende ± quartz ± zircon ± apatite. Clinopyroxene, biotite, and potassium feldspar are not present. Hornblende is generally pale green in plane-polarized light and forms stout prisms. Magmatic fabrics are sometimes overprinted by high-temperature deformational fabrics defined by ribbon quartz characterized by highly flattened and elongated grains with sutured boundaries.

Nearly all metaplutonic rocks are overprinted to varying degrees by greenschist-facies metamorphic assemblages of albite + clinozoisite + chlorite ± titanite ± epidote ± tourmaline. These metamorphic mineral assemblages are associated with zones of cataclastic deformation and brittle fractures, which cut across pre-existing and higher-temperature fabrics (Figs. 6A–6D). Plagioclase is commonly altered to albite and saussurite and has microfracturing along cleavage planes. Hornblende also commonly has microfracturing, and, in some cases, cleavage planes are filled with metamorphic titanite.

Metavolcaniclastic rocks contain a variety of phenocrysts and crystal and lithic fragments in a fine-grained groundmass. Crystal fragments consist of quartz, zoned plagioclase feldspar, and calcite. Rock fragments consist of amygdaloidal volcanic rocks, siliceous metaplutonic rocks, limestone, and recrystallized chert. Probable devitrified glass is present in some samples and displays magmatic flow banding textures. Although secondary chlorite is present in all samples, these rocks are generally not as pervasively altered as the metaplutonic rocks. Zones of cataclastic deformation are common, typically within the fine-grained groundmass (Figs. 6E–6F).

Cougar Basin Metasedimentary Rocks

Relatively coherent sequences of (meta)sedimentary rocks (Cougar Basin metasedimentary sequence) are faulted into the metaplutonic and metavolcaniclastic rocks. Metasedimentary rocks of the Cougar Basin metasedimentary sequence consist of polymictic pebble conglomerate, sandstone, tuffaceous (?) and siliceous argillite, and limestone (Figs. 5D, 6G–6H, and 7). Ferns et al. (1987) reported early Norian conodonts from limestones in these fault-bounded slabs/slices. Compared to the (meta) sedimentary rocks of the Elkhorn Ridge Argillite, the Cougar Basin rocks are not as pervasively deformed and consequently retain some of their original sedimentary features, including original bedding and flame structures. Based on crosscutting relationships, thrusting of the Cougar Basin metasedimentary rocks into metavolcaniclastic and metaplutonic rocks postdated the development of penetrative cleavage observed in the Elkhorn Ridge Argillite (cf. Figs. 3 and 4).

Siliceous argillites and sandstones in the Cougar Basin metasedimentary sequence contain detrital mineral assemblages of albite + calcite + actinolite + chlorite ± biotite (e.g., Figs. 6G–6H). These rocks are distinct from the Elkhorn Ridge Argillite in having a greater modal percentage of carbonate and albite and less abundant quartz. Fragments of fine-grained recrystallized chert and siliceous plutonic rocks are commonly observed. Flattened and recrystallized radiolarian tests are also observed in argillaceous rocks and are locally concentrated near contacts with sandstones.

Structural Observations in the Bourne Subterrane

Early Structures in the Elkhorn Ridge Argillite

Primary sedimentary layering is generally absent; it is only locally preserved in large blocks of chert-argillite surrounded by anastomosing zones of centimeter-scale cataclasite. Inverted graded bedding indicates overturning of sedimentary units. Original chert-argillite layering in the Elkhorn Ridge Argillite is disrupted by layer-parallel extension along centimeter- to meter-scale, low-angle, cataclastic shear zones.

Penetrative Fabric Development in the Elkhorn Ridge Argillite

The most prominent structural feature in the Elkhorn Ridge Argillite is the development of a

[1]GSA Data Repository item 2009189, contains a brief discussion of major and trace element data from metaigneous and metasedimentary rocks of the Barker terrane along with one table and one figure and is available at http://www.geosociety.org/pubs/ft2009.htm or by request to editing@geosociety.org.

TABLE 1. MAJOR- AND TRACE-ELEMENT DATA FOR METASEDIMENTARY AND METAPLUTONIC ROCKS OF THE BAKER TERRANE

	Metasedimentary rocks												
	Elkhorn Ridge Argillite										Burnt River Schist		
Sample no.	ERA-1	ERA-1R	EHP-04-4	EHP1-05-10	EHP1-05-2	BM97-2	BM97-3	BM97-5	BM97-7	BM97-8	BM97-10	BM97-11	BM97-12A
SiO_2	74.24	74.7	81.5	75.53	82.57	94.72	78.30	93.16	91.73	93.20	78.18	97.70	96.42
TiO_2	0.61	0.64	0.4	0.67	0.37	0.14	0.47	0.16	0.12	0.16	0.58	0.04	0.05
Al_2O_3	11.44	11.51	8.22	9.79	7.57	3.17	8.00	3.26	3.12	3.40	9.96	1.11	1.53
Fe_2O_3	3.93	4.04	3.19	4.58	3.30	0.93	4.03	1.11	1.94	1.14	3.79	0.83	0.51
MnO	0.06	0.07	0.04	0.04	0.18	0.01	0.06	0.01	0.12	0.02	0.06	0.25	0.06
MgO	2.06	2.06	1.72	2.49	1.44	0.44	1.66	0.42	1.15	0.65	1.33	0.21	0.20
CaO	0.11	0.14	0.09	0.21	0.22	0.02	1.29	0.05	0.95	0.04	0.23	0.03	0.03
Na_2O	1.09	1.15	0.34	1.10	0.98	0.07	0.93	0.19	0.23	0.26	0.78	0.02	0.06
K_2O	2.65	2.78	2.38	2.10	2.07	0.99	1.79	0.85	0.44	0.71	2.14	0.26	0.44
P_2O_5	0.09	0.08	0.01	0.13	0.06	0.02	0.11	0.03	0.03	0.02	0.15	0.03	0.03
LOI	2.68	2.68	2.13	2.71	1.48	0.90	3.25	0.87	1.04	0.90	3.05	0.42	0.44
Sum	98.97	99.84	100.01	99.73	100.23	101.41	99.90	100.12	100.88	100.51	100.24	100.90	99.77
Cr	n.d.	62	21	56	30	23	55	54	42	111	63	22	15
Ni	n.d.	n.d.	n.d.	24	22	10	34	45	63	201	53	32	21
Rb	n.d.	87	20	n.d.	73	32	58	30	21	24	73	11	16
Sr	85	86	281	48	82	7	66	22	77	10	40	9	8
Y	21	21	13.3	19.9	12.1	4.8	16.7	6.8	7.2	6.6	21.9	4.7	4.6
Zr	149	153	71	113	85	38	77	36	30	38	119	20	18
Nb	n.d.	6	4	7	4	5	9	4	3	5	12	3	3
Ba	715	715	445	737	1240	287	855	633	496	313	1473	122	288
Sc	n.d.	15.2	12.4	15.9	11.9	5.0	12.2	5.7	4.8	4.7	11.3	2.0	2.2
V	n.d.	105	72	107	66	28	80	60	19	31	91	8	9
Cu	n.d.	70	124	34	9	16	53	52	36	13	70	39	15
Zn	n.d.	61	72	70	57	24	63	32	37	34	111	23	17
Be	n.d.	n.d.	n.d.	1.4	1.0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

(*Continued*)

TABLE 1. MAJOR- AND TRACE-ELEMENT DATA FOR METASEDIMENTARY AND METAPLUTONIC ROCKS OF THE BAKER TERRANE (*Continued*)

	Cougar Basin metasedimentary rocks					Metaigneous rocks										
Sample no.	EHP-04-6	EHP-05-8	EHP1-05-6	EHP4-05-21	EHP4-05-22	EP4-5	EHP-2	EHP-3	EHP-3R	EP4-2	EP4-8	EHP-04-3	EHP-04-5	EHP-04-2	EHP-6	EHP-6R
SiO_2	77.98	64.76	78.29	74.36	72.95	77.90	54.7	49.78	49.22	47.93	49.12	65.46	66.54	49.06	53.45	53.75
TiO_2	0.38	0.83	0.44	0.52	0.37	0.38	0.85	1.01	1.04	0.83	0.45	0.44	0.41	0.66	1.22	1.2
Al_2O_3	9.66	13.22	9.27	10.57	12.71	8.14	17.43	18.72	19.27	19	16.58	16.36	16.69	20.23	14.99	15.16
Fe_2O_3	4.05	8.51	3.83	4.90	3.76	4.57	9.12	9.58	9.65	9.86	9.65	4.64	3.06	7.99	10.93	10.68
MnO	0.05	0.19	0.02	0.08	0.06	0.06	0.17	0.17	0.18	0.17	0.19	0.1	0.06	0.11	0.2	0.19
MgO	2.27	3.87	2.01	2.12	1.31	2.65	4	4.52	4.46	5.45	8.36	2.11	1.53	4.68	5.3	5.36
CaO	1.52	3.26	1.31	1.42	4.22	2.10	6.32	10.18	10.25	8.46	8.54	3.84	4.54	7.21	4.47	4.54
Na_2O	1.79	2.93	0.99	1.64	0.55	1.71	4.94	1.8	1.83	3.34	3.19	5.22	4.22	4.1	4.28	4.28
K_2O	0.88	1.00	1.33	1.53	1.46	0.52	0.38	0.04	0.05	0.1	0.51	0.71	1.23	1.2	0.8	0.81
P_2O_5	0.06	0.08	0.07	0.08	0.06	0.08	0.07	0.24	0.2	0.03	0	0.09	0.13	0.01	0.15	0.13
LOI	1.66	2.29	1.97	1.93	2.19	2.10	2.15	4.18	4.18	4.46	3.31	1.58	1.77	6.49	4.02	4.02
Sum	100.3	100.10	99.52	99.87	99.65	100.22	100.1	100.2	100.32	99.63	99.89	100.54	100.18	101.74	99.82	100.13
Cr	60	17	26	25	9	48	5	11		11	43	61	10	21	7	n.d.
Ni	n.d.	86	23	15	3	22	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Rb	71	n.d.	28	n.d.	29	9	6	3	n.d.	3	11	11	24	15	11	n.d.
Sr	58	263	503	432	1672	279	187	408	418	283	285	316	671	505	320	320
Y	11.1	22.0	15.1	16.7	33.9	11.4	24.7	19.2	19	8.6	6.3	12.9	4.6	4.0	31.5	27.3
Zr	88	73	94	92	147	47	69	36	42	17	23	111	86	7	83	85
Nb	5	0	4	0	5	0	8	14	n.d.	10	10	5	8	7	6	n.d.
Ba	2336	446	687	742	7008	309	180	30	31	70	96	298	698	349	216	226
Sc	12.4	27.3	12.1	16.6	15.4	15.2	32.5	31.0	n.d.	31.5	33.0	10.1	6.6	19.9	36.2	n.d.
V	58	212	65	74	37	103	237	253	n.d.	294	370	74	44	202	290	n.d.
Cu	77	91	43	61	26	100	85	56	n.d.	69	22	18	10	33	104	n.d.
Zn	63	101	67	96	58	84	90	103	n.d.	88	70	54	61	78	100	n.d.
Be	n.d.	0.7	1.1	0.9	1.0	0.5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

Note: Analytical details: Samples were fused in lithium metaborate and dissolved in 50 mL of 5% HCl solution for inductively coupled plasma–atomic emission spectrometry (ICP-AES) and flame-emission analysis. Relative uncertainties at the 95% confidence level are <1% for Si and Al; <2% for V; <3% for Ti, Fe, Mn, Ca, Na, Sr, Ba, and Zr; <5% for K, Mg, Y, and Rb; <10% for P, Sc, Cu and Zn; and <15% for Nb, Cr, and Ni. LOI—loss on ignition.

penetrative spaced-cleavage and folding along gently plunging east-west–trending fold axes (Avé Lallemant et al., 1980; Coward, 1983; Avé Lallemant, 1995). In the Marble Point and Cougar Basin areas, the penetrative spaced-cleavage typically strikes east-west and dips to the south. Subparallel orientations of bedding and the penetrative cleavage suggest that bedding has been locally transposed by isoclinal folds that developed during low-grade regional metamorphism. Penetrative fabric development apparently involved significant dissolution (Avé Lallemant, 1995), which may have resulted in trace-element mobilization in the Elkhorn Ridge Argillite (see Geochemistry and Isotopic Results section). The orientation of the east-west–trending fold axes is also subparallel to strike of major faults, which emplaced the metaplutonic and metavolcaniclastic rocks into the Elkhorn Ridge Argillite. Near fault contacts with the metaigneous rocks, cataclastic deformation within chert-argillite layers is more intense, and greenschist-facies fluid alteration is strongly developed. A final phase of open, steeply plunging north-south–trending folds overprints earlier fabrics, but these folds are not associated with the development of a penetrative cleavage (Coward, 1982, 1983).

TABLE 2. Nd AND Sr ISOTOPIC DATA FOR ARGILLACEOUS AND METAPLUTONIC ROCKS OF THE BAKER TERRANE

Sample	Rb (ppm)	Sr (ppm)	Rb/Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr (present)	^{87}Sr/^{86}Sr (initial)	Sm (ppm)	Nd (ppm)	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd (present)	^{143}Nd/^{144}Nd (initial)	Initial ε_{Nd}	Nd model age (Ga)
Bourne subterrane (metaplutonic rocks)													
EHP-04-3	8.68	236.08	0.04	0.1064	0.70363	0.70329	2.11	8.68	0.1474	0.512968	0.512726	8.0	0.4
EHP-04-3d	8.82	296.96	0.03	0.0860	0.70363	0.70333	2.33	11.11	0.1270	0.512926	0.512718	7.8	0.4
EHP-2	3.26	204.32	0.02	0.0462	0.70342	0.70326	2.87	9.66	0.1794	0.513004	0.512710	7.7	0.7
EP4-8							0.87	3.15	0.1675	0.513019	0.512745	8.4	0.5
EP4-8d	8.60	270.65	0.03	0.0919	0.70376	0.70343	0.87	3.15	0.1667	0.513023	0.512750	8.5	0.4
EP4-2	0.93	315.14	0.00	0.0085	0.70325	0.70321	1.25	4.22	0.1799	0.513007	0.512713	7.7	0.7
Bourne subterrane (Elkhorn Ridge Argillite)													
ERA-1	94.92	83.74	1.13	3.2840	0.71963	0.70936	4.22	21.27	0.1201	0.512263	0.512090	–5.2	1.5
EHP-04-4	68.90	53.92	1.28	3.7025	0.72053	0.70895	2.29	11.67	0.1187	0.512127	0.511956	–7.8	1.6
EHP1-05-2	63.78	67.25	0.95	2.7472	0.71804	0.70944	3.24	16.98	0.1154	0.512173	0.512007	–6.8	1.5
EHP1-05-10	61.09	46.10	1.33	3.8393	0.71935	0.70734	3.39	17.43	0.1175	0.512283	0.512114	–4.7	1.4
Bourne subterrane (Cougar Basin metasedimentary sequence)													
EHP-04-6	17.64	280.30	0.06	0.1821	0.70608	0.70551	2.94	13.11	0.1356	0.512574	0.512378	0.5	1.1
EHP-04-6d	17.51	274.23	0.06	0.1848	0.70606	0.70549	2.92	13.00	0.1358	0.512577	0.512381	0.5	1.1
EHP1-05-6	27.79	456.01	0.06	0.1763	0.70608	0.70553	2.81	13.33	0.1275	0.512373	0.512189	–3.2	1.4
EHP-05-8	18.79	257.86	0.07	0.2108	0.70460	0.70394	2.88	10.66	0.1636	0.512813	0.512577	4.3	1.0
EP4-5	9.25	301.51	0.03	0.0887	0.70601	0.70574	1.77	6.87	0.1556	0.512771	0.512547	3.8	1.0
EHP4-05-21	30.89	373.10	0.08	0.2396	0.70608	0.70533	2.87	12.08	0.1437	0.512611	0.512404	1.0	1.2
EHP4-05-22	26.67	1443.20	0.02	0.0535	0.70472	0.70455	4.15	15.29	0.1640	0.512926	0.512690	6.5	0.7

Note: Initial Nd and Sr isotopic ratios were calculated at 220 Ma for metasedimentary rocks and 250 Ma for metaplutonic rocks. Analytical details: ~80 to 100 mg of sample were dissolved in HF-HNO_3. After conversion to chlorides, one-third of the sample was spiked with ^{87}Rb, ^{84}Sr, ^{149}Sm, and ^{146}Nd. Rb, Sr, and rare earth elements (REEs) were separated by conventional cation-exchange procedures. Sm and Nd were further separated in di-ethyl-hexylorthophosphoric acid columns. All isotopic measurements were made on a VG Sector multicollector mass spectrometer at the University of Wyoming. An average ^{87}Sr/^{86}Sr isotopic ratio of 0.710251 ± 20 (2σ) was measured for NBS 987 Sr, and an average ^{143}Nd/^{144}Nd ratio of 0.511846 ± 11 (2σ) was measured for the La Jolla Nd standard. Uncertainties in Sr isotopic ratio measurements are ±0.00002, and uncertainties in Nd isotopic ratio measurements are ±0.00001 (2σ). Blanks were <50 pg for Rb, Sr, Nd, and Sm, and no blank correction was made. Uncertainties in Rb, Sr, Nd, and Sm concentrations are ±2% of the measured value; uncertainties in initial ε_{Nd} are ±0.3 epsilon units. Nd model ages were calculated based upon the depleted-mantle model of Goldstein et al. (1984).

TABLE 3. U-Pb ZIRCON ISOTOPIC ANALYSES AND AGES

Mineral properties*	Weight (mg)	Concentrations† U (ppm)	Pb (ppm)	^{206}Pb/^{204}Pb (measured)	Atomic ratios§ ^{206}Pb/^{238}U (err abs)	^{207}Pb/^{235}U (err abs)	Ages (Ma) ^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb
Metatonalite (EHP-04-3): 226.0 ± 2.0 Ma#									
28 zr, 3:1, 100 µm, clr, c, eu	0.10	38.3	1.50	204	0.03580 ± 38	0.2515 ± 88	226.8 ± 2.4	227.8 ± 7.9	238.1 ± 72.6
17 zr, 3:1, 100 µm, clr, c, eu	0.10	27.4	0.97	433	0.03535 ± 59	0.2481 ± 68	224.0 ± 3.7	225.1 ± 6.2	236.5 ± 80.7
Metadiorite (EHP1-05-3): 231.4 ± 1.0 Ma									
40 zr, 1:1–2:1, 100 µm, clr, c, anh	0.10	55.6	2.14	464	0.03659 ± 28	0.2563 ± 52	231.6 ± 1.8	231.7 ± 4.7	232.4 ± 41.8
23 zr, 1:1–2:1, 100 µm, clr, c, anh	0.10	22.2	0.89	250	0.03627 ± 66	0.2489 ± 127	229.7 ± 4.2	225.7 ± 11.5	184.1 ± 107.4
25 zr, 1:1–2:1, 100 µm, clr, c, anh	0.10	90.1	3.54	444	0.03656 ± 20	0.2592 ± 46	231.5 ± 1.3	234.0 ± 4.1	259.7 ± 36.5
24 zr, 1:1–2:1, 100 µm, clr, c, anh	0.10	109.8	4.53	281	0.03486 ± 18	0.2433 ± 36	220.9 ± 1.1	221.1 ± 3.3	223.5 ± 31.4

*Zr—zircon; aspect ratio; clr—clear; c—colorless; eu—euhedral; anh—anhedral.
†Weights were estimated and are subject to large uncertainties.
§U/Pb ratios were corrected for total blanks of Pb = 0.10 ± 0.05 ng, U = 0.002 ng, mass fractionation = 0.08 ± 0.06 percent/amu; and initial Pb (Stacey and Kramers, 1975). Errors are reported at 2σ level and refer to last digits.
#Ages were calculated from weighted average of ^{206}Pb/^{238}U ages. Errors are reported at 2σ level and refer to last digits.

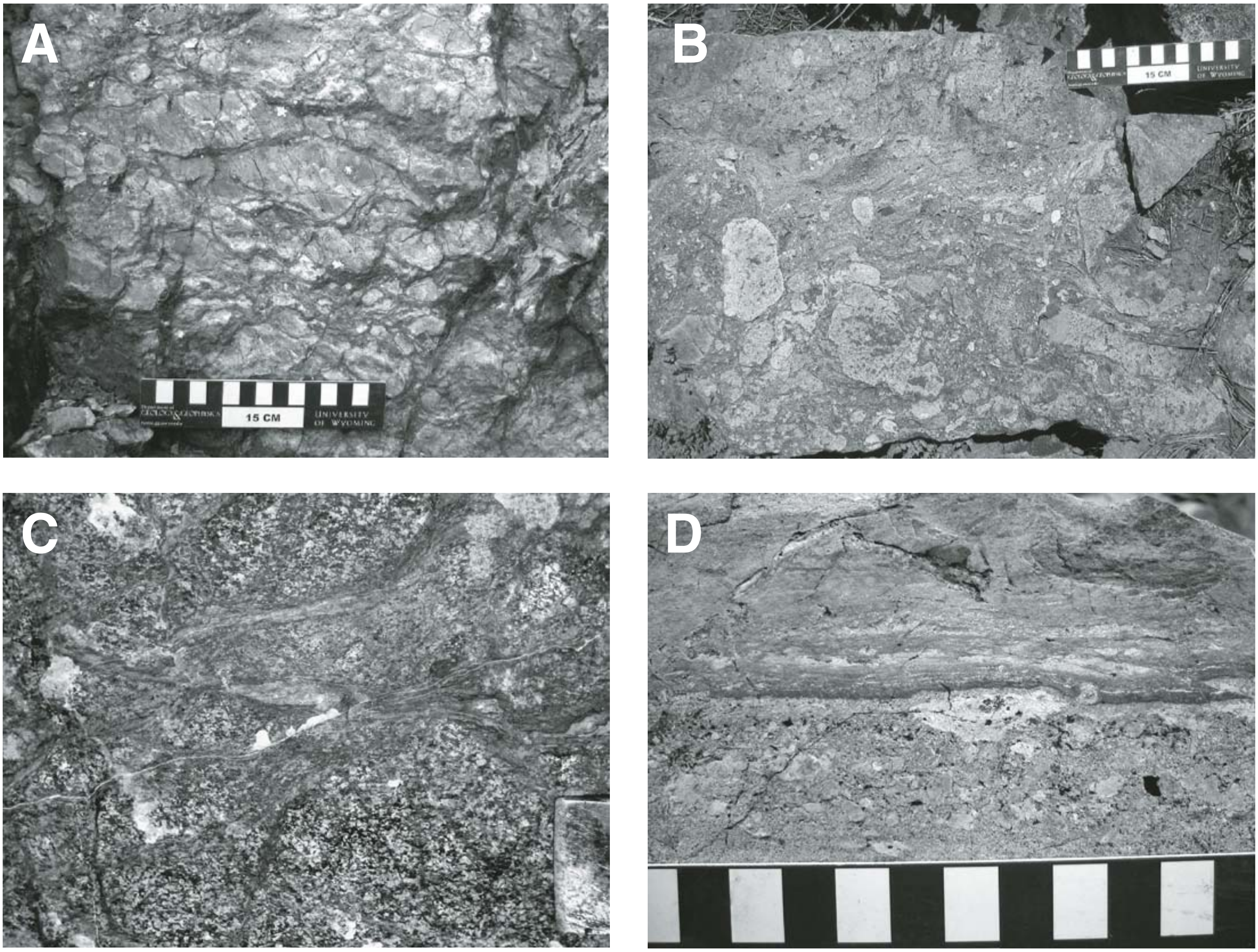

Figure 5. Photographs of various lithologic units of the Baker terrane. (A) Elkhorn Ridge Argillite displaying characteristics of type II mélange after Cowan (1985). (B) Metavolcaniclastic rock with fragments of limestone, argillite, silicic plutonic, and volcanic rocks. (C) Metamorphosed quartz diorite with high-temperature deformational fabric overprinted by low-temperature, greenschist-facies cataclastic shear bands. (D) Basal unit of a fault-bounded metasedimentary slice in the Cougar Basin area. Field of view is ~10 cm.

GEOCHEMICAL DATA

Variations in major- and trace-element concentrations of metaigneous rocks are shown in a series of Harker diagrams in Figures 8 and 9. Metaigneous rocks have a broad range in SiO_2 content, ranging from ~48 to 67 wt%, and Ferns and Brooks (1995) analyzed a plutonic rock from the Bourne subterrane exposed in the Elkhorn Mountains with SiO_2 content as high as ~74 wt% (their Table 9.3, sample EP-48). The metaplutonic rocks plot within the low- to medium-potassium field on a K_2O versus SiO_2 diagram (e.g., Ewart, 1982). A distinguishing feature of these metaplutonic rocks is that CaO and Al_2O_3 concentrations decrease from gabbroic to granitic compositions, as do CaO/Al_2O_3 ratios. Concentrations of MgO and $Fe_2O_3^t$ (total Fe expressed as $Fe_2O_3^t$) also decrease with increasing SiO_2. There is a suggestion in the data that $Fe_2O_3^t$ and TiO_2 are coupled, and they display enrichment until ~52–54 wt% SiO_2, after which, they display decreasing concentrations. Na_2O content also increases slightly from gabbroic to granitic compositions.

Concentrations of trace elements for metaigneous rocks are plotted against SiO_2 in Figure 9. The Rb, Zr, and Ba concentrations increase with increasing SiO_2. In contrast, V and Sc display decreasing concentrations from gabbroic to granitic compositions. Y behaves similarly to $Fe_2O_3^t$ and TiO_2, showing possible enrichment until ~54 wt% SiO_2, and then it displays decreasing concentrations. Sr concentrations do not show a strong relationship with respect to SiO_2 content.

Major- and trace-element concentrations for metasedimentary rocks of the Bourne subterrane are also plotted in Harker diagrams in Figures 8 and 9. The Elkhorn Ridge Argillite and Burnt River Schist consistently group together on major- and trace-element plots. They are distinguished from the Cougar Basin metasedimentary sequence rocks by lower concentrations of CaO. They also have slightly lower average concentrations of TiO_2, Al_2O_3, $Fe_2O_3^t$, MgO, Na_2O, Sr, Y, Ba, and Sc, and higher average concentrations of SiO_2, Rb, and Cr. Average concentrations of K_2O, P_2O_5, V, and Zr are indistinguishable.

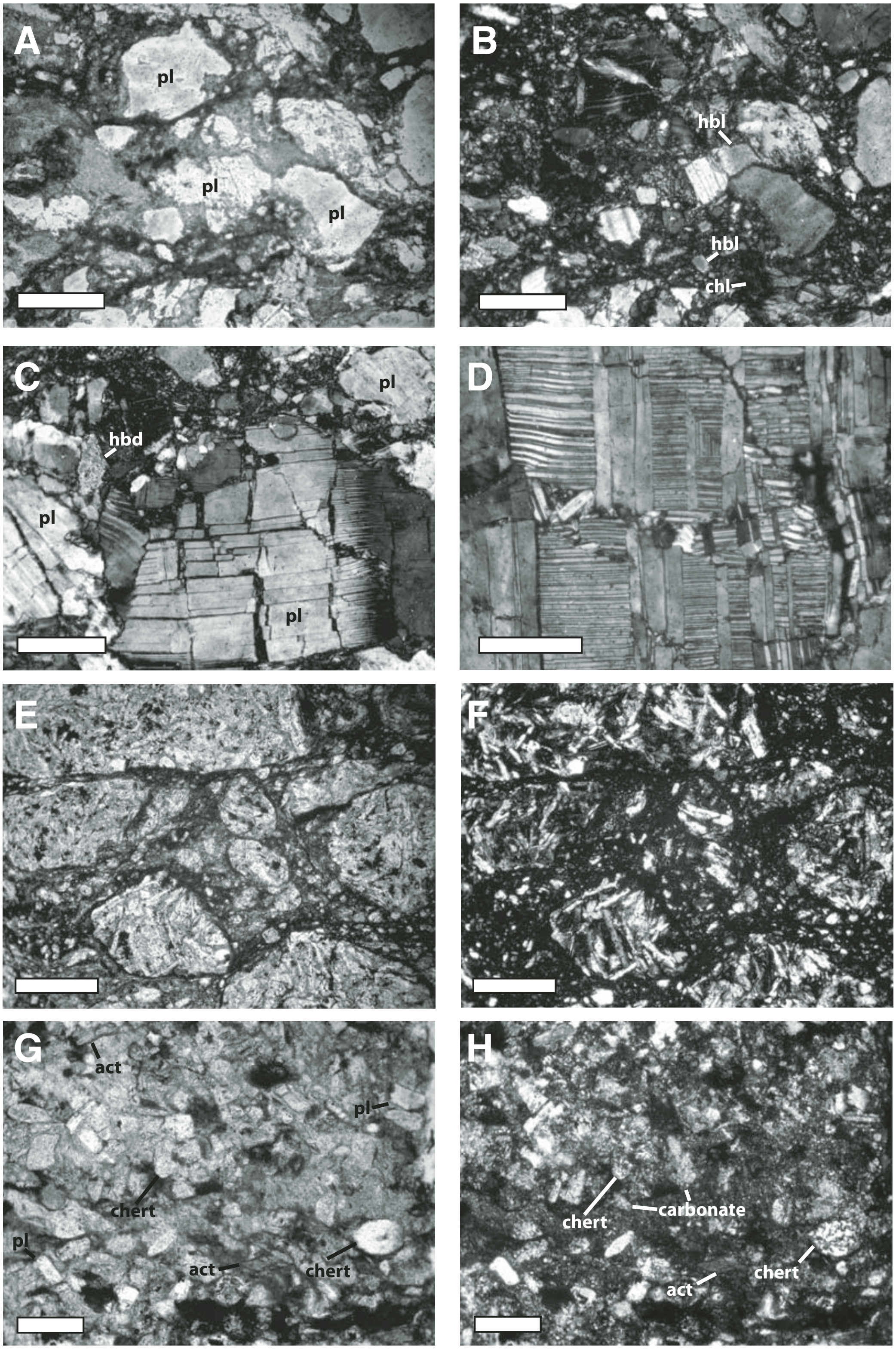

Figure 6. Photomicrographs of various rocks of the Bourne subterrane. (A–B) Plane-polarized and cross-polarized light images of a cataclastic shear zone developed in a quartz diorite. Note angular plagioclase (pl) feldspar clasts within a fine-grained matrix (hbl—hornblende). (C–D) Large plagioclase feldspars with through-going microfractures offsetting albite twinning. (E–F) Plane-polarized and cross-polarized light images of a metavolcaniclastic rock deformed by through-going cataclastic shear zones, which disrupt original porphyritic igneous textures. (G–H) Sandstone from the Cougar Basin metasedimentary sequence with detrital fragments of chert, carbonate, plagioclase feldspar, and actinolite (act). Scale bars are 200 µm.

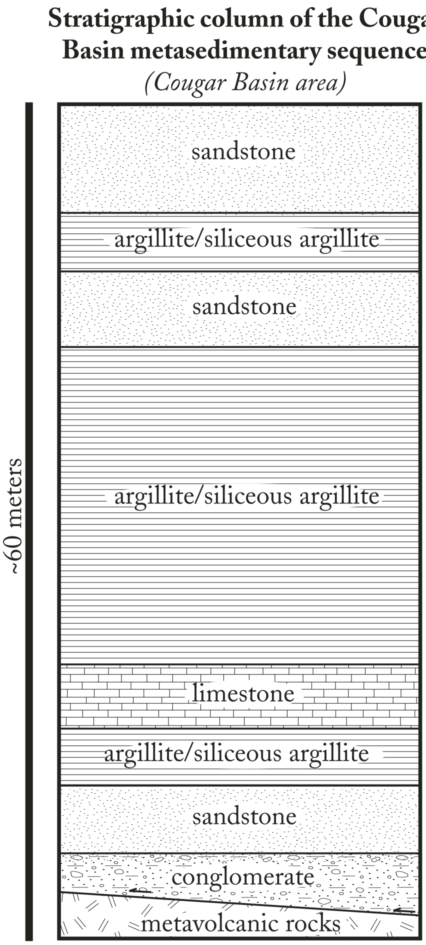

Figure 7. Stratigraphic column of the Cougar Basin metasedimentary sequence as observed in the Cougar Basin area. Note that not all slices of these metasedimentary rocks in the Cougar Basin and Marble Point areas preserve this complete stratigraphy.

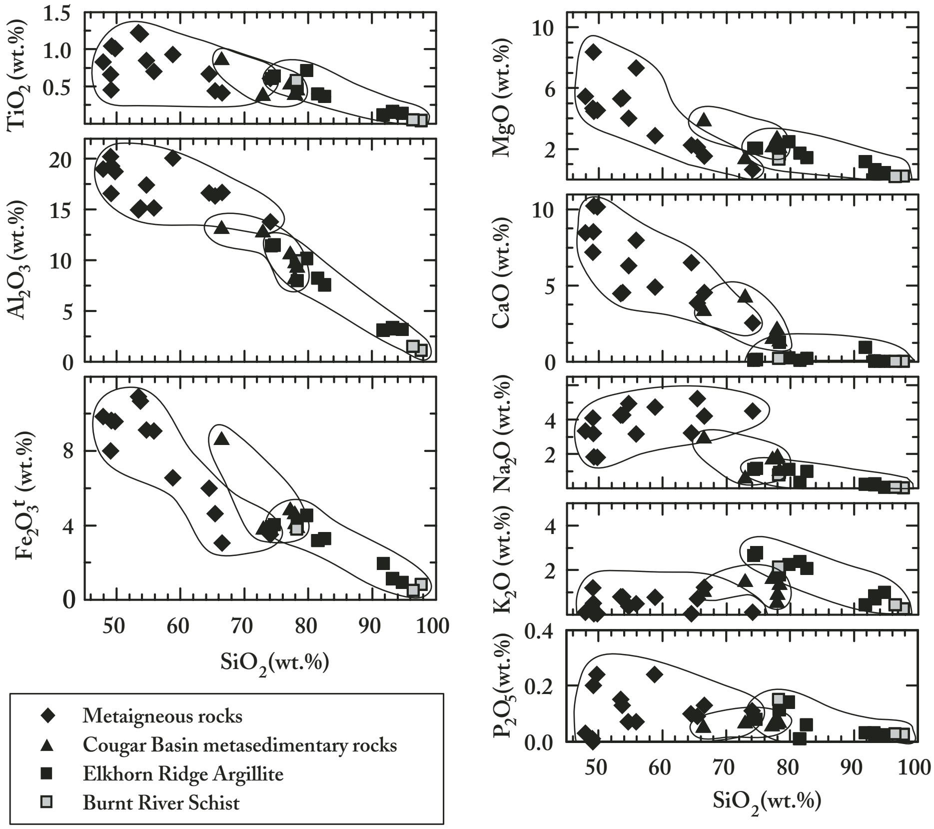

Figure 8. Major-element Harker diagrams for metaigneous and metasedimentary rocks of the Bourne subterrane (this study; Ferns and Brooks, 1995).

ISOTOPIC DATA

Metaplutonic rocks of the Bourne subterrane are characterized by strongly positive, initial ε_{Nd} values ranging from +7.7 to +8.5 (Fig. 10). Initial $^{87}Sr/^{86}Sr$ values are uniform and cluster at 0.7033–0.7034. Both initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic compositions are relatively insensitive to variations in SiO_2. The Sm/Nd values exhibited by these rocks (Sm/Nd = 0.2100–0.2974) are much higher than is typical of average eroded North American continental crust (North American Shale Composite [Gromet et al., 1984]: Sm/Nd = 0.1967).

Metamorphosed argillaceous rocks of the Elkhorn Ridge Argillite are characterized by distinctly negative initial ε_{Nd} values of –4.7 to –7.8 and initial $^{87}Sr/^{86}Sr$ values of 0.7073–0.7094 (Fig. 10). Neodymium model ages for these rocks range from 1.4 to 1.6 Ga. The range in Sm/Nd exhibited by the Elkhorn Ridge Argillite samples (0.1908–0.1986) overlaps the North American Shale Composite (Gromet et al., 1984: Sm/Nd = 0.1967).

In contrast, the Cougar Basin metasedimentary rocks associated with the metaigneous rocks have initial $^{87}Sr/^{86}Sr$ values ranging from 0.7046 to 0.7061, and initial ε_{Nd} values of +6.5 to –3.2 (Fig. 10). Calculated neodymium model ages for the Cougar Basin (meta)sedimentary rocks range from 0.7 to 1.4 Ga. The range in Sm/Nd exhibited by these rocks (Sm/Nd = 0.2109–0.2712) is also higher the North American Shale Composite (Gromet et al., 1984: Sm/Nd = 0.1967).

GEOCHRONOLOGY OF METAIGNEOUS ROCKS

Samples EHP-04–3 (metatonalite; Marble Point) and EHP1–05–3 (metadiorite; Cougar Basin) are cataclastically deformed at greenschist-facies conditions. Sample EHP1–05–3 experienced slightly higher metamorphic conditions (upper greenschist facies) associated with brittle fracturing and kinking of igneous plagioclase and hornblende and metamorphic titanite. Only minor replacement of plagioclase by chlorite and hornblende by actinolite is observed. U-Pb zircon geochronologic data for both samples are plotted on concordia diagrams in Figure 11. All analyses are concordant within uncertainty and show no evidence for inheritance.

Two multigrain zircon fractions from tonalite EHP-04–3 are concordant and yield a weighted average $^{206}Pb/^{238}U$ age of 226.0 ± 2.0 Ma (mean square of weighted deviates [MSWD] = 1.6). We interpret this age as the age of crystallization of this rock.

Four multigrain fractions from diorite EHP1–05–3 yielded concordant analyses. The large error ellipses may be attributed to low $^{206}Pb/^{204}Pb$ values, possibly associated with an increased degree of metamorphism and fluid alteration. Three of the zircon fractions yielded a weighted average $^{206}Pb/^{238}U$ age of 231.4 ± 1.0 Ma (MSWD = 0.4), which is interpreted as the crystallization age. One fraction gave a concordant age of 221.9 ± 1.0 Ma ($^{206}Pb/^{238}U$ age), which is interpreted to result from younger Pb loss during greenschist-facies metamorphism. This age is interpreted as a maximum age for the timing of Pb loss and deformation.

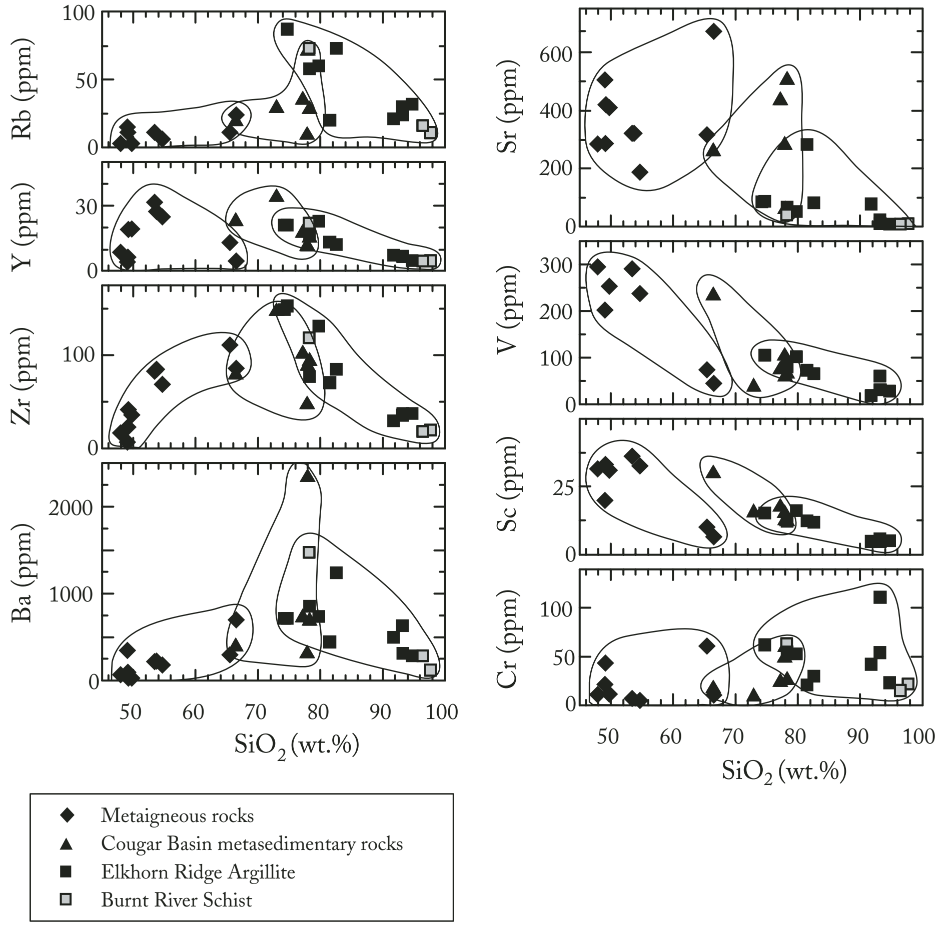

Figure 9. Trace-element Harker diagrams for metaigneous and metasedimentary rocks of the Bourne subterrane.

DISCUSSION

Interpretations of Field, Geochemical, and Isotopic Results

Metasedimentary and metaigneous rocks of the Bourne subterrane display structural, geochemical, and isotopic evidence for both tectonic and sedimentary mixing in an ancient accretionary complex. The dominant stratified rock unit of the Bourne subterrane is the Elkhorn Ridge Argillite, which provides important information about the depositional and paleotectonic setting of the Bourne subterrane in Permian to Early Jurassic time. Field and petrographic observations of the Elkhorn Ridge Argillite indicate that it contains varying contributions of volcanogenic material, including tuff, tuffaceous argillite, conglomerate with volcanic lithic clasts, and layers of altered mafic lavas (e.g., Gilluly, 1937). Nevertheless, the Elkhorn Ridge Argillite has negative initial ε_{Nd} values (–4.7 to –7.8), elevated initial $^{87}Sr/^{86}Sr$ values (0.7073–0.7094) with respect to metaigneous rocks, and Mesoproterozoic depleted-mantle Nd model ages of 1.4–1.6 Ga. If these model ages represent the weighted average age of the sources that eroded and contributed detritus to the Elkhorn Ridge Argillite, then even though the Elkhorn Ridge Argillite contains volcanogenic material, a component of detritus from Proterozoic or older continental crust must also be present.

The slabs/slices of metaigneous and related metasedimentary rocks (e.g., Cougar Basin metasedimentary sequence) tectonically intermixed along the tectonic boundary of the Baker and Wallowa terranes also have important implications for the tectonic development of the Blue Mountains province. These slabs are characterized by more juvenile and arc-related geochemical and isotopic signatures (Figs. 8–10; Fig. DR1 [see footnote 1]), which are geochemically and isotopically distinct from the more evolved Elkhorn Ridge Argillite (Figs. 8–10). They do not display evidence for extensive layer-parallel disruption as observed in the Elkhorn Ridge Argillite, suggesting that they were incorporated relatively late in the structural history of the Baker terrane. Given the close spatial proximity of these fault-bounded slabs/slices to the Wallowa island-arc terrane, their island-arc geochemical characteristics (Fig. DR1), and similarities between the early Norian Cougar Basin metasedimentary rocks and the Hurwal Formation of the Wallowa terrane (e.g., Follo, 1992), we agree with previous workers (Ferns and Brooks, 1995) in interpreting these slabs as fragments of the Wallowa island-arc terrane that were imbricated and faulted into the Bourne subterrane during a period of arc-arc collision.

An outstanding question in the tectonic development of the Blue Mountains province is the relationship between the Baker and Wallowa terranes prior to imbrication, and their respective proximity to cratonic lithosphere (e.g., western North America) in the late Paleozoic to early Mesozoic. These relationships have important implications regarding terrane origin (e.g., pericratonic versus distal), the location of lithospheric suture zones within the Blue Mountains province, and postulated Late Triassic collisions between the Baker terrane and Wallowa island-arc terrane as suggested by Follo (1992) and Dorsey and LaMaskin (2007). In the latter case, Upper Triassic sedimentary rocks of the Cougar Basin metasedimentary sequence and Hurwal Formation are believed to be derived from direct erosion of the Baker terrane, indicating a Late Triassic connection between the two terranes.

Binary Mixing Models

We evaluate the relationship between the Baker terrane and western North American margin, and possible Baker-Wallowa terrane connections, by modeling the compositions of the argillaceous rocks of the Elkhorn Ridge Argillite and Cougar Basin metasedimentary rocks as binary mechanical mixtures of a source with depleted-mantle composition (i.e., an intra-oceanic island-arc source) and average North American miogeoclinal sedimentary rocks. The composition of an intra-oceanic island-arc source was approximated by metaplutonic rocks of the Bourne subterrane (sample EP4–2 in this study: Sr = 315 ppm; initial $^{87}Sr/^{86}Sr$ = 0.7032; Nd = 4.22 ppm; initial ε_{Nd} = +7.7). The isotopic composition of the miogeocline is more difficult to characterize because of the wide variation in isotopic compositions of Proterozoic to Mesozoic sedimentary rocks exposed along the western North American margin (cf. Ghosh and Lambert, 1989; Boghossian et al., 1996; Farmer and Bell, 1997). We approximated the western

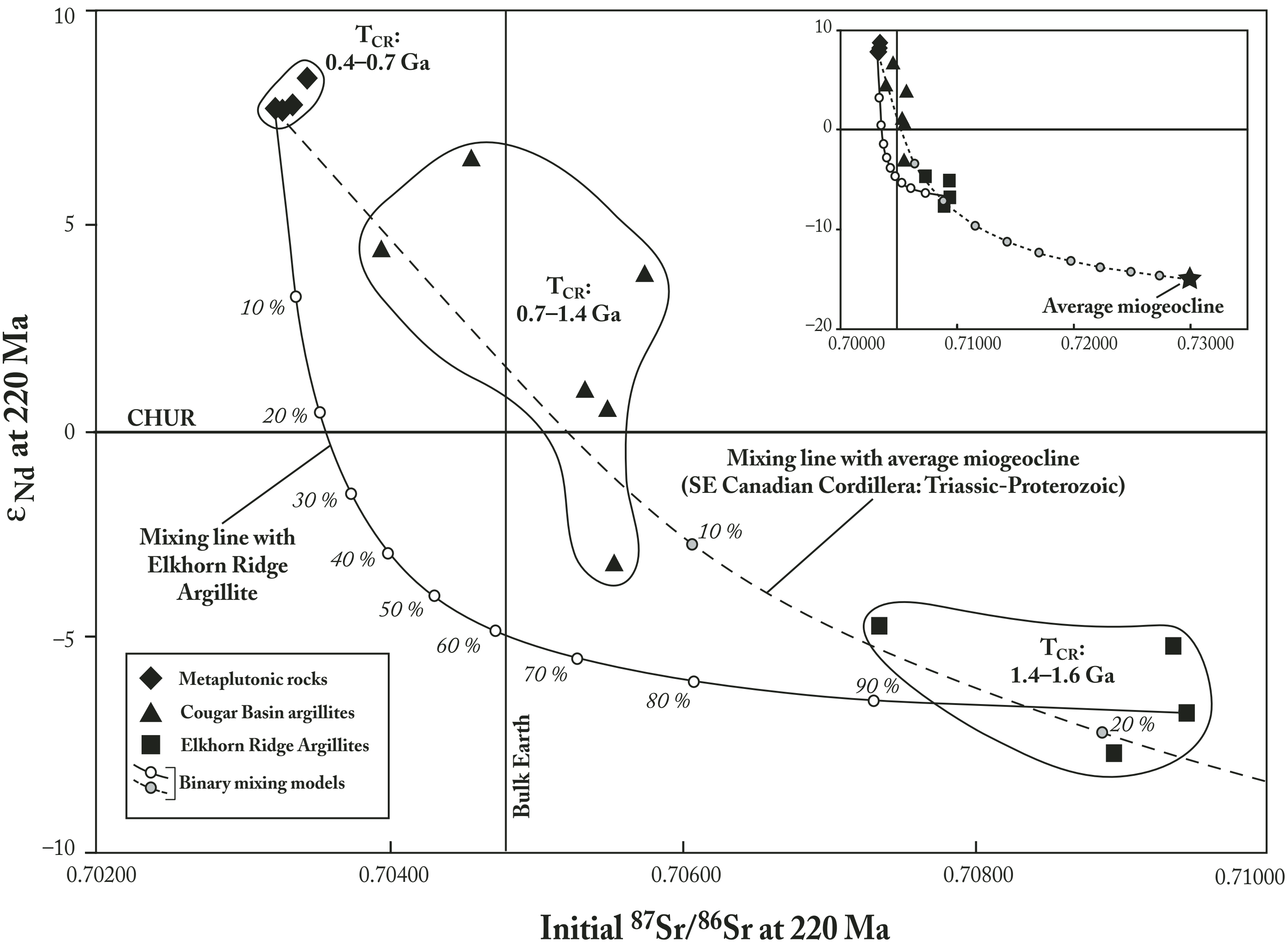

Figure 10. Plot of initial ε_{Nd} versus initial $^{87}Sr/^{86}Sr$ at 220 Ma for (meta)sedimentary and metaplutonic rocks of the Bourne subterrane. Binary mixture models are shown as curved lines. Metasedimentary rocks in the Bourne subterrane can be described as mechanical mixtures of average depleted-mantle arc rocks mixed with average North American miogeocline. T_{cr} refers to crustal residence time.

North American miogeocline by taking the average Sr and Nd isotopic compositions of Triassic through Proterozoic sedimentary rocks exposed in southeastern British Columbia (Ghosh and Lambert, 1989; Sr = 339 ppm; initial $^{87}Sr/^{86}Sr$ = 0.7300; Nd = 32 ppm; initial ε_{Nd} = –15.1). We used data from southeastern British Columbia because published isotopic data permit the use of both Sr and Nd isotopes in our binary mixture modeling, whereas data from the U.S. sector of the western North American miogeocline only report Nd isotopic compositions. However, we note that the Nd isotopic compositions used in our mixture modeling also lie within the range of compositions in the U.S. sector of the North American miogeocline. Additionally, we considered a more evolved isotopic end member as a potential source to account for the large potential variation in North American miogeoclinal end-member compositions (cf. Driver et al., 2000; Omineca crystalline belt: Sr = 133 ppm; initial $^{87}Sr/^{86}Sr$ = 0.765; Nd = 30 ppm; initial ε_{Nd} = –15).

Results of these binary mixing models are plotted on an ε_{Ndi} versus $^{87}Sr/^{86}Sr_i$ isotope variation diagram in Figure 10. The mechanical mixture of depleted mantle-derived arc source with average North American miogeoclinal rocks intersects fields for both Elkhorn Ridge Argillite and Cougar Basin metasedimentary rocks. Relative proportions of average North American miogeocline required to describe the Cougar Basin metasedimentary rocks are less than 10% and less than 20% for the Elkhorn Ridge Argillites. If an older, and more evolved, Proterozoic metasedimentary end-member composition is used (Driver et al., 2000; Omineca crystalline belt), the resulting mixing curve also intersects fields for Elkhorn Ridge Argillites and Cougar Basin metasedimentary rock, with nearly identical relative percentages of evolved end-member component (less than 10% for Cougar Basin metasedimentary rocks, and less than 20% for the Elkhorn Ridge Argillites). The binary mechanical mixture model of Elkhorn Ridge Argillite with depleted mantle-derived arc source fails to intersect the field of Cougar Basin argillites, suggesting that direct erosion of the Baker terrane and sedimentary mixing of Elkhorn Ridge Argillite with an arc source cannot describe the isotopic variability of the Cougar Basin metasedimentary sequence.

Binary mixture models presented here are most consistent with a "pericratonic" origin for the Elkhorn Ridge Argillite and support tectonic models that tie the Baker terrane to the fringing Olds Ferry island arc terrane and the North American margin (e.g., model of Avé Lallemant,

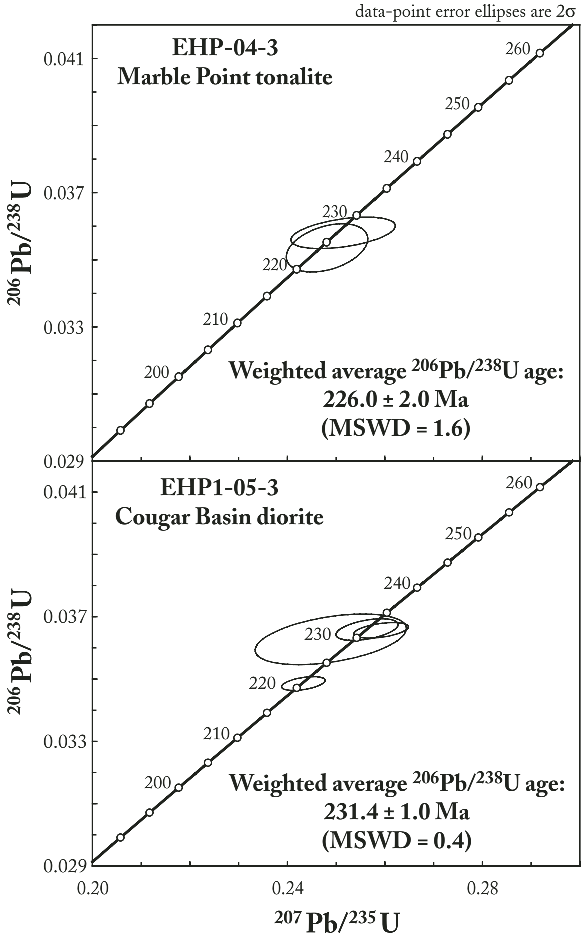

Figure 11. U-Pb concordia diagrams for zircons from metaplutonic rocks in Marble Point and Cougar Basin areas of the Bourne subterrane. Error ellipses are plotted at 95% confidence limits. MSWD—mean square of weighted deviates.

1995). They also demonstrate a limited involvement of an evolved source in the depositional history of the Cougar Basin metasedimentary sequence and Hurwal Formation, and preclude a simple two-component binary mixture of Elkhorn Ridge Argillite with a depleted-mantle arc source in their depositional history. These results suggest that either: (1) metasedimentary rocks of the Cougar Basin metasedimentary sequence and Hurwal Formation were derived from a different chert-argillite source other than the Elkhorn Ridge Argillite, or (2) components in addition to an island-arc source and Elkhorn Ridge Argillite are required to describe their isotopic variability.

Crustal Structure of the Bourne Subterrane and Blue Mountains Province

The presence of isotopically juvenile (high ε_{Nd}, low $^{87}Sr/^{86}Sr$) slabs of metaigneous and related metasedimentary rocks likely derived from the Wallowa island-arc terrane and intercalated into the more-evolved Elkhorn Ridge Argillite suggests that this broad, imbricate fault zone is a fundamental tectonic and isotopic boundary that separates the Wallowa island-arc terrane from the Baker accretionary complex. Within the Bourne subterrane, metaigneous fragments of the Wallowa island arc are distributed over a distance >25 km perpendicular to the inferred Baker-Wallowa margin (Fig. 2), suggesting widespread imbrication of the southern margin of the Wallowa plate beneath the Bourne subterrane in response to collision. These fault slices consistently dip to the south, away from the Wallowa arc terrane, a relationship suggestive of a series of arc-directed back-thrusts related to underthrusting of the Wallowa terrane beneath the Bourne subterrane. Similar-age, northwest-dipping thrust faults to the south (e.g., Conner Creek fault) place the Baker terrane structurally above the Izee terrane and underlying Olds Ferry arc, possibly suggesting a doubly verging orogenic system.

Within the Elkhorn Ridge Argillite, strain was accommodated by the development of east-west–oriented fold axes and penetrative spaced-cleavage associated with dissolution and fluid mobility (Avé Lallemant, 1995). Widespread fluid involvement during deformation is also recognized in greenschist-facies cataclastic shear zones, where metamorphic assemblages of chlorite, epidote, and clinozoisite overprint igneous and sedimentary textures. These features are consistent with the tectonic accretion of the Wallowa island-arc terrane and the Baker accretionary complex during a period of regional greenschist-facies metamorphism in a fluid-rich setting.

Our interpretation of the Bourne-Wallowa terrane boundary raises a number of questions regarding the nature of collisional terrane boundaries and their manifestation in ancient orogenic belts. For example, are diffuse zones of structurally imbricated rocks common at terrane contacts? Are sharp terrane boundaries actually younger faults that have reactivated (or more likely faulted out) original contacts and, consequently, do not preserve fundamental geologic relationships between terranes? To our knowledge, diffuse terrane boundaries are not well preserved in the North American Cordillera. One of the best-preserved Cordilleran terrane boundaries is located to the north of the Blue Mountains between the Cache Creek and Quesnel terranes; this contact also shows evidence for younger disruption by strike-slip faulting. In central British Columbia, the terrane boundary is characterized by structural stacking of disparate and apparently unrelated rock types (e.g., ultramafic rocks, blueschists, basalts, etc.) in an ancient accretionary complex (Cache Creek terrane), which is juxtaposed against island-arc volcanic rocks of the Quesnel terrane (Struik et al., 2001). This apparent imbrication may represent a paleosuture zone that has subsequently been overprinted by steeply dipping, strike-slip faults that cut across the original contact. The near-vertical strike-slip fault is commonly mapped as the terrane-bounding contact (e.g., Struik et al., 2001).

In the Klamath Mountains province (inset Fig. 1), which has served as the archetypical example of a mountain belt that developed by the progressive tectonic accretion of oceanic rocks (e.g., Snoke and Barnes, 2006), fundamental structural contacts between lithotectonic terranes are commonly dissected by younger, high-angle faults, folds, and/or intrusive plutonic bodies that obscure original terrane relationships. In fact, few, if any, original terrane boundaries are preserved in the Klamath Mountains (cf. Snoke and Barnes, 2006). The significant structural and magmatic overprint along terrane boundaries to the north and south of the Blue Mountains province highlights the uniqueness of the Baker-Wallowa terrane boundary as a well-preserved crustal-scale suture zone in the western North American Cordillera.

Timing of Fabric Development and Deformation

A key question in the tectonic development of the Blue Mountains province is the timing of fabric development and its relationship to deformational events within the Baker, Wallowa, and Olds Ferry terranes. In the Baker terrane, the earliest fabrics are layer-parallel extensional fabrics in the Elkhorn Ridge Argillite, which have been interpreted by previous workers to reflect subduction-related deformation of weakly consolidated sediments in an accretionary-prism setting (Cowan, 1985; Avé Lallemant, 1995). The development of these fabrics must predate the youngest deformed sedimentary rocks, which are Late Triassic and possibly Early Jurassic in age (Blome et al., 1983; Coward, 1983). Similar fabrics are also observed in blueschist-facies rocks from the Mitchell area, metamorphism of which was dated at ca. 223 Ma (Hotz et al., 1977). These fabrics are not present in Jurassic sedimentary rocks of the Izee Basin, suggesting that the fabrics formed before Early Jurassic time.

The most prominent structural features of the Baker terrane are the penetrative spaced-cleavage and gently plunging east-west–trending folds (Avé Lallemant, 1995) that postdate the layer-parallel extensional fabric but predate the intrusion of postkinematic, stitching plutons, such as the Bald Mountain Batholith (ca. 143 Ma: Walker, 1989). East-west–trending folds are also present in Izee Basin rocks exposed southwest of John Day, Oregon (Avé Lallemant et al., 1980), and, possibly, similar-age folds trending northeast-southwest are present in the Jurassic Weatherby Formation near Huntington, Oregon (Avé Lallemant, 1983). The youngest deformed rocks in these areas are Middle Jurassic (Callovian). Thrusting related to this event also emplaced the Baker terrane structurally above the Izee Basin sometime prior to the intrusion of the Lookout Mountain stock, which intruded both units ca. 124 Ma (Walker, 1989). Therefore, the timing of penetrative deformation is bracketed between Middle Jurassic (Callovian) and the Early Cretaceous(?) emplacement of the postkinematic Bald Mountain Batholith at ca. 143 Ma. Given the uncertainties in the timing of this event, deformation may have been relatively short-lived, as proposed by Avé Lallemant (1995), or protracted over several million years. Previous authors have interpreted this penetrative deformational event to record the collision of the Wallowa and Olds Ferry arc terranes (e.g., Avé Lallemant, 1995; Ferns and Brooks, 1995). These ideas and possible tectonic scenario for the Blue Mountains province are illustrated in Figure 12 and explored in the following section.

Tectonic Models and Relationship to Modern Arc-Arc Collisional Settings

Modern analogs for the processes that we observe in the Baker terrane may be present in the Molucca Sea (central equatorial Indo-

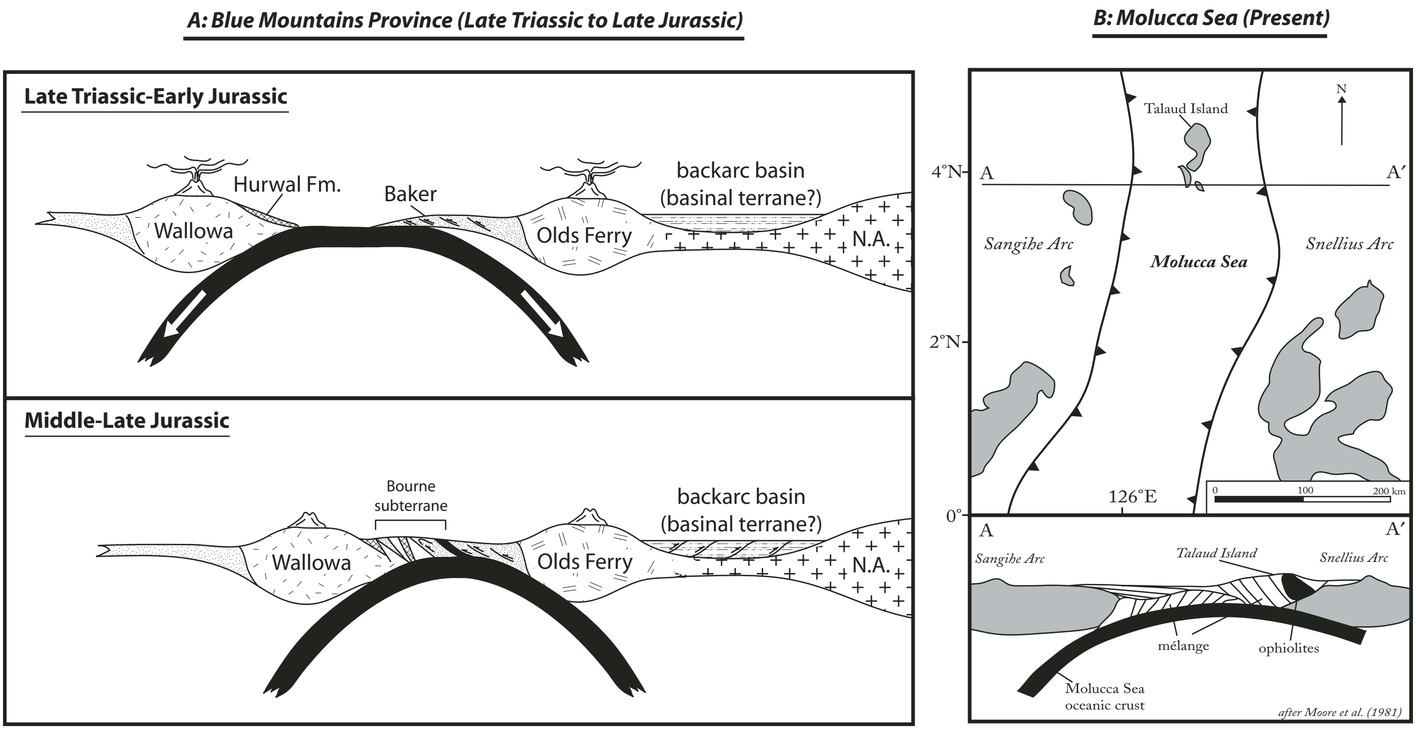

Figure 12. Tectonic scenario for the Blue Mountains province, and possible modern-day analog. (A) A possible tectonic scenario for the Baker, Wallow, and Olds Ferry terranes in the Mesozoic. In the Middle-Late Jurassic, the Wallowa and Olds Ferry island-arc terranes collided, resulting in imbrication of the southern margin of the Wallowa plate beneath the overlying Bourne subterrane. Underthrusting and synchronous imbrication of the Wallowa arc into the Elkhorn Ridge Argillite may explain the occurrence of metaigneous and metasedimentary fault-bounded slabs/slices in the Bourne accretionary complex. (B) Map of the Molucca Sea region, eastern Indonesia, and cross section showing doubly verging subduction system (from Moore et al., 1981). This modern arc-arc collision environment may be analogous to the Blue Mountains province in the Late Triassic to Late Jurassic. The early history (Late Triassic) of the Blue Mountains collisional zone may have been considerably more oblique (transpressional) than the modern Molucca Sea collision zone based on the presence of left-lateral mylonitic shear zones in the Wallowa island-arc terrane (Avé Lallemant et al., 1985; Avé Lallemant and Oldow, 1988; Avé Lallemant, 1995).

Pacific region), where two island-arc systems are colliding (e.g., Silver and Moore, 1978; McCaffrey et al., 1980; Pubellier et al., 1999) (Fig. 12B). Between these two arcs, there is a highly deformed unit of oceanic mélange consisting of blocks of peridotite, gabbro, pillow basalt, and sedimentary rocks enveloped in a scaly clay matrix (e.g., Silver and Moore, 1978; Hamilton, 1979; Sukamoto et al., 1980; Moore et al., 1981). Larger tectonic slices of high-velocity ultramafic-mafic rocks have been recognized through seismic-reflection profiling and are interpreted to be oceanic crust faulted into the accretionary wedge during the arc-arc collision (e.g., Bader et al., 1999). Geochemical data from these tectonic slabs on Talaud Island indicate that they have mid-ocean-ridge basalt (MORB) affinities (Moore et al., 1981). In the Talaud Island area, the entire mélange complex is interpreted to have been thrust over both the western arc (Sangihe forearc) and eastern arc (Snellius Ridge–Halmahera island-arc system; see Ballantyne, 1992) during collision (Moore et al., 1981). However, throughout the Molucca Sea region, deformation is heterogeneous and shows a complicated structural response to collision (cf. Pubellier et al., 1999).

In general, the features of the Molucca Sea region display many similarities to the Baker terrane and adjacent island-arc terranes of the Blue Mountains province. These similarities include: (1) two contemporaneous island-arc terranes involved in an arc-arc collision, (2) an intervening tectonic mélange terrane (Bourne subterrane), (3) tectonic slabs of metaigneous and metasedimentary rocks incorporated into the accretionary complex during collision, (4) underthrusting of an arc terrane (Wallowa terrane) beneath the accretionary complex, and (5) back thrusting of the accretionary complex over both island-arc terranes along oppositely dipping thrust faults presumably during collision. The size of the Molucca Sea region is also similar to the Baker terrane (Figs. 1 and 12). These similarities suggest that the Baker terrane may be an ancient analog to modern Molucca Sea–type arc-arc collision.

An important difference between the Molucca Sea analog and Baker terrane is the reported absence of arc-related, metaplutonic thrust slices in the Molucca Sea collisional zone. In the Blue Mountains, we interpret the arc-related, fault-bounded slices to record the imbrication of the southern Wallowa arc during collision; however, in the Molucca Sea region, strain appears to be accommodated instead by the imbrication of the underlying oceanic plate. Oceanic crustal rocks have been reported at the boundary between the Greenhorn and Bourne subterranes (Olive Creek unit: Ferns and Brooks, 1995), and they may be analogous to ultramafic-mafic (ophiolitic) slices in the Molucca collisional zone. However, these rocks in the Baker terrane are relatively minor with respect to arc-related, fault-bounded slices. This important difference could be a function of either: (1) depth of exposure and incomplete sampling of the Molucca orogenic wedge (i.e., the present erosional surface of the Bourne subterrane samples a deeper portion of the imbricated orogenic wedge); and/or (2) differences in age, thermal conditions, and rheologic behavior of the subducting oceanic plates in these two environments. If the subducting oceanic lithospheric plate in the Molucca Sea region is significantly younger than that which subducted beneath the Baker terrane, strain may have been more easily partitioned into it during collision (cf. summary of ophiolite emplacement mechanisms: Pearce, 2003).

Another difference is that the Baker terrane is interpreted to have experienced widespread subaerial uplift and erosion during collision (e.g., Follo, 1992; LaMaskin et al., 2004; Dorsey and LaMaskin, 2007), whereas in the Molucca Sea region, subaerial exposures of mélange only occur on isolated islands such as Talaud (e.g., McCaffrey et al., 1980). These differences may indicate that collision is incomplete in the Molucca Sea in comparison with the Blue Mountains province.

CONCLUSIONS

The Baker terrane is a long-lived, ancient accretionary complex that developed in association with island-arc terranes of the paleo–Pacific Ocean. The northern margin of the Baker terrane is characterized by an imbricate fault zone consisting of slabs/slices of subduction-related metaigneous and metasedimentary rocks faulted into argillite-matrix mélange. These fault-bounded slabs/slices are variable in composition, consisting of arc-related plutonic/hypabyssal, volcaniclastic, and sedimentary rocks—all metamorphosed under lower-greenschist-facies conditions. New U-Pb zircon dates indicate that metaplutonic rocks crystallized in the Middle to Late Triassic (231–226 Ma), and their isotopic compositions show that they were derived from depleted-mantle sources. In contrast, metasedimentary rocks of the argillite-matrix mélange (Elkhorn Ridge Argillite) are characterized by evolved isotopic signatures, suggesting sediment contribution from cratonic sources.

We interpret this broad, imbricate fault zone as a fundamental tectonic boundary that separates the distal Wallowa island-arc terrane from the proximal Baker accretionary-complex terrane. This zone of faulting and tectonic mixing is not significantly overprinted by younger deformation and thus preserves many original features related to subduction and upper-crustal strain localization during an inferred arc-arc collision. We propose that this terrane boundary is an exposed, on-land example of a zone of imbrication and tectonic mixing of arc-crust and oceanic lithosphere analogous to the modern Molucca Sea collisional zone of eastern Indonesia.

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REFERENCES CITED

Armstrong, R.L., Taubeneck, W.H., and Hales, P.O., 1977, Rb-Sr and K-Ar geochronometry of Mesozoic granitic rocks and their Sr isotopic composition Oregon, Washington, and Idaho: Geological Society of America Bulletin, v. 88, p. 397–411, doi: 10.1130/0016-7606(1977)88<397:RAKGOM>2.0.CO;2.

Ashley, R.P., 1967, Metamorphic Petrology and Structure of the Burnt River Canyon Area, Northeastern Oregon [Ph.D. dissertation]: Stanford, California, Stanford University, 193 p.

Ashley, R.P., 1995, Petrology and deformation history of the Burnt River Schist and associated plutonic rocks in the Burnt River Canyon area, northeastern Oregon, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington—Petrology and Tectonic Evolution of Pre-Tertiary Rocks of the Blue Mountains Region: U.S. Geological Survey Professional Paper 1438, p. 457–496.

Avé Lallemant, H.G., 1976, Structure of the Canyon Mountain (Oregon) Ophiolite Complex and its Implication for Seafloor Spreading: Geological Society of America Special Paper 173, 49 p.

Avé Lallemant, H.G., 1983, The kinematic insignificance of mineral lineations in a Late Jurassic thrust and fold belt in eastern Oregon, U.S.: Tectonophysics, v. 100, p. 389–404, doi: 10.1016/0040-1951(83)90195-6.

Avé Lallemant, H.G., 1995, Pre-Cretaceous tectonic evolution of the Blue Mountains province, northeastern Oregon, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington—Petrology and Tectonic Evolution of Pre-Tertiary Rocks of the Blue Mountains Region: U.S. Geological Survey Professional Paper 1438, p. 271–304.

Avé Lallemant, H.G., and Oldow, J.S., 1988, Early Mesozoic southward migration of Cordilleran transpressional terranes: Tectonics, v. 7, p. 1057–1075, doi: 10.1029/TC007i005p01057.

Avé Lallemant, H.G., Phelps, D.W., and Sutter, J.F., 1980, $^{40}Ar/^{39}Ar$ ages of some pre-Tertiary plutonic and metamorphic rocks of eastern Oregon and Idaho and their tectonic relationships: Geology, v. 8, p. 371–374, doi: 10.1130/0091-7613(1980)8<371:AAOSPP>2.0.CO;2.

Avé Lallemant, H.G., Schmidt, W.J., and Kraft, J.L., 1985, Major Late-Triassic strike-slip displacement in the Seven Devils terrane, Oregon and Idaho: A result of left-oblique plate convergence: Tectonophysics, v. 119, p. 299–328, doi: 10.1016/0040-1951(85)90044-7.

Bader, A.G., Pubellier, M., Rangin, C., Deplus, C., and Louat, R., 1999, Active slivering of oceanic crust along the Molucca Ridge (Indonesia-Philippine): Implication for ophiolite incorporation in a subduction wedge?: Tectonics, v. 18, p. 606–620, doi: 10.1029/1999TC900004.

Ballantyne, P., 1992, Petrology and geochemistry of the plutonic rocks of the Halmahera ophiolite, eastern Indonesia; an analogue of modern oceanic forearcs, *in* Parsons, L.M., Murton, B.J., and Browning, P., eds., Ophiolites and their Modern Oceanic Analogues: Geological Society of London Special Publication 60, p. 179–202.

Bishop, E.M., 1995, High-pressure, low-temperature schistose rocks of the Baker terrane, northeastern Oregon, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington—Petrology and Tectonic Evolution of Pre-Tertiary Rocks of the Blue Mountains Region: U.S. Geological Survey Professional Paper 1438, p. 211–219.

Blome, C.D., and Nestell, M.K., 1991, Evolution of a Permo-Triassic sedimentary mélange, Grindstone terrane, east-central Oregon: Geological Society of America Bulletin, v. 103, p. 1280–1296, doi: 10.1130/0016-7606(1991)103<1280:EOAPTS>2.3.CO;2.

Blome, C.D., Jones, D.L., and Murchey, B., 1983, Paleogeographic implications of radiolarian-rich rocks from eastern Oregon: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 371.

Blome, C.D., Jones, D.L., Murchey, B.L., and Liniecki, M., 1986, Geologic implications for radiolarian-bearing Paleozoic and Mesozoic rocks from the Blue Mountains province, eastern Oregon, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington—Geological Implications of Paleozoic and Mesozoic Paleontology and Biostratigraphy, Blue Mountains Province, Oregon and Idaho: U.S. Geological Survey Professional Paper 1435, p. 79–101.

Boghossian, N.D., Patchett, P.J., Ross, G.M., and Gehrels, G.E., 1996, Nd isotopes and the sources of sediments in the miogeocline of the Canadian Cordillera: The Journal of Geology, v. 104, p. 259–277.

Bostwick, D.A., and Koch, G.S., 1962, Permian and Triassic rocks of northeastern Oregon: Geological Society of America Bulletin, v. 73, p. 419–422, doi: 10.1130/0016-7606(1962)73[419:PATRON]2.0.CO;2.

Bostwick, D.A., and Nestell, M.K., 1965, A new species of *Polydiexodina* from central Oregon: Journal of Paleontology, v. 39, p. 611–614.

Brooks, H.C., and Vallier, T.L., 1978, Mesozoic rocks and tectonic evolution of eastern Oregon and western Idaho, *in* Howell, D.G., and McDougall, K.A., eds., Mesozoic Paleogeography of the Western United States: Los Angeles, California, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 133–145.

Brooks, H.C., Ferns, M.L., Coward, R.I., Paul, E.K., and Nunlist, M., 1982a, Geology and Gold Deposits of the Bourne Quadrangle, Baker and Grant Counties, Oregon: Oregon Department of Geology and Mineral Industries Geological Map Series GMS–19, scale 1:24,000, 1 sheet.

Brooks, H.C., Ferns, M.L., and Mullen, E.D., 1982b, Geology and Gold Deposits Map of the Granite Quadrangle, Grant County, Oregon: Oregon Department of Geology and Mineral Industries Geological Map Series GMS–25, scale 1:24,000, 1 sheet.

Burchfiel, B.C., Cowan, D.S., and Davis, G.A., 1992, Tectonic overview of the Cordilleran orogen in the western United States, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-3, p. 407–479.

Byrne, T., 1984, Structural geology of mélange terranes in the Ghost Rocks Formation, Kodiak Islands, Alaska, *in* Raymond, L.A., ed., Mélanges: Their Origin and Significance: Geological Society of America Special Paper 198, p. 21–51.

Carpenter, P.S., and Walker, N.W., 1992, Origin and tectonic significance of the Aldrich Mountains serpentinite matrix mélange, northeast Oregon: Tectonics, v. 11, p. 690–708, doi: 10.1029/91TC03013.

Cawood, P.A., Kröner, A., and Pisarevsky, S., 2006, Precambrian plate tectonics: Criteria and evidence: GSA Today, v. 16, no. 7, p. 4–11.

Cordey, F., and Schiarizza, P., 1993, Long-lived Panthalassic remnant: The Bridge River accretionary complex, Canadian Cordillera: Geology, v. 21, p. 263–266, doi: 10.1130/0091-7613(1993)021<0263:LLPRTB>2.3.CO;2.

Cowan, D.S., 1985, Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of North America: Geological Society of America Bulletin, v. 96, p. 451–462, doi: 10.1130/0016-7606(1985)96<451:SSIMAC>2.0.CO;2.

Coward, R.I., 1982, The Elkhorn Ridge Argillite: A deformed accretionary prism in northeastern Oregon: Geological Society of America Abstracts with Programs, v. 14, no. 4, p. 157.

Coward, R.I., 1983, Structure, Stratigraphy, and Petrology of the Elkhorn Ridge Argillite, Sumpter Area, Northeastern Oregon [Ph.D. dissertation]: Houston, Texas, Rice University, 144 p.

Dickinson, W.R., 1979, Mesozoic fore-arc basin in central Oregon: Geology, v. 7, p. 166–170, doi: 10.1130/0091-7613(1979)7<166:MFBICO>2.0.CO;2.

Dickinson, W.R., 2004, Evolution of the North American Cordillera: Annual Review of Earth and Planetary Sciences, v. 32, p. 13–45, doi: 10.1146/annurev.earth.32.101802.120257.

Dickinson, W.R., 2008, Accretionary Mesozoic–Cenozoic expansion of the Cordilleran continental margin in California and adjacent Oregon: Geosphere, v. 4, no. 2, p. 329–353, doi: 10.1130/GES00105.1.

Dickinson, W.R., and Thayer, T.P., 1978, Paleographic and paleotectonic implications of Mesozoic stratigraphy and structure in the John Day inlier of central Oregon, *in* Howell, D.G., and McDougall, K.A., eds., Mesozoic Paleogeography of the Western United States: Los Angeles, California, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 147–161.

Dorsey, R.J., and LaMaskin, T.A., 2007, Stratigraphic record of Triassic–Jurassic collisional tectonics in the Blue Mountains province, northeastern Oregon: American Journal of Science, v. 307, p. 1167–1193, doi: 10.2475/10.2007.03.

Driver, L.A., Creaser, R.A., Chacko, T., and Erdmer, P., 2000, Petrogenesis of the Cretaceous Cassiar batholith, Yukon–British Columbia, Canada: Implications for magmatism in the North American Cordilleran interior: Geological Society of America Bulletin, v. 112, p. 1119–1133, doi: 10.1130/0016-7606(2000)112<1119:POTCCB>2.3.CO;2.

Evans, J.G., 1986, Geologic Map of the North Fork John Day River Roadless Area, Grant County, Oregon: U.S. Geological Survey Miscellaneous Field Studies Map MF 1581–C, scale 1:48,000.

Evans, J.G., 1989, Geologic Map of the Desolation Butte Quadrangle, Grant and Umatilla Counties, Oregon: U.S. Geological Survey Quadrangle Map GQ–1654, scale 1:62,500, 1 sheet.

Evans, J.G., 1995, Pre-Tertiary deformation in the Desolation Butte quadrangle, northeastern Oregon, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington—Petrology and Tectonic Evolution of Pre-Tertiary Rocks of the Blue Mountains Region: U.S. Geological Survey Professional Paper 1438, p. 305–330.

Ewart, A., 1982, The mineralogy and petrology of Tertiary-Recent orogenic volcanic rocks: With special reference to the andesitic-basaltic compositional range, *in* Thorpe, R.S., ed., Orogenic Andesites: New York, John Wiley & Sons, Inc., p. 25–95.

Farmer, G.L., and Ball, T. T., 1997, Sources of Middle Proterozoic to Early Cambrian siliciclastic sedimentary rocks in the Great Basin: A Nd isotope study: Geological Society of America Bulletin, v. 109, p. 1193–1205.

Ferns, M.L., and Brooks, H.C., 1995, The Bourne and Greenhorn subterranes of the Baker terrane, northeastern Oregon: Implications for the evolution of the Blue Mountains island-arc system, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington—Petrology and Tectonic Evolution of Pre-Tertiary Rocks of the Blue Mountains Region: U.S. Geological Survey Professional Paper 1438, p. 331–358.

Ferns, M.L., and Ramp, L., 1988, Investigations of Talc in Oregon: Oregon Department of Geology and Mineral Industries Special Paper 18, 52 p.

Ferns, M.L., Brooks, H.C., Avery, D.G., and Blome, C.D., 1987, Geology and Mineral Resources Map of the Elkhorn Peak Quadrangle, Baker County, Oregon: Oregon Department of Geology and Mineral Industries Geologic Map Series GMS–41, scale 1:24,000, 2 sheets.

Follo, M.F., 1992, Conglomerates as clues to the sedimentary and tectonic evolution of a suspect terrane: Wallowa Mountains, Oregon: Geological Society of America Bulletin, v. 104, p. 1561–1576, doi: 10.1130/0016-7606(1992)104<1561:CACTTS>2.3.CO;2.

Follo, M.F., 1994, Sedimentology and stratigraphy of the Martin Bridge Limestone and Hurwal Formation (Upper Triassic to Lower Jurassic) from the Wallowa terrane, Oregon, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington—Stratigraphy, Physiography, and Mineral Resources of the Blue Mountains Region: U.S. Geological Survey Professional Paper 1439, p. 1–27.

Gerlach, D.C., Avé Lallemant, H.G., and Leeman, W.P., 1981a, An island-arc origin for the Canyon Mountain ophiolite complex, eastern Oregon, U.S.A.: Earth and Planetary Science Letters, v. 53, p. 255–265, doi: 10.1016/0012-821X(81)90158-8.

Gerlach, D.C., Leeman, W.P., and Avé Lallemant, H.G., 1981b, Petrology and geochemistry of plagioclase in the Canyon Mountain ophiolite, Oregon: Contributions to Mineralogy and Petrology, v. 77, p. 82–92, doi: 10.1007/BF01161505.

Ghosh, D.K., and Lambert, R.St.J., 1989, Nd-Sr isotopic study of Proterozoic to Triassic sediments from southeastern British Columbia: Earth and Planetary Science Letters, v. 94, p. 29–44, doi: 10.1016/0012-821X(89)90081-2.

Gilluly, J., 1937, Geology and Mineral Resources of the Baker Quadrangle, Oregon: U.S. Geological Survey Bulletin 879, 119 p.

Giorgis, S., Tikoff, B., and McClelland, W., 2005, Missing Idaho arc: Transpressional modification of the ^{87}Sr/^{86}Sr transition on the western edge of the Idaho batholith: Geology, v. 33, p. 469–472, doi: 10.1130/G20911.1.

Goldstein, S.L., O'Nions, R.K., and Hamilton, P.J., 1984, A Sm-Nd isotopic study of atmospheric dusts and particulates from major river systems: Earth and Planetary Science Letters, v. 70, p. 221–236, doi: 10.1016/0012-821X(84)90007-4.

Gromet, L.P., Dymek, R.F., Haskin, L.A., and Korotev, R.F., 1984, The "North American shale composite": Its compilation, major and trace element characteristics: Geochimica et Cosmochimica Acta, v. 48, p. 2469–2482, doi: 10.1016/0016-7037(84)90298-9.

Hamilton, W., 1979, Tectonics of the Indonesian Region: U.S. Geological Survey Professional Paper 1078, 345 p.

Hamilton, W.B., 1998a, Archean magmatism and deformation were not products of plate tectonics: Precambrian Research, v. 91, p. 143–179, doi: 10.1016/S0301-9268(98)00042-4.

Hamilton, W.B., 1998b, Archean tectonics and magmatism: International Geology Review, v. 40, p. 1–39.

Hawkins, J.W., Bloomer, S.H., Evans, C.A., and Melchior, J.T., 1984, Evolution of intra-oceanic arc-trench systems: Tectonophysics, v. 102, p. 175–205, doi: 10.1016/0040-1951(84)90013-1.

Hotz, P.E., Lanphere, M.A., and Swanson, D.A., 1977, Triassic blueschists from northern California and north-central Oregon: Geology, v. 5, p. 659–663, doi: 10.1130/0091-7613(1977)5<659:TBFNCA>2.0.CO;2.

Housen, B.A., and Dorsey, R.J., 2005, Paleomagnetism and tectonic significance of Albian and Cenomanian turbidites, Ochoco Basin, Mitchell Inlier, central Oregon: Journal of Geophysical Research, v. 110, p. B07102, doi: 10.1029/2004JB003458.

Johnson, K., Barnes, C.G., and Miller, C.A., 1997, Petrology, geochemistry, and genesis of high-Al tonalite and trondhjemites of the Cornucopia stock, Blue Mountains, northeastern Oregon: Journal of Petrology, v. 38, p. 1585–1611, doi: 10.1093/petrology/38.11.1585.

Jones, D.L., Pessagno, E.A., Jr., Force, E.R., and Irwin, W.P., 1976, Jurassic radiolarian chert from near John Day, Oregon: Geological Society of America Abstracts with Programs, v. 8, no. 3, p. 386.

Kays, M.A., Stimac, J.P., and Goebel, P.M., 2006, Permian-Jurassic growth and amalgamation of the Wallowa composite terrane, northeastern Oregon, *in* Snoke, A.W., and Barnes, C.G., eds., Geological Studies in the Klamath Mountains Province, California and Oregon—A Volume in Honor of William P. Irwin: Geological Society of America Special Paper 410, p. 465–494.

Krogh, T.E., 1973, A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations: Geochimica et Cosmochimica Acta, v. 37, p. 485–495, doi: 10.1016/0016-7037(73)90213-5.

Krogh, T.E., 1982, Improved accuracy of U-Pb zircon dating by the creation of more concordant systems using air abrasion technique: Geochimica et Cosmochimica Acta, v. 46, p. 637–649, doi: 10.1016/0016-7037(82)90165-X.

LaMaskin, T.A., and Dorsey, R.J., 2006, Basinal response to nascent arc-arc collision, Late Triassic–Early Jurassic of the Blue Mountains province, northeastern Oregon: Geological Society of America Abstracts with Programs, v. 38, no. 5, p. 36.

LaMaskin, T.A., Dorsey, R.J., and Northrup, C.J., 2004, Tectono-stratigraphic architecture of Upper Triassic through Middle Jurassic strata in eastern Oregon: Implications for tectonic evolution of the Blue Mountains: Geological Society of America Abstracts with Programs, v. 36, no. 4, p. 36.

Leeman, W.P., Oldow, J.S., and Hart, W.K., 1992, Lithosphere-scale thrusting in the western U.S. Cordillera as constrained by Sr and Nd isotopic transitions in Neogene volcanic rocks: Geology, v. 20, p. 63–66, doi: 10.1130/0091-7613(1992)020<0063:LSTITW>2.3.CO;2.

Leeman, W.P., Avé Lallemant, H.G., Gerlach, D.C., Sutter, J.F., and Arculus, R.J., 1995, Petrology of the Canyon Mountain complex, eastern Oregon, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington—Petrology and Tectonic Evolution of Pre-Tertiary Rocks of the Blue Mountains Region: U.S. Geological Survey Professional Paper 1438, p. 1–43.

Ludwig, K., 1984, PBDAT: A Program for Reduction of Pb-U-Th Isotope Data, for Use with HP-86/87 Microcomputers: Reston, U. S. Geological Survey, 54 p.

McCaffrey, R., Silver, E.A., and Raitt, R.W., 1980, Crustal structures of the Molucca Sea collision zone, Indonesia, *in* Hayes, D.E., ed., Geologic/Tectonic Evolution of Southeast Asia: American Geophysical Union Geophysical Monograph 23, p. 161–177.

McCall, G.J.H., 2003, A critique of the analogy between Archaean and Phanerozoic tectonics based on regional mapping of the Mesozoic-Cenozoic plate convergent zone in Makran, Iran: Precambrian Research, v. 127, p. 5–17, doi: 10.1016/S0301-9268(03)00178-5.

Miller, M.M., 1987, Dispersed remnants of a northeast Pacific fringing arc: Upper Paleozoic terranes of Permian McCloud faunal affinity, western U.S.: Tectonics, v. 6, p. 807–830, doi: 10.1029/TC006i006p00807.

Moore, G.F., Evans, C.A., Hawkins, J.W., and Kadarisman, D., 1981, Geology of the Talaud Islands, Molucca Sea collision zone, NE Indonesia: Journal of Structural Geology, v. 3, p. 467–475, doi: 10.1016/0191-8141(81)90046-8.

Moores, E.M., Wakabayashi, J., and Unruh, J.R., 2002, Crustal-scale cross-section of the U.S. Cordillera, California and beyond, its tectonic significance, and speculations on the Andean orogeny: International Geology Review, v. 44, p. 479–500, doi: 10.2747/0020-6814.44.6.479.

Mortimer, N., 1987, The Nicola Group: Late Triassic and Early Jurassic subduction-related volcanism in British Columbia: Canadian Journal of Earth Sciences, v. 24, p. 2521–2536.

Mullen, E.D., 1978, Geology of the Greenhorn Mountains, Northeastern Oregon [M.S. thesis]: Corvallis, Oregon State University, 372 p.

Mullen, E.D., 1983, Petrology and Regional Setting of Peridotite and Gabbro of the Canyon Mountain Complex, Northeast Oregon [Ph.D. dissertation]: Corvallis, Oregon State University, 277 p.

Mullen, E.D., 1985, Petrologic character of Permian and Triassic greenstones from the mélange terrane of eastern Oregon and their implications for terrane origin: Geology, v. 13, p. 131–134, doi: 10.1130/0091-7613(1985)13<131:PCOPAT>2.0.CO;2.

Nestell, M.K., 1983, Permian foraminiferal faunas of central and eastern Oregon: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 371.

Nestell, M.K., and Nestell, G.P., 1998, Middle Permian conodonts and Tethyan fusulinaceans associated with possible seamount debris in Oregon: Geological Society of America Abstracts with Programs, v. 30, no. 7, p. 151–152.

Nestell, M.K., and Orchard, M.J., 2000, Late Paleozoic and middle Late Triassic conodont assemblages from the Baker terrane, eastern Oregon: Geological Society of America Abstracts with Programs, v. 32, no. 6, p. 59.

Nestell, M.K., Lambert, L.L., and Wardlaw, B.R., 1995, Pennsylvanian conodonts and fusulinaceans of the Baker terrane, eastern Oregon: Geological Society of America Abstracts with Programs, v. 27, no. 3, p. 76.

Oldow, J.S., Bally, A.W., Avé Lallemant, H.G., and Leeman, W.P., 1989, Phanerozoic evolution of the North American Cordillera: United States and Canada, *in* Bally, A.W., and Palmer, A.R., eds., The Geology of North America: An Overview: Boulder, Colorado, Geological Society of America, The Geology of North America, Volume A, p. 139–232.

Orr, E.L., Orr, W.N., and Baldwin, E.M., 1992, Geology of Oregon (4th edition): Dubuque, Iowa, Kendall/Hunt Publishing Company, 254 p.

Pardee, J.T., and Hewett, D.F., 1914, Geology and mineral resources of the Sumpter quadrangle, Oregon: Oregon Bureau of Mines and Geology, v. 1, no. 6, p. 3–128.

Pearce, J.A., 2003, Supra-subduction zone ophiolites: The search for modern analogues, *in* Dilek, Y., and Newcomb, S., eds., Ophiolite Concept and the Evolution of Geological Thought: Geological Society of America Special Paper 373, p. 269–293.

Pessagno, E.A., and Blome, C.D., 1986, Faunal affinities and tectonogenesis of Mesozoic rocks in the Blue Mountains province of eastern Oregon and western Idaho, *in* Vallier, T.L., and Brooks, H.C., eds., Geologic Implications of Paleozoic and Mesozoic Paleontology and Biostratigraphy, Blue Mountains Province, Oregon and Idaho: U.S. Geological Survey Professional Paper 1435, p. 65–78.

Pubellier, M., Bader, A.G., Rangin, C., Deffontaines, B., and Quebral, R., 1999, Upper plate deformation induced by subduction of a volcanic arc: The Snellius Plateau (Molucca Sea, Indonesia and Mindanao, Philippines): Tectonophysics, v. 304, p. 345–368, doi: 10.1016/S0040-1951(98)00300-X.

Sample, J.C., and Fisher, D.M., 1986, Duplex accretion and underplating in an ancient accretionary complex, Kodiak Islands, Alaska: Geology, v. 14, p. 160–163, doi: 10.1130/0091-7613(1986)14<160:DAAUIA>2.0.CO;2.

Sarewitz, D., 1983, Seven Devils terrane: Is it really a piece of Wrangellia?: Geology, v. 11, p. 634–637, doi: 10.1130/0091-7613(1983)11<634:SDTIIR>2.0.CO;2.

Scholl, D.W., and von Huene, R., 2007, Crustal recycling at modern subduction zones applied to the past—Issues of growth and preservation of continental basement crust, mantle geochemistry, and supercontinent reconstruction, *in* Hatcher, R.D., Carlson, M.P., McBride, J.H., and Martinez Catalán, J.R., eds., 4-D Framework of Continental Crust: Geological Society of America Memoir 200, p. 9–32.

Schwartz, J.J., Frost, C.D., and Snoke, A.W., 2005, Contrasting Nd isotopic characteristics from the Baker terrane of northeastern Oregon: Implications for tectonic evolution: Geological Society of America Abstracts with Programs, v. 37, no. 7, p. 19.

Schwartz, J.J., Snoke, A.W., and Frost, C.D., 2006, Isotopic characteristics of the Baker terrane, NE Oregon: Implications for the relationship between the Bourne and Greenhorn subterranes: Geological Society of America Abstracts with Programs, v. 38, no. 7, p. 449.

Shervais, J.W., 2006, The significance of subduction-related accretionary complexes in early Earth processes, *in* Reimold, W.U., and Gibson, R.L., eds., Processes on the Early Earth: Geological Society of America Special Paper 405, p. 173–192.

Silberling, N.J., Jones, D.L., Blake, M.C., Jr., and Howell, D.G., 1987, Lithotectonic Terranes of the Western Conterminous United States: U.S. Geological Survey Map MF-1874-C, scale 1:2,500,000, 1 sheet with 20 p. pamphlet.

Silver, E., and Moore, J.C., 1978, The Molucca Sea collision zone, Indonesia: Journal of Geophysical Research, v. 83, p. 1681–1691, doi: 10.1029/JB083iB04p01681.

Snee, L.W., Lund, K., Sutter, J.F., Balcer, D.E., and Evans, K.V., 1995, An $^{40}Ar/^{39}Ar$ chronicle of the tectonic development of the Salmon River suture zone, western Idaho, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington— Petrology and Tectonic Evolution of Pre-Tertiary Rocks of the Blue Mountains Region: U.S. Geological Survey Professional Paper 1438, p. 359–414.

Snoke, A.W., 2005, Southern Cordillera, *in* Selley, R.C., Cocks, L.R.M., and Plimer, I.R., eds., Encyclopedia of Geology, Volume 4: Oxford, Academic Press, p. 48–61.

Snoke, A.W., and Barnes, C.G., 2006, The development of tectonic concepts for the Klamath Mountains province, California and Oregon, *in* Snoke, A.W., and Barnes, C.G., eds., Geological Studies in the Klamath Mountains Province, California and Oregon—A Volume in Honor of William P. Irwin: Geological Society of America Special Paper 410, p. 1–29.

Snyder, D.B., Prasetyo, H., Blundell, D.J., Pigram, C.J., Barber, A.J., Richardson, A., and Tjokosaproetro, S., 1996, A dual doubly vergent orogen in the Banda Arc continent-arc collision zone as observed on deep seismic reflection profiles: Tectonics, v. 15, p. 34–53.

Stacey, J.S., and Kramers, J.D., 1975, Approximation of terrestrial lead isotope evolution by a two stage model: Earth and Planetary Science Letters, v. 26, p. 207–221, doi: 10.1016/0012-821X(75)90088-6.

Stimson, E.J., 1980, Geology and Metamorphic Petrology of the Elkhorn Ridge Area, Northeastern Oregon [M.S. thesis]: Eugene, University of Oregon, 123 p.

Struik, L.C., Schiarizza, P., Orchard, M.J., Cordey, F., Sano, H., MacIntyre, D.G., Lapierre, H., and Tardy, M., 2001, Imbricate architecture of the upper Paleozoic to Jurassic Cache Creek terrane, central British Columbia: Canadian Journal of Earth Sciences, v. 38, p. 495–514, doi: 10.1139/cjes-38-4-495.

Sukamoto, R., Suwarno, N., Yusup, J., and Monoarfa, M., 1980, Geologic Map of the Talaud Islands: Bandung, Indonesia, Geological Research and Development Centre, scale 1:250,000.

Taubeneck, W.H., 1957, Geology of the Elkhorn Mountains, northeastern Oregon: Bald Mountain Batholith: Geological Society of America Bulletin, v. 68, p. 181–238, doi: 10.1130/0016-7606(1957)68[181:GOTEMN]2.0.CO;2.

Taubeneck, W.H., 1964, Cornucopia stock, Wallowa Mountains, northeastern Oregon: Geological Society of America Bulletin, v. 75, p. 1093–1116, doi: 10.1130/0016-7606(1964)75[1093:CSWMNO]2.0.CO;2.

Taubeneck, W.H., 1967, Petrology of the Cornucopia Tonalite Unit, Cornucopia Stock, Wallowa Mountains, Northeastern Oregon: Geological Society of America Special Paper 91, 56 p.

Taubeneck, W.H., 1995, A closer look at the Bald Mountain Batholith, Elkhorn Mountains, and some comparisons with the Wallowa Batholith, Wallowa Mountains, northeastern Oregon, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington—Petrology and Tectonic Evolution of Pre-Tertiary Rocks of the Blue Mountains Region: U.S. Geological Survey Professional Paper 1438, p. 45–123.

Taubeneck, W.H., and Poldervaart, A., 1960, Geology of the Elkhorn Mountains, northeastern Oregon: Part 2. Willow Lake intrusion: Geological Society of America Bulletin, v. 71, p. 1295–1322, doi: 10.1130/0016-7606(1960)71[1295:GOTEMN]2.0.CO;2.

Torrini, R., Jr., and Speed, R.C., 1989, Tectonic wedging in the forearc basin–accretionary prism transition, Lesser Antilles forearc: Journal of Geophysical Research, v. 94, p. 10,549–10,584, doi: 10.1029/JB094iB08p10549.

Tumpane, K., Crowley, J., Schmitz, M., and Northrup, C.J., 2008, New geochronological constraints on the deposition of the Huntington Formation, Olds Ferry terrane, and implications for the evolution of the Blue Mountains province: Geological Society of America Abstracts with Programs, v. 40, no. 1, p. 47.

Vallier, T.L., 1977, The Permian and Triassic Seven Devils Group, western Idaho and northeastern Oregon: U.S. Geological Survey Bulletin 1437, p. 1–58.

Vallier, T.L., 1995, Petrology of pre-Tertiary igneous rocks in the Blue Mountains region of Oregon, Idaho, and Washington: Implications for the geologic evolution of a complex island arc, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington—Petrology and Tectonic Evolution of Pre-Tertiary Rocks of the Blue Mountains Region: U.S. Geological Survey Professional Paper 1438, p. 125–209.

Vallier, T.L., and Batiza, R., 1978, Petrogenesis of spilite and keratophyre from a Permian and Triassic volcanic-arc terrane, eastern Oregon and western Idaho: Canadian Journal of Earth Sciences, v. 15, p. 1356–1369.

Vallier, T.L., and Brooks, H.C., 1986, Paleozoic and Mesozoic faunas of the Blue Mountains province—A review of their geologic implications and comments on papers, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington: Geological Implications of Paleozoic and Mesozoic Paleontology and Biostratigraphy, Blue Mountains Province, Oregon and Idaho: U.S. Geological Survey Professional Paper 1435, p. 1–6.

Vallier, T.L., Brooks, H.C., and Thayer, T.P., 1977, Paleozoic rocks of eastern Oregon and western Idaho, *in* Stewart, J.H., Stevens, C.H., and Fritsche, A.E., eds., Paleozoic Paleogeography of the Western United States, Pacific Coast Paleogeography Symposium 1: Los Angeles, California, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 455–466.

Walker, G.W., 1977, Geologic Map of Oregon East of the 121st Meridian: U.S. Geological Survey Miscellaneous Investigations Series Map I-902, scale 1:500,000.

Walker, N.W., 1986, U/Pb Geochronologic and Petrologic Studies in the Blue Mountains Terrane, Northeastern Oregon and Westernmost-Central Idaho: Implications for Pre-Tertiary Tectonic Evolution [Ph.D. dissertation]: Santa Barbara, University of California, 224 p.

Walker, N.W., 1989, Early Cretaceous initiation of post-tectonic plutonism and the age of the Connor Creek fault, northeastern Oregon: Geological Society of America Abstracts with Programs, v. 21, no. 5, p. 155.

Walker, N.W., 1995, Tectonic implications of U-Pb zircon ages of the Canyon Mountain complex, Sparta complex, and related metaplutonic rocks of the Baker terrane, northeastern Oregon, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington—Petrology and Tectonic Evolution of Pre-Tertiary Rocks of the Blue Mountains Region: U.S. Geological Survey Professional Paper 1438, p. 247–269.

Wardlaw, B.R., Nestell, M.K., and Dutro, J.T., Jr., 1982, Biostratigraphy and structural setting of the Permian Coyote Butte Formation of central Oregon: Geology, v. 10, p. 13–16, doi: 10.1130/0091-7613(1982)10<13:BASSOT>2.0.CO;2.

Westbrook, G.K., 1982, The Barbados Ridge Complex: Tectonics of a mature forearc system, *in* Leggett, J.K., ed., Trench–Forearc Geology: Sedimentation and Tectonics on Modern and Ancient Active Plate Margins: Geological Society of London Special Publication 10, p. 275–290.

Westbrook, G.K., Ladd, J.W., Buhl, P., Bangs, N., and Tiley, G.J., 1988, Cross section of an accretionary wedge: Barbados Ridge complex: Geology, v. 16, p. 631–635, doi: 10.1130/0091-7613(1988)016<0631:CSOAAW>2.3.CO;2.

Wheeler, G.R., 1976, Geology of Vinegar Hill Area, Grant County, Oregon [Ph.D. dissertation]: Seattle, University of Washington, 94 p.

White, W.H., 1973, Flow structure and form of the Deep Creek stock, southern Seven Devils Mountains, Idaho: Geological Society of America Bulletin, v. 84, p. 199–209, doi: 10.1130/0016-7606(1973)84<199:FSAFOT>2.0.CO;2.

White, J.D., White, D.L., Vallier, T.L., Stanley, G.D., Jr., and Ash, S.R., 1992, Middle Jurassic strata link Wallowa, Olds Ferry and Izee terranes in the accreted Blue Mountains island arc, northeastern Oregon: Geology, v. 20, p. 729–732, doi: 10.1130/0091-7613(1992)020<0729:MJSLWO>2.3.CO;2.

Wilson, D., and Cox, A., 1980, Paleomagnetic evidence for tectonic rotation of Jurassic plutons in Blue Mountains, eastern Oregon: Journal of Geophysical Research, v. 85, p. 3681–3689, doi: 10.1029/JB085iB07p03681.

Wyld, S.J., 2005, Early Cretaceous, margin-parallel, dextral faulting and terrane translation in the U.S. Cordillera: Geological Society of America Abstracts with Programs, v. 37, no. 4, p. 102.

Wyld, S.J., and Wright, J.E., 2001, New evidence for Cretaceous strike-slip faulting in the United States Cordillera and implications for terrane displacement, deformation patterns, and plutonism: American Journal of Science, v. 301, p. 150–181, doi: 10.2475/ajs.301.2.150.

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