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# *Nd and Sr isotopic data from argillaceous rocks of the Galice Formation and Rattlesnake Creek terrane, Klamath Mountains: Evidence for the input of Precambrian sources*

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## ABSTRACT

**Nd and Sr isotopic data are presented for argillaceous rocks from two terranes in the Klamath Mountains: the western Klamath terrane and Rattlesnake Creek terrane. In the collage of terranes exposed in the Klamath Mountains, these terranes are located farthest outboard from the North American craton and include (meta)igneous rocks of clear oceanic affinity. Nevertheless, the argillaceous rocks from these terranes preserve a strong isotopic signal of terrigenous sedimentary input. The lowermost portion of the Rattlesnake Creek terrane, the serpentinite-matrix mélange, is interpreted to have formed within an oceanic fracture zone. The argillaceous sediment incorporated into this tectonic assemblage was probably derived partly from eolian dust eroded from the continents and partly from local juvenile detritus shed from topographic highs along the fracture zone. The Upper Triassic–Lower Jurassic "cover sequence" of the Rattlesnake Creek terrane has been interpreted as an oceanic-arc assemblage, but the argillaceous rocks of the cover sequence have the most negative $\varepsilon_{Nd}$ (–8.3) and radiogenic $^{87}Sr/^{86}Sr$ (0.7114) of any samples analyzed in this study. We infer that cratonic sediment was delivered to the depocenter of the Rattlesnake Creek terrane arc, probably transported by river systems. This situation suggests proximity to a continental landmass during arc magmatism. The Galice Formation, a thick turbiditic sequence above the Late Jurassic Josephine ophiolite, appears to be composed of detritus shed from both the Rogue–Chetco oceanic arc on the west (in present geographic coordinates) and previously accreted Klamath Mountains terranes and/or North American craton to the east. The continental isotopic signal is stronger in the argillaceous rocks than in the (meta)graywackes, suggesting that the finer-grained rocks contain a greater proportion of cratonic debris, material that may have been**

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**reduced to mud-sized particles during sediment recycling. The presence of continental-derived sediment in these otherwise ensimatic terranes indicates that although continental crustal growth by accretion of oceanic terranes is an important process, such accreted terranes commonly are not composed entirely of juvenile crust.**

**Keywords:** Nd isotopes, continental crustal growth, Rattlesnake Creek terrane, western Klamath terrane, Galice Formation, Jurassic

## INTRODUCTION

An important mechanism of continental crustal growth during at least the past 2.5 billion years is accretion of juvenile terranes of oceanic affinity to the margins of continents. Large amounts of juvenile crust have been documented within the 1.95- to 1.65-Ga terranes of North America, Greenland, and northern Europe, 1.2- to 1.0-Ga Grenville orogenic belt, Arabian-Nubian shield, and the Proterozoic crust of Australia (see Samson and Patchett, 1991, and references therein). Phanerozoic examples of crustal addition by terrane accretion include the western North American Cordillera (Coney et al., 1980; Silberling et al., 1987; Armstrong, 1988; Samson and Patchett, 1991; Creaser et al., 1997; Patchett and Gehrels, 1998; Unterschutz et al., 2002), Appalachians (e.g., Secor et al., 1983), New Zealand (Frost and Coombs, 1989), and other less well-documented examples. Nd and Sr isotopic studies in the Canadian Cordillera and New Zealand have shown that parts of these collages include terranes that are composed almost entirely of oceanic rocks that formed from mantle sources, such as Stikine, Wrangellia, and Alexander terranes of the Canadian Cordillera and Brook Street terrane of New Zealand. As such, these terranes provide unequivocal evidence for Phanerozoic continental crustal addition. Other terranes within these collages are composed of rocks that reflect a mixture of juvenile and continental sources, and modeling the amount of continental crustal growth represented by these terranes is complex.

The Klamath Mountains of northwestern California and southeastern Oregon preserve a collage of tectonostratigraphic terranes of oceanic affinity and thus are a significant site of Phanerozoic crustal growth in the U.S. Cordillera. Isotopic studies of intrusive igneous rocks of the Klamath Mountains show that these magmatic rocks are juvenile (e.g., Paleozoic plutons in the eastern Klamath terrane: Petersen et al., 1991; Wallin and Metcalf, 1998; Middle Jurassic Ironside Mountain batholith: Barnes et al., this volume, Chapter 10) or have significant juvenile components (e.g., late Middle Jurassic "Wooley Creek belt" plutons; Masi et al., 1981; Barnes et al., 1990, 1992a, 1995; Gribble et al., 1990). However, isotopic data from (meta)sedimentary rocks of the terranes in the Klamath Mountains are also critical in terrane affinity and accretion history. Even in terranes that chiefly include isotopically juvenile igneous rocks, the (meta)sedimentary rocks may have more complex provenance that includes substantial recycled crustal components (e.g., Patchett and Gehrels, 1998).

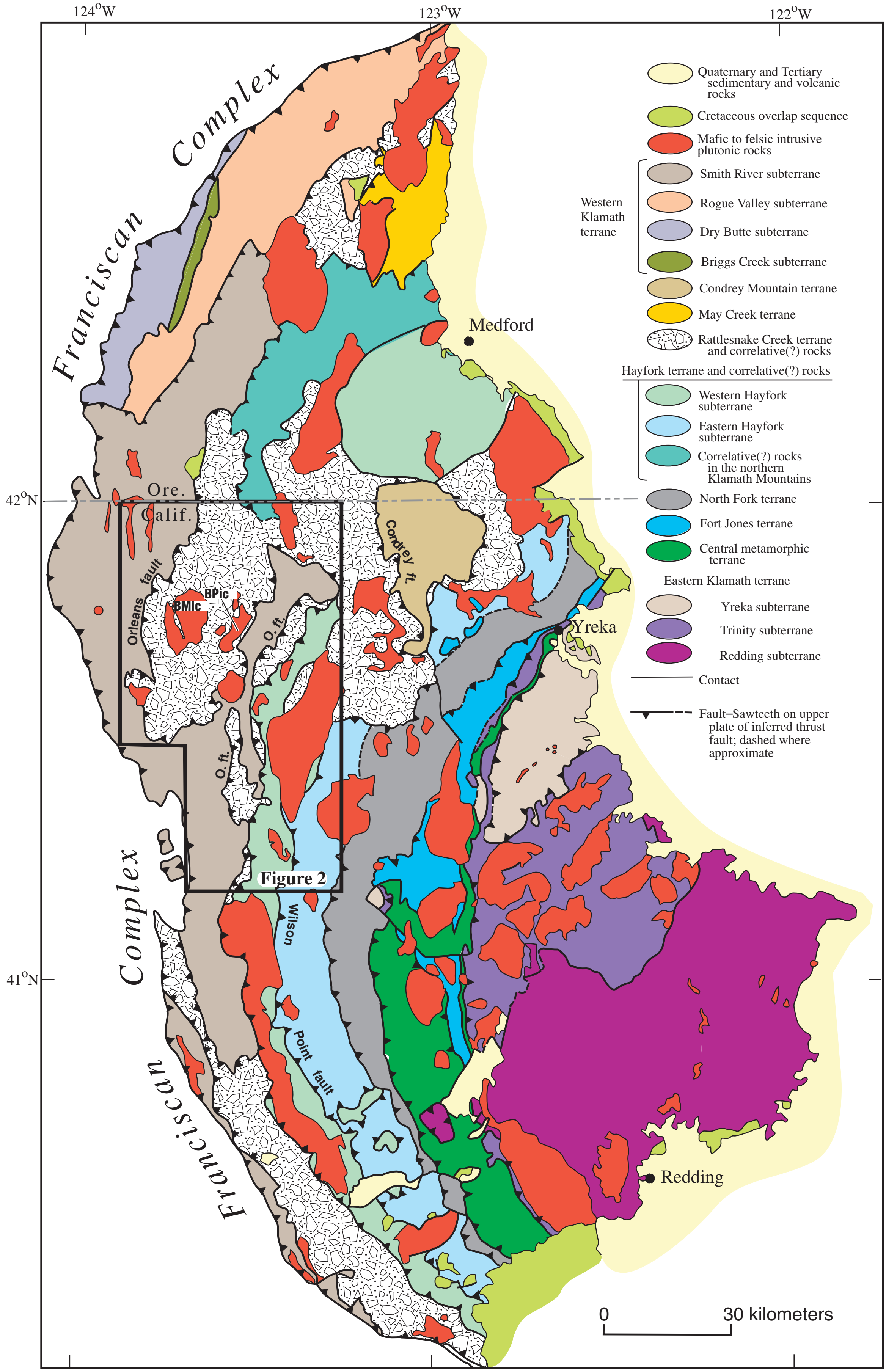
The present study provides the first extensive Sr and Nd isotopic data set for metasedimentary rocks from the Klamath Mountains. We have chosen to focus on two of the terranes that lie farthest outboard from the North American craton, which are composed almost entirely of rocks of clear oceanic affinity. The first, the western Klamath terrane, includes the Josephine ophiolite and overlying turbiditic sequence of the Upper Jurassic Galice Formation. The second, the Rattlesnake Creek terrane, has been interpreted as initially forming in an oceanic fracture zone setting upon which a younger (Late Triassic–Early Jurassic) oceanic arc was built. As such, both settings are candidate sites of new crust formation. Nevertheless, our results show that sediment of continental origin is present in argillaceous rocks of both terranes. The presence of continental detritus in these oceanic terranes is significant in terms of the paleogeographic and tectonic positions of the terranes, the origins of their detrital sediments, and their contribution to Phanerozoic continental crustal growth.

## GEOLOGIC SETTING

The Klamath Mountains of northwestern California and southwestern Oregon are a tectonic collage of tectonostratigraphic terranes of oceanic affinity imbricated along regional thrust faults (Irwin, 1972, 1994). Roughly, the age of thrust faulting is younger from east to west (Fig. 1), from the mid-Paleozoic through the Late Jurassic (Davis et al., 1978; Irwin and Wooden, 1999). During the Early Cretaceous, the westernmost thrust, the South Fork fault, emplaced the Klamath Mountain province above Jurassic and Cretaceous rocks of the Coast Ranges, including the South Fork Mountain Schist of the Pickett Peak terrane. Argillaceous rocks are abundant in many of the terranes of the Klamath Mountains and are especially widespread in the Upper Jurassic Galice Formation of the western Klamath terrane as well as within the Rattlesnake Creek terrane.

The argillaceous rocks of both the Galice Formation and Rattlesnake Creek terrane apparently formed in close spatial and temporal association with oceanic arcs, but in contrasting

Figure 1. Geologic sketch map of the tectonostratigraphic terranes of the Klamath Mountains province, California and Oregon. The area of Figure 2 is outlined. BMic—Bear Mountain intrusive complex, BPic—Bear Peak intrusive complex. Modified from Irwin (1994).



124°W
123°W
122°W
42°N
41°N
Franciscan Complex
Franciscan Complex
Ore.
Calif.
Medford
Yreka
Redding
Orleans fault
BMic
BPic
O. ft.
O. ft.
Condrey ft.
Wilson Point fault
Figure 2
0
30 kilometers
Quaternary and Tertiary sedimentary and volcanic rocks
Cretaceous overlap sequence
Mafic to felsic intrusive plutonic rocks
Western Klamath terrane
Smith River subterrane
Rogue Valley subterrane
Dry Butte subterrane
Briggs Creek subterrane
Condrey Mountain terrane
May Creek terrane
Rattlesnake Creek terrane and correlative(?) rocks
Hayfork terrane and correlative(?) rocks
Western Hayfork subterrane
Eastern Hayfork subterrane
Correlative(?) rocks in the northern Klamath Mountains
North Fork terrane
Fort Jones terrane
Central metamorphic terrane
Eastern Klamath terrane
Yreka subterrane
Trinity subterrane
Redding subterrane
Contact
Fault–Sawteeth on upper plate of inferred thrust fault; dashed where approximate

settings with regard to coeval arc magmatism. The Galice Formation is a thick Upper Jurassic turbidite sequence above the Late Jurassic Josephine ophiolite and equivalent sequences (e.g., Devils Elbow ophiolite remnant; Wyld and Wright, 1988). In the Oregon Klamath Mountains, the Galice Formation interfingers with volcanogenic rocks of the Rogue–Chetco oceanic arc (Garcia, 1979; Harper, 1983), which is also stratigraphically above the Josephine ophiolite. The age of the Galice Formation is constrained to be younger than the youngest population of detrital zircons it contains (ca. 153 Ma; Miller et al., 2003), yet older than the 151 ± 2- and 150 ± 2-Ma dikes that intrude it (Saleeby et al., 1982). Paleontological data indicate that the Galice Formation is Middle Oxfordian–Lower Kimmeridgian, based on *Buchia concentrica* (Sowerby) (Diller, 1907; Imlay, 1959, 1980). The depositional setting of the Galice Formation has been commonly interpreted to be in an inter-arc or back-arc basin (Snoke, 1977; Harper, 1980; Harper and Wright, 1984), and the structural development of this basin may be related to transtensional deformation within an older, west-facing, oceanic-arc terrane (Harper et al., 1985). This rifted, older arc terrane includes Rattlesnake Creek terrane basement (Donato et al., 1996; Yule, 1996), the Middle Jurassic western Hayfork arc sequence, and late Middle Jurassic calc-alkalic plutons (e.g., Barnes et al., 1992b). In this light, the source of Galice detritus could be from the rifted older arc and/or late Middle Jurassic igneous rocks, the coeval arc (Rogue–Chetco arc), or from still older previously accreted terranes of the Klamath Mountains.

The provenance of Galice detritus was first addressed by Snoke (1977), who studied the petrography of the metagraywackes of the Galice Formation, including the detrital, heavy-mineral assemblage. Snoke (1977) concluded that a substantial amount of the detritus in the metagraywackes of the Galice Formation could be derived from older, more easterly terranes of the Klamath Mountains. This conclusion was supported by Harper (1983, 1984) and Park-Jones (1988), who also noted a diverse heavy mineral assemblage as well as paleocurrent indicators of eastward derivation of the bulk of the detritus. These authors also recognized juvenile volcaniclastic debris presumably derived from the coeval Rogue–Chetco oceanic arc, west of the Galice basin.

In the southwestern Klamath Mountains, Wright and Wyld (1986) reported xenocrystic zircon in plagiogranite of the Devils Elbow ophiolite remnant (the southern continuation of the Josephine ophiolite). This finding was the first evidence of recycled cratonic detritus in a Klamath Mountain ensimatic environment, in this case, a supra-subduction ophiolite. Miller and Saleeby (1987, 1995) then showed that metagraywackes of the Galice Formation contain detrital Precambrian zircons with an average upper intercept of 1583 Ma, with the oldest $^{207}$Pb/$^{206}$Pb age at 2079 Ma. Recently, Miller et al. (2003) also found sparse Precambrian detrital zircons in the metagraywackes of the Galice Formation using ion probe U-Pb dating. In summary, a substantial body of diverse data links the tectonic setting of the Galice Formation to previously accreted terranes of the Klamath Mountains and to the coeval fringing Rogue arc. Detrital zircon geochronologic studies establish these same links, but also indicate the presence of Precambrian-age detritus whose origins are uncertain.

In contrast to the Galice Formation, little is known about the provenance of Rattlesnake Creek terrane metasedimentary rocks. The Rattlesnake Creek terrane was defined by Irwin (1972) as an ophiolitic mélange. However, Wright and Wyld (1994) recognized a pseudostratigraphy within the terrane, consisting of a disrupted oceanic assemblage (serpentinite-matrix mélange) overlain by coherent Upper Triassic and Lower Jurassic metavolcanic and metasedimentary rocks, which they referred to as a "cover sequence." The contact between the underlying serpentinite-matrix mélange and overlying cover sequence was interpreted as an unconformity, although this contact is commonly overprinted by brittle faulting. Wright and Wyld (1994) also documented a diverse suite of intrusive rocks (gabbroic to quartz dioritic) that intrude the mélange and cover sequence; these plutonic rocks range in age from 207 to 193 Ma (U-Pb zircon).

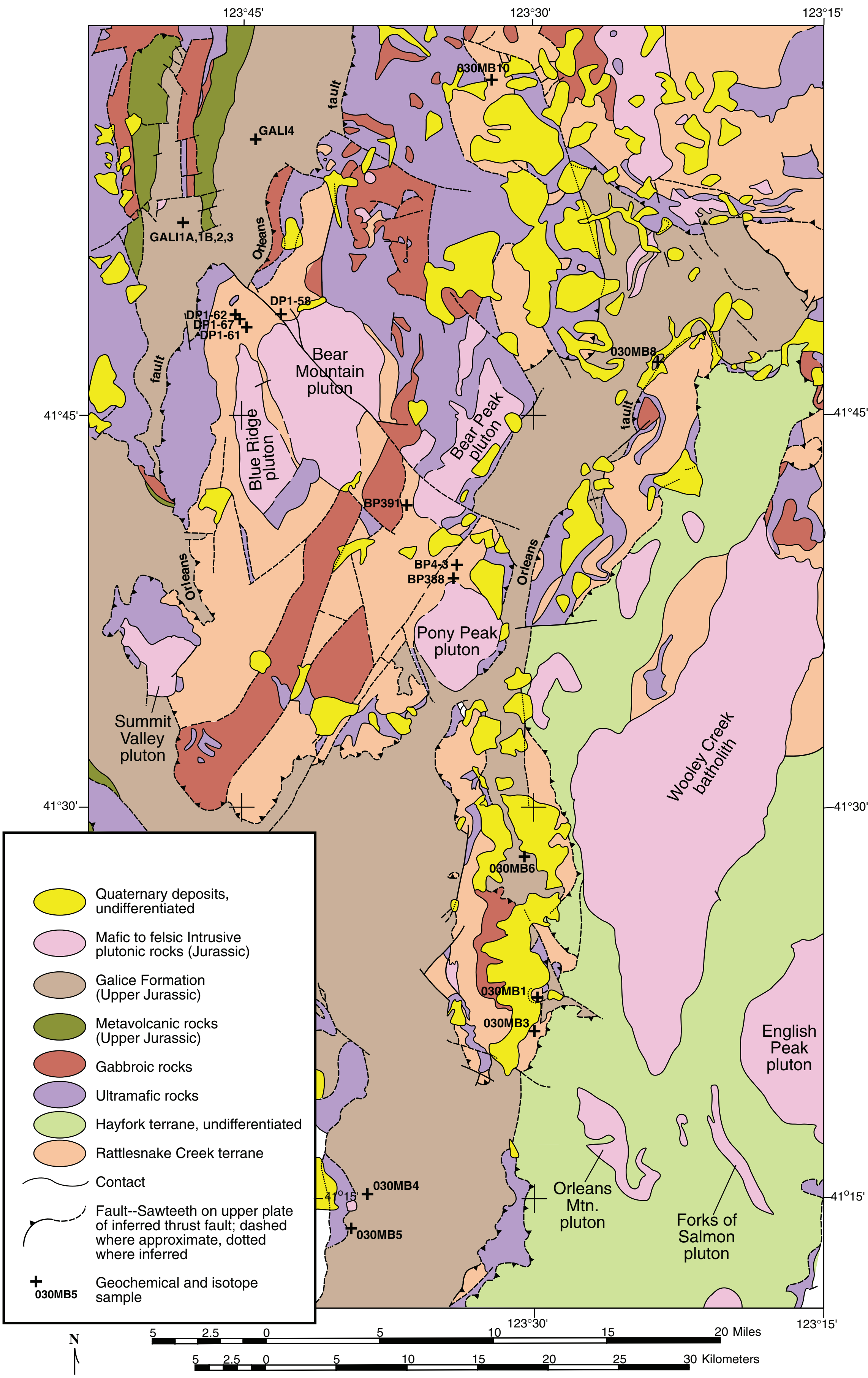
Wright and Wyld (1994) argued that the serpentinite-matrix mélange unit formed in an oceanic fracture zone setting, whereas the overlying coherent cover sequence is an oceanic-arc sequence related to eastward-dipping subduction. The paleogeographic setting of this oceanic arc was inferred to be near western North America on the basis of terrigenous detritus in Rattlesnake Creek terrane wackes, arenites, and coarser-grained detrital rocks.

In summary, the Galice Formation and Rattlesnake Creek terrane are assemblages of rocks that clearly developed in oceanic or ensimatic settings. However, both units also appear to reflect proximity to a continental margin that was a source of terrigenous sedimentary input, including sediments with ancient cratonic origins.

## SAMPLES

Geochemical and isotopic data were obtained on nine argillaceous rock samples from the Galice Formation and ten meta-argillite samples from the Rattlesnake Creek terrane. Sample locations were chosen to provide a broad geographic distribution and are summarized in Figure 2 with geographic coordinates listed in the Appendix. We also attempted to obtain samples from different stratigraphic levels within these units, but complex folding and faulting preclude a detailed determination of stratigraphic position.

Figure 2. Generalized geologic map of the north-central Klamath Mountains, California, showing the approximate locations of samples analyzed in this study. The base for this sample-location map is Wagner and Saucedo (1987).



123°45'
123°30'
123°15'
41°45'
41°30'
41°15'
fault
Orleans
GALI4
GALI1A,1B,2,3
DP1-58
DP1-62
DP1-67
DP1-61
Bear Mountain pluton
Blue Ridge pluton
Bear Peak pluton
BP391
BP4-3
BP388
Pony Peak pluton
Summit Valley pluton
030MB10
030MB8
030MB6
030MB1
030MB3
030MB4
030MB5
Wooley Creek batholith
English Peak pluton
Orleans Mtn. pluton
Forks of Salmon pluton
Quaternary deposits, undifferentiated
Mafic to felsic Intrusive plutonic rocks (Jurassic)
Galice Formation (Upper Jurassic)
Metavolcanic rocks (Upper Jurassic)
Gabbroic rocks
Ultramafic rocks
Hayfork terrane, undifferentiated
Rattlesnake Creek terrane
Contact
Fault--Sawteeth on upper plate of inferred thrust fault; dashed where approximate, dotted where inferred
Geochemical and isotope sample
N
5 2.5 0 5 10 15 20 Miles
5 2.5 0 5 10 15 20 25 30 Kilometers

### *Galice Formation*

Argillaceous rocks from the Galice Formation are typically dark gray to black slates to phyllites, locally pyrite bearing. The samples are listed in Tables 1 and 2 from north to south, geographically. Sample GALI4 was collected in the drainage of the Middle Fork of the Smith River, whereas GALI1A–3 were collected in the Siskiyou Fork of the Smith River. These samples appear to represent structurally, and presumably, stratigraphically, the upper part of the Galice Formation. Sample 03OMB6 was collected along California State Highway 96 near the entrance to the Marble Mountain Ranch. Sample 03OMB4 was also collected along California State Highway 96, south of Orleans near the confluence of Slate Creek with the Klamath River; and 03OMB5 was collected along the Klamath River near the Aikens Creek campground. Both 03OMB4 and 03OMB5 are interpreted as samples near the base of the Galice Formation, and metabasaltic rocks correlated with part of the Late Jurassic Josephine ophiolite underlie the Galice Formation south of Aikens Creek campground along the Klamath River.

Sample 03OMB8 is a crenulated, graphitic phyllite from the confluence of Little Grider Creek with the Klamath River, south of the town of Happy Camp, California. The outcrop was mapped as Galice Formation by Klein (1975, 1977) and Petersen (1982) but is surrounded by Quaternary deposits. The Orleans fault or an equivalent structure lies immediately to the east of the locality; the hanging-wall block consists of a diverse suite of rocks of the Rattlesnake Creek terrane, including ultramafic and mafic rocks metamorphosed at upper greenschist- to lower amphibolite-facies conditions (Petersen, 1982). Interestingly, Klein (1977), Hill (1985), and Saleeby and Harper (1993) show complex faulting in this area with thrust slices of different lithologic character. In Figure 2 of Hill (1985), a thrust slice of rocks correlated with the Condrey Mountain terrane (Hotz, 1979; Helper, 1986) is shown sandwiched between structurally overlying rocks of the Rattlesnake Creek terrane and structurally underlying rocks of the Galice Formation (western Klamath terrane). Likewise, a regional cross-section through the area (Saleeby and Harper, 1993, their Fig. 2) shows multiple thrust slices of rocks perhaps equivalent to the Condrey Mountain terrane in the same structural position. Thus, sample 03OMB8 was collected in a structurally complex zone near a major, regional thrust fault, and its terrane affinity is not certain. This sample may be part of the Galice Formation as previously mapped (Klein, 1975, 1977; Petersen, 1982); however, it could conceivably be a rock unit related to the older Condrey Mountain terrane. Another possibility, based strictly on the phyllitic nature of the sample, is a correlation with the South Fork Mountain Schist of the Pickett Peak terrane. However, such a correlation would require the imbrication of the Pickett Peak terrane *above* the western Klamath terrane, a relationship not reported at any other locality in the Klamath Mountains.

### *Rattlesnake Creek Terrane*

Samples from the Rattlesnake Creek terrane were chosen to include meta-argillite from blocks within the serpentinite-matrix mélange as well as argillaceous units that form part of the stratigraphy of coherent metavolcanic and metasedimentary sequences (i.e., "cover sequences" after the usage of Wright and Wyld, 1994). In the west-central Klamath Mountains, Snoke (1977) mapped a distinctive conglomerate-grit unit, characterized by a diverse suite of clasts (see his Figs. 9 and 10, p. 1652). This unit is part of a coherent metavolcanic and metasedimentary sequence (his Bear Basin Road sequence), which is now considered to be a Rattlesnake Creek terrane cover sequence (Bushey et al., this volume). Several of our meta-argillite samples (DP1-58, 61, 62, and 67) from the Rattlesnake Creek terrane were collected from this unit. Other cover sequence samples include BP4-3 and BP388, collected north of the Pony Peak pluton (Fig. 2). Samples from interpreted mélange blocks include 03OMB10, collected ~1 km south of Little Grayback Mountain; BP39, a contact metamorphosed black argillite collected 0.5 km west of the Bear Peak pluton; 03OMB1 from the southeast side of Sugarloaf Mountain near the confluence of the Salmon and Klamath Rivers; and 03OMB3, collected along California State Highway 96 ~7.5 km north of Orleans, California.

## RESULTS

### *Methods*

Bulk geochemical analysis was performed at Texas Tech University by inductively coupled plasma-atomic emission spectroscopy for major elements, plus Sr, Zr, Y, Nb, Ba, Sc, Cu, Cr, and Zn. Rb was analyzed by flame emission. Nd and Sr isotopic compositions were determined at the University of Wyoming by thermal ionization mass spectrometry. Concentrations of Sm, Nd, Rb, and Sr were determined by isotope dilution on aliquots of the same sample dissolved for isotope ratio measurements. Further analytical details are given in the footnotes to Tables 1 and 2.

### *Geochemical Data*

Galice Formation and Rattlesnake Creek terrane samples have geochemical compositions typical of argillaceous rocks (Table 1), characterized by high alumina contents (all but two samples have $Al_2O_3$ between 12 and 17 wt. %). As expected, Galice argillaceous rocks have higher $Al_2O_3$ and lower $SiO_2$ contents than found in Galice Formation metagraywackes (see MacDonald et al., this volume). Although their geochemical compositions overlap considerably, it is possible to distinguish argillaceous rocks of the Galice Formation from the meta-argillites of the Rattlesnake Creek terrane. As shown in Figure 3, argillaceous rocks of the Galice Formation have generally

## TABLE 1. GEOCHEMICAL DATA FOR ARGILLACEOUS ROCKS OF THE KLAMATH MOUNTAINS, CALIFORNIA

| | | | | | | | | | | Rattlesnake Creek terrane argillites, deposited ca. 210 Ma | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Galice argillites, deposited 153 Ma | | | | | | | | | *Cover sequence* | | | | | | *Melange blocks* | | | |
| Sample | GALI4 | GALI1A | GALI1B | GALI2 | GALI3 | 030MB6 | 030MB4 | 030MB5 | 030MB8 | DP1-58 | DP1-61 | DP1-62 | DP1-67 | BP4-3 | BP388 | 030MB10 | BP391 | 030MB1 | 030MB3 |
| $SiO_2$ | 60.46 | 60.60 | 60.10 | 59.87 | 67.30 | 61.95 | 62.00 | 63.77 | 63.82 | 68.87 | 65.38 | 75.85 | 81.71 | 68.45 | 69.81 | 66.06 | 61.23 | 63.12 | 65.70 |
| $TiO_2$ | 0.82 | 0.75 | 0.72 | 0.78 | 0.62 | 0.78 | 0.81 | 0.84 | 0.66 | 0.78 | 0.68 | 0.60 | 0.28 | 0.60 | 0.82 | 0.67 | 1.03 | 0.93 | 0.67 |
| $Al_2O_3$ | 16.98 | 15.82 | 14.74 | 15.82 | 12.13 | 16.01 | 16.62 | 17.12 | 13.90 | 12.49 | 13.45 | 10.00 | 6.18 | 12.99 | 12.55 | 13.48 | 16.19 | 12.84 | 13.72 |
| $Fe_2O_3^t$ | 7.27 | 8.68 | 5.34 | 7.90 | 8.18 | 7.31 | 7.03 | 4.62 | 7.10 | 6.46 | 6.11 | 4.68 | 4.59 | 5.77 | 5.80 | 5.92 | 6.94 | 7.65 | 6.77 |
| MnO | 0.04 | 0.07 | 0.03 | 0.04 | 0.04 | 0.06 | 0.10 | 0.04 | 0.08 | 0.05 | 0.06 | 0.04 | 0.05 | 0.13 | 0.11 | 0.07 | 0.23 | 0.37 | 0.07 |
| MgO | 2.92 | 3.44 | 2.36 | 3.20 | 3.42 | 3.46 | 3.83 | 2.56 | 3.26 | 2.69 | 3.39 | 2.42 | 2.31 | 2.66 | 2.68 | 3.28 | 2.90 | 5.52 | 3.41 |
| CaO | 0.21 | 0.95 | 0.13 | 0.54 | 0.59 | 1.40 | 0.94 | 0.86 | 2.02 | 0.88 | 1.76 | 0.82 | 0.62 | 1.62 | 0.86 | 0.94 | 2.52 | 1.29 | 1.28 |
| $Na_2O$ | 1.35 | 1.99 | 1.76 | 1.88 | 1.30 | 2.01 | 1.13 | 2.30 | 1.93 | 1.13 | 1.95 | 0.56 | 0.75 | 1.97 | 1.08 | 2.19 | 3.83 | 1.75 | 0.98 |
| $K_2O$ | 3.39 | 2.39 | 2.56 | 2.43 | 1.54 | 2.64 | 2.79 | 3.15 | 1.97 | 2.86 | 3.20 | 2.39 | 1.49 | 2.54 | 3.19 | 2.64 | 2.67 | 1.65 | 3.28 |
| $P_2O_5$ | 0.21 | 0.70 | 0.14 | 0.27 | 0.60 | 0.18 | 0.19 | 0.19 | 0.19 | 0.08 | 0.19 | 0.07 | 0.04 | 0.20 | 0.06 | 0.20 | 0.22 | 0.14 | 0.25 |
| LOI | 6.31 | 5.20 | 7.23 | 5.83 | 4.18 | 5.09 | 4.71 | 4.57 | 5.39 | 2.96 | 1.17 | 1.93 | 1.31 | 2.41 | 3.08 | 4.15 | 2.25 | 4.44 | 3.73 |
| TOTAL | 99.95 | 100.60 | 95.11 | 98.56 | 99.89 | 100.89 | 100.15 | 100.02 | 100.32 | 99.25 | 97.33 | 99.36 | 99.34 | 99.34 | 100.04 | 99.60 | 100.01 | 99.70 | 99.85 |
| Rb | 107 | 75 | 80 | 78 | 47 | | | | | 113 | 98 | 80 | 51 | | | | | | |
| Sr | 78 | 161 | 85 | 111 | 98 | 151 | 179 | 155 | 89 | 125 | 52 | 70 | 100 | 327 | 89 | 188 | 424 | 76 | 40 |
| Zr | 172 | 147 | 221 | 154 | 145 | 179 | 162 | 192 | 149 | 145 | 139 | 135 | 99 | 116 | 158 | 128 | 185 | 135 | 121 |
| Y | 27 | 33 | 23 | 26 | 29 | 26 | 21 | 27 | 22 | 25 | 15 | 20 | 18 | 23 | 22 | 22 | 24 | 26 | 22 |
| Nb | 10 | 6 | 6 | 7 | 7 | 9 | 9 | 10 | 9 | 8 | 11 | 6 | 4 | 7 | 11 | 6 | 9 | 9 | 7 |
| Ba | 1341 | 885 | 907 | 965 | 586 | 1085 | 815 | 1017 | 764 | 846 | 1203 | 1322 | 491 | 2038 | 975 | 1738 | 1120 | 747 | 645 |
| Sc | 21 | 22 | 15 | 22 | 17 | 18 | 21 | 21 | 17 | 16 | 17 | 14 | 11 | 19 | 17 | 21 | 23 | 23 | 21 |
| V | 203 | 177 | 158 | 217 | 155 | 141 | 172 | 190 | 131 | 98 | 147 | 85 | 71 | 173 | 129 | 330 | 170 | 176 | 200 |
| Cr | 99 | 97 | 105 | 110 | 95 | 95 | 89 | 93 | 69 | 66 | 108 | 65 | 36 | 50 | 60 | 104 | 44 | 94 | 112 |
| Ni | | | | | | 31 | 55 | 4 | 31 | | | | | 30 | 22 | 4 | 32 | 67 | 47 |
| Cu | 40 | 85 | 23 | 65 | 24 | 37 | 24 | 11 | 50 | 88 | 72 | 76 | 167 | 51 | 96 | 24 | 138 | 2 | 56 |
| Zn | 100 | 189 | 83 | 140 | 161 | 148 | 175 | 125 | 143 | 122 | 161 | 123 | 153 | 131 | 138 | 89 | 279 | 189 | 225 |
| Be | 5 | 4 | 4 | 4 | 3 | | | | | 5 | 5 | 5 | 0 | | | | | | |

*Notes:* Samples were fused in lithium metaborate and dissolved in 50 ml of 5% HCl solution for inductively coupled plasma-atomic emission spectroscopy 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.

### TABLE 2. Nd AND Sr ISOTOPIC DATA FOR ARGILLACEOUS ROCKS OF THE KLAMATH MOUNTAINS, CALIFORNIA

| Sample | Rb (ppm) | Sr (ppm) | $^{87}Rb/^{86}Sr$ | $^{87}Sr/^{86}Sr$ | $^{87}Sr/^{86}Sr$ (153 Ma) | $^{87}Sr/^{86}Sr$ (210 Ma) | Sm (ppm) | Nd (ppm) | $^{147}Sm/^{144}Nd$ | $^{143}Nd/^{144}Nd$ | $^{143}Nd/^{144}Nd$ (153 Ma) | Initial $\varepsilon_{Nd}$ (153 Ma) | $^{143}Nd/^{144}Nd$ (210 Ma) | Initial $\varepsilon_{Nd}$ (210 Ma) | Nd model age (Ga) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Galice argillites, deposited 153 Ma | | | | | | | | | | | | | | | |
| Gali 4 | 98.45 | 70.30 | 4.0554 | 0.71575 | 0.706934 | | 3.925 | 20.67 | 0.11484 | 0.512427 | 0.512312 | –2.5 | | | 1.12 |
| Gali 1A | 42.93 | 114.95 | 1.0809 | 0.70912 | 0.706765 | | 5.298 | 23.09 | 0.13872 | 0.512497 | 0.512359 | –1.6 | | | 1.33 |
| Gali 1B | 48.57 | 64.79 | 2.1703 | 0.71130 | 0.706579 | | 3.354 | 18.33 | 0.11068 | 0.512505 | 0.512394 | –0.9 | | | 0.96 |
| Gali 2 | 48.92 | 84.82 | 1.6697 | 0.71051 | 0.706875 | | 3.021 | 14.06 | 0.13000 | 0.512467 | 0.512337 | –2.0 | | | 1.25 |
| Gali 3* | 29.64 | 97 | 0.8895 | 0.70908 | 0.707144 | | 5.436 | 23.89 | 0.13760 | 0.512511 | 0.512373 | –1.3 | | | 1.28 |
| 03OMB6 | 87.66 | 150.93 | 1.6811 | 0.70958 | 0.705925 | | 5.296 | 27.58 | 0.11612 | 0.512504 | 0.512387 | –1.1 | | | 1.01 |
| 03OMB4 | 94.55 | 181.75 | 1.5057 | 0.70920 | 0.705930 | | 4.351 | 23.90 | 0.11008 | 0.512437 | 0.512327 | –2.2 | | | 1.05 |
| 03OMB5 | 112.46 | 159.34 | 2.0427 | 0.70950 | 0.705059 | | 5.329 | 24.55 | 0.13126 | 0.512509 | 0.512378 | –1.2 | | | 1.19 |
| 03OMB8§ | 59.54 | 82.21 | 2.0967 | 0.71260 | 0.708044 | 0.706343 | 5.189 | 26.10 | 0.12023 | 0.512201 | 0.512080 | –7.0 | 0.512036 | –6.48 | 1.55 |
| Rattlesnake Creek terrane argillites, deposited ca. 210 My | | | | | | | | | | | | | | | |
| *Cover sequence* | | | | | | | | | | | | | | | |
| DP1-58 | 91.09 | 126.13 | 2.0913 | 0.71404 | 0.709491 | 0.707794 | 5.181 | 30.78 | 0.10178 | 0.512166 | 0.512064 | –7.4 | 0.512026 | –6.67 | 1.34 |
| DP1-61 | 77.78 | 178.34 | 1.2627 | 0.71270 | 0.709955 | 0.708931 | 5.230 | 29.21 | 0.10825 | 0.512093 | 0.511985 | –8.9 | 0.511944 | –8.26 | 1.53 |
| DP1-62 | 48.90 | 42.66 | 3.3217 | 0.72131 | 0.714083 | 0.711388 | 2.335 | 11.48 | 0.12300 | 0.512182 | 0.512059 | –7.5 | 0.512013 | –6.92 | 1.63 |
| DP1-67 | 32.09 | 71.64 | 1.2969 | 0.71238 | 0.709560 | 0.708510 | 2.383 | 10.48 | 0.13744 | 0.512325 | 0.512188 | –4.9 | 0.512136 | –4.52 | 1.67 |
| BP4-3 | 99.53 | 485.65 | 0.5931 | 0.70733 | 0.706040 | 0.705559 | 5.790 | 26.95 | 0.12991 | 0.512563 | 0.512433 | –0.2 | 0.512385 | 0.34 | 1.07 |
| BP388 | 114.74 | 88.91 | 3.7381 | 0.71747 | 0.709337 | 0.706303 | 4.013 | 21.15 | 0.11474 | 0.512223 | 0.512108 | –6.5 | 0.512065 | –5.91 | 1.43 |
| *Melange blocks* | | | | | | | | | | | | | | | |
| 03OMB10 | 77.13 | 200.80 | 1.1116 | 0.70869 | 0.706273 | 0.705371 | 4.926 | 22.59 | 0.13188 | 0.512590 | 0.512458 | 0.3 | 0.512409 | 0.80 | 1.05 |
| BP391 | 85.32 | 419.55 | 0.5885 | 0.70786 | 0.706578 | 0.706101 | 3.897 | 17.46 | 0.13495 | 0.512793 | 0.512658 | 4.2 | 0.512607 | 4.68 | 0.69 |
| 03OMB1 | 54.01 | 84.48 | 1.8508 | 0.71078 | 0.706754 | 0.705252 | 5.419 | 25.42 | 0.12892 | 0.512453 | 0.512324 | –2.3 | 0.512275 | –1.80 | 1.26 |
| 03OMB3 | 76.87 | 37.27 | 5.9749 | 0.71796 | 0.704965 | 0.700116 | 5.576 | 26.53 | 0.12712 | 0.512729 | 0.512602 | 3.1 | 0.512555 | 3.65 | 0.74 |

*Notes:* Approximately 80 to 100 mg of each sample was dissolved in $HF\text{-}HNO_3$. After conversion to chlorides, one-third of the sample was spiked with $^{87}Rb$, $^{84}Sr$, $^{149}Sm$, and $^{146}Nd$. Rb, Sr, and REEs were separated by conventional cation-exchange procedures. Sm and Nd were further separated in di-ethyl-hexyl orthophosphoric acid columns.

All isotopic measurements were made on a VG Sector multi-collector mass spectrometer at the University of Wyoming. An average $^{87}Sr/^{86}Sr$ isotopic ratio of 0.710251 ± 20 (2 standard deviations) was measured for NBS 987 Sr, and an average $^{143}Nd/^{144}Nd$ ratio of 0.511846 ± 11 (2 standard deviations) 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 (2 standard deviations). Blanks are 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 on initial $\varepsilon_{Nd}$ are ± 0.3 epsilon units. The Nd model ages are calculated based upon the depleted mantle model of Goldstein et al. (1984).

*Sr concentration for Gali 3 by inductively coupled plasma-atomic emission spectroscopy (Table 1).

§Initial Nd and Sr isotopic ratios for 03OMB8 calculated for 153 Ma and for 210 Ma, due to the uncertain assignment of this sample to the Galice Formation.

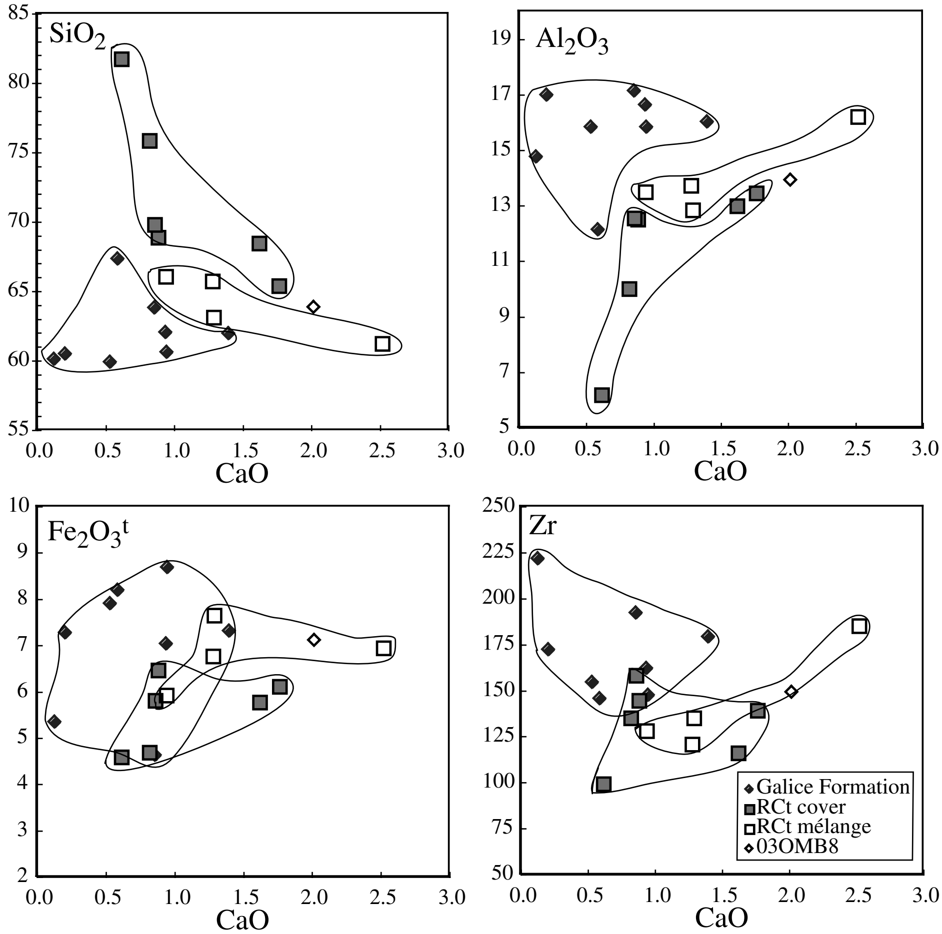



Figure 3. Geochemical compositions of Galice Formation argillites and Rattlesnake Creek terrane meta-argillites. Galice argillites are distinguished by lower $SiO_2$ and CaO, and higher $Fe_2O_3^t$, $Al_2O_3$, and Zr compared to Rattlesnake Creek terrane samples. The meta-argillite from the Rattlesnake Creek terrane cover sequences is more siliceous and has lower $Al_2O_3$ and $Fe_2O_3^t$ than does meta-argillite from the serpentinite-matrix mélange.

lower $SiO_2$ and CaO, and higher $Fe_2O_3^t$, $Al_2O_3$, and Zr abundances. Meta-argillite from the inferred cover sequences of the Rattlesnake Creek terrane is more siliceous and has correspondingly lower $Al_2O_3$ and $Fe_2O_3^t$ than does meta-argillite from the serpentinite-matrix mélange.

Two samples from the cover sequences of the Rattlesnake Creek terrane, DP1-62 and DP1-67, have higher $SiO_2$ and lower $Al_2O_3$ than found in all other samples from this study. These rocks are best described as siliceous or cherty meta-argillite, and there is a complete spectrum from meta-argillite to siliceous argillite to impure chert in the Rattlesnake Creek terrane. This range is true of meta-argillite from the serpentinite-matrix mélange as well as metamorphosed argillaceous rocks from the inferred cover sequences.

Sample 03OMB8, collected from an outcrop that has been mapped as Galice Formation (Klein, 1975, 1977; Petersen, 1982), is geochemically distinct from the other analyzed Galice samples. Although 03OMB8 falls within fields defined by the analyzed Rattlesnake Creek terrane samples, it has experienced lower-grade metamorphism than Rattlesnake Creek terrane metasedimentary rocks in the adjacent hanging-wall block of the Orleans fault. We thus conclude that either this sample has an unusual composition for argillaceous rocks of the Galice Formation, or as discussed previously, this sample may be a fault-bounded slice of Condrey Mountain terrane, a third argillaceous unit that is widely exposed in a structural window (Hotz, 1979; Helper, 1986) east-northeast of Happy Camp, California.

### *Isotopic Data*

Sm-Nd and Rb-Sr isotopic data are presented in Table 2; the ages used to calculate initial isotopic ratios are 153 Ma for samples from the Galice Formation and 210 Ma for samples from the Rattlesnake Creek terrane, respectively. Isotopic data for metamorphosed argillaceous rocks from the Galice Formation are more uniform than are the data for meta-argillite samples from the Rattlesnake Creek terrane. Galice samples (apart from 03OMB8) have initial $^{87}Sr/^{86}Sr$ of 0.7051–0.7071 and initial $\varepsilon_{Nd}$ of –0.9 to –2.5 (Fig. 4). Meta-argillites of the Rattlesnake Creek terrane exhibit greater ranges both in initial $^{87}Sr/^{86}Sr$ (0.7001–0.7114) and initial $\varepsilon_{Nd}$ (+4.7 to –8.3). The calculated initial $^{87}Sr/^{86}Sr$ ratio of 0.7001 is unrealistically low, suggesting that Rb and/or Sr mobility has affected this and possibly other samples. Sample 03OMB8 is distinct from the other Galice samples, falling within the range defined by Rattlesnake Creek terrane samples with an initial Sr isotopic ratio of 0.7080 and initial $\varepsilon_{Nd}$ of –7.0. The range in $^{147}Sm/^{144}Nd$ exhibited both by Galice Formation and Rattlesnake Creek terrane samples ($^{147}Sm/^{144}Nd$ = 0.1018–0.1387) extends to higher ratios than are typical of upper continental crust ($^{147}Sm/^{144}Nd$ = 0.090–0.125).

Meta-argillites from the Rattlesnake Creek terrane cover sequence have in general higher initial $^{87}Sr/^{86}Sr$ and more negative initial $\varepsilon_{Nd}$ than do meta-argillites from the serpentinite-matrix mélange. Meta-argillites from the cover sequences also tend to have lower $P_2O_5$ than found in meta-argillite samples from the Rattlesnake Creek terrane serpentinite-matrix mélange (Fig. 5A). Cover sequence meta-argillite sample BP4–3 is the exception; it falls within the range of Nd and Sr isotopic compositions defined by the meta-argillite samples collected from inferred mélange blocks. Possibly we have misidentified this sample as part of the cover sequence, and it might instead have been collected from a very large mélange block. However, this sample has much higher Sr and Ba than other cover sequence argillites (Table 2 and Fig. 5B) and one of the highest CaO and $Na_2O$ contents. These geochemical traits, which are consistent with a greater volcanogenic component, appear to correlate with its more radiogenic initial Nd isotopic ratio. It is possible, then, that this meta-argillite from the cover sequence incorporates a larger proportion of young, oceanic detritus than other meta-argillites from the cover sequence. A similar correlation of high Sr with radiogenic initial $\varepsilon_{Nd}$ is observed for the meta-argillite sample from the serpentinite-matrix mélange that exhibits the most radiogenic Nd isotopic ratio, sample BP391 (Fig. 5B).

## DISCUSSION

### *Provenance of Galice Formation Argillaceous Rocks*

The metamorphosed argillaceous rocks of the Galice Formation analyzed in this study are distinguished by their geochemical and isotopic homogeneity, despite their varying geographic locations and stratigraphic positions. The Sm-Nd isotopic data preserve evidence both for ancient continental crust and younger crust and/or mantle-derived components in these argillaceous rocks. Evidence for incorporation of the latter is preserved in the $^{147}Sm/^{144}Nd$ ratios of the samples, which range from 0.1101 to 0.1387. Half of the samples have ratios

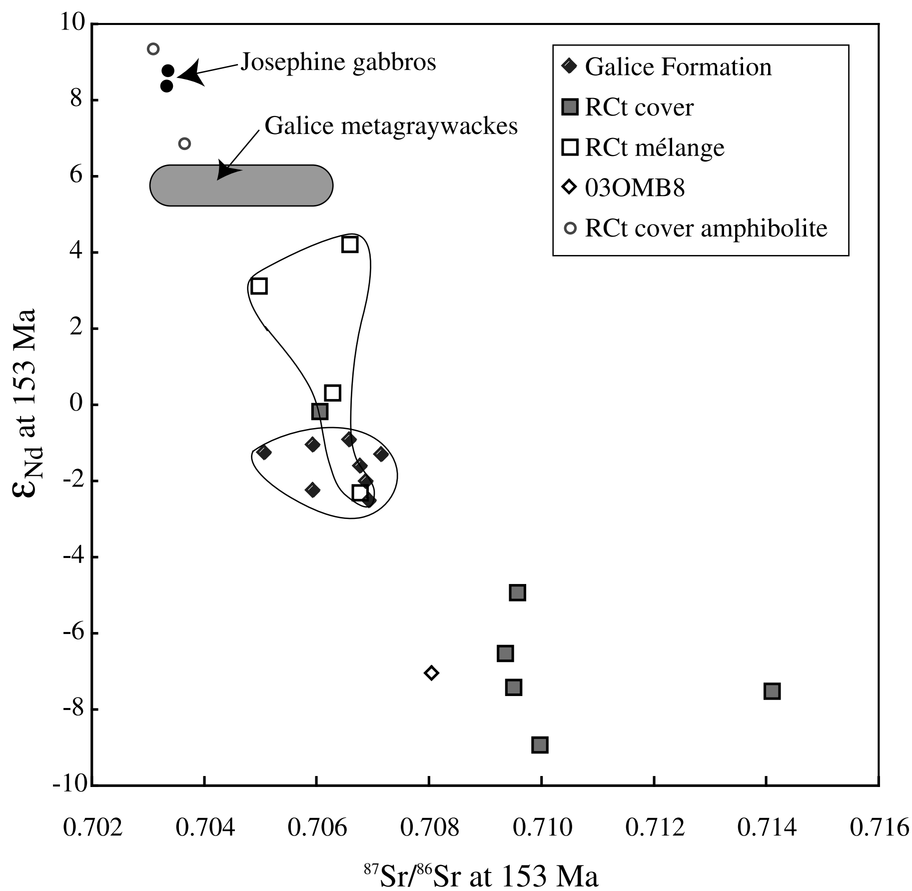



Figure 4. Nd and Sr isotopic data for Galice Formation and Rattlesnake Creek terrane metasedimentary rocks calculated at 153 Ma, the estimated time of Galice deposition. Galice Formation argillites have relatively uniform initial $\varepsilon_{Nd}$ of –0.9 to –2.5, and initial $^{87}Sr/^{86}Sr$ of 0.7051–0.7071, distinct from the initial $\varepsilon_{Nd}$ and $^{87}Sr/^{86}Sr$ of Galice (meta)graywackes. Rattlesnake Creek terrane meta-argillites have less uniform initial $\varepsilon_{Nd}$ and $^{87}Sr/^{86}Sr$, and in general, cover sequence samples have higher initial $^{87}Sr/^{86}Sr$ and lower initial $\varepsilon_{Nd}$ than do samples from the serpentinite-matrix mélange. No metasedimentary sample has a depleted mantle signature like those exhibited by gabbros from the Josephine ophiolite (Shaw and Wasserburg, 1984) or Rattlesnake Creek terrane amphibolites from the cover sequence (C.D. Frost, unpublished data, 2003).

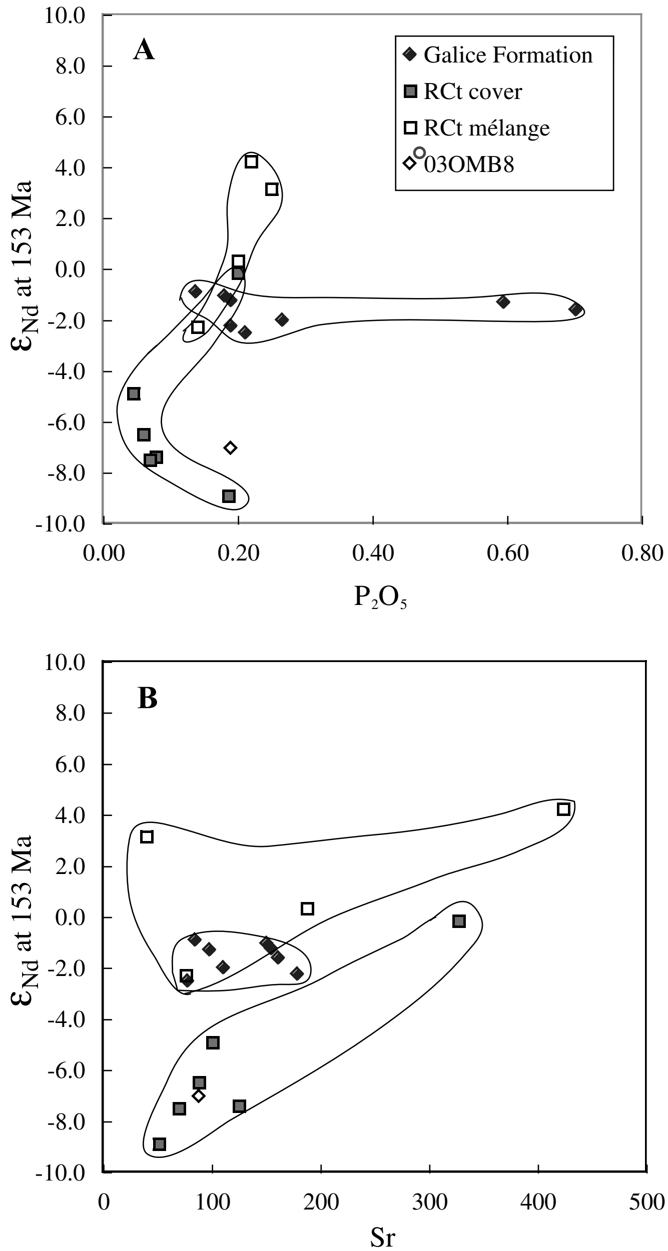



Figure 5. (A) Plot of $P_2O_5$ content (in wt. %) vs. $\varepsilon_{Nd}$ at 153 Ma, showing generally lower $P_2O_5$ content of Rattlesnake Creek terrane cover sequence meta-argillites compared to Rattlesnake Creek terrane mélange and Galice argillaceous rocks. (B) Plot of Sr content (in ppm) vs. $\varepsilon_{Nd}$ at 153 Ma, showing that the most radiogenic samples within the Rattlesnake Creek terrane cover and the Rattlesnake Creek terrane mélange also have high Sr and suggesting that these samples may have incorporated a greater volcanogenic component than the other samples within each group.

higher than 0.125 and thus exceed $^{147}Sm/^{144}Nd$ ratios typical of continental crust (Fig. 6). However, the samples have slightly negative initial $\varepsilon_{Nd}$ and Mesoproterozoic depleted mantle Nd model ages of 0.96–1.25 Ga. These model ages represent the weighted average crust-formation age of the sources that eroded and contributed detritus to the Galice Formation. They strongly imply that although the argillaceous rocks of the Galice Formation were deposited upon the Late Jurassic Josephine ophiolite, their sediment sources were not restricted to proximal arc materials but instead included detritus ultimately derived from Precambrian continental crust. The initial Sr isotopic compositions of the samples also suggest that they are a mixture of continental and mantle-derived sources: initial $^{87}Sr/^{86}Sr$ of between 0.7051 and 0.7071 are more radiogenic than depleted mantle and island-arc magmas, but less radiogenic than a North American cratonic source (Fig. 6).

Limited Nd and Sr isotopic data from metagraywackes of the Galice Formation provide an instructive comparison with our meta-argillite data. Initial Sr isotopic ratios of metagraywackes reported by Coleman (1972: $^{87}Sr/^{86}Sr = 0.7030–0.7066$) are on average less radiogenic than those of the meta-argillites. An analysis of Galice metagraywacke reported by Miller et al. (2003) yielded an initial $\varepsilon_{Nd}$ of +5.6, considerably more radiogenic than the initial $\varepsilon_{Nd}$ of –0.9 to –2.5 obtained from our argillaceous samples (Fig. 4). The Miller et al. (2003) sample also contained an abundant population of detrital zircons with an age of 153 Ma. Both the Sr and Nd isotopic compositions and the detrital zircon ages suggest that Galice Formation metagraywackes incorporate detritus from a Late Jurassic oceanic arc source, probably the Rogue–Chetco arc. Miller et al. (2003) documented a less well-defined peak in detrital zircon ages at 227 Ma and sparse older zircon, indicating that the metagraywacke also incorporated detritus from older sources, including sediment that ultimately was eroded from the North American Precambrian basement (Miller et al., 2003). Interpreting U-Pb detrital zircon ages from a larger number of Galice metagraywacke samples, Miller and Saleeby (1995) also concluded that the Galice Formation was deposited within the range of terrigenous input from a recycled continental source, and identified the older Klamath terranes as suitable sediment sources. The data presented in our study are consistent with the hypothesis of these workers that the turbidites of the Galice Formation contain both a young arc-derived component and an older cratonic source. However, the more negative $\varepsilon_{Nd}$ of the argillaceous rocks compared to the metagraywacke sample analyzed by Miller et al. (2003) and more radiogenic initial Sr isotopic compositions of the argillaceous rocks compared to the metagraywackes analyzed by Coleman (1972) suggest that the proportions of detritus from various sources are different in the argillaceous rocks compared to the metagraywackes in this turbidite sequence.

Differences in initial $\varepsilon_{Nd}$ for coarse-grained and fine-grained portions of turbidite flows have been documented in both modern (McLennan et al., 1989) and ancient (Frost and Coombs, 1989) environments. These differences may arise if

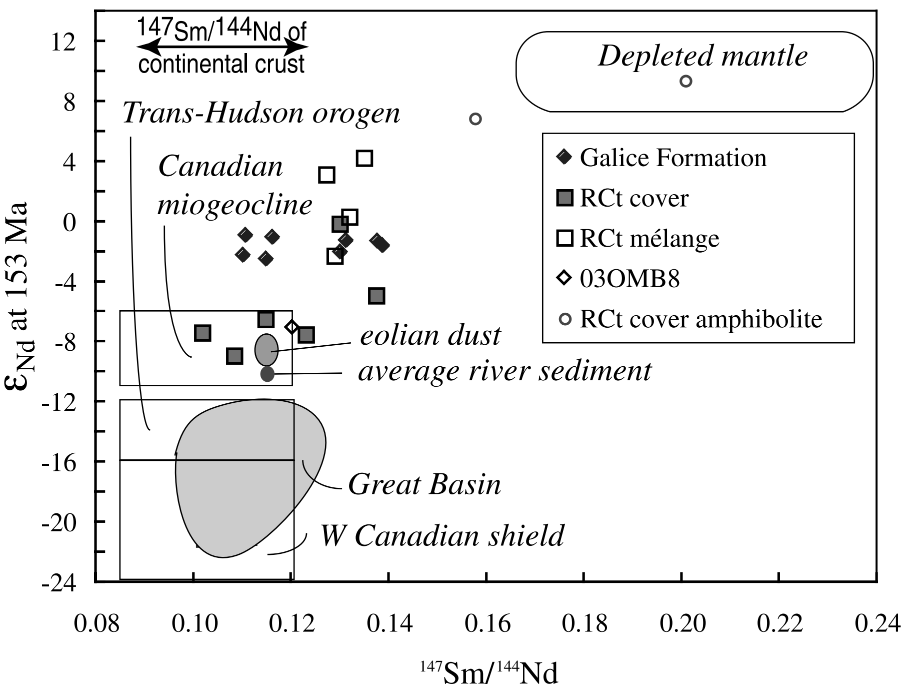



Figure 6. Plots of $^{147}Sm/^{144}Nd$ data vs. $\varepsilon_{Nd}$ at 153 Ma for Galice and Rattlesnake Creek terrane meta-argillite samples and possible sediment sources. The Klamath metasedimentary samples have Sm-Nd isotopic characteristics that are intermediate between depleted mantle and North American crust. Fields for the latter include Neoproterozoic metasedimentary rocks of the Great Basin (Farmer and Ball, 1997), western Canadian shield and Trans-Hudson orogen (Chauvel et al., 1987; Boghossian et al., 1996), and Devonian to Jurassic Canadian miogeocline (Boghossian et al., 1996; Patchett and Gehrels, 1998). Rattlesnake Creek terrane cover sequence meta-argillites have Sm-Nd isotopic characteristics comparable to eolian dust and particulates from major river systems (Goldstein et al., 1984). Galice Formation argillite samples and meta-argillite from Rattlesnake Creek terrane serpentinite-matrix mélange have incorporated a greater proportion of juvenile detritus.

different source areas are shedding debris of contrasting grain size; for example, if coarser debris is eroding from proximal arcs and fine-grained material is carried from more distant source areas (i.e., as suspended particulate in rivers; Frost and Coombs, 1989). A second factor is the concentration or preferential breakdown of certain components such as volcanic glass or unstable minerals during weathering and transport, and their incorporation in the finer-grained sediment (McLennan et al., 1989). A third mechanism is the preferential incorporation of heavy minerals in the coarser-grained sediment during sedimentary transport and sorting. A modest enrichment of minerals such as zircon or monazite in the sand-sized portion of a turbidite flow can significantly affect its Sm and Nd budget and hence its Nd isotopic mass balance (Frost and Winston, 1987). Because the argillaceous rocks have the more unradiogenic initial $\varepsilon_{Nd}$ compared to the metagraywacke sample, we conclude that the finer-grained rocks contain a greater proportion of recycled cratonic debris, material that may have been reduced to mud-sized particles during repeated episodes of erosion, transport, and deposition.

It is noteworthy, however, that in some cases, no correlation is observed between grain size and $\varepsilon_{Nd}$ value. For example, in a study of Quesnel terrane strata in the Canadian Cordillera Unterschutz et al. (2002) documented variable $\varepsilon_{Nd}$ for metasedimentary rocks of all grain sizes.

## SEDIMENT SOURCES FOR META-ARGILLITES FROM THE RATTLESNAKE CREEK TERRANE MÉLANGE BASEMENT AND COVER SEQUENCE

With one exception, meta-argillites from the Rattlesnake Creek terrane cover sequence have initial Sr and Nd isotopic compositions that are distinct from meta-argillite samples from the serpentinite-matrix mélange. Meta-argillites from Rattlesnake Creek terrane cover sequences are characterized by radiogenic initial $^{87}Sr/^{86}Sr$ of 0.7063–0.7114, negative initial $\varepsilon_{Nd}$ from –4.5 to –8.3, and depleted mantle Nd model ages of 1.34–1.67 Ga. Meta-argillite samples from serpentinite-matrix mélange, however, have less radiogenic initial Sr isotope ratios (≤0.7061), less negative initial $\varepsilon_{Nd}$ (+4.7 to –1.8), and younger model ages (0.69–1.26 Ga). As discussed below, these isotopic differences reflect a shift in the provenance of the argillaceous rocks from the basement to the cover portions of the Rattlesnake Creek terrane.

Wright and Wyld (1994) hypothesized that the mélange basement was formed by disruption of oceanic crust far removed from arc or continental landmasses, perhaps in an oceanic fracture zone setting. The blocks within the mélange are composed of rock types that make up the oceanic crust and uppermost mantle, including pillow basalt and diabase, gabbro, pyroxenite/peridotite, and amphibolite. The sedimentary rocks are restricted to chert, argillite, and limestone; no blocks contain clastic material of terrigenous or volcanic-arc provenance. The positive to only slightly negative initial $\varepsilon_{Nd}$ and unradiogenic Sr isotopic compositions of the argillites analyzed in this study are consistent with an oceanic tectonic setting. Moreover, the samples all have elevated $^{147}Sm/^{144}Nd$ compared to typical continental crust (Fig. 6). However, no argillite sample has radiogenic Nd and unradiogenic Sr isotopic compositions of contemporary depleted mantle, so even in this oceanic setting, the sediments must include continental components. The absence of siliceous clastic rocks among the sedimentary blocks of the Rattlesnake Creek terrane mélange basement argues against its formation within the range of terrigenous sedimentation. Although this distance is highly variable, depending upon the amount of sediment being discharged into the oceans by rivers, the width of the continental shelf and slope, and the potential for transport of sediment long distances in submarine canyons and along trenches, Patchett and Gehrels (1998) suggest that 1500 km is a reasonable limit. For sedimentation occurring beyond this distance, far-traveled hemipelagic sediment or eolian dust are potential sources of continental material.

The Nd isotopic compositions and Sm/Nd ratios of modern river particulates and eolian dusts are very uniform and yield depleted mantle Nd model ages of 1.70 ± 0.35 Ga (Goldstein et al., 1984; Jones et al., 1994). Correcting for radiogenic growth since Late Triassic time, this continental source of detritus would have had an initial $\varepsilon_{Nd}$ of approximately –8 to –10 at the time the Rattlesnake Creek terrane mélange basement was deposited (Fig. 6). Assuming that continental material with this Nd isotopic composition is an appropriate estimate of far-traveled detritus that could have been incorporated into Rattlesnake Creek terrane basement argillite blocks, and taking into account the higher Nd concentration in atmospheric dusts and river particulates compared to oceanic crust, it is possible to estimate the proportion of continental material present in Rattlesnake Creek terrane basement argillite samples. Accordingly, the range of initial $\varepsilon_{Nd}$ of the blocks analyzed ($\varepsilon_{Nd}$ = +4.7 to –1.8) can be modeled as mixtures of ~15–45% continental material and the remainder of juvenile oceanic sources. This result contrasts with the less radiogenic $\varepsilon_{Nd}$ values of modern pelagic sediment in the central North Pacific Ocean. Jones et al. (1994) concluded that this pelagic sediment is composed almost entirely of eolian sediment and includes little to no juvenile detritus. In contrast, the high proportion of mantle-derived sources in Rattlesnake Creek terrane basement argillite blocks suggests that the inferred oceanic fracture zone setting of these argillites must have produced abundant argillaceous detritus of juvenile origin that was mixed in varying proportions with far-traveled continental sediment.

The Rattlesnake Creek terrane cover sequence that unconformably overlies the mélange basement was interpreted by Wright and Wyld (1994) as a volcanic-arc suite. The igneous rocks of the cover sequence have geochemical signatures suggesting an island-arc environment (Wright and Wyld, 1994). The Nd and Sr isotopic data from amphibolitic rocks (contact-metamorphosed metabasalt) of the cover sequence (C.D. Frost, unpublished data; Figs. 4 and 6) confirm the arc signature of these rocks. The quartzose and argillaceous nature of the sedimentary rocks of the cover sequence suggested to Wright and Wyld (1994) that the metasedimentary rocks of the cover sequence were likely derived from a terrigeneous source, possibly Paleozoic rocks of western North America. The isotopic data for Rattlesnake Creek terrane meta-argillite samples presented here—namely, more radiogenic initial $^{87}Sr/^{86}Sr$, more negative initial $\varepsilon_{Nd}$, and generally lower $^{147}Sm/^{144}Nd$ for meta-argillites of the cover sequence compared to those of the mélange basement (Figs. 4 and 6)—are consistent with this general hypothesis that continental input is more pronounced in the cover sequence than in the mélange basement.

We note a similarity both in absolute $\varepsilon_{Nd}$ values and variability between the argillaceous rocks of the Rattlesnake Creek terrane cover sequence and Late Quaternary pelagic sediments from the Circum-Pacific rim analyzed by Jones et al. (1994). The latter were suggested to be composed of volcanic ash, hemipelagic sediments derived from volcanic arcs, and eolian loess. These fine-grained sediments are less radiogenic than modern turbidites from the same locations (McLennan et al., 1990). Jones et al. (1994) explained this discrepancy by noting that the turbidites are probably dominated by debris from island-arc sources, but that the finer pelagic sediment would contain both material from these sources of sediment and more distally derived continental loess.

Our sample set from the Rattlesnake Creek terrane cover sequence includes samples with a range of $SiO_2$ and $Al_2O_3$ contents that vary from true argillite to cherty or siliceous argillite. The sample with the isotopic characteristics suggesting the greatest proportion of juvenile arc component, BP4-3, has geochemical characteristics expected of clastic rocks with a significant volcanogenic component, including relatively high Sr, CaO, $Na_2O$, and $Al_2O_3$. Sample DP1-67, which has the second highest initial $\varepsilon_{Nd}$ after sample BP4-3, is the most siliceous of the Rattlesnake Creek terrane cover sequence samples. Thus it appears that the range in isotopic compositions of meta-argillite samples from the Rattlesnake Creek terrane cover sequence reflects varying proportions of local arc and more distal continental components, the latter being more pronounced in the finer-grained, less siliceous samples.

### *Implications for Tectonic Evolution of Klamath Terranes*

The lithologic and isotopic characteristics of the blocks of metamorphosed argillaceous rocks in the Rattlesnake Creek terrane are consistent with development of a serpentinite-matrix mélange distal from a continent. In addition, the presence of (meta)limestone blocks in the mélange suggests significant seafloor topography and the possibility that oceanic basement was exposed and available for weathering, and consequently was a source of juvenile detritus in the argillaceous rocks. These conclusions are consistent with the higher $\varepsilon_{Nd}$ and lower initial $^{87}Sr/^{86}Sr$ ratios among these samples than would be expected if their source was entirely derived from a continental source. Thus, our data are consistent with the oceanic fracture-zone setting postulated by Wright and Wyld (1994) for the serpentinite-matrix mélange unit of the Rattlesnake Creek terrane (Fig. 7A).

In contrast, the cover sequence of the Rattlesnake Creek terrane contains abundant evidence for deposition in an oceanic-arc setting (Wright and Wyld, 1994). However, argillaceous samples from the cover sequence exhibit Nd isotopic compositions typical of continental detritus, with little evidence for admixture of primitive-arc detritus (Fig. 6). The distinctly “continental” isotopic compositions of the argillites of the cover sequence may be explained by an absence of fine-grained arc

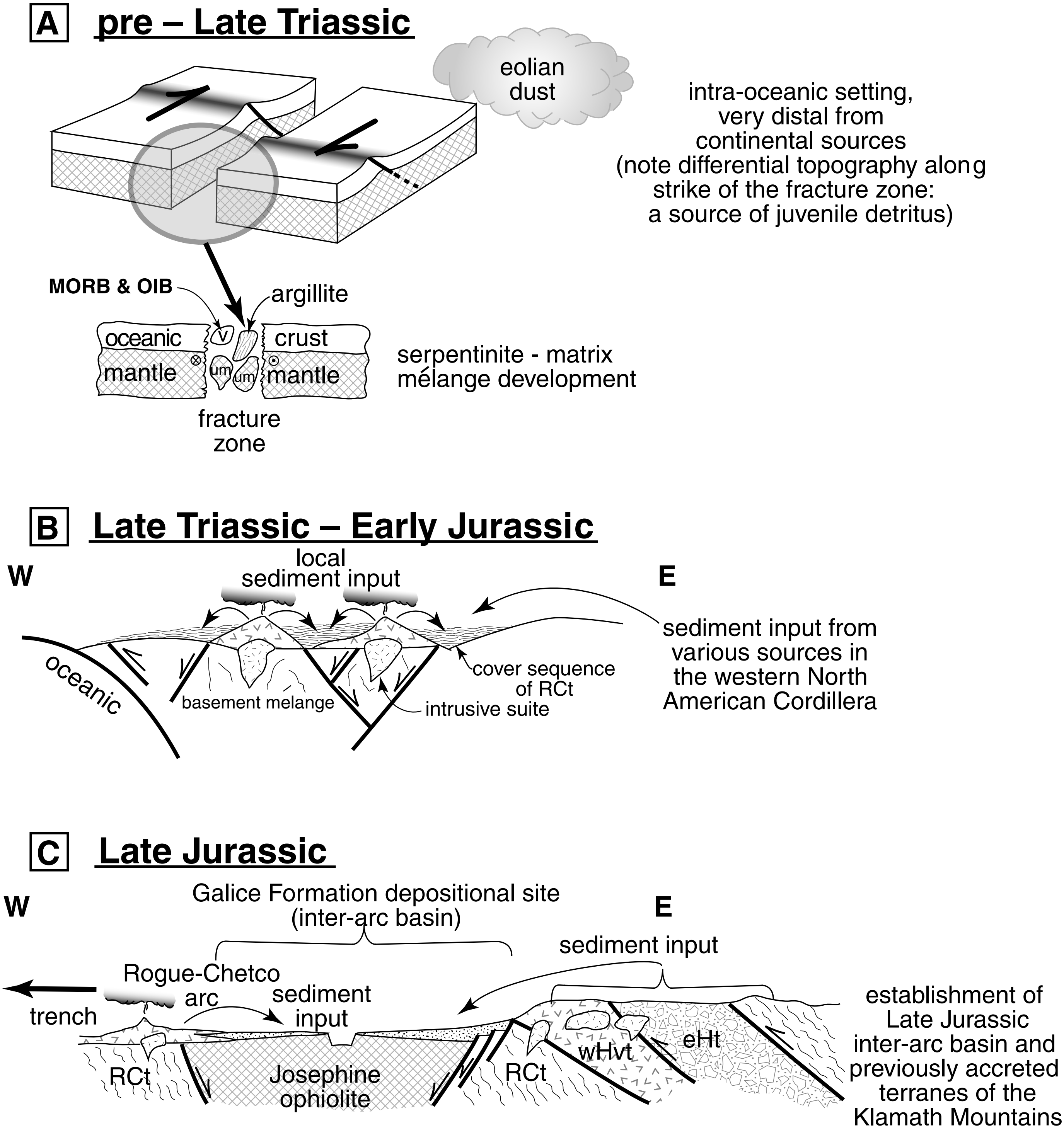



Figure 7. Inferred tectonic settings (pre-Late Triassic through Late Jurassic) for the argillaceous rocks analyzed in this study. (A) Development of serpentinite-matrix mélange (basement of the Rattlesnake Creek terrane) in a pre-Late Triassic oceanic fracture zone; (B) Late Triassic–Early Jurassic oceanic-arc setting for deposition of the cover sequence of the Rattlesnake Creek terrane. (C) Development of the Late Jurassic, inter-arc Galice basin through transtensional rifting of older, previously accreted terranes of the Klamath Mountains.

detritus. For example, if the arc was composed primarily of lava erupted subaqueously rather than of abundant submarine debris-flow or epiclastic deposits, then little of this juvenile arc component may be incorporated into the cover sequence meta-argillites. An alternative explanation may lie in our sampling technique: we specifically tried to sample the finest grained rocks available at each locality. If the arc detritrus was incorporated preferentially into sand-sized sediment, then such detrital rocks were preferentially excluded from the sample set.

By Middle Jurassic time, sedimentary rocks of the western Hayfork arc terrane were deposited directly on Rattlesnake Creek terrane rocks (Wright and Fahan, 1988; Donato et al., 1996). The western Hayfork terrane contains quartz-rich sedimentary rocks that suggest a position proximal to a continental landmass (Barnes et al., this volume, Chapter 10), presumably North America. Paleomagnetic data (Mankinen et al., 1989) show that by Middle Jurassic time, the Klamath province was close to its present latitudinal position relative to North America, although minor shifts are permissible. Therefore, the isotopic data support the concept that the Rattlesnake Creek terrane mélange formed in an oceanic setting. By the time the cover sequence was deposited, the Rattlesnake Creek terrane was presumably near a continental-affinity landmass (Fig. 7B). It subsequently became the basement for a near-margin, albeit oceanic-affinity, arc (western Hayfork terrane) in Middle Jurassic time. This inferred scenario thus suggests that the Middle Jurassic western Hayfork arc was not “exotic” to western North America and favors that this Middle Jurassic arc was west-facing (relative to present geographic coordinates).

The isotopic composition of metamorphosed argillaceous rocks from the Upper Jurassic Galice Formation stand in marked contrast to the meta-argillites of the Rattlesnake Creek terrane cover sequence. The relative homogeneity and intermediate compositions of the argillaceous rocks of the Galice Formation suggest significant and uniform mixing of arc and continental detritus. Whether the continental detritus was primary (i.e., directly from a continental drainage) or recycled (e.g., from terranes in the eastern Klamath Mountains) is more difficult to determine and will probably require thorough sampling of a variety of stratigraphic units (Fig. 7C). At least two explanations for the well-mixed nature of the argillaceous rocks of the Galice Formation are possible: (1) the continental component was part of the suspended load from riverine input direct from North America and was mixed with fine-grained, relatively juvenile input from proximal, outboard Rogue–Chetco arc as well as the Middle Jurassic inboard arc components (e.g., western Hayfork terrane); and (2) the source was entirely from the Klamath province, in which case mixing occurred in the source regions, which already contained arc and continental detritus (Miller and Saleeby, 1991; Gehrels and Miller, 2000; Wallin et al., 2000). In the latter case, no new input from continental drainages is necessary. There is no evidence for drainage systems that crossed the Great Basin during Jurassic time. Therefore, the first explanation implies either that the Klamath province was in a more southerly paleolatitude during Galice deposition, as suggested by Wyld and Wright (2001), or that wind-borne detritus associated with Early Jurassic Navajo/Aztec–type sands reached the drainages that fed the Galice basin. In contrast to the first alternative, no implications about paleolatitude may be made from the second explanation because no external source of sedimentary detritus is necessary.

## CONCLUSIONS

This study represents the first extensive Nd and Sr isotopic examination of metasedimentary rocks from the Klamath Mountains. Our results from the two terranes farthest outboard of the North American craton show that all of the sedimentary rocks of these oceanic terranes contain a significant continental component. The pre-Late Triassic serpentinite-matrix mélange of the Rattlesnake Creek terrane is interpreted as forming in an oceanic fracture zone. The continental component in its argillaceous rocks was apparently supplied by eolian processes. In contrast, the cover sequence of the Rattlesnake Creek terrane was deposited when the terrane was more proximal to a continental landmass, presumably North America, and its metasedimentary rocks are mixtures of varying proportions of volcanic-arc debris and river-borne terrigenous sediment. The Nd and Sr isotopic compositions of the argillaceous rocks of the Upper Jurassic Galice Formation are remarkably uniform, a particularly striking feature in view of the likelihood that sediment was shed into the Galice basin from both the previously accreted terranes of the Klamath Mountains as well as the outboard, west-facing Rogue–Chetco oceanic arc.

The isotopic data presented here are consistent with the general observation that sedimentary rocks from accreted terranes preserve a stronger signal of continental input than do the contemporaneous igneous rocks within the terrane. Although this observation has been made previously (i.e., Samson et al., 1991; Patchett and Gehrels, 1998), the results of this study suggest that variations in the homogeneity of the isotopic compositions also preserve important information. In particular, the striking homogeneity of Nd and Sr isotopic compositions of Galice argillaceous metasedimentary samples contrasts with the variability in Nd isotopic composition observed in metasedimentary rocks of other oceanic terranes. For example, the variability of initial $\varepsilon_{Nd}$ composition of strata from the Quesnel terrane was explained by differing proportions of primitive and evolved sources present along the North American continental margin (Unterschutz et al., 2002). This terrane was interpreted to lie on or near the North American margin, such that there was no opportunity for homogenization of these sources by sedimentary processes. In contrast, the remarkable uniformity of isotopic compositions of Galice Formation argillaceous rocks requires that arc and continental detritus were well homogenized prior to deposition upon the Josephine ophiolite. Although the ability of major rivers to homogenize the isotopic composition of sediments they transport is well known (Goldstein et al., 1984), the processes resulting in isotopic uniformity of sediment in an arc terrane setting clearly require further investigation.

Although the present study represents an important first step, a more detailed understanding of sediment sources, the importance of sediment recycling, and paleogeographic and tectonic positions of Klamath Mountains terranes requires additional detailed investigations. In particular, isotopic characteristics of a variety of lithologic units from the other Klamath terranes will help to determine whether the continental material contributed to the western Klamath and Rattlesnake Creek terranes was derived from adjacent, previously accreted terranes, or whether it was delivered directly from the North American craton. A corollary study of the collage of time-correlative tectonostratigraphic terranes in the western Sierra Nevada would also be interesting and potentially informative in the evaluation of contrasting tectonic models for the Klamath Mountains and western Sierra Nevada. For example, comparison of lithologic, geochemical, and isotopic characteristics of the Upper Jurassic Galice and Mariposa Formations may help distinguish between postulated tectonic accretion scenarios (e.g., Schweickert and Cowan, 1975; Harper and Wright, 1984; Ingersoll and Schweickert, 1986). For nearly a hundred years since Diller (1907) originally suggested that the Galice and Mariposa Formations are correlative units, it has been recognized that a thorough understanding of the tectonic setting and depositional history of these important Upper Jurassic stratigraphic units is fundamental to the mid-Mesozoic history of the continental margin of western U.S. Cordillera.

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## APPENDIX. SAMPLE LOCALITIES WITH UTM COORDINATES

| Sample | UTM coordinates (easting, northing) |
|---|---|
| Argillaceous rocks of the Rattlesnake Creek terrane: inferred cover sequence | |
| DP1-58 | 0440761, 4629350 |
| DP1-61 | 0438312, 4628546 |
| DP1-62 | 0437732, 4692112 |
| DP1-67 | 0437865, 4629149 |
| BP4-3 | 0453336, 4611678 |
| BP388 | 0453163, 4610102 |
| Argillaceous rocks of the Rattlesnake Creek terrane: inferred blocks in serpentinite-matrix mélange | |
| 03OMB1 | 0458847, 4580800 |
| 03OMB3 | 0458350, 4578617 |
| 03OMB10 | 0455807, 4646294 |
| BP391 | 0449840, 4615794 |

| Sample | UTM coordinates (easting, northing) |
|---|---|
| Argillaceous rocks of the Upper Jurassic Galice Formation | |
| GALI1A | 434795, 4635549 |
| GALI1B | 434795, 4635549 |
| GALI2 | 434848, 4635482 |
| GALI3 | 434610, 4635529 |
| GALI4 | 438774, 4642048 |
| 03OMB4 | 0446277, 4566604 |
| 03OMB5 | 0445357, 4564287 |
| 03OMB6 | 0457702, 4591098 |
| 03OMB8 | 0467288, 4625712 |

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