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Arc plutonism following regional thrusting: Petrology and geochemistry of syn- and post-Nevadan plutons in the Siskiyou Mountains, Klamath Mountains province, California

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ABSTRACT

A group of plutons were emplaced in the western Klamath Mountains province during the waning stages of the Late Jurassic Nevadan orogeny. Published U-Pb (zircon) ages indicate that the "western Klamath plutonic suite" was emplaced in the age range of 151–144 Ma. Crosscutting relationships, development of contact metamorphic aureoles, and the presence of distinctive inherited zircon populations indicate that the magmas intruded the footwall and hanging-wall rocks of the principal Nevadan thrust fault. The plutons are chiefly gabbroic to dioritic in composition, but commonly include ultramafic rocks and contain smaller volumes of tonalite and granodiorite. Hornblende is the most common mafic phase, except for some ultramafic rocks in which clinopyroxene ± olivine are locally distinctive, the two-pyroxene dioritic to monzodioritic rocks of the Buck Lake unit of the Bear Mountain pluton, and the most felsic rocks in which biotite is the most abundant mafic phase.

Compositions of fine-grained mafic dikes suggest the presence of two principal parental, H_2O-rich magmas: primitive basalt and evolved basalt/basaltic andesite. The former was parental to the ultramafic rocks of this suite. It was also parental to the basalt/basaltic andesite magmas by deep-seated fractional crystallization pro-

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cesses. The latter magmas were parental to the gabbroic and dioritic units. Many of the felsic rocks show evidence of origins by partial melting of metabasaltic crustal rocks, particularly their low heavy rare-earth element concentrations and high Sr/Y ratios. Mixing of crustal melts with primitive basaltic magmas was locally important (e.g., Pony Peak pluton). The mafic parental magmas show trace element features typical of an origin by partial melting of a subduction-modified mantle wedge. It is unclear whether subduction was coeval with western Klamath magmatism or whether the subduction signature developed as the result of Middle Jurassic subduction.

Keywords: arc magmatism, Nevadan orogeny, differentiation, crustal melting, Jurassic, western Klamath plutonic suite

INTRODUCTION

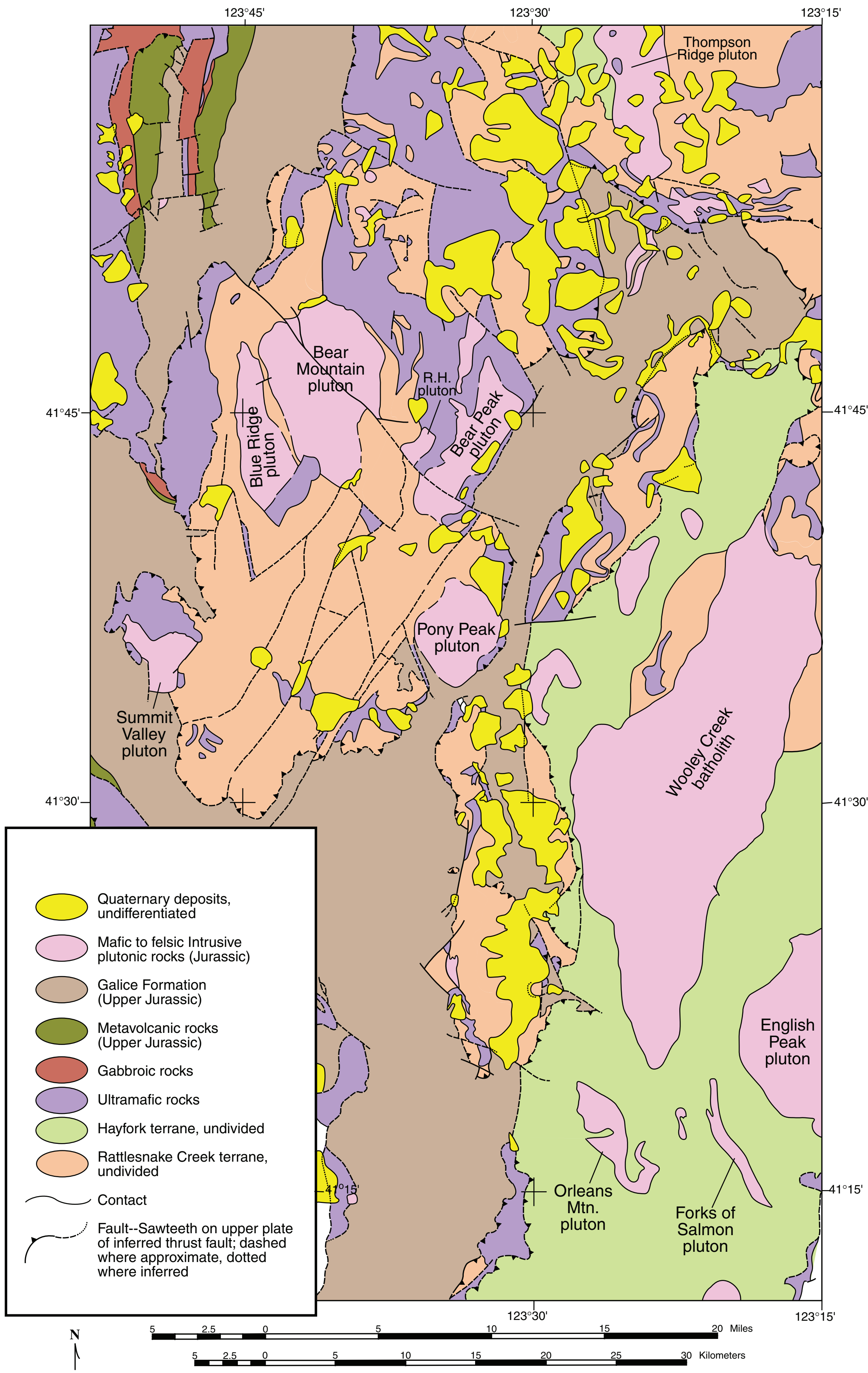
During Jurassic and Early Cretaceous time, arc magmatism in the Klamath Mountains province was episodically punctuated by contractional deformation (Wright and Fahan, 1988; Hacker and Ernst, 1993; Hacker et al., 1995). These contractional events are represented by regional thrust faults that separate distinct, commonly arc-related, tectonostratigraphic terranes (Irwin, 1960, 1972, 1981, 1994; Davis, 1968). Episodic contraction is apparently lacking in many modern intraoceanic arcs, in which arc crust appears to be in nearly continuous extension (Hawkins et al., 1984; Hamilton, 1988) due to slab rollback. Dewey (1980) discussed a plate-tectonic model for convergent margins where increased coupling, in part related to the age of the lithosphere being subducted, could lead to contraction within a continental magmatic arc (his Peruvian-type). Busby (2004) argued that during Late Cretaceous time, the continental arc of Baja California, Mexico, was a "compressional arc" (see her Fig. 22).

In the Klamath Mountains province, one of the most intensively studied contractional events is the Late Jurassic Nevadan orogeny (Saleeby et al., 1982; Harper and Wright, 1984; Harper et al., 1994), during which tectonostratigraphic terranes of the western Paleozoic and Triassic belt and structurally higher units were thrust over a supra-subduction zone complex that included the Rogue–Chetco arc, Josephine ophiolite, and overlying flysch of the Upper Jurassic Galice Formation. Thrusting began at ca. 155 Ma and ended by 150 Ma, according to Saleeby et al. (1982), Harper and Wright (1984), and Harper et al. (1994), although Nevadan deformation continued until at least 146 Ma (Harper et al., 1994). Recent high-precision radiometric dating has shown that arc-style magmatism was active in both the hanging wall and footwall of the key Nevadan thrust fault (Orleans fault of Hershey, 1906, 1911; Preston Peak fault [thrust] of Snoke, 1977; Fig. 1) until 156 Ma (Yule, 1996), and detrital zircons in the footwall flysch (Galice Formation; Fig. 1) are as young as ca. 153 Ma (Miller et al., 2003). These data support the ideas of Harper and Wright (1984) and Harper et al. (1994) that Nevadan thrusting and deposition of the Galice flysch were, at least in part, synchronous. Moreover, the work of Miller et al. (2003) indicates that somewhere in the source region of the footwall Galice Formation, magmatism lasted until ca. 153 Ma.

Magmatism in the footwall of the Orleans thrust may have been continuous during thrusting, because Saleeby and Harper (1993) and Harper et al. (1994) reported deformed dikes with ages as old as ca. 151 Ma, and the Orleans thrust is intruded by a number of plutons with ages as old as ca. 150 Ma (Harper et al., 1994). Furthermore, the studies of Snoke et al. (1981), Harper et al. (1994), Allen and Barnes (this volume), Bushey et al. (this volume), and McFadden et al. (this volume) indicate that large volumes of mafic to felsic magma were emplaced into the footwall and hanging wall of the Orleans thrust from 150 to 144 Ma.

The combination of new (Allen and Barnes, this volume; Chamberlain et al., this volume) and existing geochronologic data (e.g., Harper et al., 1994; Irwin and Wooden, 1999) combined with new field, geochemical, and isotopic data on these syn- and immediately post-Nevadan plutonic rocks provides a means of characterizing the nature of magmatic activity before, during, and after contractional deformation. In this chapter, we emphasize the compositions and origins of syn- and post-Nevadan magmatism, herein referred to as the "western Klamath plutonic suite." Questions that we address include the origins and evolution of parental magmas; interactions with, and effects on, the crust through which these magmas passed; and the significance of arc magmatism that closely followed an episode of thrust faulting during a regional contractional orogeny.

Figure 1. Generalized geologic map of the north-central Klamath Mountains, California, showing most of the plutons of the western Klamath plutonic suite: Bear Mountain intrusive complex (Blue Ridge and Bear Mountain plutons), Bear Peak pluton, Red Hill Creek pluton (R.H. pluton), Pony Peak pluton, and Summit Valley pluton. The syn-Nevadan dikes and sills are not shown on this geologic map. The locations of the Lower Coon Mountain intrusion, Ammon Ridge pluton, and Glen Creek gabbro-ultramafic complex are shown in Figure 1 in Allen and Barnes (this volume). The basis for this map is Wagner and Saucedo (1987).



123°45'
123°30'
123°15'
41°45'
41°30'
41°15'
Thompson Ridge pluton
Bear Mountain pluton
R.H. pluton
Bear Peak pluton
Blue Ridge pluton
Pony Peak pluton
Summit Valley pluton
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, undivided
Rattlesnake Creek terrane, undivided
Contact
Fault--Sawteeth on upper plate of inferred thrust fault; dashed where approximate, dotted where inferred
N
5 2.5 0 5 10 15 20 Miles
5 2.5 0 5 10 15 20 25 30 Kilometers

GEOLOGIC SETTING

Regional Setting

In the western Klamath Mountains, the Nevadan orogeny is associated with juxtaposition of terranes of the western Paleozoic and Triassic belt (Irwin, 1960) over rocks of the western Jurassic belt along the Orleans fault (Hershey, 1906, 1911; Preston Peak fault [thrust] of Snoke, 1977; Fig. 1). Hanging-wall rocks immediately above the Orleans thrust belong to the Rattlesnake Creek terrane (Fig. 1), which consists of an ophiolitic mélange overlain by various cover sequences of Upper Triassic to Lower Jurassic arc volcanic and volcaniclastic rocks (Gray, 1986; Wright and Wyld, 1994) and argillaceous to siliceous metasedimentary rocks (Frost et al., this volume). The Rattlesnake Creek terrane, in turn, is overlain by the western Hayfork terrane (cf. Wright, 1982; Fig. 1). This contact is a low-angle fault that has been interpreted as a minor thrust that modified a depositional contact (Wright and Fahan, 1988; Donato et al., 1996).

In the area of study (Fig. 1), the footwall consists of the basal Josephine ophiolite and overlying (meta)sedimentary rocks of the Upper Jurassic Galice Formation. The latter consist of interbedded metawacke, arenaceous phyllite, slate, and scarce metaconglomerate (e.g., Snoke, 1977; Harper, 1984; Pinto-Auso and Harper, 1985). To the north of the area, the footwall also encompasses late Middle Jurassic arc rocks of the Rogue Formation (Garcia, 1982) and their presumed intrusive equivalents (Chetco intrusive complex; Jorgenson, 1970; Hotz, 1971; Yule, 1996). The Rogue Formation was deposited on the Josephine ophiolite, whereas the Chetco intrusive complex was intruded into it.

In the western Klamath Mountains, we have identified a suite of magmatic rocks that were synchronous with or immediately post-dated Nevadan thrusting. These rocks either intrude the Galice Formation or show geologic or geochonrologic evidence of post-dating Galice deposition. They are characteristically hornblende-rich, have associated ultramafic cumulates, and show evidence for an Mg-rich parental magma. Syn-thrusting magmatism is represented by a suite of variably deformed dikes and sills (Harper et al., 1994; Harper, this volume; see below). Post-thrusting plutonism encompasses ultramafic to tonalitic plutons that were emplaced along the length of the western part of the province (Irwin and Wooden, 1999). In the study area, these plutons are Summit Valley, Pony Peak, Bear Peak, and Red Mountain Creek, and the cluster of plutons of the Bear Mountain intrusive complex. We additionally discuss the Lower Coon Mountain pluton (Harper et al., 1994), Buckskin Peak, Ammon Ridge, and Glen Creek plutons (Young, 1978; Irwin and Wooden, 1999; see Fig. 1 *in* Allen and Barnes, this volume).

Two younger plutonic suites were emplaced after western Klamath magmatism. One consists of a group of tonalite-trondhjemite-granodiorite plutons (142–136 Ma; "ttg suite") and the other of a group of granodioritic plutons (139–136 Ma; "granodiorite suite"). These younger suites are discussed in Allen and Barnes (this volume).

Magmatism during and after Nevadan Thrusting

Syn-Nevadan Dikes and Sills. A suite of distinctive porphyritic dikes and sills intrudes footwall rocks beneath the Orleans thrust (Josephine ophiolite and Galice Formation; see Harper et al., 1994; Harper, this volume). These rocks have U-Pb (zircon) ages and deformational features that indicate emplacement during and after Nevadan thrusting (Saleeby and Harper, 1993; Harper et al., 1994). The intrusions range in thickness from ~12 cm to 2 m. Most are mafic to intermediate in composition and range in color from dark gray to medium grayish green. They are distinguished in the field by the presence of hornblende phenocrysts and/or acicular hornblende in the groundmass. These traits are in contrast to those of dikes of the Josephine ophiolite, which are generally aphyric and lack igneous hornblende.

The oldest dated sample is broadly granodioritic; it yielded an age of 151 ± 1.5 Ma (Harper et al., 1994). A basaltic dike yielded an age of 150.5 ± 1.5 Ma, and a dike with basaltic andesite composition was dated at 146 ± 1 Ma (Harper et al., 1994).

Summit Valley Pluton. This 150 ± 1-Ma pluton (Harper et al., 1994) is the oldest known pluton to intrude the Orleans (Preston Peak) thrust; there are well-developed contact-metamorphic assemblages in both hanging-wall and footwall rocks (Norman, 1984). The pluton is heterogeneous and shows complex crosscutting intrusive relationships. It is predominantly hornblende gabbro, but ranges from hornblendite and scarce olivine clinopyroxenite to hornblende diorite (Norman, 1984). Hypersolidus and subsolidus deformation fabrics are common; some are cut by dikes that themselves are deformed (Griesau, 1992). High-temperature shear zones reach ~300 m in thickness and occur within variably deformed gabbro. These high-temperature, banded mylonites consist of granoblastic-polygonal brown hornblende, diopsidic augite, and plagioclase. Epidote-prehnite veins with slickenfibers are common and are interpreted to have formed during cooling of the pluton to the ambient temperature of the host rocks, which were undergoing lower greenschist-facies regional metamorphism (Griesau, 1992; Griesau and Harper, 1992).

Bear Mountain Intrusive Complex. The Bear Mountain intrusive complex consists of several plutons described in detail by Snoke et al. (1981) and Bushey et al. (this volume). The complex consists of two large bodies, the Blue Ridge and Bear Mountain plutons, and a number of small, related intrusions (Bushey et al., this volume; Fig. 1).

The Blue Ridge pluton consists chiefly of wehrlite and hornblende ± olivine clinopyroxenite, with subordinate dunite and various gabbroic rocks, including hornblende gabbro pegmatite. This pluton is undated, but it is intruded by a biotite-hornblende quartz diorite to tonalite pluton with a U-Pb (zircon) age of 150.5 ± 0.61 Ma (Chamberlain et al., this volume).

The Bear Mountain pluton consists of at least three major intrusive units. These are detailed in Bushey et al. (this volume) and are named the "Punchbowl plutonic unit" (pyroxene-hornblende gabbro and diorite), "Buck Lake plutonic unit" (biotite–two-pyroxene ± hornblende diorite to monzodiorite), and "Doe Flat plutonic unit" (biotite-hornblende quartz diorite to tonalite). The U-Pb (zircon) ages of the Punchbowl and Buck Lake units are identical with analytical uncertainty (ca. ± 0.5 Ma) at 148 Ma (Chamberlain et al., this volume). Snoke (1972) and Snoke et al. (1981) showed that the Bear Mountain pluton intrudes a high-angle fault that offsets the Orleans (Preston Peak) thrust. Therefore, the pluton must post-date the thrust. This conclusion is consistent with the 147- to 148-Ma U-Pb (zircon) ages.

A number of small tonalitic to granitic intrusive bodies cuts all three of the main intrusive units (Bushey et al., this volume). The largest of these bodies is called the "Wilderness Falls plutonic unit," after good exposures at Wilderness Falls along Clear Creek (Snoke et al., 1981). This body is petrographically similar to tonalite intruded into the Blue Ridge pluton, but must be younger, because it intrudes ca. 148-Ma rocks of the Bear Mountain pluton.

Two sets of mafic dikes are present in the aureole between the Blue Ridge and Bear Mountain plutons (Snoke and Barnes, 2002; Bushey et al., this volume). One set, referred to as the "gabbroic dikes," is Mg-rich and typically contains augite phenocrysts or their reaction products. The second set, the "dioritic dikes," is mafic but poorer in MgO and contains hornblende and plagioclase phenocrysts. Field relations (Snoke and Barnes, 2002; Bushey et al., this volume) show that these dikes were intruded and deformed during development of the dynamothermal aureole of the Bear Mountain pluton and are therefore coeval with the Bear Mountain intrusive complex.

Bear Peak and Red Hill Creek Plutons. The Bear Peak pluton (Fig. 1) is an elongate pluton with a central, structurally deep zone of hornblende clinopyroxenite and gabbroic to dioritic rocks (McFadden et al., this volume). Structurally higher parts of the pluton consist of gabbroic through granodioritic rocks that were emplaced as a series of sheetlike intrusions. The pluton clearly intrudes and contains xenoliths of the hanging-wall Rattlesnake Creek terrane, but a contact with the footwall Galice Formation is not exposed at the present level of erosion. However, samples of the Galice Formation collected within ~600 m of the pluton have undergone contact metamorphism (e.g., these samples contain biotite and scarce chiastolite porphyroblasts). This relationship, along with the 143.7 ± 1.3-Ma U-Pb (zircon) age from the Bear Peak pluton (Allen and Barnes, this volume), indicates that this pluton is a member of the western Klamath plutonic suite. Allen and Barnes (this volume) reported a population of inherited zircon with an age spectrum similar to that of detrital zircons from the Galice Formation (Miller et al., 2003).

The small Red Hill Creek pluton crops out west of the Bear Peak pluton (Fig. 1). It is predominantly tonalite and granodiorite and is intruded by fine-grained microgabbroic dikes. Evidence for magma mingling (e.g., mafic magmatic enclaves, synplutonic dikes) is abundant in both Bear Peak and Red Hill Creek plutons.

Pony Peak Pluton. The Pony Peak pluton (Fig. 1) ranges from hornblende (±pyroxene) gabbro to biotite hornblende tonalite and granodiorite. It has a dynamothermal contact aureole in the footwall Galice Formation (Harper et al., 1994), and semipelitic rocks in the Galice Formation contain andalusite porphyroblasts. Contact effects in the hanging-wall Rattlesnake Creek terrane are primarily limited to hornfels development. Two U-Pb (zircon) ages of 146 ± 3 and 144.2 ± 2.5 Ma were determined by Harper et al. (1994) and Allen and Barnes (this volume), respectively. The multicrystal dating of Harper et al. (1994) resulted in a Middle Proterozoic upper intercept and laser-ablation inductively coupled plasma mass spectrometry dating (Allen and Barnes, this volume) confirmed the presence of a suite of inherited zircons similar to detrital zircons from the Galice Formation.

Evidence for magma mingling in the Pony Peak pluton is primarily in the form of mafic magmatic enclaves. Synplutonic dikes, such as seen in the Bear Peak pluton, were not observed, and the proportion of isolated enclaves and enclave swarms is smaller than in the Bear Peak pluton.

Lower Coon Mountain, Buckskin Peak, Ammon Ridge, and Glen Creek Plutons. At least two other plutons exposed in the north-central Klamath Mountains appear to be part of the western Klamath plutonic suite. These are the Lower Coon Mountain and Buckskin Peak plutons. Moreover, at least two plutons in the southern Klamath Mountains should probably be considered members of this plutonic suite: the Ammon Ridge pluton (Young, 1978) and Glen Creek gabbro-ultramafic complex (Irwin et al., 1974; Irwin and Wooden, 1999; see Fig. 1 in Allen and Barnes, this volume).

The Lower Coon Mountain pluton is a subhorizontal, ≥300-m-thick, sill-like body that intrudes the Galice Formation (Harper, 1980; Gray and Page, 1985). It consists of >90% ultramafic rocks, mostly olivine ± plagioclase clinopyroxenite, along with less abundant olivine gabbronorite, and hornblende diorite. Scarce granitic dikes intrude the Galice Formation along the margins of the pluton and have yielded U-Pb zircon ages of ca. 142 and ca. 145 Ma (with Proterozoic upper intercepts; Harper et al., 1994). Ultramafic rocks are exposed from the base to the roof of the pluton, suggesting that it has a cumulate origin. No igneous layering, foliation, or solid-state deformation fabrics were observed. The narrow contact aureole consists of pelitic hornfels with relict andalusite (now muscovite) that overprints the pervasive slaty cleavage of the Galice Formation. The plutonic rocks are partially altered to low-grade metamorphic mineral assemblages. The ca. 149-Ma Buckskin Peak pluton intrudes the Josephine peridotite (Irwin and Wooden, 1999; Fig. 1 *in* Allen and Barnes, this volume). It consists of biotite + hornblende quartz diorite (Harper et al., 1994), but has otherwise received little study. The Ammon Ridge pluton was mapped and described by Young (1978), and Wright and Fahan (1988) reported Late Jurassic U-Pb zircon ages (147–151 Ma). Young (1978) described the pluton as chiefly consisting of hornblende ± biotite ± augite diorite with variable amounts of quartz. Young (1978) also described a distinctive, chiastolite-bearing dynamothermal contact aureole in the Upper Jurassic Galice Formation. The Glen Creek gabbro-ultramafic complex was mapped by Irwin et al. (1974), who described it as consisting of medium-grained to pegmatitic hornblende gabbro with subordinate hornblendite and peridotite. He mapped a hornfelsic contact aureole in the Galice Formation. Wright and Fahan (1988) reported 147- to 151-Ma U-Pb ages from this pluton. Thus, the ages and intrusive relationships of the Ammon Ridge and Glen Creek plutons are consistent with other members of the western Klamath plutonic suite. Moreover, the presence of hornblende-bearing cumulates and of hornblende as a near-liquidus phase in gabbroic to dioritic rocks supports inclusion in the western Klamath suite.

Emplacement Conditions

The presence of andalusite (chiastolite) in the aureoles of the Pony Peak (Harper et al., 1994), Bear Peak (McFadden et al., this volume), Lower Coon Mountain, and Ammon Ridge (Young, 1978) plutons, and of cordierite in the aureole of the Bear Mountain pluton (Snoke et al., 1981) indicate relatively shallow emplacement (pressure ≤ 4 kb, depth ≤ 14 km; Pattison, 1992). Use of Al-in-hornblende barometry (Anderson and Smith, 1995, calibration) yielded 3.7–4.2 kb for the Pony Peak pluton and 2.8–4.8 kb for the Bear Peak pluton. Calculated Al-in-hornblende pressures on the Bear Mountain pluton resulted in a range of pressure estimates from 3.5 to 5.0 kb, and pressure estimates from syn-emplacement dikes in the host rocks were 3.1–3.7 kb (Bushey et al., this volume). In summary, aureole assemblages and Al-in-hornblende barometry indicate emplacement of the western Klamath magmas in the upper crust at depths ≤15 km.

GEOCHEMISTRY

Introduction

The narrow time interval of the western Klamath plutonic suite, the predominance of hornblende-bearing mafic to intermediate compositions, and the distribution of these plutons in the western part of the province suggest that they belong to a single magmatic suite. In the following section, the geochemical compositions of the rocks are characterized and compared, and the compositions of dikes associated with the Bear Mountain intrusive complex are used to infer parental compositions. The data show that most western Klamath plutons had two H_2O-rich parental magmas: one a primitive basalt and the other an evolved basalt or basaltic andesite. H_2O-poor parental magma was much less common.

Petrographic summaries of the western Klamath suite plutons are given in Appendix A1, geochemical data are compiled in Appendix A2, and analytical methods are given in Appendix A3, all on the CD-ROM accompanying this volume or in the GSA Data Repository.[1]

Major and Trace Element Compositions

The suite of samples shows a wide range of SiO_2 contents, ranging from <40 to 74% (Fig. 2). However, several of the western Klamath suite plutons have a less extended SiO_2 range. For example, few samples of the Bear Mountain pluton have SiO_2 contents >55 wt%, silica contents in the Blue Ridge ultramafic-mafic pluton are <52 wt%, and Summit Valley pluton samples are <58 wt%. In contrast, the Bear Peak and Pony Peak plutons and syn-Nevadan dikes range in SiO_2 contents from as low as 47 wt% to as high as 74 wt%. Most samples are metaluminous, but a small group of tonalitic and granodioritic rocks from the Wilderness Falls, Bear Peak, and Pony Peak intrusions is mildly peraluminous.

In the classification of Frost et al. (2001), most samples plot in the magnesian field (Fig. 2A), although samples from the Bear Mountain pluton straddle the magnesian-ferroan boundary. Similarly, most Bear Mountain pluton samples are calc-alkaline (Fig. 2B) but show scatter on either side of the calc-alkaline field. Most Bear Peak samples and late-stage tonalitic intrusions associated with the Bear Mountain intrusive complex and Summit Valley plutons are calcic, and Pony Peak samples straddle the calcic–calc-alkaline boundary (Fig. 2B). Samples of the syn-Nevadan dikes and sills scatter between the calcic and alkalic fields in Figure 2B. This scatter is very probably the result of alkali metasomatism (Appendix A1).

Because the plutonic rocks discussed in this chapter are similar in age and geologic setting, one might expect them to have similar magmatic histories. Here we use the largest and best documented of these intrusions, the Bear Mountain intrusive complex (Snoke et al., 1981; Bushey et al., this volume), as a model to which the other plutonic rocks may be compared.

Bear Mountain Intrusive Complex. The Bear Mountain intrusive complex was derived primarily from basaltic parental magmas (Snoke et al., 1981). At least three basaltic parents were present, two of which are represented by mafic dikes in the Bear Mountain aureole. The petrogenetic relationships determined by Bushey et al. (this volume) are summarized here and as insets in Figure 3A and B. The most primitive of the parental magmas are represented by the compositions of the Mg-rich gabbroic dikes (black star in Fig. 3A and B). The Blue Ridge pluton is interpreted as a cumulate from such magmas, with cumulus olivine ± augite ± plagioclase. Fractionation of gabbroic dike-type magma gave rise to the second parental magma (gray star in

[1]GSA Data Repository item 2006201, Appendices 1–3, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

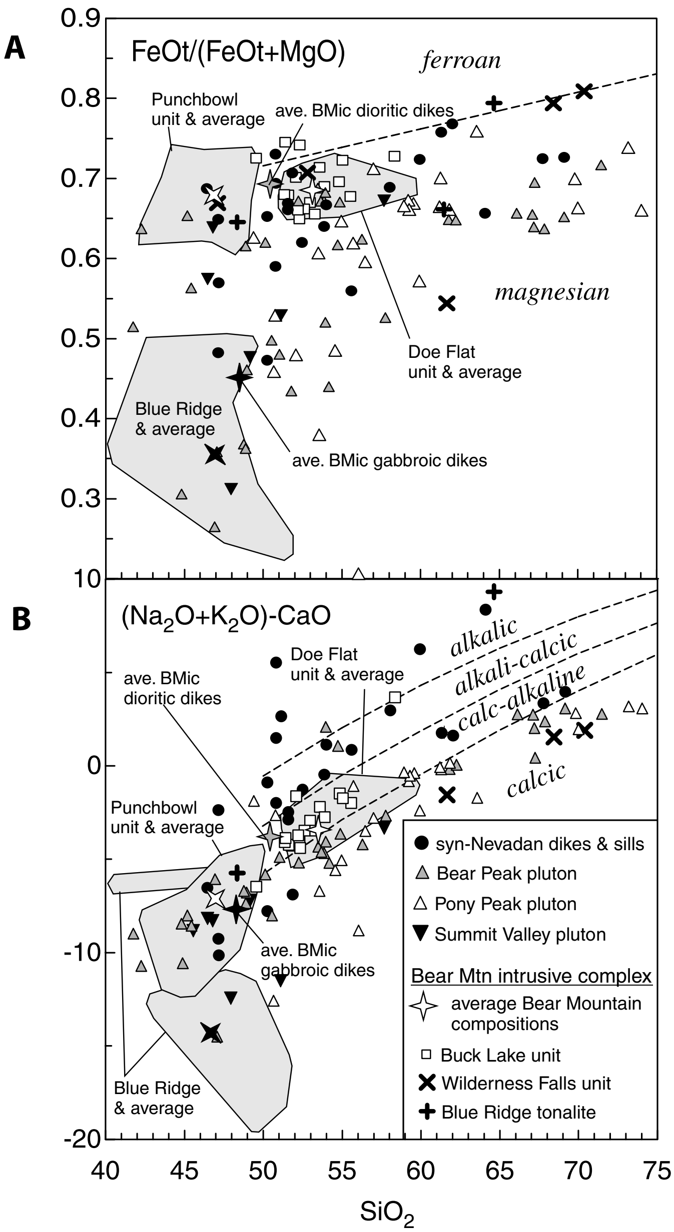


Figure 2. Geochemical classification according to Frost et al. (2001). (A) Most samples are magnesian, but parts of the Bear Mountain intrusive complex plot in the ferroan field. (B) Similarly, most samples are either calcic or calc-alkaline. Fields are shown for the Blue Ridge pluton and Punchbowl and Doe Flat units of the Bear Mountain pluton. Star symbols are average compositions of the Blue Ridge pluton (diagonal black), Punchbowl (diagonal white), and Doe Flat (white) units of the Bear Mountain pluton, and gabbroic (black) and dioritic (gray) dikes associated with the Bear Mountain intrusive complex. Bmic—Bear Mountain intrusive complex.

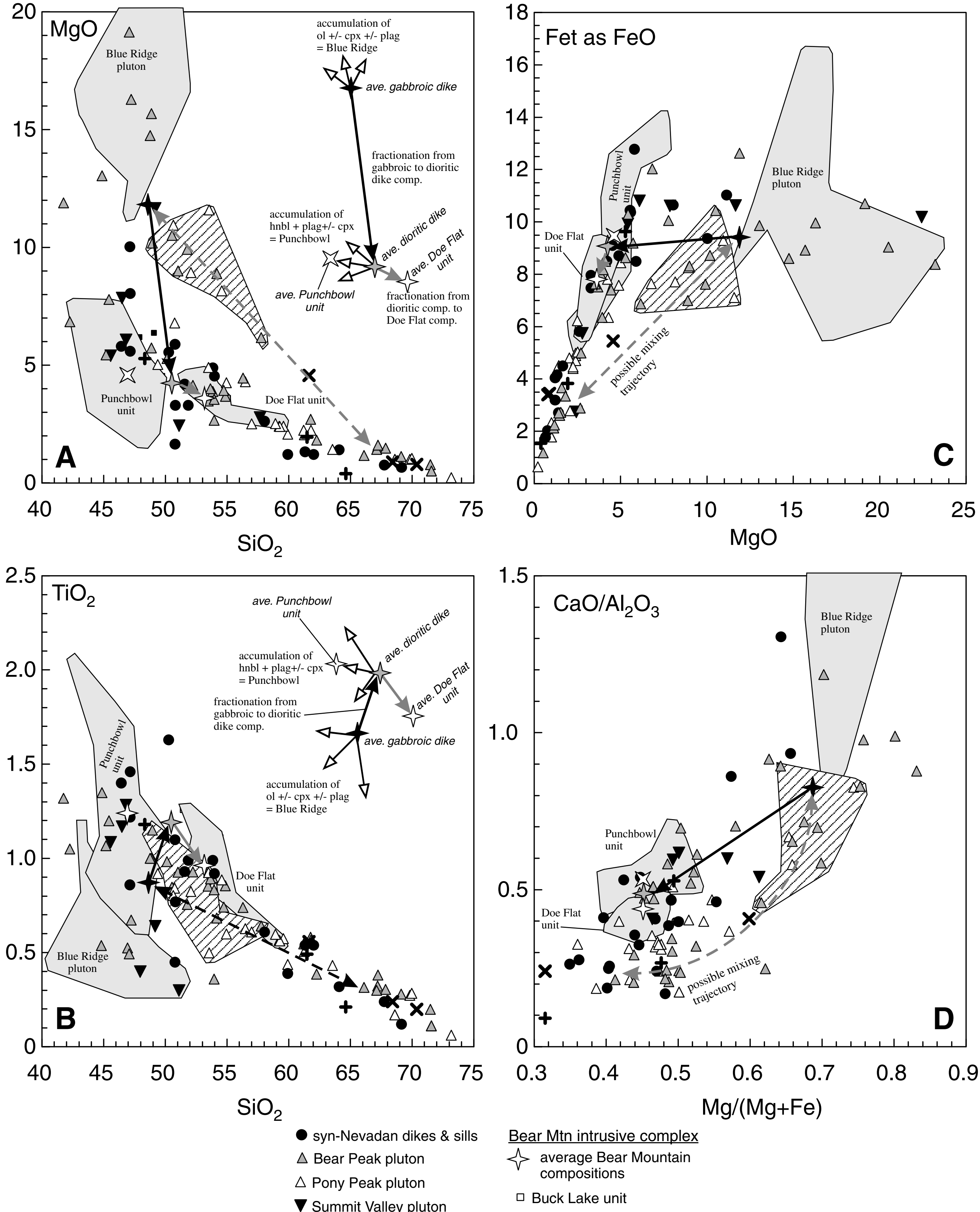
Fig. 3A and B), the plagioclase + hornblende-phyric dioritic dikes. Crystal-liquid separation of this parental magma type yielded cumulates (i.e., the gabbro/diorite Punchbowl unit of the Bear Mountain pluton) and fractionated magma (the Doe Flat unit; Fig. 3A and B). The third parental magma, that of the more potassic Buck Lake unit, was compositionally similar to the dioritic dike magmas but had higher K_2O and lower H_2O contents (Bushey et al., this volume).

The close petrogenetic relationship between gabbroic and dioritic dikes is illustrated by their having very similar rare-earth-element (REE) patterns (Fig. 4A). Both groups of dikes have moderate negative slopes, little or no Eu anomaly, and a slight hump from Pr to Sm. These patterns are mirrored in the REE patterns of most samples from the Bear Mountain pluton (Fig. 4B), which is consistent with magmas similar to the gabbroic and dioritic dikes as parental magmas. The positive and negative Eu anomalies seen in samples of the Bear Mountain pluton indicate plagioclase accumulation or fractionation, respectively.

Late-stage tonalitic and granitic intrusions associated with the Bear Mountain intrusive complex are characterized by high Sr contents (500 to ~1250 ppm; Fig. 5). Their REE patterns (Fig. 4C) are distinct from those of the main plutonic units, in that they have steeper slopes, generally higher light REE (LREE) abundances, and heavy REE (HREE) contents that are less than seven times chondritic abundances. Furthermore, the HREE parts of the patterns are nearly flat. The high Sr contents, LREE enrichment, steep REE patterns, and low HREE contents are all characteristic of an origin by partial melting of metabasic rocks in which garnet ± amphibole were residual phases (e.g., Martin, 1987; Drummond and Defant, 1990; Barnes et al., 1996).

Syn-Nevadan Dikes and Sills. Detailed petrologic discussion of this suite of samples is complicated by their nearly pervasive alteration and by their lack of a single parental magma composition. Nevertheless, these rock compositions tend to plot in a trend that is coincident with the evolutionary path inferred for the Bear Mountain intrusive complex (particularly Fig. 3A and C), which implies evolution primarily by fractional crystallization. In addition, the majority of the dikes and sills have REE patterns similar to those of Bear Mountain intrusive complex gabbroic and dioritic dikes (Fig. 4D). The most mafic samples straddle the Bear Mountain intrusive complex gabbroic dike patterns, and LREE contents for the suite of samples are broadly correlated to SiO_2. The REE patterns of the majority of samples (ruled pattern in Fig. 4D) differ slightly from the Bear Mountain intrusive complex dioritic dikes in the somewhat steeper patterns of the latter group (Fig. 4D).

Two of the most evolved samples of the syn-Nevadan dikes and sills (quartz diorite and tonalite) have crossing REE patterns, HREE abundances greater than fifteen times that of chondrites (Fig. 4D), and Sr contents <600 ppm (Fig. 5). These features are also consistent with a fractional crystallization trend, as inferred from compositional variation in the Bear Mountain intrusive complex, and particularly with fractionation of calcic amphibole (e.g., Arth et al., 1978).


MgO
Blue Ridge pluton
accumulation of ol +/- cpx +/- plag = Blue Ridge
ave. gabbroic dike
fractionation from gabbroic to dioritic dike comp.
accumulation of hnbl + plag+/- cpx = Punchbowl
ave. dioritic dike
ave. Doe Flat unit
ave. Punchbowl unit
fractionation from dioritic comp. to Doe Flat comp.
Punchbowl unit
Doe Flat unit
A
SiO2
Fet as FeO
Punchbowl unit
Doe Flat unit
Blue Ridge pluton
possible mixing trajectory
C
MgO
TiO2
ave. Punchbowl unit
ave. dioritic dike
accumulation of hnbl + plag+/- cpx = Punchbowl
ave. Doe Flat unit
fractionation from gabbroic to dioritic dike comp.
ave. gabbroic dike
accumulation of ol +/- cpx +/- plag = Blue Ridge
Punchbowl unit
Doe Flat unit
Blue Ridge pluton
B
SiO2
CaO/Al2O3
Blue Ridge pluton
Punchbowl unit
Doe Flat unit
possible mixing trajectory
D
Mg/(Mg+Fe)
syn-Nevadan dikes & sills
Bear Peak pluton
Pony Peak pluton
Summit Valley pluton
Bear Mtn intrusive complex
average Bear Mountain compositions
Buck Lake unit
Wilderness Falls unit
Blue Ridge tonalite

Summit Valley Pluton. The Summit Valley pluton is, like the Bear Mountain intrusive complex, predominantly mafic to intermediate (Appendix A1). Compositional variation appears to follow an evolutionary path similar to that of the Bear Mountain intrusive complex gabbroic and dioritic dikes (Fig. 3A and C). With the exception of two samples, an ultramafic cumulate (Norman, 1984) and a hornblende diorite, Summit Valley samples have Al_2O_3 contents >18.5% (Appendix A2). This is similar to values seen in the Punchbowl unit of the Bear Mountain intrusive complex and suggests that plagioclase is probably a cumulate phase in many Summit Valley rocks. This inference is supported by the high Sr contents of these rocks: 582–1151 ppm (Fig. 5A; Appendix A2).

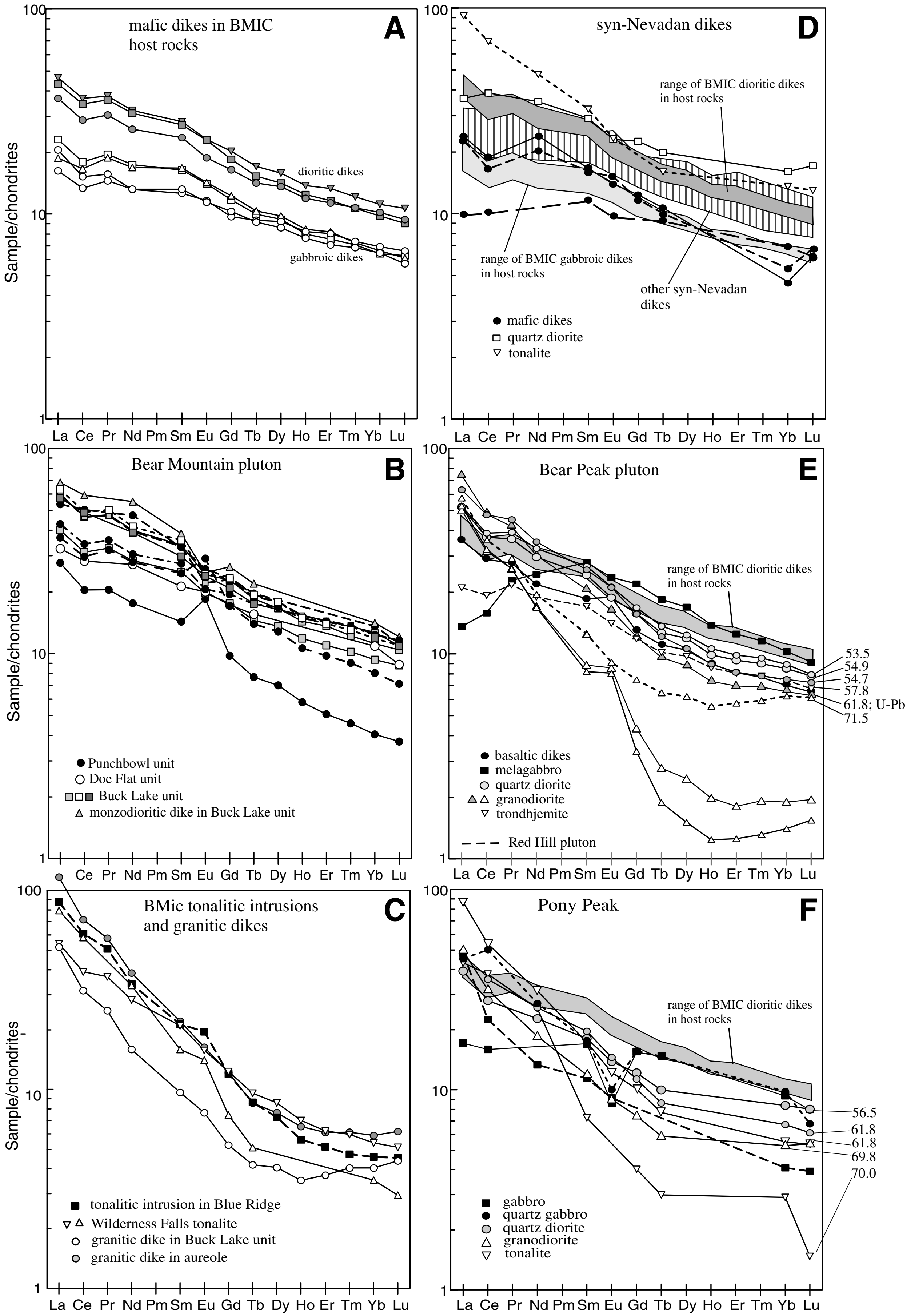
Bear Peak and Pony Peak Plutons. The geochemistry of the Bear Peak and Pony Peak plutons is discussed together, because both plutons have similar extended compositional ranges, with SiO_2 contents as high as 74 wt% (Fig. 3), and because they contain rocks that diverge from the Bear Mountain intrusive complex fractional crystallization trend. In Figure 3A, it is apparent that cumulate rocks from the structurally deepest, central part of the Bear Peak pluton have compositions similar to the Blue Ridge pluton. Because of their high contents of MgO and FeOt, we infer a similar origin for these rocks: accumulation of augite ± hornblende ± olivine. In addition, some of the Mg-rich aspects of the Bear Peak cumulates may have resulted from assimilation of metaserpentinite host rocks (McFadden et al., this volume). Figure 3 (especially Fig. 3A and C) shows that some samples from the Bear Peak and Pony Peak plutons follow the Bear Mountain intrusive complex fractional crystallization trend. However, another group of samples, shown with a diagonally ruled field in Figure 3, contains significantly higher MgO contents than do Bear Mountain intrusive complex samples with the same SiO_2 values. These samples are typically equigranular, medium- and fine-grained rocks whose compositions are probably close to melt compositions. In Figure 3, this field encompasses, or extends away from, the average composition of Bear Mountain intrusive complex gabbroic dikes.

Bear Peak and Pony Peak samples with SiO_2 >64 wt% have major element concentrations similar to those of the syn-Nevadan dikes and sills and tonalitic units of the Bear Mountain intrusive complex (Fig. 3). Trace element abundances and REE patterns (Figs. 4 and 5) show that this overlap does not imply similar origins. For example, compared to the syn-Nevadan dikes and sills, most evolved Bear Peak and Pony Peak samples have higher Sr contents (Fig. 5A), higher Ba/Y and Sr/Y ratios (Fig. 5D and E), and steeper REE patterns (Figs. 4 and 5C). Moreover, the REE patterns of evolved Bear Peak and Pony Peak samples generally have flat chondrite-normalized HREE abundances (reverse J-shape). Two granodiorites from the Bear Peak pluton have especially low HREE values (<2.5 times chondrites; Fig. 4E) and slight positive Eu anomalies.

When compared to the Bear Mountain intrusive complex, intermediate Bear Peak samples are distinct, because they show decreasing REE abundances with differentiation, whereas Bear Mountain intrusive complex rocks show overall increase of REE abundances (Figs. 4A and 5B). The same is true for the middle and heavy REEs in Pony Peak samples (Fig. 4E and F). These decreases may result from fractionation of REE-rich accessory minerals. However, if fractional crystallization controlled differentiation of Bear Peak and Pony Peak magmas with SiO_2 >55%, then one would expect plagioclase removal to cause a significant decrease in Sr contents. This process may be the case for some samples with Sr <700 ppm, but it cannot account for the samples with Sr >700–800 ppm (Fig. 5). Furthermore, fractional crystallization in the Bear Mountain intrusive complex system resulted in a decrease in Mg/(Mg + Fe) from ~0.68 to ~0.45 (Figs. 3 and 5), with an increase in Sr from ~300 ppm to ~700 ppm, followed by a decrease in Sr abundance. (Note that the higher Sr contents in the Bear Mountain intrusive complex Punchbowl unit are probably the result of plagioclase accumulation.) The Sr-rich samples from Bear Peak and Pony Peak are distinct in having higher SiO_2 and also higher Mg/(Mg + Fe) than the probable parental magma to the Punchbowl unit. These elevated values suggest that a fractional crystallization origin for these rocks is unlikely.

The steep REE slopes, high Sr contents, plus high Sr/Y and Ba/Y ratios of Bear Peak and Pony Peak samples with SiO_2 greater than ~65 wt% are characteristic of magmas derived by partial melting of metabasic rocks in which garnet ± amphibole ± clinopyroxene are residual phases (Martin, 1987; Drummond and Defant, 1990). In addition, plagioclase may not be a residual phase during partial melting of metabasic rocks. In such cases, positive Eu anomalies such as those seen in the Bear Peak granodiorites are possible, because residual phases such as clinopyroxene have negative Eu anomalies. Therefore, we suggest that a likely origin for Bear Peak and Pony Peak samples

Figure 3. Major element variation diagrams (wt%). Variation of (A) MgO, (B) TiO_2, and (C) total iron as FeO as functions of SiO_2 content. (D) Variation of CaO/Al_2O_3 as a function of Mg/(Mg + Fe). Oxides were chosen to illustrate the influence of cumulate assemblages on possible liquid lines of descent and magma mixing. Fields are shown for the Blue Ridge pluton and Punchbowl and Doe Flat units of the Bear Mountain pluton. Data for the Buck Lake unit of the Bear Mountain pluton are not shown; see Bushey et al. (this volume). Star symbols are average compositions of gabbroic (black) and dioritic dikes (gray) associated with the Bear Mountain intrusive complex, and Doe Flat (white) and Punchbowl (diagonal white) units. Solid arrows with filled heads show the inferred fractional crystallization trends of the various Bear Mountain intrusive complex units. In A and B, the inset diagrams show this path, along with the effects of crystal accumulation (arrows with unfilled heads) in the Blue Ridge pluton and Punchbowl unit. The field with a ruled pattern represents rocks from the Bear Peak and Pony Peak plutons with high MgO compared to the Bear Mountain intrusive complex fractional crystallization path. The double-headed, dashed arrow is the inferred mixing trajectory for mixtures of Mg-rich parental magmas with crustally derived tonalitic and granodioritic magmas in the Bear Peak and Pony Peak plutons. Abbreviations: cpx—clinopyroxene, hnbl—hornblende, plag—plagioclase.



mafic dikes in BMIC host rocks
A
dioritic dikes
gabbroic dikes
syn-Nevadan dikes
D
range of BMIC dioritic dikes in host rocks
range of BMIC gabbroic dikes in host rocks
other syn-Nevadan dikes
mafic dikes
quartz diorite
tonalite
Bear Mountain pluton
B
Punchbowl unit
Doe Flat unit
Buck Lake unit
monzodioritic dike in Buck Lake unit
Bear Peak pluton
E
range of BMIC dioritic dikes in host rocks
53.5
54.9
54.7
57.8
61.8; U-Pb
71.5
basaltic dikes
melagabbro
quartz diorite
granodiorite
trondhjemite
Red Hill pluton
BMic tonalitic intrusions and granitic dikes
C
tonalitic intrusion in Blue Ridge
Wilderness Falls tonalite
granitic dike in Buck Lake unit
granitic dike in aureole
Pony Peak
F
range of BMIC dioritic dikes in host rocks
56.5
61.8
61.8
69.8
70.0
gabbro
quartz gabbro
quartz diorite
granodiorite
tonalite
Sample/chondrites
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu

with high Sr/Y and Ba/Y and steep, reverse J-shaped REE patterns is by partial melting of metabasites, presumably at garnet-amphibolite to eclogite facies.

The previous discussion explains the existence of both basaltic (Bear Mountain intrusive complex gabbroic dikes) and felsic (granodioritic to tonalitic) magmas beneath the Bear Peak and Pony Peak plutons. Figure 3 shows that the MgO-rich samples with SiO_2 between 50 and 58 wt% could result from mixing of two such magmas. This scenario is consistent with the inverse correlation between HREEs and SiO_2 in these plutons (Fig. 4E and F). A similar explanation (magma mixing) is possible for MgO-poor samples with SiO_2 from 56 to 64 wt%. In this case, the mafic end member would be similar to evolved basaltic magma (diorite dike magma of the Bear Mountain intrusive complex) and the felsic end-member would be similar to granodioritic and tonalitic crustal magmas. As with the MgO-rich intermediate rocks, mixing would explain the inverse correlation between HREEs and SiO_2.

Isotopic Compositions

With the exception of the Bear Mountain intrusive complex, few isotopic data are available for the western Klamath plutonic rocks (Allen and Barnes, this volume; Fig. 6). Bushey et al. (this volume) showed that the Bear Mountain intrusive complex has low initial $^{87}Sr/^{86}Sr$ (0.70297–0.70347, with an average value of 0.70325 ± 0.00009 for the Bear Mountain pluton) and high ε_{Nd} (5.4–8.1; average of 6.4 ± 0.1 for the Bear Mountain pluton). All initial values are calculated at 147 Ma. Oxygen isotope ratios vary from $\delta^{18}O$ as low as +5.9‰ in clinopyroxenite to as high as +9.9‰ in a late-stage granitic dike (Bushey et al., this volume). The average $\delta^{18}O$ for seven samples of the Bear Mountain pluton is +7.2 ± 0.04‰, and for three samples of the Blue Ridge pluton, it is +6.6 ± 0.5‰. Initial Sr isotope data (at 145 Ma) are also available for five samples from the Pony Peak pluton (Allen and Barnes, this volume). They average 0.70356 ± 0.00008. Three of these samples were analyzed for oxygen isotope ratios, with values of $\delta^{18}O$ from +8.4 to +9.7‰.

Although initial $^{87}Sr/^{86}Sr$ values for the Bear Mountain and Pony Peak plutons are very similar, they are statistically distinct (Fig. 6). This distinction is also apparent in their $\delta^{18}O$ values. The Bear Mountain pluton has average $\delta^{18}O$ slightly higher than accepted "mantle values" (~5.5–6.2‰; Eiler et al., 1995), whereas $\delta^{18}O$ in samples from the Pony Peak pluton is at least 1.5‰ higher than the mantle range. Although the problems inherent in interpreting $\delta^{18}O$ values are well known (particularly deuteric equilibration and isotopic exchange with circulating fluids), the differences in $\delta^{18}O$ between the two plutons are suggestive that the Pony Peak pluton has a larger proportion of crustal material than does the Bear Mountain pluton.

Figure 4. Chondrite-normalized rare-earth-element plots. (A) Gabbroic and dioritic dikes in the host rocks of the Bear Mountain intrusive complex. These dikes are thought to represent parental magmas to the Bear Mountain intrusive complex. (B) Bear Mountain pluton. (C) Tonalitic intrusions and granitic dikes of the Bear Mountain intrusive complex. (D) Syn-Nevadan dikes. The ranges of gabbroic and dioritic Bear Mountain intrusive complex dikes are shown as shaded fields. (E) Bear Peak pluton. (F) Pony Peak pluton. In E and F, the field of Bear Mountain intrusive complex dioritic dikes is shown. Numbers on the right side of panels E and F indicate the SiO_2 contents of the samples. Bmic—Bear Mountain intrusive complex.

Trace-Element Discrimination Diagrams

Because western Klamath magmatism overlapped with and immediately followed Nevadan contractional deformation, the tectonic setting of this magmatism is of interest. Figure 7A is a tectonic discrimination diagram developed by Pearce and Peate (1995) that uses ratios of three elements, Th, Ta, and Yb, which are incompatible during fractional crystallization of basaltic magmas. All mafic and intermediate samples of the western Klamath plutons plot in the calc-alkaline zone of the volcanic arc field in Figure 7A, and the mafic dikes associated with the Bear Mountain intrusive complex plot in the center of the data cluster. All samples that plot in or near the shoshonite field are evolved rocks, primarily tonalite, granodiorite, and granite. Such rock types are inappropriate for use in this type of discrimination diagram and are plotted here to show the effects of HREE depletion on the element ratios.

Figure 7B shows chondrite-normalized multi-element plots of the gabbroic and dioritic dikes associated with the Bear Mountain intrusive complex. The patterns show distinct depletion of Nb, Ta, and Ti and enrichments of K and Sr; all characteristics of arc-related magmas.

DISCUSSION

The origin and compositional evolution of western Klamath suite plutons provide a snapshot of nascent epicontinental arc magmatism. The oldest magmatism in this event, the earliest syn-Nevadan sills and dikes, apparently overlapped waning stages of Nevadan thrusting. Moreover, emplacement of pluton-scale magmas occurred within 1 or 2 m.y. of the end of thrusting, at a time when Nevadan deformation was still active (e.g., high-temperature mylonites in the Summit Valley pluton). Minor mylonitic deformation is present in plutons as young as the 144-Ma Pony Peak pluton (Harper et al., 1994). Therefore, on the basis of age data, crosscutting relationships, and zircon inheritance, we view the syn-Nevadan dikes and sills, Bear Mountain intrusive complex, Summit Valley, Bear Peak, Pony Peak, and Lower Coon Mountain intrusions as part of a single magmatic episode. It is probable that the Buckskin Peak, Ammon Ridge, and Glen Creek plutons are also part of this episode, but this suggestion must be tested with geochemical and petrologic study.

The most obvious feature of western Klamath magmatism, relative to pre-Nevadan magmatism and to younger ttg

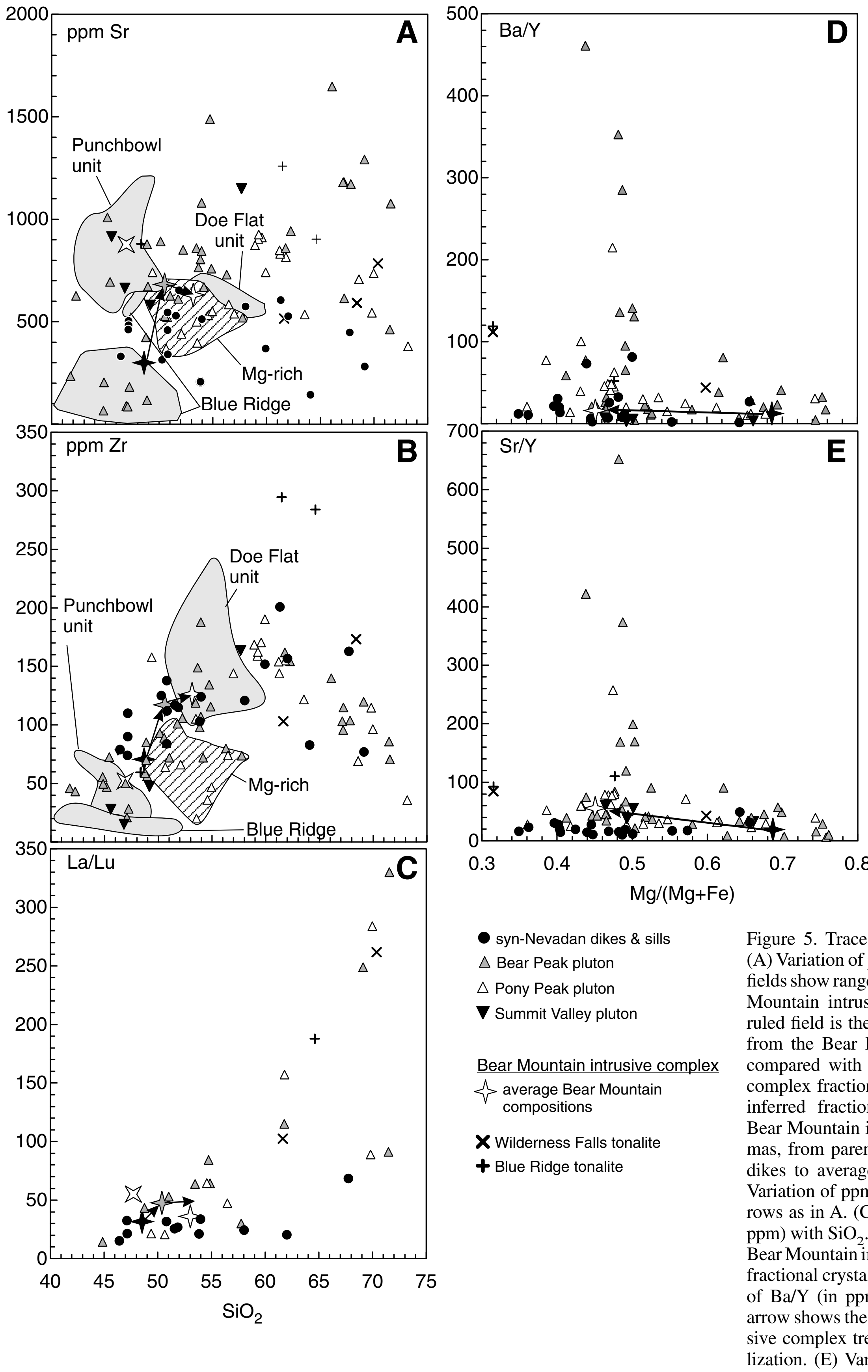


Figure 5. Trace element variation diagrams. (A) Variation of ppm Sr with SiO_2. The shaded fields show ranges of intrusive units in the Bear Mountain intrusive complex; the diagonally ruled field is the range of high MgO samples from the Bear Peak and Pony Peak plutons compared with the Bear Mountain intrusive complex fractionation path. Arrows show the inferred fractional crystallization trend for Bear Mountain intrusive complex mafic magmas, from parental gabbroic dikes to dioritic dikes to average Doe Flat composition. (B) Variation of ppm Zr with SiO_2. Fields and arrows as in A. (C) Variation in La/Lu ratio (in ppm) with SiO_2. The arrows show the inferred Bear Mountain intrusive complex trends due to fractional crystallization as in A. (D) Variation of Ba/Y (in ppm) with Mg/(Mg + Fe). The arrow shows the inferred Bear Mountain intrusive complex trends due to fractional crystallization. (E) Variation of Sr/Y (in ppm) with Mg/(Mg + Fe). The arrow shows the inferred Bear Mountain intrusive complex trends due to fractional crystallization.

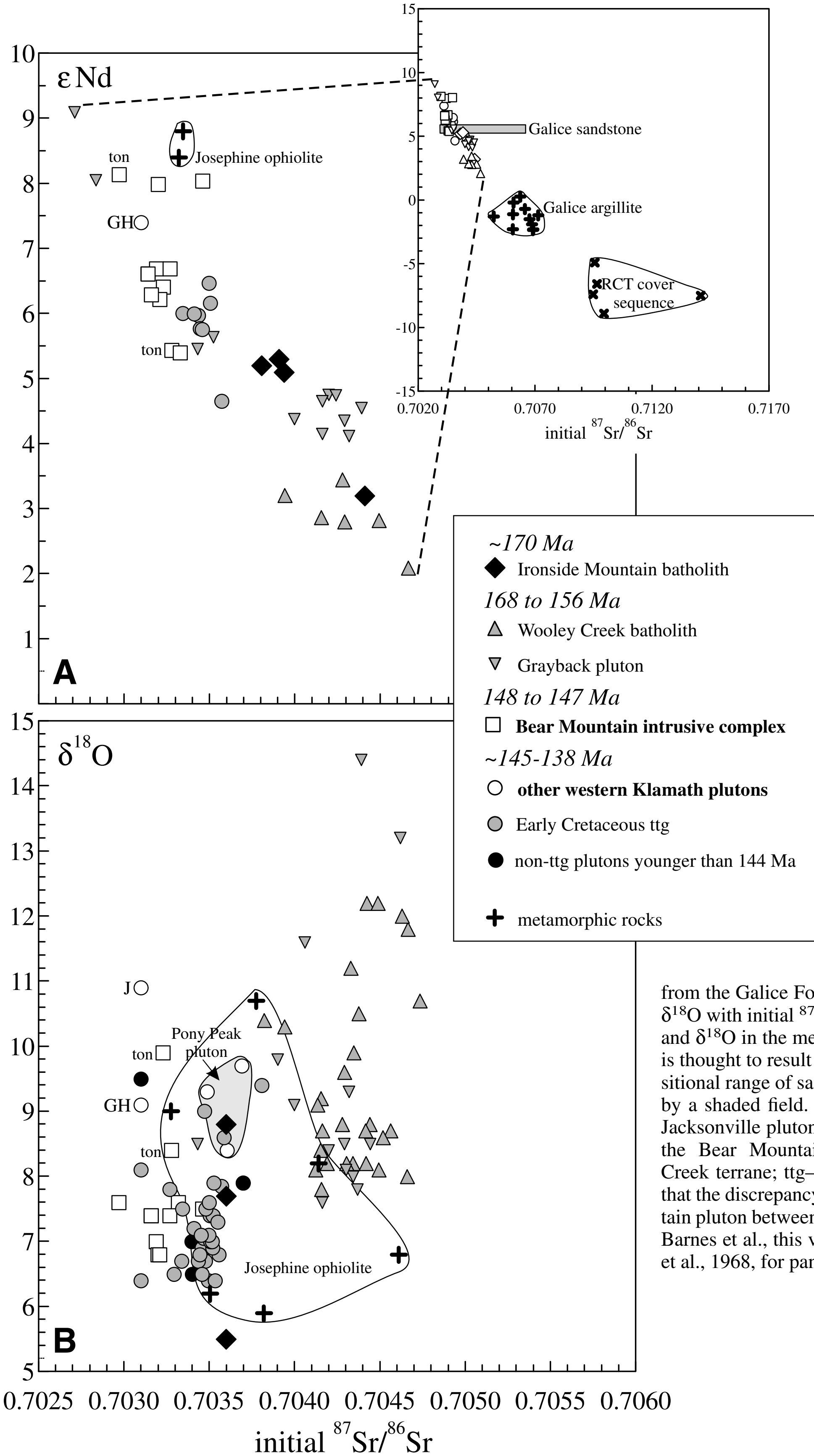


Figure 6. Isotopic compositions, showing the range of Bear Mountain intrusive complex and Pony Peak plutons, other Middle Jurassic to Early Cretaceous plutonic rocks, and metamorphic rocks from the western Klamath Mountains. (A) Variation of ε_{Nd} with initial $^{87}Sr/^{86}Sr$ (calculated at the age of the specific pluton). The Bear Mountain intrusive complex is noteworthy for its comparatively high ε_{Nd} and low initial $^{87}Sr/^{86}Sr$. Two metabasic samples from the Josephine ophiolite overlap the initial $^{87}Sr/^{86}Sr$ of the Bear Mountain intrusive complex but have slightly higher ε_{Nd}. The inset shows the compositional ranges of argillaceous rocks from the Galice Formation and Rattlesnake Creek terrane (Frost et al., this volume) and the range of initial $^{87}Sr/^{86}Sr$ of metasandstones from the Galice Formation (Coleman, 1972). (B) Variation of $\delta^{18}O$ with initial $^{87}Sr/^{86}Sr$. The large range of initial $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ in the metabasic rocks from the Josephine ophiolite is thought to result from hydrothermal alteration. The compositional range of samples from the Pony Peak pluton is shown by a shaded field. GH—Gold Hill pluton (ca. 145 Ma); J—Jacksonville pluton (ca. 154 Ma); ton—tonalitic intrusions of the Bear Mountain intrusive complex; RCt—Rattlesnake Creek terrane; ttg—tonalite-trondhjemite-granodiorite. (Note that the discrepancy in initial $^{87}Sr/^{86}Sr$ for the Ironside Mountain pluton between panels A and B is due to different sources: Barnes et al., this volume, Chapter 10, for panel A; Lanphere et al., 1968, for panel B.).

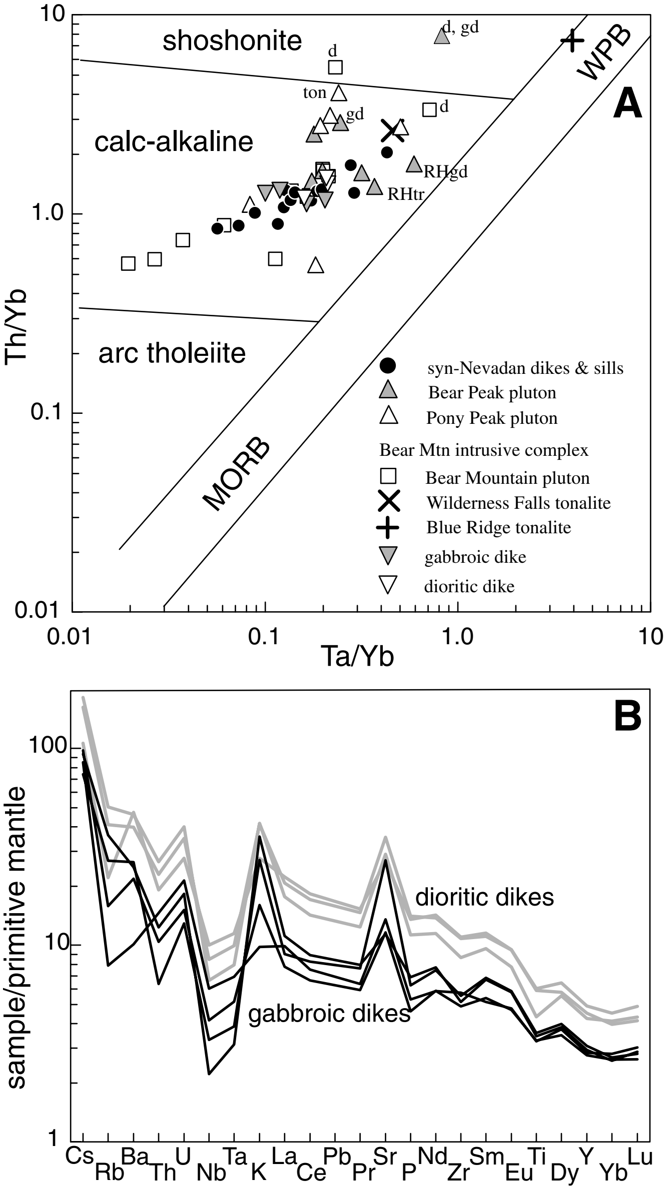


Figure 7. (A) Tectonic discrimination diagram (Pearce and Peate, 1995). All mafic samples plot in the calc-alkaline field. Samples that plot outside this field are tonalitic or granodioritic and contain a large component of crustal material (see text). They are, therefore, not appropriate for projection into this system and are shown as examples of the effects of crustal interaction. Abbreviations: d—dike sample; gd—granodiorite; MORB—mid-ocean ridge basalt; RH—Red Hill intrusion (part of the Bear Peak plutonic sequence); ton—tonalite; tr—trondhjemite; WPB—within-plate basalt. (B) Primitive mantle-normalized multielement plot of the gabbroic and dioritic dikes associated with the Bear Mountain intrusive complex.

magmatism, is the predominance of primitive, hydrous basaltic parental magmas. REE and major element data suggest that these parental magmas were similar throughout the western Klamath suite, although certainly not identical to one another. They were typically MgO-rich, enriched in LREE, and had olivine + augite ± plagioclase as near-liquidus phases. Most were H_2O-rich, as shown by early stability of hornblende, but the Buck Lake unit of the Bear Mountain intrusive complex requires an H_2O-poor mafic parent.

The western Klamath suite plutons are also similar in their petrogenetic histories. In the oldest members of the suite (syn-Nevadan dikes, Summit Valley pluton, and most of the Bear Mountain intrusive complex), compositional variation was primarily due to crystal-liquid fractionation, either fractional crystallization or crystal accumulation. Despite the clear importance of crystal-liquid separation, deep-seated interaction with crustal rocks is apparent in all plutons of the suite. In the Bear Mountain intrusive complex, this interaction takes the form of late-stage, predominantly tonalitic intrusions, such as the dated tonalite of the Blue Ridge pluton and the Wilderness Falls unit of the Bear Mountain pluton; whereas in the Summit Valley pluton, the presence of inherited zircon as old as Proterozoic (Harper et al., 1994) indicates some contribution from (meta) sedimentary rocks. Younger members of the suite (e.g., Bear Peak, Pony Peak, Lower Coon Mountain plutons) all contain felsic rocks with significant inherited zircon populations (Harper et al., 1994; Allen and Barnes, this volume). In the Bear Peak and Pony Peak plutons, REE patterns indicate residual garnet in crustal source rocks and therefore deep-seated melting. Moreover, the inverse correlation of HREE and SiO_2 contents in intermediate Pony Peak and Bear Peak samples suggests mixing of HREE-richer, mantle-derived magmas with HREE-depleted crustal magmas.

Petrogenesis

Our petrogenetic interpretations are shown schematically in Figure 8. This figure is derived from data presented here and from other chapters in this volume (Allen and Barnes; Bushey et al.; McFadden et al.). In Figure 8, the emplacement depth of the plutons is constrained by pressure estimates cited above. Magma differentiation at deeper levels is less well constrained, as discussed below.

Primitive, hydrous, basaltic magmas were emplaced early in the western Klamath magmatic event as gabbroic dikes associated with the Bear Mountain intrusive complex, as the parental magma to the Blue Ridge intrusion, and presumably as parental magma to at least some of the syn-Nevadan dikes (Fig. 8). Similar magmas were parental to the central cumulate zone of the Bear Peak pluton. Some of this primitive magma ponded deep in the crust (Fig. 8). The depth(s) of ponding is not known; however, for reasons discussed below, one possible location is within and/or near the top of the mafic part of the Josephine ophiolite. The ponded magmas underwent fractional crystallization along Fe-enrichment trends to produce evolved basaltic to andesitic magmas, which were emplaced to form dioritic dikes associated with the Bear Mountain intrusive complex, parental magmas to the Punchbowl unit of the Bear Mountain pluton, and hornblende gabbro to biotite-hornblende quartz

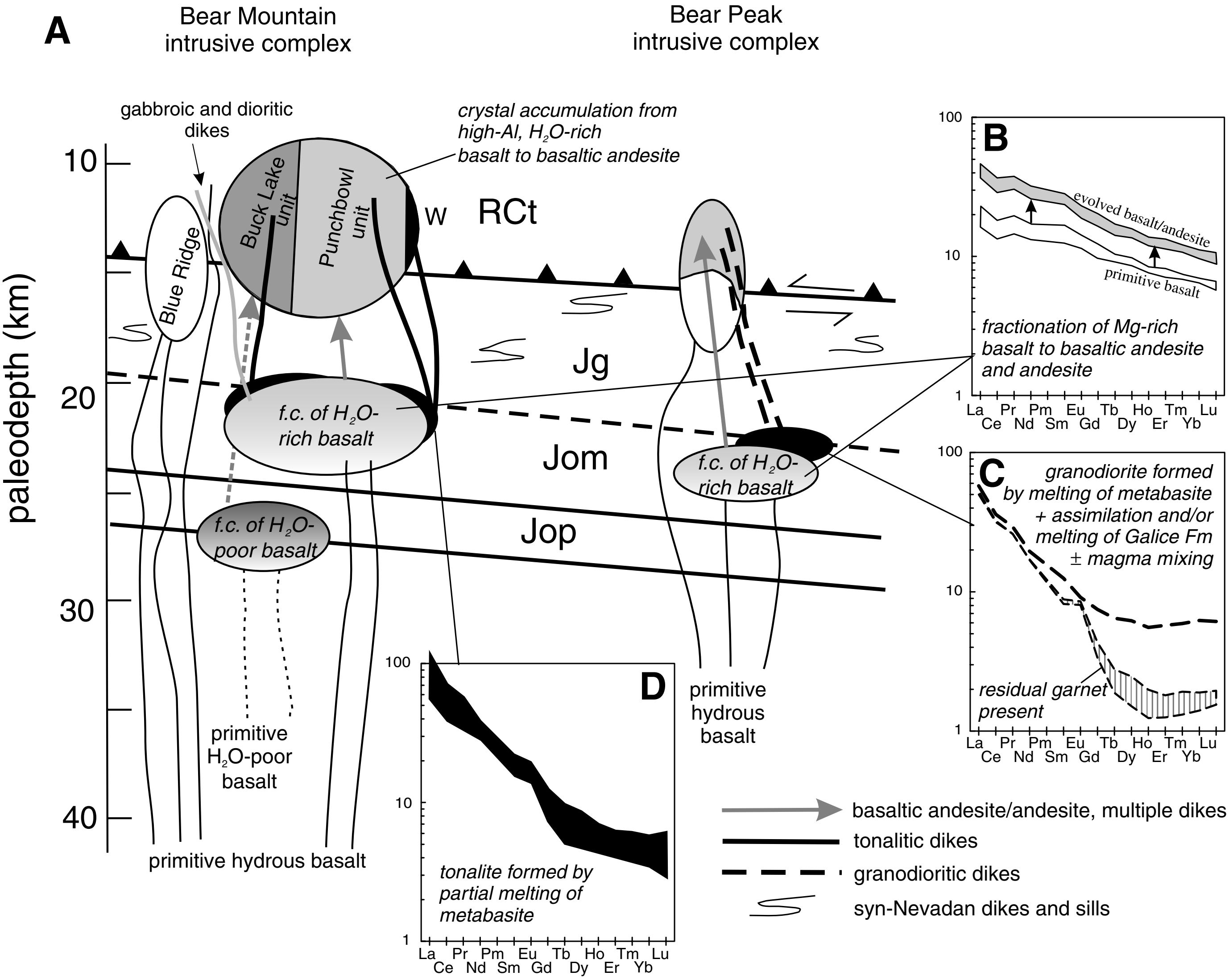


Figure 8. (A) Schematic cross-section to illustrate depth and types of western Klamath magma differentiation processes. Abbreviations: f.c.—fractional crystallization; Jg—Jurassic Galice Formation; Jom and Jop—the crustal section and peridotite, respectively, of the Josephine ophiolite; RCt—Rattlesnake Creek terrane. (B,C) Rare-earth-element patterns associated with various petrogenetic processes, including deep-seated fractional crystallization of parental high-Mg basaltic magmas, partial melting of metabasic rocks to form tonalite of Wilderness Falls, and hybridization of magmas with Galice Formation metasedimentary rocks/melts to form granodioritic rocks of the Bear Peak complex. Paleodepth estimates from Bushey et al. and McFadden et al. (this volume); Thickness estimates of Josephine ophiolite and Galice Formation from Harper (1980), Jachens et al. (1986), and Evans (1987).

diorite units in the Bear Peak pluton. This differentiation process is characterized by the uniform increase in REEs from parental basalt to evolved andesite (Fig. 8). Some mafic magma in the Bear Mountain intrusive complex was also poor in H_2O. This magma was similar to the primitive hydrous basalt except in terms of H_2O content. It differentiated to H_2O-poor andesitic magma that was emplaced as the Buck Lake unit of the Bear Mountain pluton (Fig. 8).

Tonalitic to granodioritic members of the suite (e.g., Wilderness Falls intrusion, much of the Pony Peak pluton, dikes in Bear Peak pluton) have trace element signatures consistent with an origin by partial melting of metabasic rocks (see above and Fig. 8). Thorough evaluation of the source of the crustal magmas is problematic, primarily because of a paucity of isotope data. Possible sources include the Upper Jurassic Galice Formation, mafic rocks of the Josephine ophiolite, or possible (cryptic) underlying terranes. The Galice Formation as a primary source of crustal magmas is unlikely for at least two reasons. First, much of the Galice Formation consists of intercalated meta-arenite and meta-argillite, and metawacke is common. Partial melting of such sedimentary protoliths results in peraluminous to strongly peraluminous magmas (e.g., Vielzeuf and Montel, 1994). However, even the most felsic rocks in the Bear Peak and Pony Peak plutons have an alumina saturation index <1.02. Second, the average $^{87}Sr/^{86}Sr$ of Galice Formation metawackes (at 147 Ma) is 0.7050 (range, 0.70296–0.70585; Coleman, 1972; Fig. 5) and the average of Galice Formation argillaceous rocks is 0.70646 (Frost et al., this volume). In contrast, the initial $^{87}Sr/^{86}Sr$ of the Pony Peak pluton is nearly uniform (0.70366–0.70379) in samples that range in SiO_2 content from 50.7 to 70 wt%. These values are significantly lower than those of the Galice rocks.

The $^{87}Sr/^{86}Sr$ values of mafic rocks from the Josephine ophiolite (at 147 Ma) have an average of 0.70373 ± 0.00044 (Shaw and Wasserburg, 1984; Barnes et al., 1996; Fig. 6), which is within the range of the Pony Peak samples. Therefore, on the basis of Sr isotope compositions, metabasic rocks of the Josephine ophiolite are possible sources of the evolved tonalitic and granodioritic rocks of the Pony Peak (and Bear Peak?) plutons. Mixing of such crust-derived magmas with mafic magmas would cause little or no change in initial $^{87}Sr/^{86}Sr$ but would result in higher $\delta^{18}O$ values than expected from fractional crystallization of a mantle-derived basaltic magma.

Figure 8 illustrates the simplest explanation for these signatures, in which primitive hydrous basalt ponded in the mafic section of the Josephine ophiolite. Heat released during cooling and crystallization of these magmas caused partial melting of the adjacent mafic rocks to form tonalitic magmas. These magmas were then emplaced as small tonalitic plutons, such as the Wilderness Falls intrusion and similar dikes. In some cases, particularly in the Pony Peak and Bear Peak systems, these crust-derived magmas mixed with basaltic magmas, giving rise to their extended compositional ranges and Mg-rich rocks that characterize both plutons (Fig. 3). The principal objection to this model is that the REE patterns of these tonalitic rocks suggest a pressure of origin of at least 8–10 kb. Simple cross-sections of the region do not place the mafic section of the Josephine ophiolite at such depths (25–35 km; Fig. 8). If further study shows the inferred depth of the Josephine mafic section to be correct, then the source of western Klamath crustal magmas is presumably in a deeper, cryptic mafic terrane.

Evolved rocks from the Pony Peak and Bear Peak plutons contain inherited zircons (Allen and Barnes, this volume), and these zircons show an age spectrum essentially identical to that of the detrital zircons in the Galice Formation (Miller et al., 2003). Chamberlain et al. (this volume) also found evidence for inherited Proterozoic zircon in units of the Bear Mountain intrusive complex, and Harper et al. (1994) reported Proterozoic inheritance in the Summit Valley pluton and granodiorites in the margin of the Lower Coon Mountain pluton. It is clear that these inherited zircons did not originate from the Josephine ophiolite, which formed in a narrow time span (166–162 Ma) and whose tectonic setting was oceanic (Pessagno, this volume). Moreover, the zircons were not inherited from rocks of the Rattlesnake Creek terrane, because inherited zircons are as young as 153 Ma, but the age of the Rattlesnake Creek terrane is Triassic to no younger than Middle Jurassic. It is conceivable that the inherited zircons came from a cryptic subduction-related accretionary wedge assemblage beneath the Josephine ophiolite. We consider this possibility unlikely, because such a source would need a detrital zircon population identical to that of the Galice Formation and yet should produce metaluminous magmas with $^{87}Sr/^{86}Sr$ ratios <0.7038 at 148 Ma.

We interpret the inherited zircons to be derived from the Galice Formation (Allen and Barnes, this volume; Fig. 8). If such inherited, Galice-like zircons were present only in plutons with evidence for hybridization of mantle-derived and of crustal magmas (Bear Peak and Pony Peak plutons), one could conclude that crustal melting involved metabasic rocks of the Josephine ophiolite *and* Galice metasedimentary rocks. (This possibility is shown schematically in Fig. 8.) However, the presence of inherited zircon in plutons that lack any evidence for mixing of crustal melts (Bear Mountain intrusive complex, Summit Valley?) suggests that some zircons were entrained by assimilation of Galice metasedimentary rocks during transport and emplacement. Such assimilation would have little influence on the initial $^{87}Sr/^{86}Sr$ ratios in these plutons because (1) the $^{87}Sr/^{86}Sr$ values of the Galice metasedimentary rocks are not drastically higher than those of the plutons and (2) because the magmas were generally Sr-rich (e.g., 647 ppm average in Pony Peak), whereas Galice rocks have lower Sr contents (average 136 ppm; Coleman, 1972; Frost et al., this volume).

Tectonic Setting

The trace element plots in Figure 7, the high concentrations of MgO, Ni, and Cr (Fig. 3, Appendix A2) in the primitive basaltic rocks, and evidence for high H_2O contents in these primitive magmas (e.g., the nearly ubiquitous presence of hornblende) are characteristic of mantle-derived magmas in an arc-related tectonic setting. Primitive H_2O-rich magmas are also characteristic of many modern arcs, the closest of which is the High Cascade arc (e.g., Wagner et al., 1995; Bacon et al., 1997; Grove et al., 2002). Therefore, the most probable source of these parental basaltic magmas is mantle modified by arc-related metasomatism. However, western Klamath magmatism was contemporaneous with and immediately followed contractional deformation (Nevadan orogeny). This orogenic event has commonly been considered to accompany collapse of an arc–back-arc assemblage (Rogue–Chetco arc, Josephine ophiolite, and Galice back-arc basin). It is not clear whether subduction was active during this deformation or the source of the magmas was metasomatized during a previous time of subduction.

Comparison with Other Klamath Plutonic Suites

On the basis of our data, it appears that early in the western Klamath plutonic event, large magma batches evolved primarily by fractional crystallization, with late assimilation of host rocks during transport and/or emplacement. Crustal melting was minor and probably restricted to the aureoles of the plutons, perhaps because the middle and lower crust was cool (Snoke et al., 1981; Bushey et al., this volume). In contrast, younger plutons show clear evidence for crustal melting and for incorporation of crust-derived magmas by magma mixing. This evidence suggests that with time, deep-seated crustal rocks were sufficiently hot to undergo partial melting and that these magmas were large enough in volume to interact and mix with mafic, mantle-derived magmas. Presumably, the increase in crustal magmas with time resulted from heating of the crust by basaltic magma trapped in middle or lower crustal depths. In other words, the western Klamath magmas changed from being primarily mantle-derived, with fractional crystallization driving magma evolution, to a combined derivation from mantle and crustal sources, with fractional crystallization, magma mixing, and assimilation driving magma evolution. Similar sequences characterize many High Cascade volcanoes, for example, Crater Lake (Bacon, 1983; Druitt and Bacon, 1989), Mount Shasta (Baker et al., 1994; Grove et al., 2002), and Medicine Lake Highlands (Grove and Donnelly-Nolan, 1986; Grove et al., 1997).

A similar, ~15 m.y.-long sequence of magmatic events began in Middle Jurassic time (Barnes et al., this volume, Chapter 10). In this case, the Ironside Mountain pluton and related rocks were emplaced soon after the end of thrusting along the Wilson Point thrust. These plutons resulted primarily from mantle melting and subsequent fractional crystallization (and crystal accumulation). As with the Bear Mountain intrusive complex, they were characterized by evolution to relatively low values of Mg/(Mg + Fe), but generally had lower H_2O and higher K_2O contents than did typical western Klamath magmas. Younger plutons (Wooley Creek suite) had higher H_2O contents, commonly had granitic units of crustal origin, and showed abundant evidence for mixing and assimilation of crustal magmas and rocks (Allen and Barnes, this volume, and references therein).

There are broad similarities between this Middle Jurassic magmatism and the western Klamath episode. Early western Klamath magmas evolved primarily by fractional crystallization, whereas later ones had larger crustal components (Pony Peak and Bear Peak). One can stretch this comparison to a regional scale by noting that no tectonic break exists between western Klamath magmatism and the slightly younger, but compositionally distinct, Late Jurassic to Early Cretaceous ttg plutons of the eastern part of the Klamath Mountains province (Fig. 1 in Allen and Barnes, this volume). These ttg plutons are primarily due to melting of metabasic crustal rocks (Barnes et al., 1996). Thus, if the western Klamath and ttg events are part of a single magmatic episode, then the change from early, predominantly mantle-derived magmatism to later, predominantly crustal magmatism is quite pronounced. Moreover, the time span of such a post-Nevadan magmatic episode (150–136 Ma) is essentially identical to that of the Middle Jurassic event that followed Wilson Point thrusting (170–156 Ma). Evidently, the Klamath Mountains province provides two excellent examples of the birth, growth, and demise of epicontinental arc systems that each encompass ~15 m.y. of geologic time.

CONCLUSIONS

The western Klamath plutonic suite represents magmatism synchronous with and immediately following regional contractional deformation. The entire suite results from emplacement of primitive, mantle-derived, primarily H_2O-rich basalt at various levels in the crust. Differentiation of these basalts yielded ultramafic cumulates (Blue Ridge and Lower Coon Mountain plutons and the ultramafic part of the Bear Peak pluton) and differentiated basaltic magma. The latter was parental to gabbroic cumulates (e.g., Punchbowl unit of the Bear Mountain pluton) and dioritic differentiates (e.g., Doe Flat unit of the Bear Mountain pluton). Heat from ponded basaltic magmas caused local crustal melting to form tonalitic magmas. Some of these crustal melts were emplaced with little modification, whereas others mixed with evolved basaltic magmas (Pony Peak and Bear Peak plutons). Assimilation of metasedimentary crustal rocks was widespread, especially in the youngest members of the suite (e.g., Pony Peak, Bear Peak plutons). In sum, magmatism of the western Klamath suite involved most of the crustal section.

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