The Geological Society of America
Field Guide 15
2009

Mesozoic sedimentation, magmatism, and tectonics in the Blue Mountains Province, northeastern Oregon

Todd A. LaMaskin
Department of Geological Sciences, University of Oregon, Eugene, Oregon 97405, USA

Joshua J. Schwartz
Department of Geological Sciences, University of Alabama, Box 870338 Tuscaloosa, Alabama 35487, USA

Rebecca J. Dorsey
Department of Geological Sciences, University of Oregon, Eugene, Oregon 97405, USA

Arthur W. Snoke
Department of Geology and Geophysics, University of Wyoming, Laramie, Wyoming 82071, USA

Kenneth Johnson
Department of Natural Sciences, University of Houston Downtown, Houston, Texas 77002, USA

Jeffery D. Vervoort
School of Earth and Environmental Sciences, Washington State University, Pullman, Washington 99164, USA

ABSTRACT

This field trip guide describes a two-day excursion through Mesozoic accreted terranes of the Blue Mountains Province in northeastern Oregon. Day 1 is focused on sedimentary rocks of the Izee terrane. These deposits are divided into two unconformity-bounded megasequences, MS-1 and MS-2 that record two stages of syntectonic basin formation. MS-1 (Late Triassic to Early Jurassic) accumulated in fault-bounded marine sub-basins on the flank of an inferred growing Baker terrane thrust belt. MS-1 sandstones, derived from the Baker terrane, contain abundant Paleozoic, Late Paleoproterozoic, and Late Archean detrital-zircon grains. These observations suggest affinity of the Baker terrane and MS-1 in the Izee area to portions of the Klamath and Sierra Nevada terranes that contain similar detrital-zircon age distributions. MS-2 (Early to early-Late Jurassic) accumulated in a large marine basin that received input from low-grade metavolcanic rocks to the east (modern coordinates). Detrital zircons are dominated by Mesozoic, Neoproterozoic, and Mesoproterozoic grains. Two possible interpretations for MS-2 are: (1) the Jurassic Izee basin was fed directly by the large Mesozoic trans-cratonal sediment-dispersal system, or (2) trans-cratonal sediment was deposited in a Triassic backarc basin in Nevada and was later recycled into the Jurassic Izee basin during Cordilleran orogenesis.

LaMaskin, T.A., Schwartz, J.J., Dorsey, R.J., Snoke, A.W., Johnson, K., and Vervoort, J.D., 2009, Mesozoic sedimentation, magmatism, and tectonics in the Blue Mountains Province, northeastern Oregon, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 1–XXX, doi: 10.1130/2009. fld015(09). For permission to copy, contact editing@geosociety.org. ©2009 The Geological Society of America. All rights reserved.

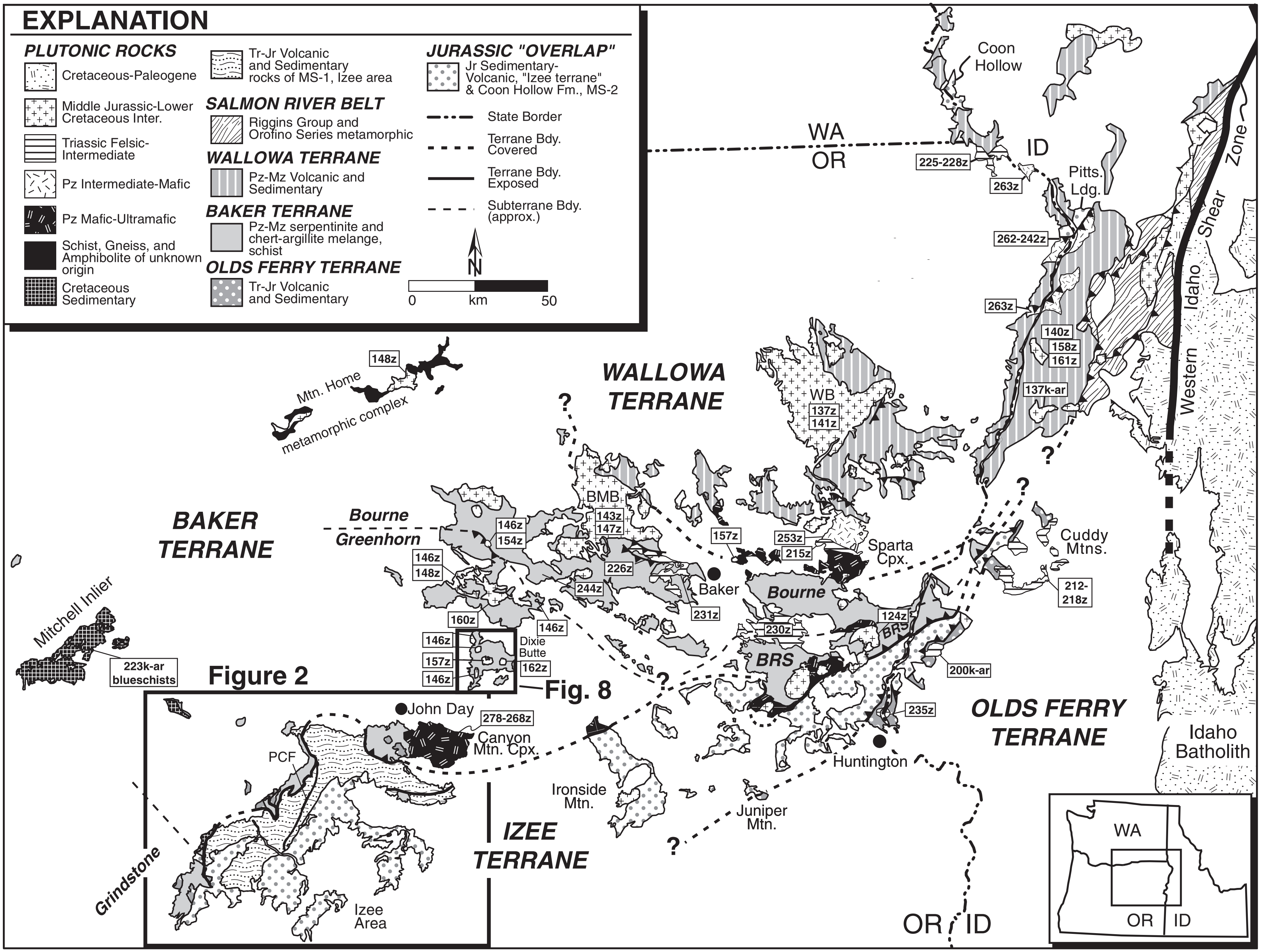
Day 2 of the field trip is focused on Jurassic–Cretaceous magmatism in the Baker terrane. Late Middle Jurassic to Early Cretaceous igneous rocks in the Blue Mountains Province record three distinct pulses of plutonism that are characterized by distinctive spatial and geochemical signatures. These episodes consist of: (1) late Middle to Late Jurassic small gabbro to quartz diorite plutons (ca. 162–154 Ma; low Sr/Y); (2) Late Jurassic to Early Cretaceous plutons and batholiths (ca. 148 and 137 Ma; includes spatially distinct belts of low and high Sr/Y at 147–145 Ma); and (3) Early Cretaceous small plutons of tonalitic and trondhjemitic composition (ca. 124–111 Ma). Temporal transitions in geochemical characteristics between these suites raise fundamental questions regarding the origins of plutonism in the Baker terrane. In particular, the transition from low Sr/Y (group 1) to high Sr/Y (group 2) magmatism in the Greenhorn subterrane occurred ~ 7 Ma after regional contraction, and may record partial melting of thickened crust as a direct result of Late Jurassic orogenesis.

INTRODUCTION

This field trip ~~will~~ examine Mesozoic rocks in northeastern Oregon that make up part of the Blue Mountains Province, an allochthonous group of variably metamorphosed, arc- and non-arc–related rocks in Oregon, Idaho, and Washington (Fig. 1) (Hamilton, 1963; Armstrong et al., 1977; Vallier, 1977; 1995; Dickinson and Thayer, 1978; Brooks and Vallier, 1978; Silberling et al., 1984). Recent stratigraphic analysis (Dorsey and LaMaskin, 2007, 2008) and new geochronologic and geochemical data (Johnson et al., 1995; Johnson and Barnes, 2002; LaMaskin et al., 2008; Parker et al., 2008; Schwartz and Snoke, 2008; Unruh et al., 2008; LaMaskin, 2009; Schwartz et al., 2010) challenge traditional models and suggest intriguing new ideas for tectonic and magmatic development of the Blue Mountains region. The primary objectives of this field trip are to familiarize participants with fundamental tectonic problems in the region, explore the implications of new data that are being generated in these studies, and assess how the Blue Mountains Province may fit into the larger context of Cordilleran tectonics, including relationships with southern British Columbia terranes to the north, Klamath-Sierran terranes to the south, and a Mesozoic thrust belt in western Nevada. Day 1 of the trip will focus on the boundary zone between the Baker terrane and younger sedimentary rocks of the Triassic-Jurassic Izee terrane. Day 2 of the trip will focus on Jurassic magmatism and related rocks within the Baker terrane. An important goal of the trip is to integrate information and emerging new data from the two study areas.

Rocks of the Blue Mountains Province are commonly divided into two late Paleozoic to early Mesozoic volcanic island-arc assemblages (the Wallowa and Olds Ferry terranes), a Paleozoic to early Mesozoic subduction-accretionary complex (Baker terrane), and a Triassic–Jurassic clastic sedimentary succession (Izee terrane). The *Wallowa terrane* (Fig. 1) is a succession of island-arc related plutonic, volcanic, and sedimentary rocks of Permian through Early Jurassic age (Vallier, 1977, 1995; Walker, 1986, 1995). The *Olds Ferry terrane* (Fig. 1) contains island-arc related Upper Triassic to Lower Jurassic, volcanic, and marine volcaniclastic and epiclastic rocks, as well as small Middle (ca. 235 Ma) and Upper Triassic (ca. 218–212 Ma) mafic to felsic intrusions (Brooks and Vallier, 1978; Vallier, 1995; Walker, 1986, 1995; Tumpane et al., 2008; LaMaskin, 2008; Unruh et al., 2008). The *Baker terrane* accretionary-subduction complex (Fig. 1) is situated between the Wallowa and Olds Ferry terranes and includes both island-arc and non-arc–related rocks (Jones et al., 1976; Hotz et al., 1977; Carpenter and Walker, 1992; Ferns and Brooks, 1995; Leeman et al., 1995; Vallier, 1995; Schwartz et al., 2010). At least four subterrane-level units within the Baker terrane include the Grindstone, Bourne, and Greenhorn subterranes, and the Burnt River Schist (Kays et al., 1987; Ashley, 1995; Ferns and Brooks, 1995; Schwartz et al., 2006; Schwartz and Snoke, 2008). Sedimentary units in the Baker terrane include Devonian through Triassic clastic and carbonate successions with minor occurrences of Jurassic strata. Rocks traditionally included in the *Izee terrane* (Fig. 1) consist of Triassic and Jurassic dominantly sedimentary rocks that rest in depositional or fault contact with rocks of the Baker terrane in central Oregon. Correlation of Middle Jurassic rocks of the Izee

Figure 1. Geologic map of the Blue Mountains Province, modified from LaMaskin (2009). Ages of plutons shown where data are available; z—U-Pb zircon age; K-Ar—potassium-argon age. Question marks indicate uncertain terrane affiliations and/or terrane boundary locations. The Bourne and Greenhorn subterranes, Grindstone terrane, and Burnt River Schist are here considered sub-terrane level units of the Baker terrane. MS—megasequence (after Dorsey and LaMaskin, 2007); BRS—Burnt River Schist; BMB—Bald Mountain batholith; WB—Wallowa batholith; PCF—Poison Creek fault; Cpx.—complex; Ldg.—landing; WA—Washington; OR—Oregon; ID—Idaho. Compiled from numerous sources including Dickinson and Vigrass (1965); Brown and Thayer (1966; 1977); Thayer and Brown (1966); Hendricksen et al. (1972); Brooks et al. (1976); Dickinson and Thayer (1978); Brooks (1979); Walker and MacLeod (1991); Walker (1986; 1995); Vallier (1995; 1998); Ashley (1995); Ferns and Brooks (1995); Leeman et al. (1995); Ferns et al., (2001); Lewis (2002); Lund (2004); Kays et al. (2006); Dorsey and LaMaskin (2007); Mann and Vallier (2007); Parker et al. (2008); Unruh et al. (2008); J. Schwartz (unpublished data); K. Johnson (unpublished data).


EXPLANATION
PLUTONIC ROCKS
Cretaceous-Paleogene
Middle Jurassic-Lower Cretaceous Inter.
Triassic Felsic-Intermediate
Pz Intermediate-Mafic
Pz Mafic-Ultramafic
Schist, Gneiss, and Amphibolite of unknown origin
Cretaceous Sedimentary
Tr-Jr Volcanic and Sedimentary rocks of MS-1, Izee area
SALMON RIVER BELT
Riggins Group and Orofino Series metamorphic
WALLOWA TERRANE
Pz-Mz Volcanic and Sedimentary
BAKER TERRANE
Pz-Mz serpentinite and chert-argillite melange, schist
OLDS FERRY TERRANE
Tr-Jr Volcanic and Sedimentary
JURASSIC "OVERLAP"
Jr Sedimentary-Volcanic, "Izee terrane" & Coon Hollow Fm., MS-2
State Border
Terrane Bdy. Covered
Terrane Bdy. Exposed
Subterrane Bdy. (approx.)
N
0
km
50
Coon Hollow
WA
OR
ID
225-228z
263z
Pitts. Ldg.
262-242z
263z
140z
158z
161z
137k-ar
Western Idaho Shear Zone
Idaho Batholith
WALLOWA TERRANE
WB
137z
141z
148z
Mtn. Home metamorphic complex
?
BMB
143z
147z
157z
253z
215z
Sparta Cpx.
Cuddy Mtns.
212-218z
BAKER TERRANE
Bourne
Greenhorn
146z
154z
146z
148z
226z
244z
Baker
231z
Bourne
230z
124z
BRS
BRS
200k-ar
Mitchell Inlier
223k-ar blueschists
160z
146z
157z
146z
146z
Dixie Butte
162z
Figure 2
Fig. 8
John Day
278-268z
Canyon Mtn. Cpx.
PCF
Grindstone
Izee Area
IZEE TERRANE
Ironside Mtn.
Juniper Mtn.
Huntington
235z
OLDS FERRY TERRANE
OR
ID
WA
OR
ID

terrane with the Coon Hollow Formation in the Wallowa terrane suggests that the Izee terrane represents a stratigraphic overlap assemblage that links the Blue Mountains terranes by Early to Middle Jurassic time (i.e., Pessagno and Blome, 1986; White et al., 1992; Dorsey and LaMaskin, 2007, 2008; LaMaskin et al., 2008). Regional contractile deformation affected all rocks of the Blue Mountains Province in Late Jurassic time (Avé Lallemant, 1995), and terrane amalgamation prior to ca. 144 Ma is suggested by Late Jurassic to Early Cretaceous granodioritic stitching plutons (Fig. 1; Walker, 1986, 1989).

Historically, some workers have interpreted rocks of the Blue Mountains Province to represent a single, complex far-traveled island arc (e.g., Pessagno and Blome, 1986; White et al., 1992; Vallier, 1995). Others have suggested that the Blue Mountains Province contains both intraoceanic (Wallowa) and continent-fringing (Olds Ferry) island-arc systems that are separated by a subduction/accretionary complex (Baker terrane) (e.g., Dickinson, 1979, 2004). Recent work by Dorsey and LaMaskin (2007), LaMaskin et al. (2008), and Schwartz et al. (2010) suggests that this region underwent an early Mesozoic, Molucca-Sea style arc-arc collision that involved portions of the Wallowa, Baker, and Olds Ferry terranes. In addition, Dorsey and LaMaskin (2007, 2008) and LaMaskin et al. (2008) proposed that Jurassic sedimentary rocks across the region were deposited in a subsiding flexural basin adjacent to a growing Jurassic orogenic belt in western Nevada (Luning-Fencemaker fold-and-thrust belt). The diversity of tectonic models reflects the geologic complexity in the region and ongoing attempts to interpret emerging new data using comparisons to present-day, plate-tectonic settings.

STRATIGRAPHY AND STRUCTURE OF THE IZEE AREA

Paleozoic–Mesozoic serpentinite-matrix mélange of the Baker terrane and Triassic to Jurassic sedimentary rocks of the Izee terrane are exposed in a large erosional inlier southwest of the town of John Day, Oregon (Figs. 1 and 2A; Dickinson and Vigrass, 1965; Dickinson and Thayer, 1978). Triassic and Jurassic sedimentary rocks can be divided into two regional-scale, unconformity-bounded megasequences (Dorsey and LaMaskin, 2007). Rocks of megasequence 1 include Upper Triassic to Lower Jurassic marine strata that experienced significant syndepositional deformation and are derived dominantly from rocks of the Baker terrane (i.e., an outboard provenance; Dickinson and Thayer, 1978; Dorsey and LaMaskin, 2007). Deposits of megasequence 1 occur in two distinct packages located east and west of the southeast-directed Poison Creek reverse fault (Figs. 2A and 2B). Units west of the Poison Creek fault include the Upper Triassic Vester Formation (~4000 m) and small erosional remnants of the overlying Late Triassic Rail Cabin Argillite (~600 m) and Early Jurassic Graylock Formation (~150 m). These marine successions rest nonconformably on, and are locally infolded and faulted with, serpentinite-matrix mélange of the Baker terrane (Grindstone and Greenhorn subterranes; Dickinson and Vigrass, 1965; Dickinson and Thayer, 1978; Ferns and Brooks, 1995). East of the Poison Creek fault, sedimentary rocks of megasequence 1 are age-equivalent to the Rail Cabin Argillite and Graylock Formation and include a thick package of marine argillite and turbidites called the Aldrich Mountains Group (~10,000 m; Dickinson and Thayer, 1978). All rocks of megasequence 1 were affected by Late Triassic to Early Jurassic deformation and are overlain by rocks of megasequence 2 along a regional angular unconformity.

Sedimentary rocks of megasequence 2 in the Izee area include the Lower to Upper(?) Jurassic Mowich Group (~500 m) and Snowshoe (~1000 m), Trowbridge (~1000 m) and Lonesome formations (~3000 m; Fig. 2B). These deposits accumulated in a marine basin that experienced regional transgression from Early through Middle Jurassic time (ca. 190–161 Ma; Mowich Group through Trowbridge Formation) followed by regional regression in Middle and Late(?) Jurassic time (Lonesome Formation; Dickinson 1979; Dickinson et al., 1979). All deposits of megasequences 1 and 2 were affected by Late Jurassic contractile deformation (Avé Lallemant, 1995).

DETRITAL-ZIRCON DATA

Detrital-zircon data from rocks of megasequence 1 and megasequence 2 in the Izee area record a major shift in provenance from Late Triassic to Middle Jurassic time, consistent with provenance trends in sandstone detrital modes identified by Dickinson et al. (1979). Late Triassic sediments of the Vester Formation are interpreted to be derived from the Baker terrane (Dickinson and Thayer, 1978), and the detrital-zircon age distributions are dominated by Paleozoic, Late Paleoproterozoic, and Late Archean ages (LaMaskin, 2009). Crystalline basement rocks older than Permian are not known to be present in the Baker terrane, and thus detrital-zircon grains in megasequence 1 were likely reworked from Paleozoic and Mesozoic(?) clastic rocks of the Baker terrane. In contrast, the Jurassic deposits are inferred to be derived from inboard sources (Dickinson and Thayer, 1978). Detrital-zircon age distributions in Jurassic samples are dominated by Mesozoic ages and include significant quantities of Neoproterozoic and Mesoproterozoic ages with lesser amounts of Late Paleoproterozoic ages.

Other accretionary-subduction complexes within terranes of the Klamath Mountains and Sierra Nevada are dominated by Paleozoic, Late Paleoproterozoic, and Late Archean detrital-zircon grains such as those eroded from the Baker terrane and deposited as megasequence 1 in the Izee region (e.g., Harding et al., 2000; Scherer, 2006). This similarity in detrital-zircon age distributions suggests that pre-Triassic portions of the Baker terrane and megasequence-1 sediments have a genetic affinity to portions of the Klamath and Sierra Nevada terranes.

In Jurassic samples, significant quantities of Neoproterozoic and Mesoproterozoic detrital-zircon grains with lesser amounts of Late Paleoproterozoic grains indicate derivation from a previously documented trans-cratonal sediment-dispersal system

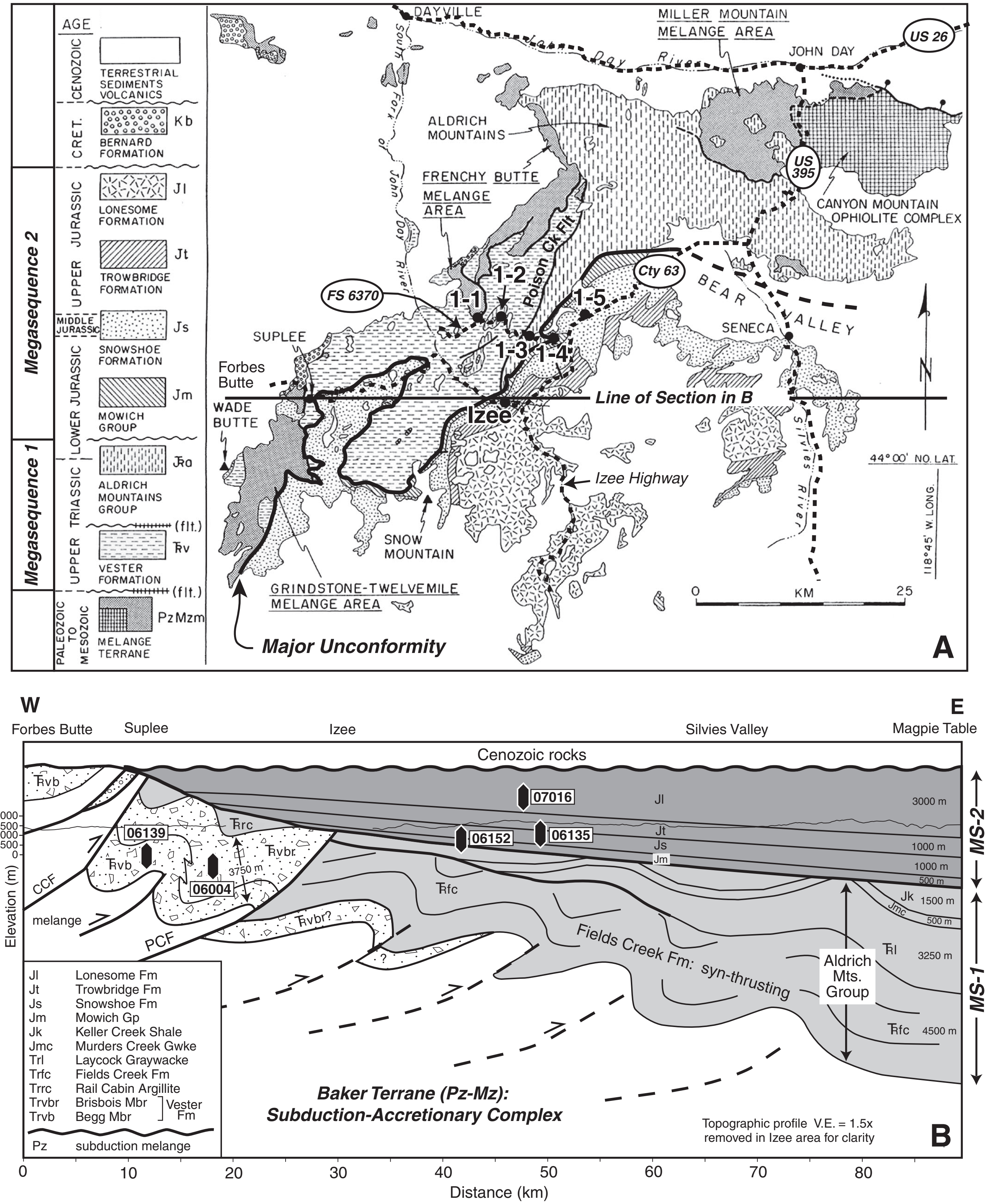


Figure 2. (A) Geologic map of the Izee area, modified from Dickinson and Thayer (1978), showing location of stops for Day 1. (B) Stratigraphic reconstruction of Izee area prior to Late Jurassic deformation, projected into E-W line of section (in A) using maps and data from Dickinson and Thayer (1978), Dickinson and Vigrass (1965), and Brown and Thayer (1966). Total structural relief of east- to southeast-directed thrust belt is ~10–15 km based on thickness of Triassic–Jurassic syn- to post-thrusting stratigraphic section. CCF—Camp Creek fault; PCF—Poison Creek fault. Black zircon crystals and sample numbers indicate approximate position of detrital-zircon samples discussed in text.

during Jurassic time (i.e., Rahl et al., 2003; Dickinson and Gehrels, 2003, 2009), and suggest proximity of the Jurassic Izee basin to the Cordilleran margin. Alternatively, these detrital-zircon grains may have originally been deposited in the Triassic back-arc basin in Nevada (i.e., Dickinson and Gehrels, 2008) and subsequently eroded from the Luning-Fencemaker fold-and-thrust belt during Jurassic uplift and erosion (Wyld, 2002; Wyld et al., 1996, 2003). Both explanations support a model for moderate post-Jurassic northward translation (~400 km) of the Blue Mountains Province (e.g., Wyld and Wright, 2001).

JURASSIC–EARLY CRETACEOUS MAGMATISM IN THE BAKER TERRANE

Late Middle Jurassic to Early Cretaceous magmatism in the Blue Mountains Province consists of three distinct pulses of plutonism, which occurred between 162 and 154 Ma, 148 and 137 Ma, and 124 and 111 Ma (Walker, 1986, 1989, 1995; Johnson et al., 1995; Johnson and Barnes, 2002; Parker et al., 2008; Schwartz and Snoke, 2008; Unruh et al., 2008; J. Schwartz and K. Johnson, unpublished data; Fig. 3; Table 1). These plutons define spatially distinct belts that parallel major tectonic features of the amalgamated Blue Mountains terranes (Wallowa, Baker, and Izee terranes), and formed prior to ~60° of post-Cretaceous clockwise rotation (Wilson and Cox, 1980). The oldest belt consists of late Middle–Late Jurassic plutons in the Wallowa terrane (Unruh et al., 2008) and Baker terrane (Fig. 1) (Parker et al., 2008; J. Schwartz, unpublished data). These plutons are typically <3 km^2 in areal extent and range in composition from gabbro to quartz diorite. Geochemically, they are magnesian, calcic to calc-alkalic, and metaluminous, and characterized by low Na, Al, Sr, but high Y concentrations (Fig. 4). This phase of magmatism is coeval with a short-lived episode of regional contraction in the Baker terrane that is bracketed between 159 and 154 Ma (D$_2$ of Avé Lallemant, 1995; Schwartz and Snoke, 2008).

A second distinct pulse of magmatism occurred between ca. 148 and 137 Ma and consists of two spatially and geochemically distinct belts of high Sr/Y (high Na, Al, Sr, but low Y) plutons in the Greenhorn subterrane of the Baker terrane, and low Sr/Y (low Na, Al, Sr, but high Y) plutons and batholiths in the Bourne subterrane of the Baker terrane and the Wallowa terrane. In the Bourne subterrane and Wallowa terrane, low Sr/Y plutons and batholiths (148–137 Ma) intrude island-arc and related metasedimentary rocks and are similar in composition to older Middle–Late Jurassic plutons (162–154 Ma belt). In contrast, high Sr/Y plutons in the Greenhorn subterrane (147–145 Ma) spatially overlap the older low Sr/Y plutons, but are much more compositionally restricted (Fig. 4; Table 1).

The transition from low Sr/Y (162–154 Ma belt) to high Sr/Y magmatism (147–145 Ma) in the Greenhorn subterrane occurred ~7 Ma after regional contraction, and raises fundamental questions regarding the origin of high Sr/Y plutons in the Baker terrane. Several geochemical characteristics of the high Sr/Y magmas suggest an origin for these rocks by partial melting in the presence of a plagioclase-poor to absent, hornblende + garnet-bearing source (depths >40 km). These features include: steeply fractionated rare earth element (REE) patterns, high Sr/Y values, and little to no Eu anomaly. Does the observed change in geochemistry from low Sr/Y to high Sr/Y reflect partial melting of orogenically thickened crust as a direct result of Late Jurassic orogenesis?

The last stage of magmatism in the region (pre-Idaho batholith emplacement) consists of small plutons of tonalitic and trondhjemitic composition. This group can subdivided into two sub-groups: (1) 124–120 Ma metaluminous hornblende-biotite tonalite plutons in a northeast-southwest–trending belt eastward (inboard) of the Late Jurassic belt, and (2) 125–111 Ma, strongly peraluminous tonalite and trondhjemite plutons that mostly occur in a belt subparallel to the initial Sr isotopic 0.706 line in western Idaho. These plutons were emplaced >10 Ma after Late Jurassic–Early Cretaceous magmatism in the Baker terrane (146–137 Ma) and represent a distinct phase of magmatism which postdates regional contraction (e.g., Snee et al., 1995; Gray and Oldow, 2005) and peak metamorphism (550–600 °C, 8–9 kbar) at 128 ± 3 Ma in the Salmon River suture zone (Selverstone et al., 1992; Getty et al., 1993).

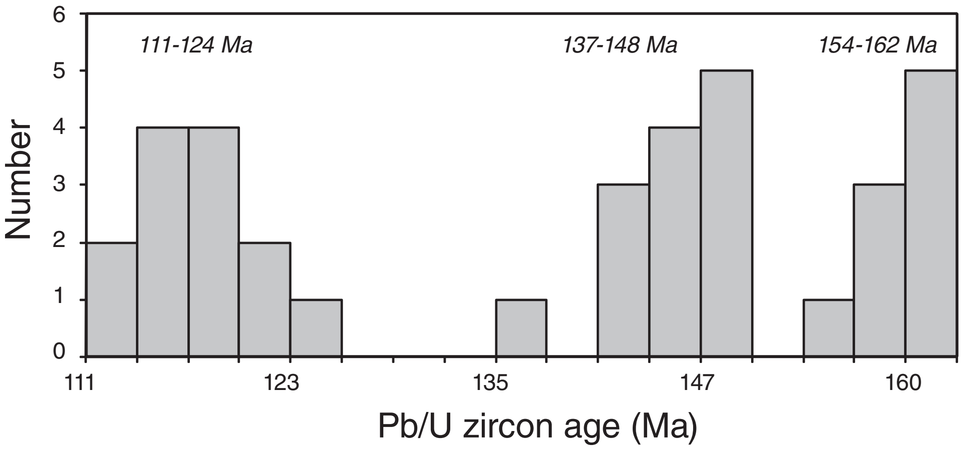


Figure 3. Histogram of U-Pb zircon ages showing the distribution of Middle Jurassic to Early Cretaceous magmatic rocks in the Blue Mountains Province. Data compiled from Walker (1986; 1989), Manduca (1993), Lee (2004), McClelland and Oldow (2007), Parker et al. (2008), Unruh et al. (2008), and J. Schwartz and K. Johnson (unpublished data).

TABLE 1. SUMMARY OF CHARACTERISTICS OF MIDDLE JURASSIC–EARLY CRETACEOUS PLUTONIC BELTS IN THE BLUE MOUNTAINS PROVINCE, NORTHEAST OREGON

	Setting (terrane/subterrane)	Rock type	Age (Ma)	Associated volcanics?	Associated mafic rocks?	Fe-number	MALI	Na_2O/K_2O	~Sr	Sr/Y (ave.)	La/Lu (ave.)	Residual minerals
LoSY	Wallowa and Baker terrane	hbl gabbro, hbl ± biotite diorite	162–154	Unknown	Yes	bimodal: ferroan/ magnesian	bimodal: alkalic/ calcic	4.4	300	12	33	pyroxene, plagioclase
LoSY	Wallowa and Baker terrane (*Bourne subterrane*)	gabbro, hbl diorite, tonalite granodiorite, granite	148–137	No	Yes	magnesian	calcic-calc alkalic	3.1	469	39	61	pyroxene, plagioclase
HiSY	Baker terrane (*Greenhorn subterrane*)	biotite ± muscovite tonalite-granodiorite	147–145	No	No	magnesian	calcic-calc alkalic	2.7	612	57	120	Amphibole, garnet (±plagioclase)

Note: LoSY—low Sr/Y; HiSY—high Sr/Y; hbl—hornblende; MALI—modified alkali–lime index.

REGIONAL TECTONIC IMPLICATIONS

Rocks examined during this field trip highlight an apparent temporal partitioning of sedimentation and magmatism, and suggest a systematic shift in the locus of crustal-thickening, sedimentation and magmatism over time. The majority of Mesozoic sedimentation appears to have taken place from Late Triassic (ca. 225 Ma) to late Middle Jurassic time (ca. 160 Ma; Dickinson and Thayer, 1978; LaMaskin, 2009); in contrast, magmatism in the Baker terrane appears to have initiated (?) in late Middle Jurassic time (ca. 162 Ma) and continued into the Cretaceous.

We propose a model in which Jurassic sedimentation in the Blue Mountains occurred in a subsiding collisional basin adjacent to an area of crustal thickening in western Nevada (i.e., the Luning-Fencemaker fold-and-thrust belt; Wyld and Wright, 2001; Dorsey and LaMaskin, 2007, 2008). Sedimentation in the Blue Mountains ceased when crustal thickening jumped outboard, to a location within the Blue Mountains (Greenhorn subterrane of the Baker terrane; Ferns and Brooks, 1995). This shift in the locus of crustal thickening appears to be recorded by a regional contraction event at ca. 159–154 Ma (i.e., D_2 of Avé Lallemant, 1995; Schwartz and Snoke, 2008) and by the emplacement of high Sr/Y plutons in Late Jurassic to Early Cretaceous time. Subsequently, the locus of crustal thickening in the region shifted back to the east (i.e., the Salmon River suture zone) and was closely followed by intrusion of small Early Cretaceous tonalitic and trondhjemitic plutons.

DAY 1

Directions to Stop 1-1

Begin field trip directions at the intersection of U.S. Highway 26 and U.S. Highway 395 in John Day, Oregon (Fig. 2A). Travel south on U.S. Highway 395 ~18 miles to the intersection with County Route 63 (Izee-Paulina Lane). Turn right on County Route 63 and travel ~18.4 miles, then turn right onto Forest Service Road (FSR) 6370. Continue on winding roads of FSR 6370 for ~15 miles. Turn right onto FSR 304, a small jeep trail located at UTM coordinates 307072E, 4891572N (UTM zone 11, datum NAD 83), and follow ~0.3 miles. Park at the entrance to a closed FSR at UTM coordinates 307022E, 4891985N. On foot, follow closed FSR due west ~1.2 miles, bearing left at intersection with FSR 328, to unvegetated hills of serpentinite on the north side of the road (end hike on road at UTM coordinates 305460W, 4892121N). Hike ~0.25 mi due north to chromite mine pits at UTM coordinates 305393W, 4892252N.

Stop 1-1. Upper Triassic Vester Formation and Rocks of the Baker Terrane

Throughout the Izee region of central Oregon, the Baker terrane forms the basement to the Triassic through Jurassic basinal assemblage. Upper Triassic sedimentary rocks of the Vester

Formation (megasequence 1) are the oldest deposits of the Triassic basinal assemblage, and this is a key locality where they rest in depositional contact on the Baker terrane (Fig. 2). At this location we will observe field evidence for the depositional contact between the Baker terrane and overlying Vester Formation, and view typical rock types of the Vester Formation (participants are referred to Brown and Thayer, 1977: U.S. Geological Survey [USGS] Map I-1021).

In this area, rocks of the Baker terrane include two dominant rock types: (1) strongly sheared serpentinite, and (2) metavolcanic greenstone (Brown and Thayer, 1977). In the immediate vicinity of Stop 1-1, serpentinite has been mined for chromite and abandoned mine pits can be found at several locations. The Vester Formation has been divided into two members: (1) the Begg Member (~2500 m) is dominantly chert-rich conglomerate and sandstone with lesser amounts of black shale, polymict breccia, and local volcanic rocks, and (2) the Brisbois Member (~1250 m) is dominantly thin-bedded chert-grain sandstones with local calcarenite and limestone olisostromes (Dickinson and Vigrass, 1965; Brown and Thayer, 1977; Dickinson and Thayer, 1978). Paleocurrent indicators reported by Dickinson and Thayer (1978) suggest southeast-directed transport (modern coordinates). The age of the Begg Member is poorly constrained and may be Late Triassic (Carnian) or older, whereas diagnostic pelycepod and ammonite faunas in the Brisbois Member suggest a Late Triassic, Carnian age (*subbullatus* zone; Dickinson and Vigrass, 1965; Blome, 1984; Blome et al., 1986).

The sandstone detrital mode of the Vester Formation is noteworthy for abundant chert and meta-chert grains in conjunction with a relatively low abundance of monocrystalline quartz grains (Dickinson et al., 1979). The unique framework-grain assemblage, paleocurrent indicators suggesting flow away

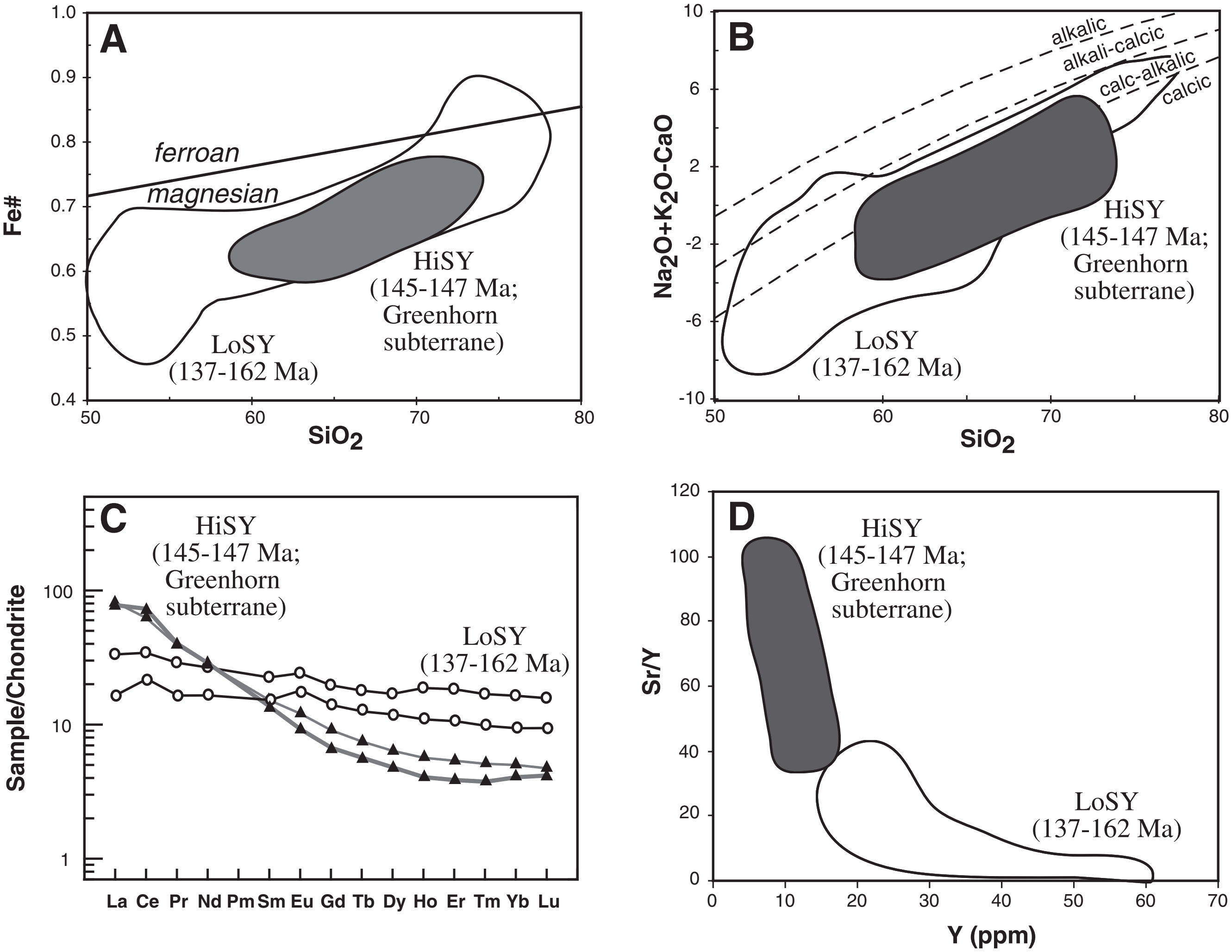


Figure 4. Representative geochemical data for high Sr/Y (HiSY) and low Sr/Y (LoSY) plutons. (A) Both suites are magnesian; however, high Sr/Y plutons have more restricted SiO_2 compositions. (B) Both suites are calcic to calc-alkalic. (C) High Sr/Y plutons have strongly fractioned REE patterns. (D) High Sr/Y plutons have high Sr/Y values (>40) and low Y values (<20 ppm), whereas low Sr/Y plutons have low Sr/Y values (<40) and higher Y values (15–60 ppm). Data from J. Schwartz and K. Johnson (unpublished data).

from likely source rocks in the Baker terrane, and numerous syn-depositional faults, indicate that the Vester Formation was derived from uplifted rocks of the Baker terrane during Late Triassic deformation and related basin formation (Dickinson and Thayer, 1978; Brown and Thayer, 1977; Dickinson, 1979; Avé Lallemant, 1995).

Mapping by Brown and Thayer (1977) at this location shows that the Begg Member of the Vester Formation rests in depositional contact on both serpentinite and metavolcanic greenstone of the Baker terrane. The contact is highly irregular and nonplanar, unlike a fault contact, and the mapped attitudes of bedding within the Vester Formation generally follow the Vester-Baker contact. Following a brief orientation, participants will spend some time exploring the contact between rocks of the Baker terrane and the Vester Formation and viewing exposures of chert-pebble conglomerate and chert-grain sandstone.

Medium-grained, chert-rich sandstone samples from the Begg and Brisbois members of the Vester Formation yield abundant detrital-zircon grains (Fig. 5). The majority are well-rounded pink, yellow, or green grains. The samples include minor quantities of Mesozoic-age grains (~2% of grains) and are dominated by Paleozoic- (~41%) and Precambrian-age grains (57%). Prominent peaks in the probability distribution for Mesozoic and Paleozoic ages are present at 374 Ma (Devonian), 311 Ma (Pennsylvanian), and 274 Ma (Permian). The majority of Precambrian-age grains are late Paleoproterozoic in age and fall within the range of ca. 2.05–1.7 Ga with peaks present at 1.87 and 1.99 Ga. Late Archean ages are represented by grains in the range of 2.75–2.5 Ga.

Directions to Stop 1-2

Return on foot to vehicles and backtrack to Forest Service Road 6370. Turn left onto FSR 6370 and travel 0.4 miles to small exposures of limestone on the north side of the road (UTM coordinates 307590E, 4891144N).

Stop 1-2. Upper Triassic Rail Cabin Argillite at Graylock Butte

Here we will make a brief stop to examine bioclastic limestone and calcareous quartzose sandstones and pebble conglomerates of the Rail Cabin Argillite (Fig. 2A). In this area, Upper Triassic and Lower Jurassic rocks that rest on the Vester Formation consist of a relatively thin (~760 m) succession of shallow-water facies including limestone lenses containing well-preserved specimens of *Halorella* that suggest shoaling of the former deep-marine setting (Brown and Thayer, 1977). Correlative rocks on the east side of the Poison Creek fault approach 10,000 m in thickness, thus syn-depositional faulting along the Poison Creek fault appears to have exerted a major structural control on deposition, with uplift in the west and subsidence in the east during Late Triassic to Early Jurassic time (Brown and Thayer, 1977; Dickinson and Thayer, 1978).

Sandstone and pebble conglomerate samples at this locality contain distinctive quartz grains and clasts that display a wide range of sedimentary and metamorphic fabrics. These include grains of quartz arenite sandstone, recrystallized quartz displaying polygonal grain boundaries and stretched and flattened fabrics (i.e., stretched metamorphic quartz). These types of quartz grains and clasts are also present in sediments of the Aldrich Mountains Group east of the Poison Creek fault (Fields Creek Formation), but they are not observed in the underlying Vester Formation. This suggests erosion of a metamorphic source area, and supports a model for progressive regional orogenesis in the Baker terrane during Upper Triassic and Lower Jurassic time (i.e., Dorsey and LaMaskin, 2007; LaMaskin et al., 2008).

Directions to Stop 1-3

Continue traveling east on FSR 6370 4.1 miles to prominent exposures on the north side of the road (UTM coordinates 311540E, 4889821N).

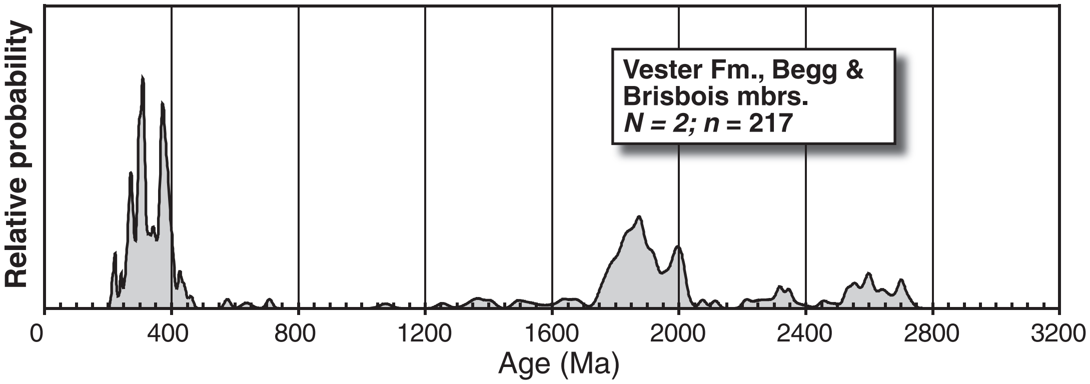


Figure 5. Combined detrital-zircon age distributions from the Begg (n = 105) and Brisbois (n = 112) members of the Vester Formation, representative of megasequence-1 rocks. Data from LaMaskin (2009).

Stop 1-3. Upper Triassic Fields Creek Formation (Aldrich Mountains Group) Bouldery Mudstone and Olistostromal Slide Blocks

We have crossed over the Poison Creek fault (poorly exposed in this area) and passed into exposures of the Fields Creek Formation, the lower unit of the Aldrich Mountains Group (Fig. 2). Rocks at this stop include an anomalous unit of bouldery mudstone and olistostromal slide blocks of limestone and quartz sandstone-conglomerate. To the north, exposures of the Fields Creek Formation are more typical and include thin- to medium-bedded turbidite sandstones.

The Aldrich Mountains Group rests locally in depositional contact on serpentinite-matrix mélange of the Baker terrane (Fig. 2; Dickinson and Thayer, 1978). The Fields Creek Formation (~4500 m) is a thick turbiditic succession of fine-grained sandstone and black shale with slide breccias and olistostromes of igneous and sedimentary rock types in the lower part (Brown and Thayer, 1977; Dickinson and Thayer, 1978). Radiolarian faunas from the Fields Creek Formation indicate a Late Triassic, Norian age and suggest reworking of older Middle to Late Triassic deposits (Blome et al., 1986; Yeh, 1989). The uppermost unit of the Aldrich Mountains Group is the Keller Creek Shale (~1500 m) which includes volcaniclastic greywacke and is Early Jurassic in age (Brown and Thayer, 1977; Imlay, 1986).

A large olistostromal block of quartzose sandstone and conglomerate is present just past where the road turns to the south (when driving east). The lithology is identical to sandstone and conglomerate in the Rail Cabin Argillite west of the Poison Creek fault (Stop 1-2). Quartzose grains and clasts display a wide range of sedimentary and metamorphic fabrics. Other basal sections of the Fields Creek Formation along Fields Creek road to the north contain slide blocks and olistostromes of plutonic rocks identical to small plutons in the Baker terrane (Carpenter and Walker, 1992; LaMaskin, 2009). These relationships and recycled radiolarian faunas (Blome, 1984; Yeh, 1989) show that the Fields Creek Formation was eroded from both the uplifted Baker terrane and from Triassic sedimentary rocks of the Rail Cabin Argillite, and deposited in a complex fault-bounded basin at the margin of a large active thrust belt (Baker terrane).

Directions to Stop 1-4

Continue traveling due east on FSR 6370 ~3.4 miles to outcrops of gray calcareous sandstone on the north side of the road (UTM coordinates 314780E, 4889265N). Fossil-bearing outcrops are present at ~3.4 to 3.7 miles from Stop 1-3.

Stop 1-4. Lower Jurassic Suplee Formation—Fossil Collecting Locality

We have now crossed over the regional unconformity between megasequence 1 and overlying sedimentary rocks of megasequence 2 (Fig. 2). Megasequence-2 deposits record a second major phase of subsidence and sedimentation in the Izee region. Sediments are dominantly volcaniclastic and were derived predominantly from inboard locations to the east and northeast (modern coordinates; Dickinson and Thayer, 1978). The basal portion of megasequence 2 consists of the transgressive, shallow- to deep-marine Mowich Group (~690 m; Brown and Thayer, 1977). We will stop to view a 10–20-m-thick, bioturbated calcareous sandstone unit in the Suplee Formation. The Suplee Formation is mainly Pliensbachian age (Imlay, 1968) and is richly fossiliferous. Numerous fossils have been collected at localities in the Suplee Formation, including ammonites, pelycypods, brachiopods, and gastropods.

Turbidite sandstone of the Hyde Formation overlies the Suplee Formation and contains abundant detrital-zircon grains (Fig. 6A). All zircon grains are Mesozoic and define a unimodal probability distribution that spans 191–172 Ma, yielding an Early Jurassic peak at ca. 180 Ma.

Directions to Stop 1-5

Continue traveling east on FSR 6370 back to the intersection with County Route 63. Turn left on Route 63 and travel ~6.1 miles. Turn left onto National Forest Road 24 and travel ~1.0 mile to prominent exposures on the east side of the road (UTM coordinates 321958E, 4894830N).

Stop 1-5. Middle Jurassic Snowshoe Formation along Wikiup Creek

The final stop of the day is in Middle Jurassic turbidites of the Snowshoe Formation (Fig. 2), stratigraphically higher within megasequence 2. The Snowshoe Formation is mainly Middle Jurassic in age (Imlay, 1986) and is dominated by volcaniclastic turbidites such as those seen at this locality. Here, interbedded mudstone, siltstone and gray sandstone are characteristic of the South Fork Member of the Snowshoe Formation (Smith, 1980). A weighted mean age of ca. 167 Ma for the youngest group of two or more detrital zircon grains overlapping at 1-sigma for this locality suggests a depositional age at the Bathonian-Bajocian boundary, consistent with the biostratigraphic age of the South Fork Member (Smith, 1980; Imlay, 1986; LaMaskin, 2009).

Detrital-zircon grains from this locality are both euhedral-prismatic, clear-colorless and sub-rounded, pink to yellow grains. The sample includes ~64% Mesozoic, 5% Paleozoic, and 31% Precambrian ages (Fig. 6B). Mesozoic-age zircons form a complex, multimodal age distribution with peaks and shoulders in relative probability between 207 and 168 Ma. Abundant Mesoproterozoic grains define peaks at ca. 1.46, 1.29, 1.15 and 1.04 Ga. A Paleoproterozoic peak is present at ca. 1.84 Ga. Additional sandstone samples collected from megasequence-2 turbidite sandstone of the Lonesome Formation yield detrital-zircon ages similar to those found in the Snowshoe Formation (Fig. 6C). Precambrian grains are dominated by Neoproterozoic and Mesoproterozoic ages with fewer Paleoproterozoic and only scattered Archean ages. A comparison of Precambrian detrital-zircon ages from the Triassic Vester Formation to the Jurassic Snowshoe and Lonesome formations indicates the clear difference in provenance between outboard-derived sands (Vester Formation) and inboard-derived sands (Fig. 7; Snowshoe and Lonesome formations).

End of Day 1.

DAY 2

Directions to Stop 2-1

From John Day, drive east on E. Main Street/U.S.-26 and continue for 30.8 miles to the northeast. Turn left at National Forest Development Road (NFD) 2600-437. Drive 1.2 miles. Turn right (north) on NFD 369. Drive 0.5 miles and park at intersection with NFD 352. Hike 0.15 miles N30°E to NFD 301 (UTM coordinates 370710E, 4932988N).

Stop 2-1. Basal Section of the Dixie Butte Meta-Andesite Complex

At this stop, we will examine the basal section of the Dixie Butte Meta-andesite (Fig. 8). The Dixie Butte Meta-andesite is exposed over >80 km^2, making it one of the largest continuous volcanogenic complex in the Blue Mountains Province (Brooks et al., 1984; Ferns and Brooks, 1995). It consists of a lower sequence of tuffaceous sedimentary rocks and volcaniclastic breccias, and an upper sequence of flow rocks and subordinate volcaniclastic breccias and sills.

The basal portion of the Dixie Butte Meta-andesite is best exposed on Dad's Creek (this stop) and consists of ~2000–2200 ft of thick-bedded andesitic lithic tuff, lithic-clast volcaniclastic breccia, tuffaceous sandstone, graphitic argillite, and pebble conglomerate. Dominant lithic clasts in the pebble conglomerates are trachytic basaltic andesite with subordinate diorite, microdiorite, reworked lithic tuff, and fine-grained chert and argillite (Fig. 9A). Lithic clasts are subrounded to angular in

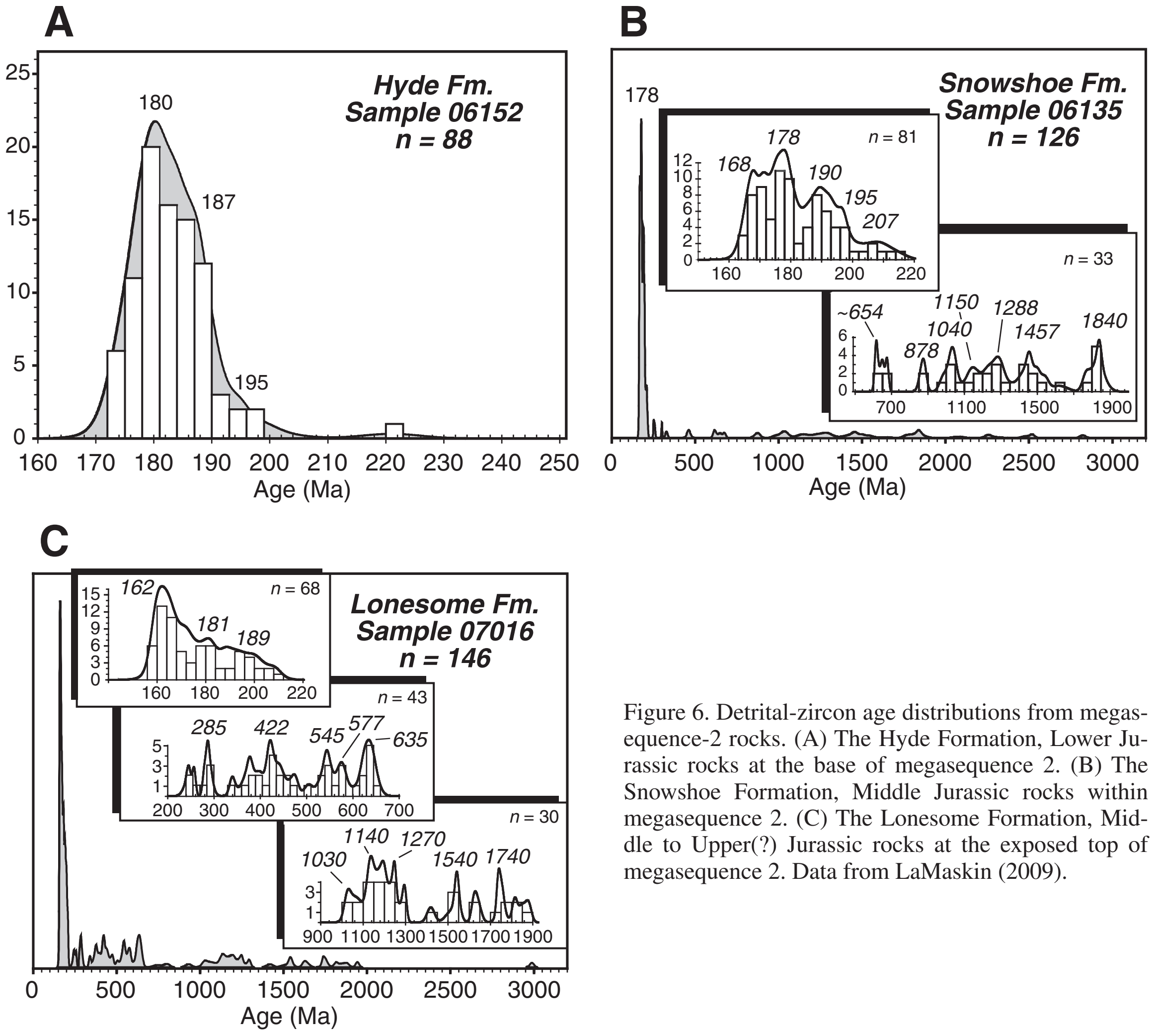


Figure 6. Detrital-zircon age distributions from megasequence-2 rocks. (A) The Hyde Formation, Lower Jurassic rocks at the base of megasequence 2. (B) The Snowshoe Formation, Middle Jurassic rocks within megasequence 2. (C) The Lonesome Formation, Middle to Upper(?) Jurassic rocks at the exposed top of megasequence 2. Data from LaMaskin (2009).

shape. Volcanogenic sandstones locally display normally graded bedding. Argillites and fine- to medium-grained sandstones grade upsection into coarser, lithic-clast volcaniclastic breccias. These rocks are in turn overlain by volcanic flows and tuffs in the upper portion of Dixie Butte (e.g., Fig. 9B; see Stop 2-4).

The relationship between Dixie Butte Meta-andesite and older units (e.g., serpentinite-matrix mélange, Badger Creek unit [Upper Triassic–Permian]) is poorly understood. Nearby chert argillites similar to those found at the base of Dixie Butte (this stop) contain Wolfcampian (i.e., Late Permian) radiolarians which provide a maximum age for the Dixie Butte Meta-andesite complex. Middle to Late Jurassic plutons (Stop 2-2) intrude the Dixie Butte Meta-andesite. Together these relationships suggest an age between Late Permian and Middle to Late Jurassic. Ongoing detrital zircon work and targeted U-Pb zircon dating of andesites are aimed at further constraining the age of the Dixie Butte Meta-andesite complex.

Directions to Stop 2-2

Backtrack to U.S.-26. Turn left and continue 2.1 miles northeast. Turn left at NFD 2610. Drive 150 feet and turn left at NFD 096. Continue 0.9 miles (UTM coordinates 372006E, 4933394N).

Stop 2-2. Dixie Summit Pluton: 162 Ma, Low Sr/Y Magmatism

At this stop, we will examine the Dixie Summit pluton in the eastern portion of the Dixie Butte area (Fig. 8), where late Middle Jurassic plutonic rocks intrude serpentinite-matrix mélange and volcanic and related rocks of the Dixie Butte Meta-andesite complex. The Dixie Summit pluton ranges in composition from gabbro to quartz diorite, and contains the following primary igneous mineral phases: clinopyroxene + plagioclase feldspar ± orthopyroxene ± zircon ± apatite. Ophitic texture is common in gabbroic and dioritic samples (e.g., Fig. 9C). The primary igneous minerals are extensively altered at and/or near dike and dikelet contacts by secondary minerals such as chlorite, calcite, albite, or actinolite.

Geochemically, the Dixie Summit plutonic rocks are metaluminous, magnesian, and calcic as defined by the classification of Frost et al. (2001) and Frost and Frost (2008). They display high Al_2O_3 (>19 wt%), CaO (>10 wt%) and positive Eu anomalies suggestive of plagioclase accumulation. They also display slight light rare earth element (LREE) enrichment (La/Lu < 30) and low Sr/Y (<26) values. A diorite from this location yielded a Pb/U age of 162.0 ± 2.9 Ma (J. Schwartz, unpublished data).

Several features suggest a possible consanguineous relationship between the Dixie Summit pluton and the Dixie Butte Meta-andesite. Potential comagmatic relationships include: (1) the intrusion of 162 Ma gabbro-diorite of the Dixie Summit pluton into basaltic andesite; (2) fragments of gabbro, diorite, and microdiorite in lithic-clast volcaniclastic breccias throughout the Dixie Butte Meta-andesite; (3) intrusion of fine-grained plagioclase-phyric meta-andesites dikes and dikelets into the Dixie Summit pluton and other similar-age plutons at 161.6 ± 2.0 Ma (J. Schwartz, unpublished data); and (4) complementary positive Eu anomalies in the Dixie Summit and negative Eu anomalies in the Dixie Butte Meta-andesite as well as other major-element and trace-element geochemical characteristics

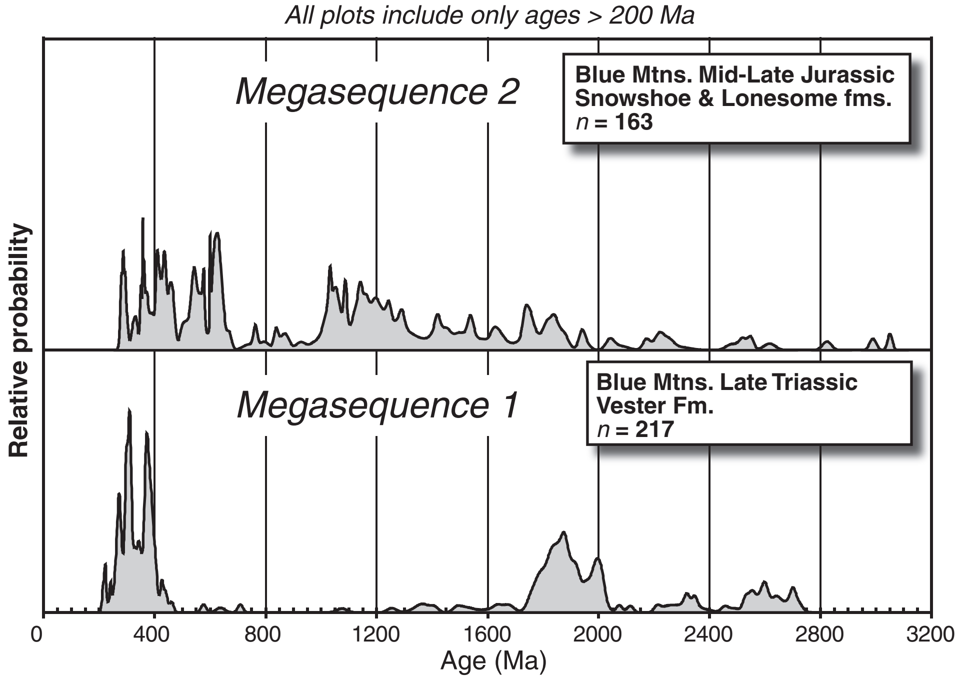


Figure 7. Comparison of >200 Ma detrital-zircon age distributions from megasequence-1 and megasequence-2 rocks. Note the dramatic difference between detrital-zircons derived from the outboard Baker terrane (megasequence 1) and from inboard locations (megasequence 2). Data from LaMaskin (2009). Megasequence-2 plot includes unpublished data from the Lonesome Formation provided by J. Wright.

suggestive of a cogenetic relationship (compare with Dixie Butte Meta-andesite geochemical data: Stop 2-4).

Other Middle to Late Jurassic plutons in the Dixie Butte area display similar geochemical characteristics to the Dixie Summit pluton (e.g., small plutons and plugs north of Dixie Creek); however, along Standard Creek, a Late Jurassic pluton dated at 157.7 ± 1.5 Ma (Parker et al., 2008) displays ferroan and alkalic geochemical characteristics, suggestive of at least two distinct sources for Middle-Late Jurassic magmatism and/or different modes of differentiation (open-versus closed-system) in the Dixie Butte area.

Directions to Stop 2-3

Backtrack to U.S.-26. Turn right and continue 9.0 miles southwest. In Prairie City, turn right at NW Johnson Avenue which becomes Dixie Creek Road. Continue 4.6 miles (UTM coordinates 364462E, 4931445N).

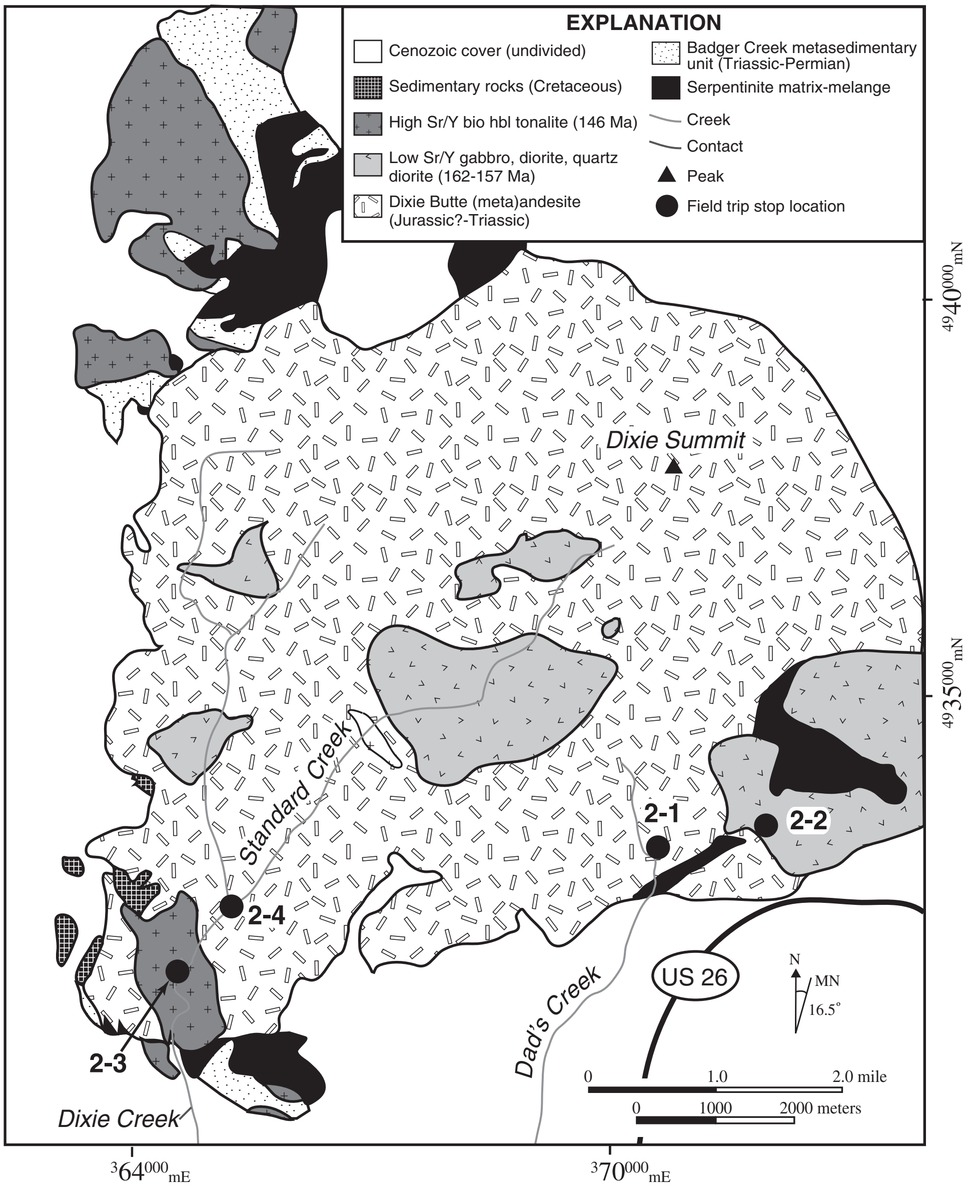


Figure 8. Geologic map of the Dixie Butte area, Greenhorn subterrane of the Baker terrane, showing location of field-trip stops for Day 2. Dixie Butte (meta)andesites and related volcaniclastic rocks are intruded by two geochemically distinct suites of low Sr/Y plutons at ca. 162–157 Ma, and high Sr/Y plutons at ca. 146 Ma. Modified from Brooks et al. (1984).

Stop 2-3. Dixie Creek Pluton: 146 Ma High Sr/Y Magmatism

At this stop, we will examine the Dixie Creek pluton, which is characteristic of latest Jurassic (ca. 146 Ma) plutonism in the Greenhorn subterrane of the Baker terrane (see 146 Ma plutons in Fig. 3). The Dixie Creek pluton intrudes metavolcanic rocks of the Dixie Butte Meta-andesite and Badger Creek metasedimentary unit (Ferns and Brooks, 1995), which contains Permian–Late Triassic fauna (Brooks et al. 1984; Ferns and Brooks, 1995). The Dixie Creek pluton consists of biotite-hornblende tonalite with minor K-feldspar and accessory zircon, sphene, and apatite (e.g., Fig. 9D). Graphic intergrowths of quartz and plagioclase are common in some rocks. Secondary (deuteric?) alteration of biotite to chlorite is typical, but minor, in samples of this plutonic unit.

In contrast to the 162–157 Ma plutons in the Dixie Butte area, the Dixie Creek pluton is more compositionally restricted (Figs. 4A and 4B), and much less affected by low-temperature (greenschist-facies) metamorphism. Dixie Creek plutonic rocks displays steeply fractionated REE patterns (Fig. 4C), lack Eu anomalies, and have elevated Sr concentrations and Sr/Y values (typically >600 ppm and >40, respectively; Fig. 4D). These features are fundamentally distinct from the older, low Sr/Y 162–157 Ma suite, and represent a change in the character of magmatism following regional contraction at 159–154 Ma (Schwartz and Snoke, 2008).

Directions to Stop 2-4

Drive 0.8 miles north along Dixie Creek Road until road forks. Park (UTM coordinates 365140E, 4932498).

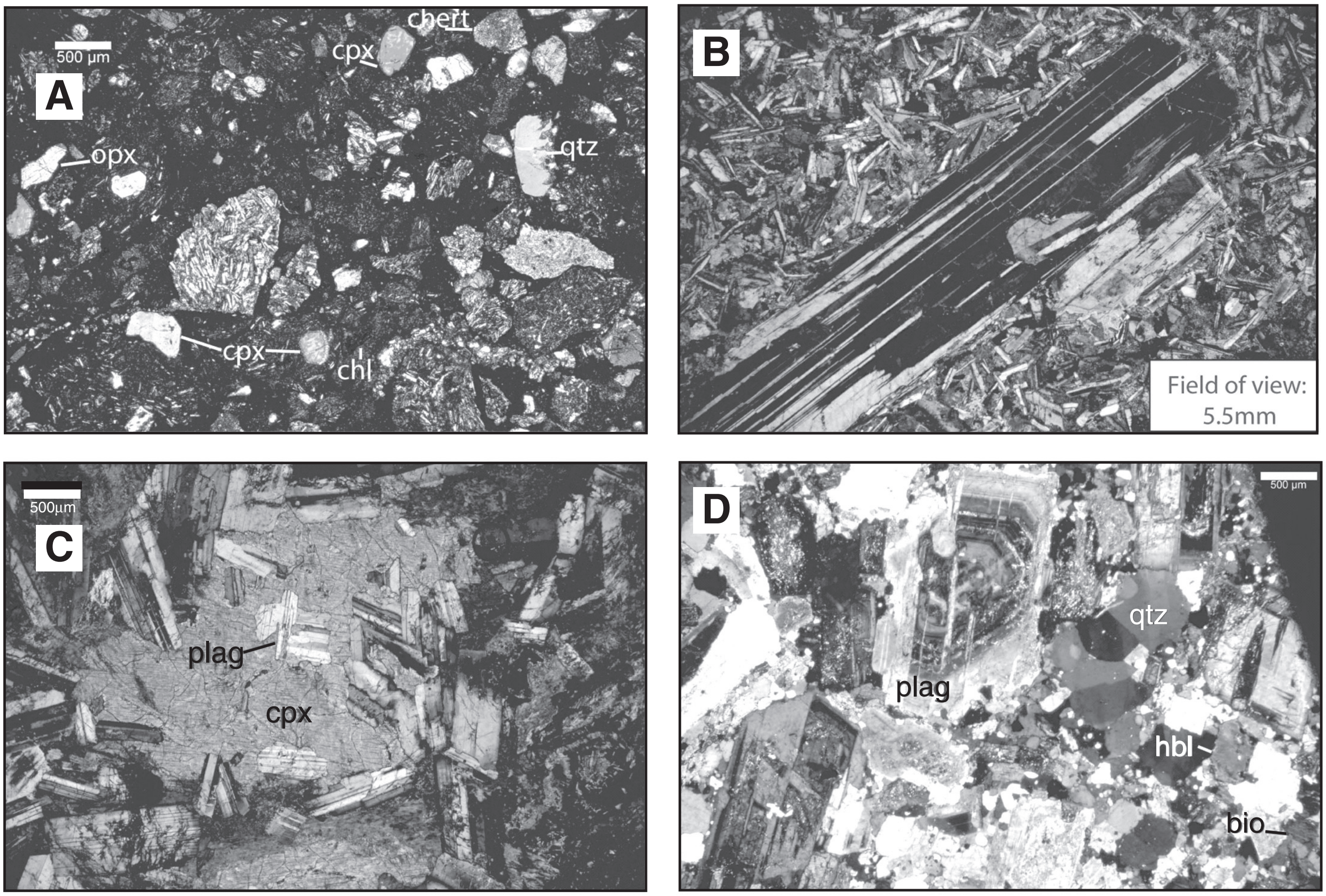


Figure 9. Photomicrographs of metavolcanic and plutonic rocks of the Dixie Butte area. (A) Crystal lithic-clast volcaniclastic breccia contains abundant angular to subrounded trachytic basaltic andesite clasts and detrital augite and plagioclase, with minor chert, graphitic argillite, orthopyroxene, quartz, and carbonate grains. (B) Representative example of the Dixie Butte Meta-andesite flow rock displaying porphyritic texture consisting of large plagioclase phenocrysts in a fine-grained matrix of clinopyroxene and plagioclase microlites. (C) Dixie Summit diorite (ca. 162 Ma) displays ophitic texture with resorbed (?) plagioclase surrounded by clinopyroxene. (D) Dixie Creek biotite-hornblende tonalite (ca. 146 Ma) has seriate texture consisting of large plagioclase feldspar and quartz with minor hornblende and biotite.

Stop 2-4. Volcanic Rocks of the Dixie Butte Meta-Andesite Complex

At this stop, we will examine representative volcanic rocks of the Dixie Butte Meta-andesite. This outcrop consists of trachytic plagioclase-phyric basaltic andesite, and is characteristic of the upper section of the Dixie Butte Meta-andesite. Locally, the upper section consists of green to gray, plagioclase- and augite-phyric basaltic andesite and andesite flows, subordinate volcaniclastic breccias, keratophyre, dark-gray basalt, and pale-green silicic flows and tuffs (Brooks et al., 1984; Ferns and Brooks, 1995). The primary igneous mineral phases of the volcanic rocks are plagioclase and augite ± orthopyroxene ± quartz (e.g., Fig. 9B). Vesicles are common in some rocks and are typically filled with calcite, quartz, and/or chlorite. No pillow structures have been observed. Alteration is typically less intense than other areas of the Greenhorn subterrane (e.g., Ferns and Brooks, 1995) and is highly localized at the meter scale. Low-grade metamorphism of these rocks may be related to hydrothermal fluid flow associated with Jurassic and/or Tertiary magmatism in the area (Mark Ferns, 2008, personal commun.). Alteration minerals include: chlorite + albite + calcite + actinolite. Flow rocks and volcaniclastic breccias in the upper section are intruded by fine-grained microgabbro and microdiorite sills and dikes with chilled margins. Andesitic and silicic dikes locally crosscut flows, sills, and tuffaceous rocks, as well as the late Middle Jurassic (ca. 162 Ma) plutonic rocks (see Stop 2-2). One such dike was dated at ca. 162 Ma (see Stop 2-2). No dikes have been are observed cross-cutting the 146-Ma high Sr/Y plutons.

Geochemically, volcanic rocks of the Dixie Butte Meta-andesite range from ~53 to 56 wt% SiO_2 and are characterized by high Al_2O_3 (16–22 wt%), CaO (6–10 wt%) and Y (16–27 ppm), Ni (70–190 ppm), and Cr (150–480 ppm) values, moderate TiO_2 (1.0–1.5 wt%) and MgO (3–9 wt%) values, and low Sr (<365 ppm), Nb (<9 ppm), Sr/Y (<16) and La/Lu (<40) values. Overall, these geochemical features are similar to late Middle Jurassic (162 Ma) plutons in the Dixie Butte area (e.g., Stop 2-2).

ACKNOWLEDGMENTS

Funding for our research in the Blue Mountains Province has been provided by the National Science Foundation to Dorsey (EAR-0537691), Vervoort (EAR-0537913), and Snoke and C.D. Frost (EAR-0711470). LaMaskin acknowledges grants from the Geological Society of America, Sigma Xi, and University of Oregon. Jim Wright (University of Georgia) provided additional data from the Lonesome Formation for use in Figure 7. This manuscript benefited from constructive and insightful reviews by Cal Barnes, Mark Ferns, and the GSA editorial staff.

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MANUSCRIPT ACCEPTED BY THE SOCIETY 26 JUNE 2009

Printed in the USA