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Geological Society of America
Special Paper 410
2006

Structural and petrologic evolution of the Bear Peak intrusive complex, Klamath Mountains, California

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ABSTRACT

The Bear Peak intrusive complex is a Late Jurassic (ca. 144 Ma) composite plutonic suite that ranges in composition from ultramafic to silicic. Clinopyroxene- and hornblende-rich ultramafic cumulate rocks form an intrusion breccia that is complexly intruded by multiple generations of crosscutting gabbroic to dioritic dikes. The bulk of the intrusive complex consists of mappable gabbroic to quartz dioritic to tonalitic/granodioritic units.

The Bear Peak intrusive complex was emplaced into rocks of the Rattlesnake Creek terrane, producing a dynamothermal contact aureole. Contact metamorphism was chiefly at hornblende-hornfels-facies conditions and grades into regional greenschist-facies metamorphism. Andalusite, cordierite, and chloritoid form small porphyroblasts in some of the more aluminous metasedimentary rocks, indicating low-pressure contact metamorphism (<4 kb). Al-in-hornblende geobarometry in quartz dioritic to tonalitic rocks also suggests pressure conditions of ~4 kb. Pseudomorphs of original chiastolite porphyroblasts developed during contact metamorphism of pelitic horizons in the Upper Jurassic Galice Formation, which lies in the footwall of the regional Orleans thrust fault, indicate that the Bear Peak intrusive complex was emplaced after regional contraction related to the Nevadan orogeny.

The Bear Peak intrusive complex is an example of the extended compositional range characteristic of some oceanic-arc plutonic suites and demonstrates how multiple, chiefly magmatic processes, can yield a broad range of rock compositions within a single intrusive complex. Mafic magmatic enclaves are common in most of the plutonic units of the Bear Peak intrusive complex, and distinctive migmatitic amphibolite enclaves indicate that magma temperatures were sufficient to facilitate dehydration-melting of metabasic rocks. The distribution of host-rock enclaves and screens suggest that much of the gabbroic to quartz dioritic parts of the Bear Peak intrusive complex were emplaced as magmatic sheets that coalesced into mappable, relatively homogeneous units that grew by piecemeal intrusion. Ultramafic-mafic cumulates and hornblende gabbro crystallized from a high-Mg, low-Al basaltic parent, whereas

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McFadden, R.R., Snoke, A.W., and Barnes, C.G., 2006, Structural and petrologic evolution of the Bear Peak intrusive complex, Klamath Mountains, California, *in* Snoke, A.W., and Barnes, C.G., eds., Geological studies in the Klamath Mountains province, California and Oregon: A volume in honor of William P. Irwin: Geological Society of America Special Paper 410, p. 333–355, doi: 10.1130/2006.2410(16). For permission to copy, contact editing@geosociety.org. ©2006 Geological Society of America. All rights reserved.

high-Al, low-Mg contents in quartz dioritic rocks suggest an evolved basaltic or basaltic andesite parent. The biotite tonalite/granodiorite rocks have high Sr values (>700 ppm), large Sr/Y and Ba/Y ratios, and reverse J-shaped rare-earth-element (REE) patterns. These features are characteristic of partial melting of metabasic rocks in which amphibole ± garnet are residual phases. Thus, major, trace, and REE compositions indicate at least two batches of magma were involved in the petrogenesis of the Bear Peak intrusive complex. Complex field relationships and geochemical data suggest that multiple magmas passed through the cumulates and presumably fed structurally higher mafic units in the complex.

Keywords: Jurassic, oceanic-arc pluton, ultramafic rocks, enclaves, contact metamorphism, migmatitic amphibolite, Rattlesnake Creek terrane, Galice Formation, Siskiyou Mountains

INTRODUCTION

The emplacement of juvenile magmas into accreted, oceanic terranes is an important mechanism for the growth of crust along active continental margins. Although this igneous process and the accretion of the wall rocks (oceanic terranes) are broadly related to the subduction of oceanic lithosphere, detailed knowledge of the interplay between magmatism, tectonism, and recycling of accreted crust is still poorly understood.

The ca. 144-Ma Bear Peak intrusive complex is one of a suite of upper mesozonal plutonic complexes that were emplaced after Late Jurassic regional thrust faulting (i.e., Orleans thrust fault; Barnes et al., this volume, Chapter 17). This thrusting has been interpreted as an important structural feature related to the collapse of a Late Jurassic back-arc basin (Snoke, 1977; Saleeby et al., 1982; Harper and Wright, 1984). Bear Peak magmatism thus represents a post-contractional event. Our new geologic mapping of the Bear Peak intrusive complex indicates that it was constructed in piecemeal fashion by the intrusion of numerous dikes or magmatic sheets that coalesced into a plutonic complex. Furthermore, the extended compositional range from ultramafic to silicic indicates that this plutonic complex is characteristic of some oceanic-arc plutonic suites (Snoke et al., 1981; Pearcy et al., 1990; DeBari, 1997; Snoke et al., 2001). Deep incision of the Bear Peak intrusive complex provides ~1300 m of topographic (structural) relief, so that the combination of detailed geologic mapping, petrography, and geochemical studies reveal the types of magmatic processes that can yield a broad range in rock composition in a single plutonic complex.

REGIONAL GEOLOGIC SETTING

The Klamath Mountains province is composed of arcuate, west-directed regional thrust sheets of oceanic rocks that form distinct tectonostratigraphic terranes (Fig. 1). The province is part of an extensive, diverse megabelt of accreted oceanic terranes that forms much of the western half of the North American Cordilleran orogen (Dickinson, 2004). These tectonostratigraphic terranes were accreted onto the North American continental margin from early Paleozoic through Late Jurassic time. The regional thrust sheets were intruded by ultramafic to felsic plutons, which range in age from Silurian to Early Cretaceous. These plutons expose the roots of several long-lived, composite oceanic-arc systems.

Regional contraction, intra-arc extension, and plutonism were important deformational events during the development of the Klamath Mountains. However, relationships among these processes in the province are still debated (e.g., Saleeby et al., 1982; Harper and Wright, 1984; Wright and Fahan, 1988; Harper et al., 1994; Hacker et al., 1995; Irwin and Wooden, 1999; Barnes et al., 2003). Our study focuses on a Late Jurassic, composite, oceanic-arc pluton; thus, relationships to regional events center on tectonic activity during Jurassic and Early Cretaceous time, when arc magmatism was closely associated with multiple contractional deformations as well as an intervening regional extensional history (i.e., development of the Josephine and related ophiolites).

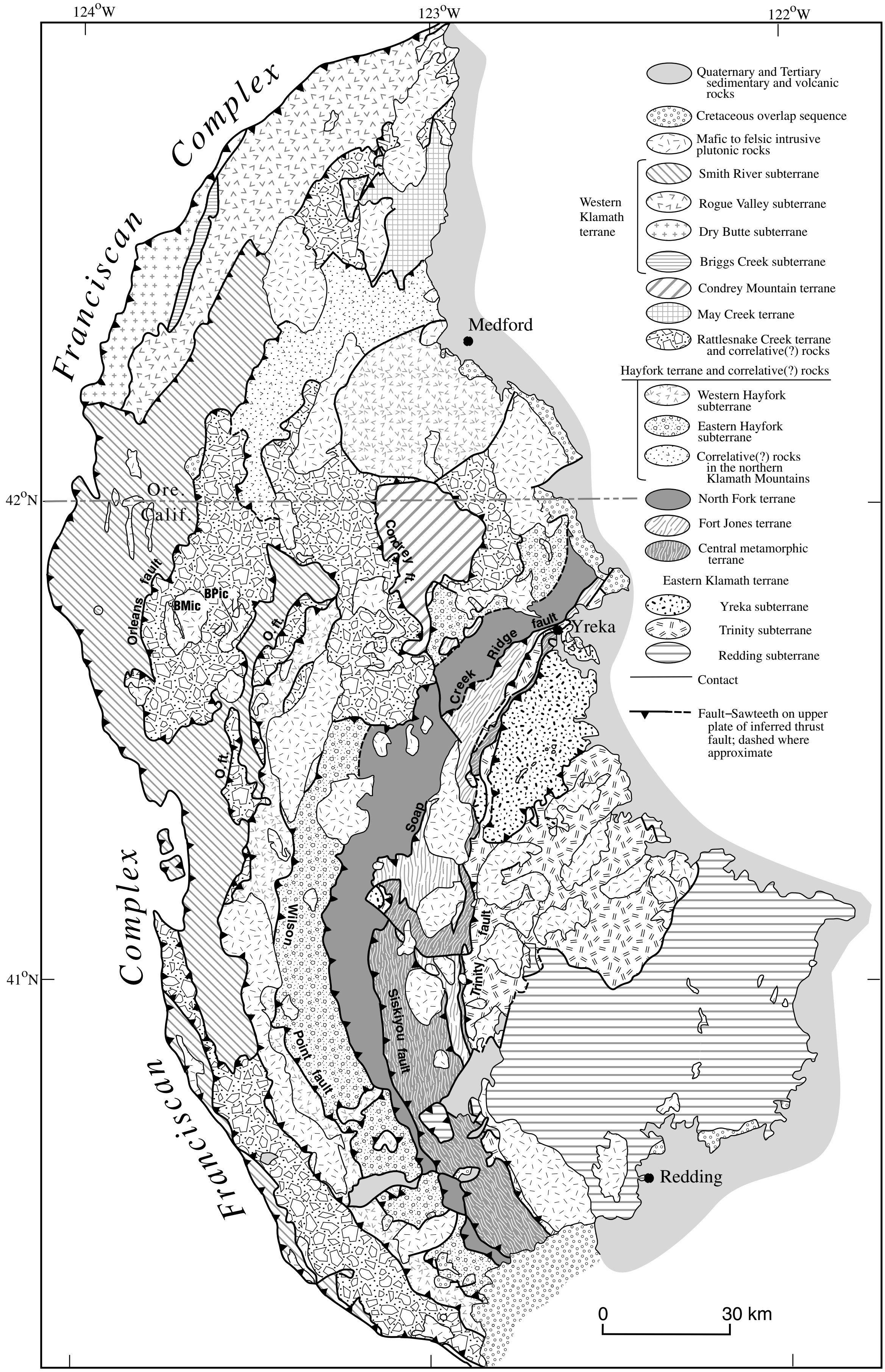
FIELD RELATIONS

Introduction

The Bear Peak intrusive complex is a Late Jurassic (ca. 144 Ma), composite plutonic suite that intruded the Rattlesnake Creek terrane (Wright and Wyld, 1994) and Upper Jurassic Galice Formation, the hanging wall and footwall of the Orleans thrust fault, respectively (Fig. 1). This relationship indicates that the Bear Peak intrusive complex was emplaced after regional thrust faulting along the Orleans fault.

A dynamothermal contact aureole in rocks of the Rattlesnake Creek terrane and Galice Formation is indicated by solid-state plastic deformation of the wall rocks as well as an increase

Figure 1. Generalized geologic map of the Klamath Mountains province. BMic—Bear Mountain intrusive complex, BPic—Bear Peak intrusive complex, O. ft.—Orleans fault. Modified from Irwin (1994).


124°W
123°W
122°W
42°N
41°N
Franciscan Complex
Complex
Franciscan
Medford
Yreka
Redding
Ore.
Calif.
Orleans fault
BMic
BPic
O. ft.
O. ft.
Condrey ft.
Creek Ridge fault
Soap
Wilson Point fault
Siskiyou fault
Trinity fault
0
30 km
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

in metamorphic grade toward the intrusive complex. Contact metamorphism was chiefly under hornblende-hornfels–facies conditions and grades into the regional greenschist-facies metamorphism characteristic of this part of the Klamath Mountains (Coleman et al., 1988).

The Bear Peak intrusive complex is a heterogeneous body consisting of distinct intrusions that vary in mineral composition and texture. There are abundant mafic dikes that crosscut the intrusive units, and the units commonly contain mafic magmatic enclaves. Also, wall-rock xenoliths and migmatitic amphibolite enclaves are conspicuous throughout the complex (Fig. 2; Plate 1 on the CD-ROM accompanying this volume and in the GSA Data Repository[1]). Five lithologic units comprise the Bear Peak intrusive suite and are displayed in Figure 2. From oldest to youngest they are: (1) ultramafic-mafic complex, (2) hornblende gabbro, (3) biotite-hornblende quartz diorite, (4) biotite tonalite/granodiorite, and (5) synplutonic mafic dikes.

Ultramafic-Mafic Complex

The ultramafic-mafic complex forms a centrally located, topographically low mass within the Bear Peak intrusive complex (Fig. 2). This unit varies in composition from coarse-grained hornblende (±olivine) clinopyroxenite to hornblendite and hornblende melagabbro. The typical mineral assemblage is diopsidic augite + hornblende ± olivine ± orthopyroxene. Hornblende and clinopyroxene oikocrysts that can reach ~6 cm are locally common. The hornblendite commonly contains relict enclaves of hornblende (±olivine) clinopyroxenite (Fig. 3A). The hornblendite grades into hornblende melagabbro with an increase in the abundance of interstitial plagioclase. An important aspect of the ultramafic-mafic complex is that these cumulate rocks were intruded by numerous gabbroic to dioritic dikes (Figs. 3B–D and 4). The complexity of these intrusive relationships has yielded a map-scale intrusion breccia, consisting of ultramafic-mafic rocks as the host unit and crisscrossed by numerous mafic to intermediate dikes.

Hornblende (±olivine) clinopyroxenite consists chiefly of subhedral to anhedral diopsidic augite that is commonly partially to completely replaced by olive-green (Z tint) hornblende. Olivine (~Fo_{85}–Fo_{75}) is commonly partially replaced by a mixture of serpentine-group minerals and magnetite. Orthopyroxene grains are typically scarce, anhedral, and partially replaced by hornblende. Poikilitic hornblende grains in the hornblendite commonly contain many relict clinopyroxene grains. The hornblende (±olivine) clinopyroxenite does not contain intercumulus plagioclase, whereas hornblendite has scarce intercumulus (i.e., interstitial) plagioclase (~An_{65}). Hornblende melagabbro is texturally similar to the hornblendite, except that it contains more interstitial plagioclase.

[1]GSA Data Repository item 2006200, Plate 1, Geologic map of Bear Peak intrusive complex, Siskiyou County, 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.

Hornblende Gabbro

The hornblende gabbro unit crosscuts the ultramafic-mafic rocks and contains enclaves of clinopyroxenite and hornblendite. The unit is texturally and mineralogically heterogeneous. Grain size varies from fine-grained, equigranular to pegmatitic. Rock types that are part of this unit include massive; fine-, medium-, to coarse-grained hornblende gabbro; porphyritic hornblende-clinopyroxene gabbro; pegmatitic hornblende gabbro; and scarce medium-grained pyroxene-hornblende gabbro. Hornblende gabbro is the most common rock type. It is equigranular, characterized by subhedral to euhedral hornblende grains, and has a high color index (>60). Leucocratic, plagioclase-rich segregations and dikelets are common throughout the hornblende gabbro unit. The pegmatitic hornblende gabbro and porphyritic hornblende-clinopyroxene gabbro are found as dikes and plugs throughout the intrusive complex.

Intermediate to calcic plagioclase and abundant olive-green to brown (Z tint) hornblende are the main mineral phases. Plagioclase exhibits weak normal zoning, ranging from ~An_{52} to An_{65}. Clinopyroxene, biotite, and quartz are minor constituents in some samples. Titanite, Fe-Ti oxides, and apatite are common accessory minerals in these gabbroic rocks. The porphyritic hornblende-clinopyroxene gabbro as well as pegmatitic hornblende gabbro contain large grains of prismatic hornblende that can reach ~4 cm in length. The groundmass in the porphyritic gabbro consists of hornblende, clinopyroxene, plagioclase, quartz, and titanite. The most widespread deuteric alteration is the replacement of hornblende by epidote + chlorite + Fe-Ti oxides. The sericitization of plagioclase and replacement of biotite by chlorite ± white mica are other common post-magmatic alterations in the gabbroic rocks.

Biotite-Hornblende Quartz Diorite

Biotite-hornblende quartz diorite is medium-grained and equigranular with a color index between 30 and 50. It is the most extensive map-scale unit of the intrusive suite. Magmatic to hypersolidus foliation defined by plagioclase and hornblende is common and dips steeply toward the interior of the pluton. Fabric development ranges from massive (nonfoliated) to strongly foliated, whereas lineation is not present. Mafic dikes intrude the quartz diorite and mingling relationships are widespread. Mafic biotite-hornblende (quartz) diorite magmatic enclaves are also common throughout the quartz diorite unit. Melting and injection relationships are conspicuous where migmatitic amphibolite enclaves are incorporated into the quartz diorite.

The major igneous minerals in the quartz diorite unit are plagioclase, hornblende, biotite, quartz, and Fe-Ti oxides. Titanite and apatite are common accessory minerals. Trace amounts of alkali feldspar occur in some samples. Hornblende grains are typically prismatic and dark green (Z tint). Biotite is brown, shows no preferred orientation, and commonly forms patchy grains that have partially replaced hornblende. Augite armored by rims of hornblende locally occurs. The Fe-Ti oxides are typically closely associated with the mafic minerals, especially hornblende. Interstitial quartz is anhedral and weakly strained. Local subgrain development in quartz indicates intracrystalline strain at subsolidus conditions. Various deuteric alterations are conspicuous throughout the quartz diorite unit, including the replacement of hornblende by epidote + chlorite and the sericitization of plagioclase. Biotite is also commonly replaced by white mica ± chlorite ± epidote.

Biotite Tonalite/Granodiorite

The tonalite/granodiorite unit consists of equigranular, medium-grained biotite ± hornblende tonalite and granodiorite with trace to ~7 modal% alkali feldspar. It is the least extensive map-scale unit of the Bear Peak intrusive complex. Biotite tonalite/granodiorite is generally homogeneous and weathers yellow; the color index ranges from 10 to 30. The unit is generally massive, but a magmatic fabric defined by oriented biotite plates and tabular plagioclase is evident at some localities. Enclaves of mafic microdiorite locally occur near contacts with the quartz diorite unit. Mafic dikes, fine-grained mafic magmatic enclaves, and migmatitic amphibolite enclaves also occur in this unit.

The common igneous minerals are subhedral biotite, blocky oscillatory-zoned plagioclase (~An_{20-35}), anhedral quartz, and sparse alkali feldspar. Subgrain development and grain-boundary suturing in quartz indicate intracrystalline strain at subsolidus conditions. Apatite, titanite, and Fe-Ti oxides are common accessory phases. Acicular to prismatic deep blue-green hornblende (Z tint) occurs in some samples. Deuteric alteration of biotite to chlorite ± white mica ± epidote and of plagioclase to sericite is widespread in the tonalite/granodiorite unit.

Mafic Dikes and Mafic Magmatic Enclaves

Northwest-striking mafic dikes commonly intrude the quartz diorite unit and locally intrude the hornblende gabbro and biotite tonalite/granodiorite units (Fig. 2, Plate 1). Conspicuous mingling zones are found along the margins of these mafic dikes where enclaves have pillow shapes, and lobate bulb-and-cusp contacts are conspicuous. Mutual back-veining is apparent along many contacts. Flow fabrics in the dikes, where present, are parallel to contacts with the host. Locally, mafic dikes have chilled margins and exhibit abrupt textural variations from fine-grained to very coarse over a meter scale. The fragmentation of once-continuous dikes occurs where they have been dismembered and mechanically incorporated into the magma, leading to trains of subangular to rounded enclaves (Fig. 5). The mafic magmatic enclaves are commonly lobate and flattened in the plane of foliation. They are petrographically similar to the mafic dikes.

Hornblende in the mafic dikes is olive green (Z tint) and is typically acicular to prismatic in habit. Plagioclase is tabular and sometimes aligned by magmatic flow, whereas quartz, a minor component in these rocks, is anhedral and exhibits undulatory extinction, indicating modest solid-state strain. Patchy brown biotite is common in the mafic dikes, and Fe-Ti oxides, titanite, and apatite are the accessory minerals. Hornblende is locally altered to a colorless amphibole, and patchy biotite has also locally overgrown hornblende. Epidote ± chlorite are deuteric alteration products of hornblende and, white mica + chlorite replace biotite.

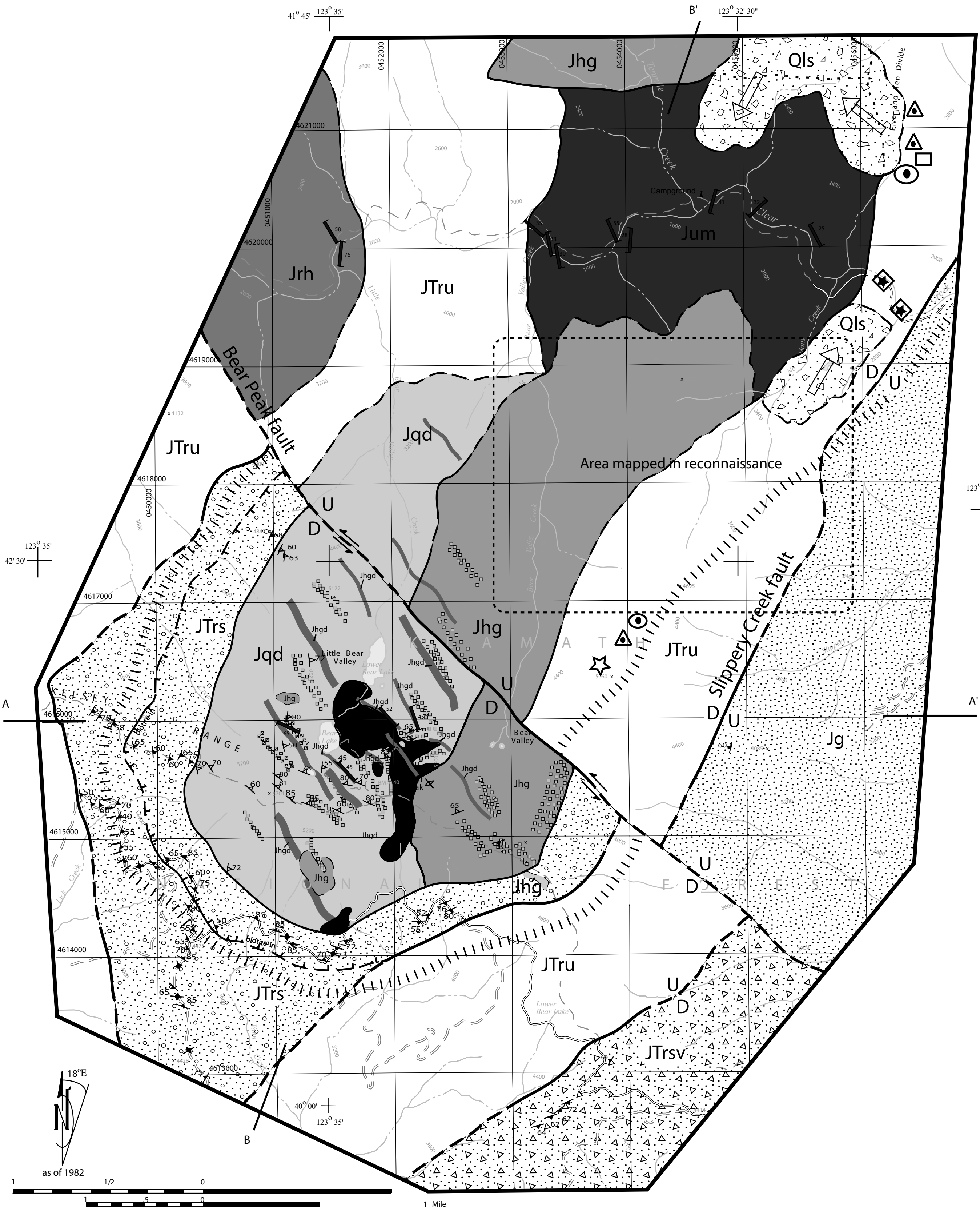
Red Hill Creek Pluton

The intrusive rocks that comprise the Red Hill Creek pluton are massive, generally equigranular, coarse-grained biotite tonalite, trondhjemite, and granodiorite. This relatively small intrusion is shown as an undifferentiated body on the Bear Peak intrusive complex map (Plate 1), although future, more detailed work would probably yield distinct mappable units. The Red Hill Creek rocks consist chiefly of plagioclase, quartz, and biotite, whereas alkali feldspar is a greatly subordinate varietal mineral. Quartz accounts for ~25–35 modal% of the granitic rocks of the Red Hill Creek pluton; color index ranges from 10 to 20. The Red Hill Creek pluton is significantly more quartzofeldspathic than the adjacent Bear Peak intrusive complex. North–northwest-striking dikes, which intrude the granitic rocks, include fine-grained mafic rocks (microdiorite to microgabbro), fine- to medium-grained biotite + hornblende gabbro, and aplite/pegmatite. Xenoliths of clinopyroxenite occur in the Red Hill Creek pluton. Also, dikes and small masses of fine-grained gabbro, characterized by scattered hornblende phenocrysts and a groundmass consisting hornblende + plagioclase + clinopyroxene, intrude the pluton.

Plagioclase forms blocky subhedral grains that exhibit conspicuous oscillatory zoning (An_{15}–An_{45}). Quartz grains are anhedral, with subgrain development and evidence of grain-boundary suturing (migration). Dark brown to reddish-brown (Z tint) biotite occurs as subhedral, tabular grains. Alkali feldspar forms scarce interstitial grains. Blue-green hornblende occurs in a few samples. Apatite, titanite, zircon, and Fe-Ti oxides are accessory phases. White mica and epidote are common deuteric alterations of biotite, and sericitization of plagioclase grains is common.

Host Rocks

Galice Formation. The Galice Formation consists of light- to medium-gray metagraywacke interlayered with black slate. The metagraywacke is predominantly an impure chert/cherty argillite-clast lithic wacke with quartz and subordinate plagioclase grains. Bedding is locally preserved, but transposed by a pervasive cleavage (S_1) related to near-isoclinal folding and synchronous pressure solution. The Galice Formation is contact metamorphosed near the northeast contact of the Bear Peak intrusive complex. This contact metamorphism is manifested by



Topographic base derived from U.S.G.S. Bear Peak, California 7.5 minute quadrangle

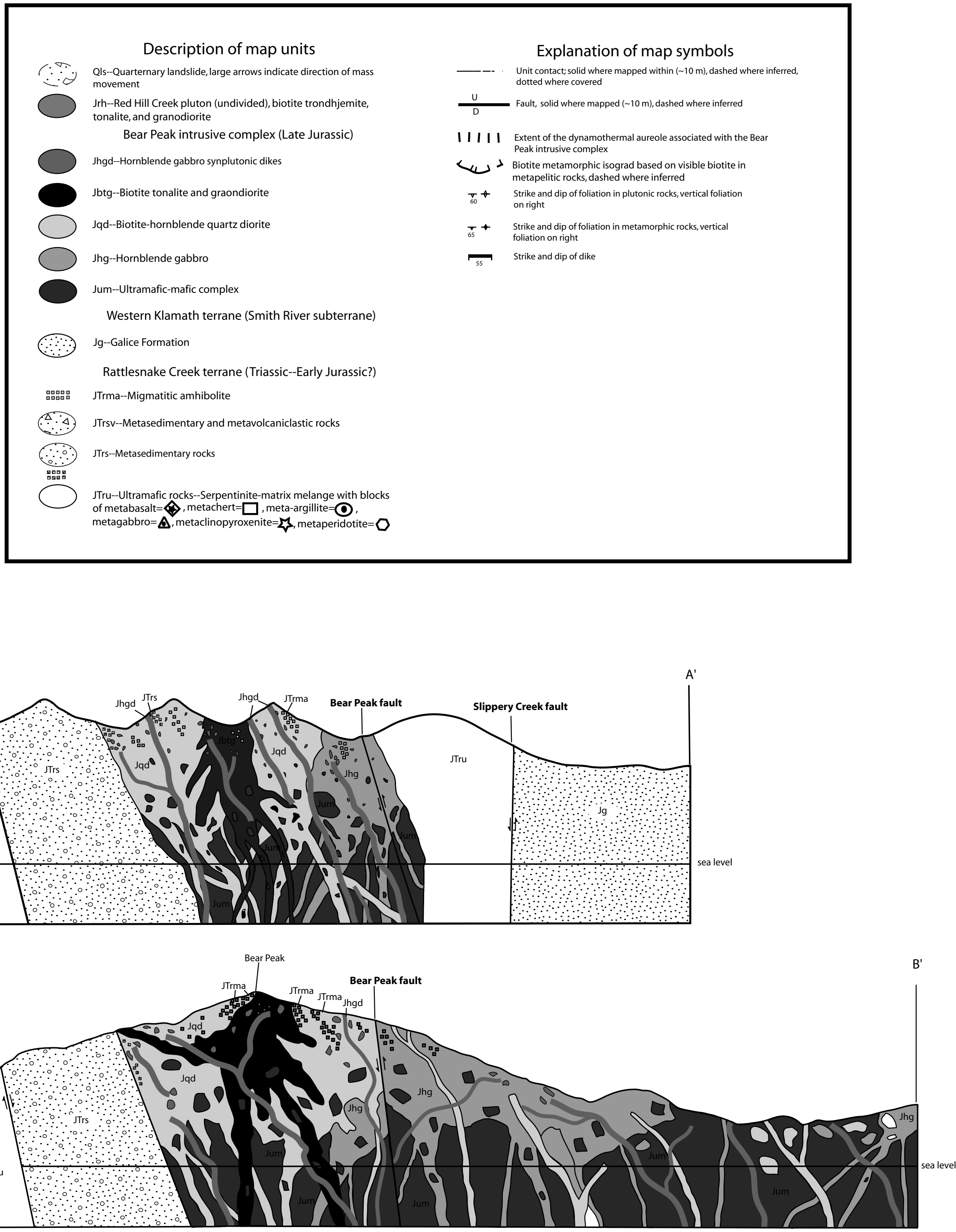


Figure 2. (A) Generalized geologic map of the Bear Peak intrusive complex, Siskiyou County, California. (B) Cross-sections of Bear Peak intrusive complex, Siskiyou County, California. Unit descriptions are given in the figure. Refer to Plate 1 (on the CD-ROM accompanying this volume and in the GSA Data Repository [see footnote 1]) for a colored geologic map of the Bear Peak intrusive complex on a topographic base with cross-sections.

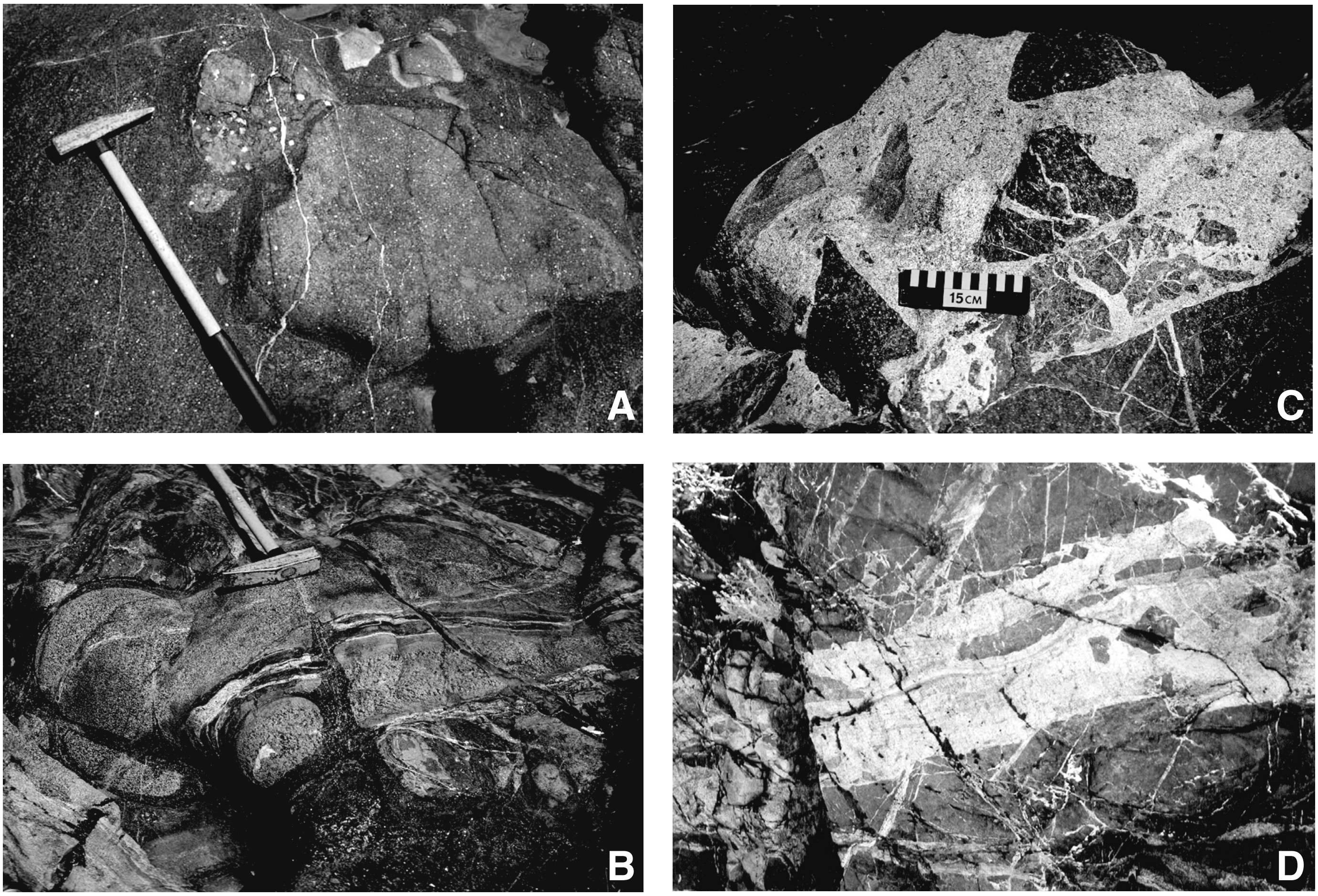


Figure 3. Field photographs of the ultramafic-mafic complex, showing the complexity and heterogeneity of the unit. (A) Subangular hornblende clinopyroxenite enclave within hornblendite. The clasts near the top of the photograph are xenoliths of metaserpentinite that has been altered chiefly to talc + Fe-Ti oxides + chlorite; relict Fe-Cr spinel grains also occur in these rocks. (B) Crosscutting relationships in the intrusion breccia of the ultramafic-mafic complex. (C) Intrusion breccia engulfing angular enclaves of hornblendite. (D) Dioritic dike with angular enclaves of hornblendite. The dike also shows the development of veins within the hornblendite rocks.

chloritoid and scarce pseudomorphs of porphyroblastic chiastolite, developed in pelitic horizons of the Galice Formation. The presence of contact-metamorphic assemblages localized near the Bear Peak intrusive complex contact indicates that the pluton intruded lower-plate rocks structurally below the Orleans thrust fault.

Foliation in contact-metamorphosed metapelitic rocks of the Galice Formation is defined by strongly aligned, fine-grained biotite and graphite. These rocks also include fine-grained, granoblastic aggregates of quartz. Chloritoid porphyroblasts have grown across the foliation, suggesting a post-kinematic development. Prismatic pseudomorphs of chiastolite porphyroblasts are aggregates of phyllosilicates and carbonaceous material. The biotite-graphite fabric wraps around these porphyroblasts.

Interlayered Metasedimentary and Metavolcaniclastic Rocks of the Rattlesnake Creek Terrane. The metasedimentary and metavolcaniclastic unit crops out in the southeast corner of the map area (Fig. 2, Plate 1). These rocks are interpreted as part of a coherent cover sequence of the Rattlesnake Creek terrane that originally was deposited unconformably upon serpentinite-matrix mélange (Wright and Wyld, 1994). The metasedimentary rocks consist of metachert, siliceous meta-argillite, and slaty meta-argillite. The metavolcaniclastic rocks range from felsic to mafic in composition. The metasedimentary and metavolcaniclastic rocks were regionally metamorphosed at greenschist-facies conditions. The metasedimentary rocks consist chiefly of tabular brown biotite, anhedral quartz, and subordinate plagioclase. The metavolcaniclastic rocks consist chiefly of calcic

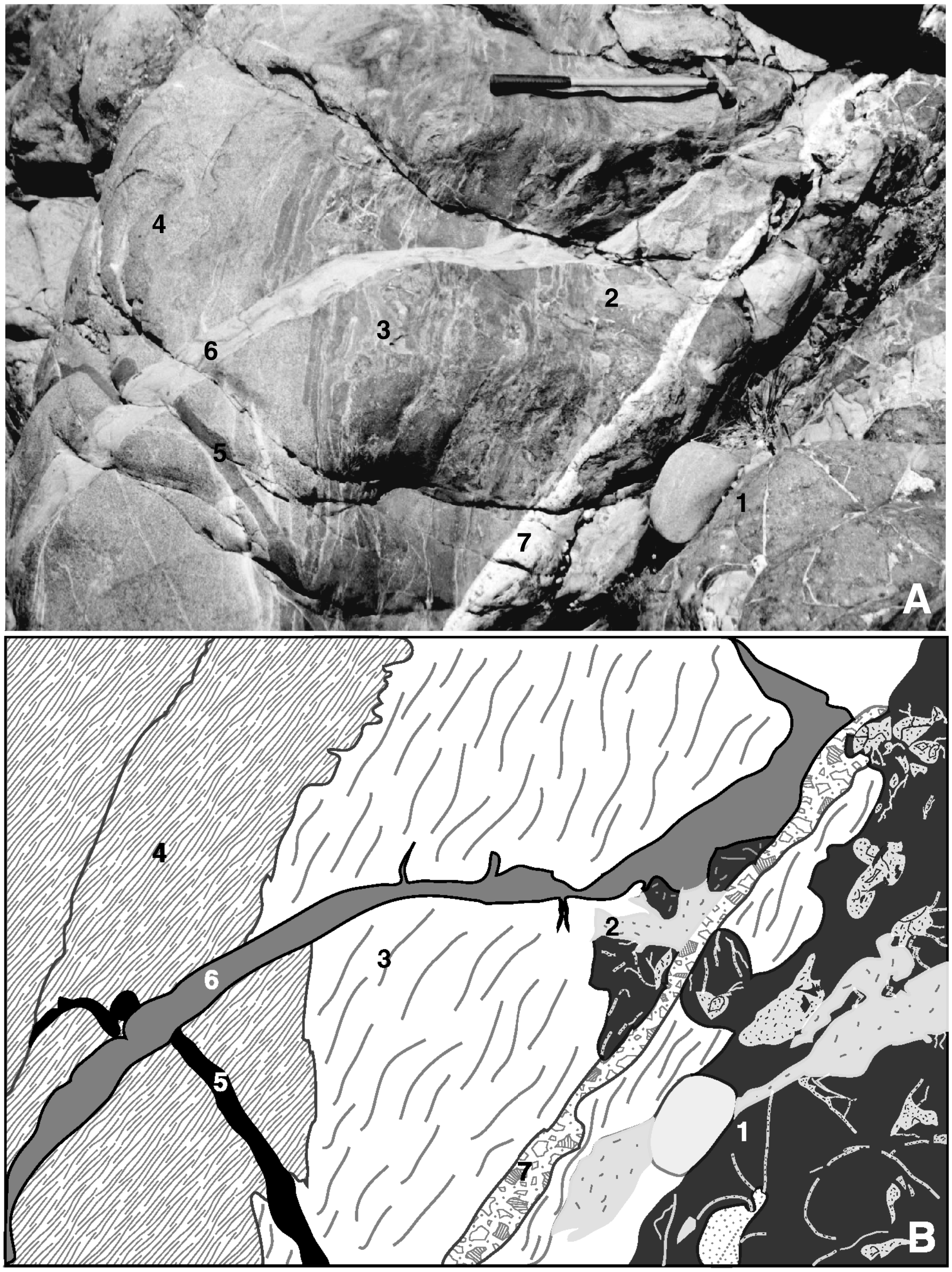


Figure 4. (A) Photograph of crosscutting relationships that are conspicuous in the ultramafic-mafic complex of Bear Peak intrusive complex. The order of intrusive units is based on crosscutting relationships and is shown from oldest to youngest (earliest unit, clinopyroxenite not shown): (1) hornblendite, (2) fine-grained diorite forming intrusion breccia, (3) hornblende gabbro displaying mingling and mixing relationships with foliated hornblende diorite, (4) foliated hornblende diorite, (5) late hornblende diorite dike, (6) late fine-grained hornblende gabbro dike, and (7) pegmatitic hornblende diorite dike. (B) Sketch of the intrusive relationships drawn from photograph in A.

amphibole (actinolite?), brown biotite, clinozoisite, plagioclase, and quartz.

Metasedimentary Rocks of the Rattlesnake Creek Terrane. This unit is in contact with the southern part of the Bear Peak intrusive complex (Fig. 2, Plate 1). The unit consists of interlayered metachert, meta-argillite, siliceous meta-argillite, and slaty meta-argillite. In the contact aureole, metamorphic grade is hornblende-hornfels facies characterized by megascopic biotite, a hornfelsic texture, crystal-plastic deformation, and local partial melting of pelitic rocks. Scarce porphyroblasts of chloritoid, cordierite, andalusite, garnet, and muscovite are also present. This rock unit may be a large composite block within the mélange of the Rattlesnake Creek terrane; or alternatively, it may be part of the originally overlying "cover sequence," subsequently down-faulted into the mélange.

The mineral assemblages of the metasedimentary rocks consist chiefly of fine-grained, anhedral quartz, strongly aligned biotite grains, and anhedral Fe-Ti oxides. Biotite-rich domains

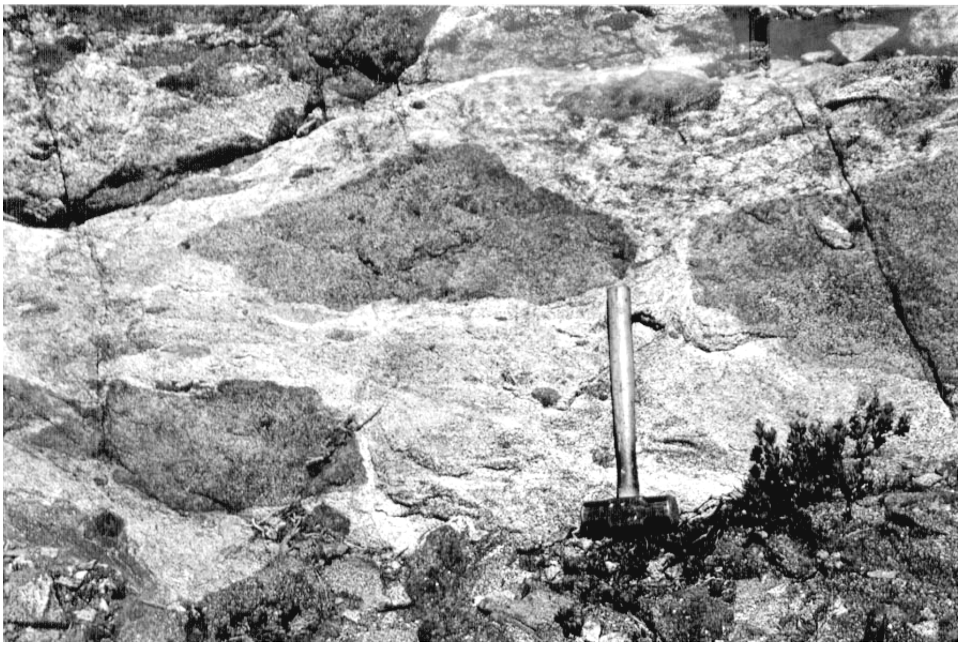


Figure 5. Photograph of mafic magmatic enclaves (dismembered dike) in biotite-hornblende quartz diorite, Upper Bear Lake area. Such synplutonic dikes are evidence of coexisting gabbroic and dioritic magmas during the development of the Bear Peak intrusive complex.

wrap around the garnet porphyroblasts, suggesting synkinematic growth. Chloritoid and muscovite porphyroblasts cut across the foliation indicating post-kinematic growth. Probable original cordierite and/or andalusite porphyroblasts are now chiefly pseudomorphosed to elliptical aggregates of phyllosilicate minerals and quartz.

Ultramafic Rocks of the Rattlesnake Creek Terrane. The ultramafic host rocks are the matrix of the serpentinite-matrix mélange. The mélange contains blocks of metabasalt, metachert, meta-argillite, metagabbro, and metaclinopyroxenite (Plate 1). The metaserpentinite rocks are fine-grained, range in color from dark green to blue black to black, and consist chiefly of an aggregate of serpentine-group minerals, talc, tremolite, and opaque oxides. The metaserpentinite is commonly massive and forms angular outcrops that weather brown to deep orange.

Xenoliths of metaserpentinite wall rock are found in the ultramafic-mafic complex (Figs. 3A and 6). The fragmentation of these inclusions may be due to a combination of thermal stresses and dehydration reactions. The presence of ultramafic xenoliths in the Bear Peak intrusive complex suggests that wall-rock assimilation (e.g., Kelemen and Ghiorso, 1986) may have played a role in the development of the ultramafic-mafic complex.

Serpentine-group minerals in the metaserpentinites are texturally variable and occur as interlocking aggregates, as pseudomorphs after olivine and/or pyroxene, and in veinlets. A colorless, bladed serpentine-group mineral is especially common in the metaserpentinites. It is probably antigorite and may reflect thermal metamorphism related to the Bear Peak intrusive complex. Tremolite forms colorless, acicular to prismatic grains and is commonly associated with talc. Forsteritic olivine, developed during contact metamorphism, was found in some metaserpentinites exposed in Clear Creek between the intrusive contacts of the Bear Peak intrusive complex and Red Hill Creek pluton. Various opaque oxides (probably magnetite and Fe-Cr spinel) as well as magnesite are also common in the metaserpentinites. The typical prograde contact metamorphic mineral assemblage is antigorite + talc + opaque oxides ± tremolite ± olivine ± chlorite ± magnesite. The xenoliths found in the ultramafic-mafic complex consist of talc + magnetite + Fe-Cr spinel + chlorite.

Migmatitic Amphibolite and Metasedimentary Enclaves

The enclaves of migmatitic amphibolite and metasedimentary rocks are abundant, recognizable units in the Bear Peak intrusive complex. They are oriented subparallel to the magmatic foliation in the host plutonic rocks and strike northwest–southeast (subparallel to the synplutonic mafic dikes). These enclaves appear to separate distinct, sheetlike bodies of plutonic rock and thereby provide evidence for an important mode of magmatic emplacement during the development of this plutonic complex (Fig. 2, Plate 1; see discussion below). Near the eastern host-rock–intrusive complex contact, migmatitic amphibolite and hornblende gabbro form a sheeted margin.

The migmatitic amphibolite enclaves are metabasites that preserve relict lithic clasts, heterogeneous grain size in the matrix, and relict pyroxene and plagioclase. These rocks are described as "migmatitic" because they consist of variable proportions of amphibolitic melanosome pervasively injected by leucosome veinlets. The leucosomes consist of quartz and plagioclase with minor biotite, hornblende, and alkali feldspar,

Figure 6. Field photographs depicting the ultramafic xenoliths in the ultramafic-mafic complex. (A) The rock above the hammer is an ultramafic xenolith that has been boudinaged. A thin reaction zone consisting chiefly of tremolite occurs along the contact with hornblendite. The mineral assemblage in the xenolith is talc + Fe-Ti oxides + Fe-Cr spinel + chlorite. (B) Fragmented ultramafic xenoliths (~3 cm). The reaction zone developed around the xenoliths is a narrow rim of tremolite in turn surrounded by hornblendite.

whereas the melanosome (including the relict lithic clasts) consists chiefly of hornblende and plagioclase with minor biotite and clinozoisite/epidote.

Metapelitic and siliceous argillite enclaves are found near the pluton-host rock contact toward Red Hill (Fig. 2, Plate 1). The melanosome mineral assemblage in metapelitic rocks is biotite + quartz + cordierite, whereas in siliceous argillite, it is biotite + quartz. Both metasedimentary rock types are injected by leucosome with the mineral assemblage quartz + plagioclase with minor biotite.

Late Crosscutting Faults

The Bear Peak fault is a left-lateral, oblique-slip fault with a northwest-strike and unknown displacement. The northeast block is the upthrown side. There is noticeable map-scale offset of the intrusive contacts of the Bear Peak intrusive complex, with many intrusive and host rock units truncated by the fault.

The Slippery Creek fault is a high-angle, northeast-striking normal fault. This fault juxtaposes Rattlesnake Creek terrane rocks in the hanging wall of the Orleans fault on the west with footwall rocks of the Galice Formation on the east. The Slippery Creek fault is a late normal fault that cuts the regional Orleans thrust fault.

GEOCHEMISTRY

Samples from the Bear Peak intrusive complex have a wide variation in SiO_2 content, ranging from 42 to 72 wt%. Based on the classification of Frost et al. (2001), the sample suite is chiefly calcic to calc-alkaline, magnesian, and metaluminous, although some tonalitic and granodioritic samples are mildly peraluminous (Fig. 7). Also, several samples of quartz diorite straddle the magnesian-ferroan boundary.

The ultramafic-mafic rocks are characterized by high MgO and low Al_2O_3 contents. They show considerable scatter in minor elements (not shown) that may reflect chemical interaction with the mafic and/or intermediate dikes, or possibly these characteristics reflect multiple processes (i.e., crystal accumulation and/or assimilation of metaserpentinite). It is evident that Cr and Ni are abundant in clinopyroxenite and hornblende melagabbro samples (Fig. 8D and E). The Bear Peak intrusive complex ultramafic-mafic rocks are similar to other ultramafic-mafic complexes in the Klamath Mountains, such as the Blue Ridge intrusion (e.g., Snoke et al., 1981). The hornblende gabbro, quartz diorite, and tonalite/granodiorite units have chemical trends that contrast with one another (Fig. 8, Table 1). The amount of Al_2O_3 increases with increasing SiO_2 in the high-MgO hornblende gabbros, whereas Al_2O_3 decreases with increasing SiO_2 in the biotite tonalite/granodiorite unit. The low-MgO quartz dioritic rocks show approximately constant high Al_2O_3 contents of ~18–19 wt%. Trends similar to those for Al_2O_3 can be seen in Sr abundances, but the data are more scattered (Fig. 8C). The quartz diorite and biotite tonalite/granodiorite samples show low concentrations of Rb, Ni, and Cr that are characteristic of calc-alkaline rocks. However, the gabbroic samples, interpreted as cumulates, have extremely high Cr and Ni abundances. The biotite tonalite/granodiorite rocks (62–72 SiO_2 wt%) are characterized by large Sr/Y and Ba/Y ratios and high Sr (>700 ppm) values.

A sample of hornblende melagabbro (1188) from the ultramafic-mafic complex shows a concave downward rare-earth-element (REE) pattern with an overall negative slope (Fig. 9, Table 2). The pattern reaches maximum normalized REE abundances at Sm, and heavier REE (HREE) abundances are higher than all other analyzed samples (Fig. 9). In contrast, the light REEs (LREEs) have a normalized La/Sm ratio <1. This pattern is typical of rocks whose REE abundances are controlled by accumulation of clinopyroxene and/or hornblende and accessory minerals. The biotite-hornblende quartz diorite and hornblende gabbro samples display parallel, negative slopes (normalized La/Yb ratios range from 5 to 8), and HREE concentrations are about ten times those of chondrites. Europium anomalies are absent or slightly positive (Fig. 9). The biotite tonalite/granodiorite rocks exhibit distinctive steep negative slopes (Ce/Yb = 16.70 and 22.98) and some have nearly flat chondrite-normalized HREE (reverse J-shape). Such patterns are common among high-Al_2O_3 tonalite and trondhjemite rocks (Arth and Hanson, 1972; Barker and Arth, 1976; Arth et al., 1978; Barnes et al., 1996).

CONDITIONS OF EMPLACEMENT

Age of Emplacement

Although a contact between the Bear Peak intrusive complex and Upper Jurassic Galice Formation is not exposed, contact-metamorphic textures and assemblages in the Galice Formation within ~600 m of the contact argue for an intrusive relationship. If so, the pluton intruded both the hanging wall and footwall of the Orleans thrust fault. This assertion is consistent with recent U-Pb (zircon) dating of a late-stage granodiorite (Allen and Barnes, this volume), which yielded an age of 143.7 ± 1.3 Ma. As the Orleans thrust is pinned by the ca. 150-Ma Summit Valley pluton (Harper et al., 1994), the Bear Peak intrusive complex must have passed through and thermally metamorphosed the Galice Formation. Furthermore, Allen and Barnes (this volume) reported distinctive zircon inheritance that is similar to detrital zircon from basal metagraywacke of the Galice Formation (Miller and Saleeby, 1995; Miller et al., 2003). These data led Barnes et al. (this volume, Chapter 17) to place the Bear Peak intrusive complex in their "western Klamath plutonic suite" (151–144 Ma).

Estimates of Contact-Metamorphic Conditions

Adjacent to the ultramafic-mafic complex, the host rocks are mainly metaserpentinite. The peak metamorphic assemblage is olivine + tremolite + talc + magnetite + Fe-Cr spinel that suggests temperatures between 550 and 600 °C at pressures of ~3 kb (Tracy and Frost, 1991). The metamorphic grade reached hornblende-hornfels–facies metamorphism in the semipelitic host rocks, and the lack of clinopyroxene in the semipelitic rocks is consistent with temperatures below 675 °C (Russ-Nabelek, 1989). Spotted slaty argillite in the Rattlesnake Creek terrane contains porphyroblasts of andalusite and chloritoid, as well as inferred cordierite porphyroblasts, now pseudomorphs consisting of an aggregate of phyllosilicate minerals, quartz, and opaque oxides. Hornfelsic metapelitic rocks in the Galice Formation contain chloritoid porphyroblasts and scarce chiastolite pseudomorphs, now chiefly altered to phyllosilicate minerals. Pattison and Tracy (1991) summarized experimental data, indicating that andalusite is stable at ~4.5 kb (450 MPa) at 550 °C, and at 650 °C, andalusite has a maximum pressure stability of ~3.5 kb (350 MPa). Therefore, the contact-metamorphic assemblages in the Bear Peak aureole indicate emplacement pressures of ~3–4.5 kb and maximum aureole temperatures of ~550–675 °C.

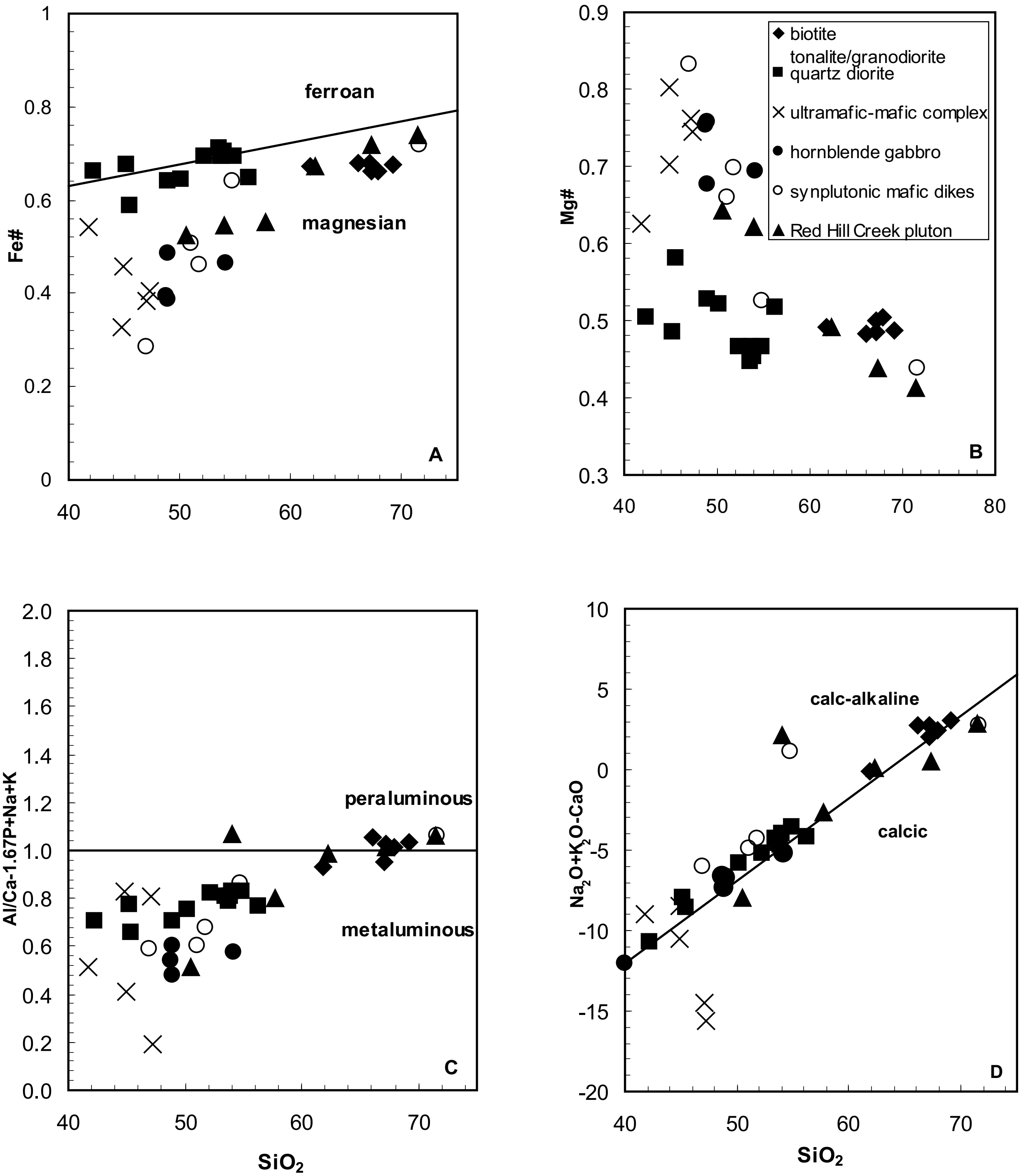


Figure 7. Geochemical plots of the Bear Peak intrusive complex, based on geochemical classification scheme developed by Frost et al. (2001). (A) Chemical plot that shows most of the Bear Peak intrusive complex is magnesian in character, whereas numerous quartz diorite samples straddle the ferroan-magnesian line. (B) Plot of magnesium number (Mg#) Mg/(Mg + Fe) vs. SiO_2, which displays two distinct groups of samples. (C) Plot of the aluminum-saturation index, which shows that most Bear Peak samples are metaluminous, except for some samples from the biotite tonalite/granodiorite unit and Red Hill Creek pluton. (D) Plot of the modified alkali-lime index, which shows the Bear Peak intrusive complex samples straddle the calcic–calc-alkalic line.

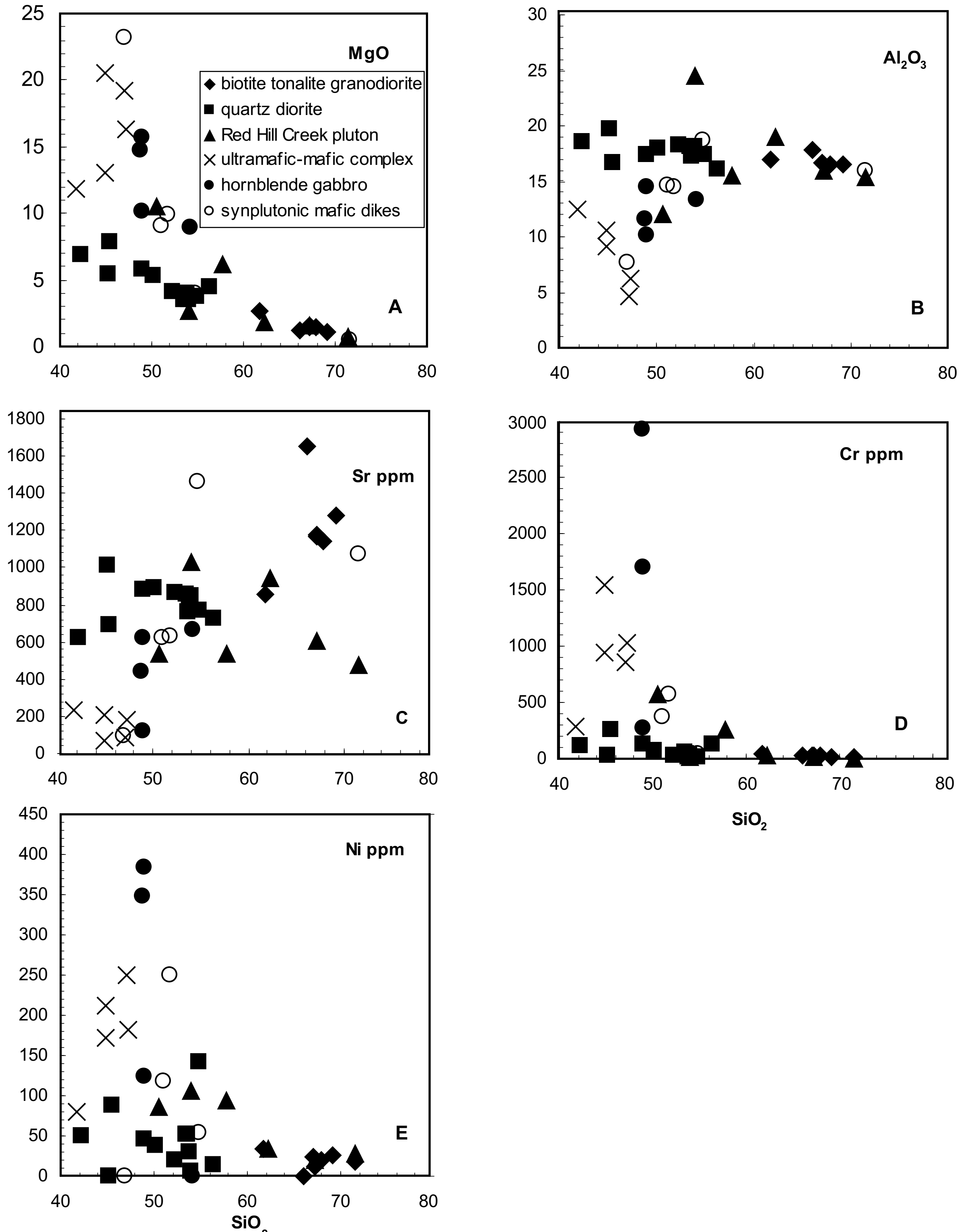


Figure 8. Major and trace element variation diagrams for the Bear Peak intrusive complex. (A) Plot of MgO vs. SiO_2 exhibits two distinct trends: one high-MgO trend for the hornblende gabbro unit and a low-MgO trend for the quartz diorite unit. (B) The Al_2O_3 vs. SiO_2 plot shows an increase in Al_2O_3 for the hornblende gabbros and constant high Al_2O_3 for the quartz diorites. (C) The Sr vs. SiO_2 plot shows very high concentrations for the biotite tonalite/granodiorite unit that may suggest melting from a crustal source region. (D) Plot of Cr vs. SiO_2 displays high Cr values for the ultramafic-mafic rocks as well as some hornblende gabbros. (E) Concentrations of Ni are also high in the ultramafic-mafic complex and hornblende gabbros.

TABLE 1. REPRESENTATIVE WHOLE-ROCK GEOCHEMICAL DATA FOR ROCKS FROM THE BEAR PEAK INTRUSIVE COMPLEX

	BP4	BP988A	BP350A	BP382	BP18	BP253	BP279	BP291	BP357	BP348A	BP340A	BP430B
Sample	Ultramafic-mafic rocks		Hornblende gabbro		Biotite-hornblende quartz diorite		Biotite tonalite/ granodiorite		Synplutonic mafic dikes		Red Hill Creek pluton	
SiO_2	47.07	47.24	48.96	48.89	50.15	54.89	69.14	67.21	51.04	54.75	71.48	50.55
TiO_2	0.49	0.67	1.15	0.88	0.98	0.85	0.28	0.32	0.93	0.74	0.20	0.85
Al_2O_3	4.70	6.23	14.44	10.16	18.03	17.42	16.59	16.49	14.60	18.77	15.42	12.00
FeO_t	11.90	11.08	9.70	9.92	9.60	8.36	2.37	3.04	9.25	7.06	2.20	11.59
MnO	0.19	0.15	0.14	0.22	0.19	0.17	0.06	0.08	0.19	0.14	0.08	0.25
MgO	19.15	16.29	10.19	15.69	5.29	3.69	1.14	1.54	9.00	3.94	0.78	10.52
CaO	15.18	16.74	10.35	9.93	10.05	8.22	3.44	3.99	9.55	6.02	3.30	10.73
Na_2O	0.62	0.99	2.65	0.99	3.18	3.29	5.03	4.49	3.62	6.65	3.83	2.16
K_2O	0.08	0.13	0.95	1.62	1.08	1.31	1.52	1.55	1.08	0.48	2.28	0.59
P_2O_5	0.02	0.07	0.09	0.07	0.33	0.34	0.07	0.09	0.08	0.24	0.09	0.20
LOI	0.92	1.17	1.31	1.22	1.05	1.09	0.79	1.09	1.09	0.97	0.72	0.70
Total	100.33	100.76	99.93	99.59	99.94	99.62	100.44	99.90	100.44	99.77	100.38	100.14
Mg#	0.76	0.74	0.68	0.74	0.52	0.47	0.49	0.50	0.66	0.53	0.41	0.64
Fe#	0.38	0.40	0.49	0.39	0.64	0.69	0.68	0.66	0.51	0.64	0.74	0.52
MALI	–14.48	–15.62	–6.76	–7.32	–5.79	–3.61	3.11	2.05	–4.86	1.11	2.81	–7.98
ASI	0.81	0.19	0.60	0.48	0.76	0.83	1.04	1.02	0.60	0.86	1.06	0.52
Rb	2.00	22.00	14.00	17.00	25.00	3.00	33.00	36.00	37.00	51.00	23.00	13.00
Sr	182.00	425.31	669.39	672.11	805.52	86.94	1292.38	1182.42	614.78	1081.10	846.00	765.00
Zr	28.40	59.07	n.d.	56.31	97.98	n.d.	119.90	95.75	115.00	188.00	107.00	149.00
Y	11.30	14.53	11.68	14.67	17.47	8.14	3.46	5.93	8.22	11.86	19.70	22.00
Nb	11.00	n.d.	14.11	n.d.	n.d.	13.39	n.d.	n.d.	n.d	n.d.	13.00	16.00
Ba	54.70	475.10	271.76	298.78	458.02	14.18	986.00	835.16	637.80	959.89	415.00	401.00
Sc	85.50	40.96	38.30	66.03	21.09	75.30	3.89	7.43	6.08	6.25	19.40	28.40
V	280.00	242.97	194.00	299.23	199.01	191.00	46.63	58.68	54.45	50.39	191.00	233.00
Cr	1025.00	2958.00	407.00	269.71	18.42	860.00	20.55	21.84	8.32	13.88	32.00	41.00
Ni	182.00	347.14	94.51	124.00	29.24	250.00	25.01	11.45	19.05	105.36	7.00	53.00
Cu	202.00	70.53	9.24	35.22	11.63	288.00	23.18	24.56	12.39	4.00	13.00	11.00
Zn	n.d.	60.21	72.72	62.88	116.00	49.90	42.41	41.76	70.50	36.67	n.d.	n.d.
Be	n.d.	0.48	1.07	0.62	0.90	0.30	1.20	1.20	0.89	1.62	n.d.	n.d.

Notes: Major elements in wt%, trace elements in ppm. The classification scheme used is based on Frost et al. (2001). ASI—Aluminum saturation index, which classifies granitic rocks as peraluminous or metaluminous; Fe#—Fe/(Fe + Mg); LOI—loss on ignition; MALI—modified alkali-lime index, which indicates whether a granitic rock is calcic, calc-alkalic, or alkalic; Mg#—(Mg/40.3)/[(Mg/40.3) + (2 × Fe/159.7)]; n.d.—not detected.

Geothermobarometry

To estimate temperature and pressure of final mineral equilibration, rim compositions of hornblende and plagioclase grains were determined on the University of Wyoming, Laramie, automated JEOL JXA-8900 electron probe microanalyzer. The Al-in-hornblende geobarometer correlates Al^{tot} content of magmatic hornblende linearly with crystallization pressure of intrusion (Hammarstrom and Zen, 1986). In amphibole-bearing tonalitic to granodioritic rocks, the magmatic system can be described by ten components: SiO_2–TiO_2–Al_2O_3–Fe_2O_3–FeO–MgO–CaO–Na_2O–K_2O–H_2O. Commonly, tonalite and granodiorite are nine-phase systems: hornblende + biotite + plagioclase + potassic feldspar + quartz + titanite + Fe-Ti oxide + melt + fluid phase. Such systems are trivariant, with three degrees of freedom, which leads to three intensive variables (Hollister et al., 1987). The fO_2 may be buffered by a second Fe-Ti oxide or epidote. If temperature lies close to the wet solidus (nearly isothermal), then pressure is the only variable (Hollister et al., 1987; Schmidt, 1992). In cases where the solidus temperature is poorly known, the barometer is sensitive to both fO_2 and temperature (Anderson and Smith, 1995). Therefore, it is important to correct for the temperature of equilibration of the nine-phase assemblage and to analyze rocks that fall within the experimental calibrations, which is the case for most of the Bear Peak intrusive complex samples. All samples have the appropriate assem-

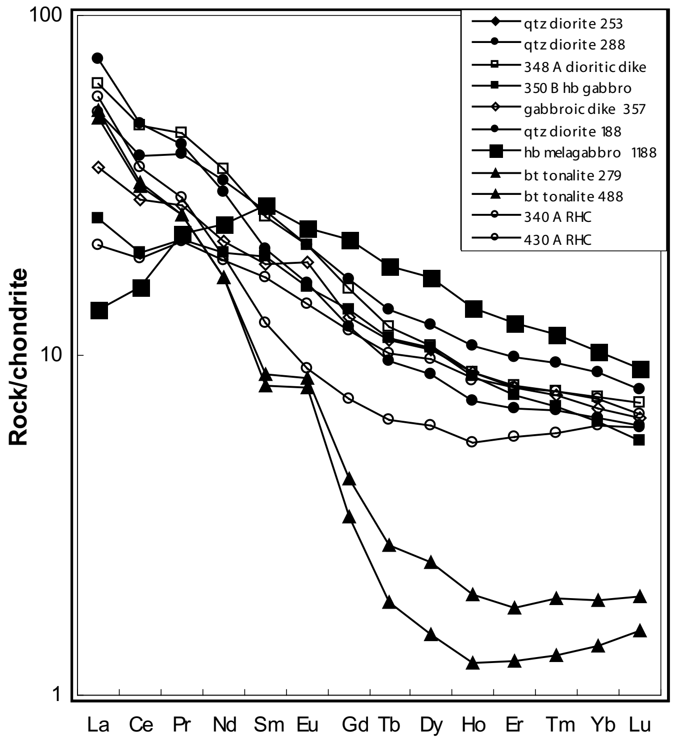


Figure 9. Rare-earth-element (REE) diagram of the Bear Peak intrusive complex rocks. The REE plot of the hornblende melagabbro sample (1188) shows a concave-downward trend with an overall negative slope. There is also a depletion of heavy and light REEs. The quartz diorite and hornblende gabbro display a negative slope with light REE enrichment. The biotite tonalitic/granodioritic rocks are strongly fractionated; have small, positive Eu anomalies; and exhibit a flat heavy-REE pattern. These trends show a reverse J-shaped pattern characteristic of high-Al_2O_3 tonalitic/trondhjemitic rocks (Barnes et al., 1996).

blage for Al-in-hornblende barometry: hornblende + plagioclase + biotite + quartz + potassic feldspar + titanite + Fe-Ti oxides (Hammarstrom and Zen, 1986; Hollister et al., 1987).

We used the approach of Anderson and Smith (1995), in which temperature is calculated from the two plagioclase-hornblende thermometers (Thb1 and Thb2) developed by Holland and Blundy (1994), and pressure estimates are corrected using the estimated temperature by iteration. Temperature estimates based on Thb2 are preferred, due to the possibility that quartz crystallized after the equilibration of plagioclase and hornblende (Anderson and Smith, 1995).

Table 3 shows the rock types and estimated pressure and temperature for the four samples. Quartz diorite samples, BP19b and BP251, yielded hornblende–plagioclase equilibrium temperatures from 750 to 770 °C (±20 °C) and pressures from 3.7 to 3.9 kb (±0.7 kb). Samples from the biotite tonalite/granodiorite unit, BP174 and BP288, have estimated temperatures from 690 to 720 °C (±30 °C) and pressures of 4.5–4.7 kb (±0.5 kb).

Pressure estimates derived from the two rock types overlap (within analytical uncertainty), although the overlap is slight. This near lack of agreement may be the result of lack of equilibrium among the analyzed phases; however, care was taken to analyze minerals in apparent textural equilibrium (McFadden, 2004). Different pressure estimates may also be related to differences in bulk composition or the lack of quartz as a SiO_2-buffering phase when amphibole and plagioclase were in equilibrium. If the precision of the pressure estimates are assumed to be correct, then the data suggest that late-stage parts of the Bear Peak intrusive complex crystallized at higher pressure than the early units. If this scenario is true, the higher pressure estimated for the younger stage of the pluton could result

TABLE 2. REPRESENTATIVE RARE-EARTH-ELEMENT DATA FROM THE BEAR PEAK INTRUSIVE COMPLEX

Sample	BP253 qd	BP279 btg	BP288 qd	BP340A RHC	BP348A dike	BP350B hg	BP357 dike	BP430A RHC	BP1188 umc	BP188 qd	BP488 btg
La	17.08	16.49	24.52	18.98	20.81	8.30	11.73	6.93	4.48	17.23	17.37
Ce	32.50	27.78	42.10	31.59	41.81	17.69	25.31	16.95	13.91	34.07	28.40
Pr	4.06	2.90	4.66	3.27	5.05	2.46	3.10	2.43	2.55	4.38	2.91
Nd	17.71	10.23	18.07	11.70	21.05	12.04	13.02	11.34	14.67	19.56	10.11
Sm	4.38	1.59	3.71	2.26	4.64	3.55	3.36	3.08	5.03	4.84	1.48
Eu	1.29	0.59	1.12	0.63	1.45	1.10	1.30	0.97	1.62	1.46	0.55
Gd	3.91	1.08	3.02	1.86	3.89	3.38	3.22	2.94	5.46	4.18	0.83
Tb	0.59	0.13	0.45	0.30	0.57	0.53	0.52	0.48	0.86	0.64	0.09
Dy	3.57	0.74	2.62	1.86	3.18	3.14	3.12	2.92	5.07	3.70	0.45
Ho	0.69	0.14	0.51	0.39	0.62	0.61	0.62	0.60	0.97	0.74	0.09
Er	1.86	0.36	1.39	1.15	1.63	1.53	1.62	1.61	2.50	1.97	0.25
Tm	0.27	0.06	0.21	0.18	0.23	0.21	0.23	0.23	0.35	0.29	0.04
Yb	1.69	0.38	1.31	1.25	1.50	1.28	1.40	1.49	2.06	1.78	0.28
Lu	0.26	0.07	0.21	0.21	0.25	0.19	0.22	0.23	0.31	0.27	0.05

Notes: All values in ppm. Abbreviations: btg—biotite tonalite/grandiorite; hg—hornblende gabbro; qd—quartz diorite; RHC—Red Hill Creek pluton; umc—ultramafic-mafic complex.

TABLE 3. CALCULATED CRYSTALLIZATION TEMPERATURE AND PRESSURE FOR THE BEAR PEAK INTRUSION COMPLEX USING ALUMINUM-IN-HORNBLENDE GEOTHERMOBAROMETRY

Rock unit	Sample	T_B (°C)	Pressure at T_B (kb)	T_A (°C)	Pressure at T_A (kb)
Quartz diorite	BP19b	771.1 ± 20.6	3.71 ± 0.70	805.2 ± 24.3	2.84 ± 0.78
Quartz diorite	BP251	757.2 ± 19.3	3.91 ± 0.54	785.6 ± 21.0	3.25 ± 0.57
Biotite tonalite	BP174	691.7 ± 31.1	4.48 ± 0.55	722.8 ± 27.3	4.05 ± 0.59
Biotite granodiorite	BP288	720.7 ± 24.4	4.76 ± 0.43	745.3 ± 21.4	4.32 ± 0.37

Note: See text for definitions of T_A and T_B.

from foundering of the intrusive complex during emplacement, to magma loading at higher structural levels, or to hornblende crystallization at higher pressure and a lack of equilibration at the pressure of emplacement.

DISCUSSION

Development of the Bear Peak Intrusive Complex

Abundant enclaves, distinct intrusions that vary in mineral composition and texture, and the overall heterogeneity of the Bear Peak intrusive complex imply growth by piecemeal intrusion. Also, wall-rock xenoliths, migmatitic amphibolite enclaves (see below), and solid-state foliation in the wall rocks suggest that the Bear Peak intrusive complex formed by coalescence of multiple magmatic sheets (Fig. 10). The magmatic fabric intensity and enclave density is variable across the complex, further supporting sheetlike assembly of the pluton. Field evidence from the ultramafic-mafic complex and the calcic to calc-alkalic units indicates a multistage emplacement history. Emplacement of the Bear Peak intrusive complex originated with intrusion of basaltic magma, from which olivine + diopsidic augite + hornblende accumulated to form the ultramafic-mafic complex. The cumulate rocks were subsequently intruded by numerous gabbroic to dioritic dikes (Figs. 3 and 4), forming an intrusion breccia. The dikes incorporated angular/subangular to subrounded enclaves of clinopyroxenite and hornblendite, thereby indicating that the cumulate rocks were sufficiently solidified to undergo brittle deformation. The ultramafic-mafic complex also incorporated and perhaps assimilated meta-serpentinite xenoliths.

Back-veining by the intrusive units, bulb-and-cusp contacts, conformity of flow fabrics in the mafic dikes and intrusive rocks, and progressive fragmentation indicate that the mafic dikes and intrusive units were essentially contemporaneous. The mingled margins suggest that hot, mafic magmas were under-cooled against a cooler but still mobile host. The presence of synplutonic mafic dikes and associated mafic magmatic enclaves is commonly attributed to mingling of mafic and intermediate to felsic magmas at the level of emplacement (Barnes, 1983; Barbarin, 1991; Bussel, 1991), whereas dispersed mafic magmatic enclaves are attributed to mingling below the level of exposure (Vernon, 1983; Barnes et al., 1992; McNulty et al. 1996). The presence of both synplutonic dikes and dispersed mafic magmatic enclaves suggests that magma mingling occurred prior to, during(?), and after emplacement of the Bear Peak intrusive complex magmas. On the basis of geochemical analysis (Barnes et al., this volume, Chapter 17), it is also possible to infer that significant magma mixing affected some Bear Peak magmas.

During the emplacement of the Bear Peak intrusive complex, a dynamothermal aureole developed in the wall rocks through solid-state deformation. Finally, after the Bear Peak intrusive complex had solidified, oblique-slip displacement along the Bear Peak fault and minor displacement along the Slippery Creek fault occurred.

Migmatitic Amphibolite Enclaves

The migmatitic amphibolite enclaves in the Bear Peak intrusive complex are of problematic origin for at least two reasons: (1) lithologically similar rocks are not exposed along the contacts of the intrusive complex and (2) the enclaves show evidence for partial melting, yet none of the exposed aureole rocks underwent significant anatexis. An exception to item 1 is the presence of mafic hornfels (i.e., amphibolitic rocks) adjacent to the eastern margin of the Bear Peak intrusive complex in the Clear Creek area (Fig. 2, Plate 1). However, these rocks are relatively small blocks in serpentinite-matrix mélange of the Rattlesnake Creek terrane and therefore are not areally extensive. The evidence for partial melting (item 2) comes from the presence of crosscutting leucosomes, which suggest a mobile, leucocratic magma capable of dilational intrusion. The tonalitic compositions of the leucosomes is consistent with hornblende-dehydration melting of mafic to intermediate amphibolitic protoliths (Drummond and Defant, 1990; Beard and Lofgren, 1991; Rapp et al., 1991; Rushmer, 1991; Wolf and Wyllie, 1994).

At least some of the migmatitic enclaves had a volcaniclastic protolith, because fragmental textures and structures are preserved in less-strained parts of the amphibolite. Local presence of relict clinopyroxene and plagioclase phenocrysts also suggests that the protolith had heterogeneous grain size, which is typical of volcaniclastic rocks in the province. In contrast,

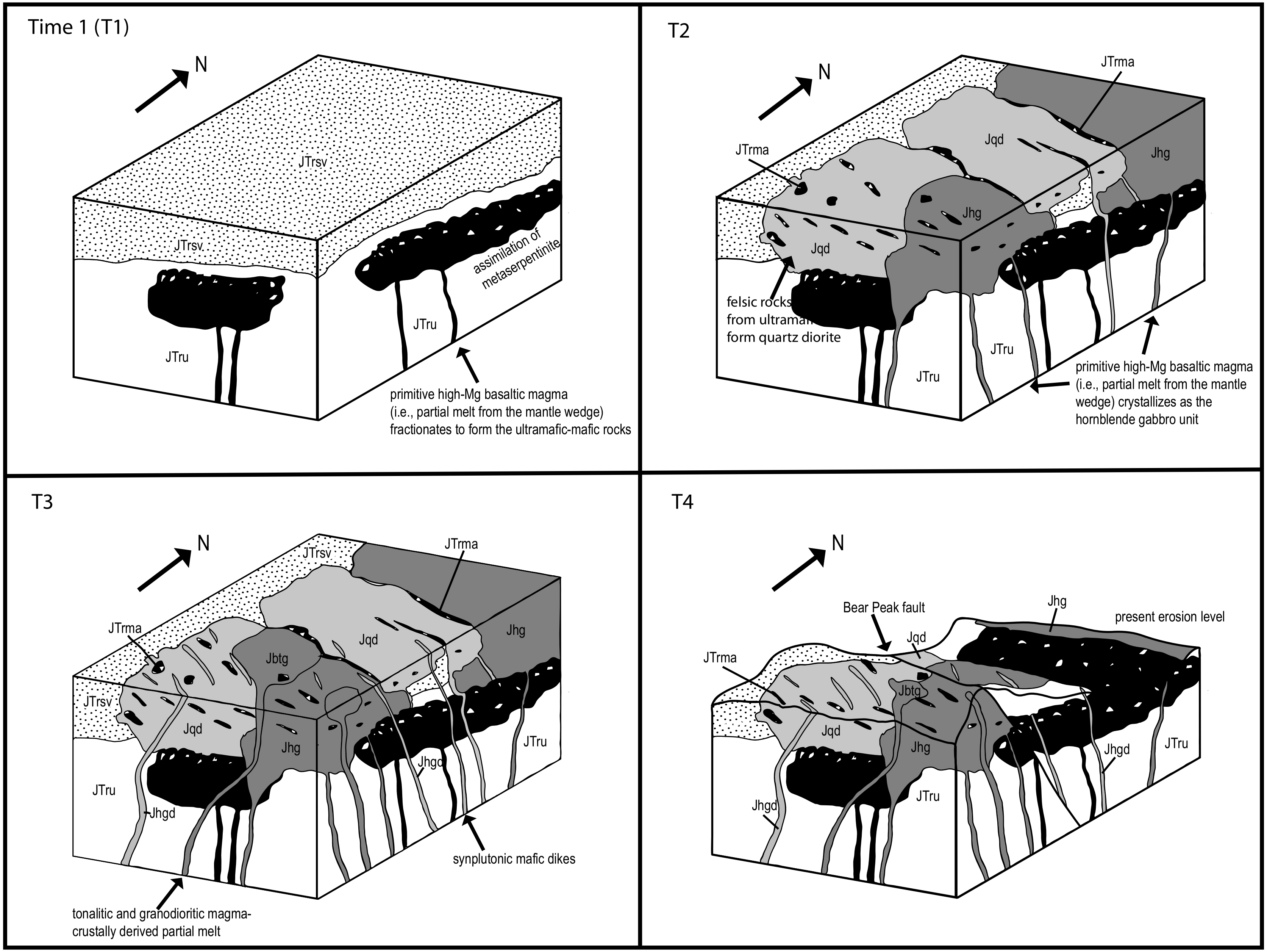


Figure 10. Petrogenetic model, which summarizes the evolution of the Bear Peak intrusive complex. Jhgd—synplutonic mafic dikes; Jbtg—biotite tonalite/granodiorite; Jqd—biotite-hornblende quartz diorite; Jhg—hornblende gabbro; Jum—ultramafic-mafic rocks; Jtrma—migmatitic amphibolite enclaves; JTrsv—metasedimentary and meta-volcaniclastic rocks of the Rattlesnake Creek terrane cover sequence; Jtru—ultramafic rocks (serpentinite-matrix mélange) of the Rattlesnake Creek terrane.

many of the migmatitic enclaves consist chiefly of leucosome and melanosome, and relict textures of the original protolith are absent. The origin of these rocks becomes less problematic if one takes a regional view. Mafic to intermediate volcaniclastic and volcanic rocks form part of the Rattlesnake Creek terrane cover sequence between Bear Peak and Pony Peak (Figs. 1 and 2, Plate 1) and are common in the klippe of Rattlesnake Creek terrane between Dillon Creek and Orleans (i.e., Prospect Hill area; Gray, 1985).

Dehydration-melting of amphibolitic rocks requires temperatures greater than 850–900 °C at 3 kb (Beard and Lofgren, 1991), although melting in the presence of interstitial H_2O (water-saturated conditions) can occur at lower temperatures, depending on the ambient pressure (Beard and Lofgren, 1991). The compositions of typical magmas in the Bear Peak intrusive complex suggest that thermal conditions were appropriate to achieve the partial melting of the basic to intermediate enclaves. As an example, liquidus temperatures were calculated for two Bear Peak intrusive complex samples using the program PELE (Boudreau, 1999). A basaltic dike (BP258) with 2.0 wt% H_2O has a liquidus temperature of 1311 °C at 4 kb. Quartz diorite sample BP288 with 1 wt% H_2O yielded a calculated liquidus temperature of 1174 °C. The latter sample would be ~70% crystalline at 1000 °C; therefore, one can infer that most magmas emplaced in the Bear Peak intrusive complex were hotter than 1000 °C. Clearly, thermal conditions for partial melting of the migmatitic enclave protoliths were possible in the pluton.

Nevertheless, questions remain: how did the enclaves come to be in the intrusive complex and what was their source? At least three hypotheses of origin are possible for the enclaves (Fig. 11): (1) sheets of magma coalesced and surrounded screens of mafic volcaniclastic rock, leading to in situ partial melting; (2) amphibolitic or metabasic xenoliths were torn from a deep conduit and entrained in Bear Peak magmas; and (3) mafic volcaniclastic rocks from the Rattlesnake Creek terrane cover sequence (possible roof of the Bear Peak intrusive complex) were stoped into the intrusive complex and sank to their present level.

Data in support of the in situ screen hypothesis (1) include the northwest-southeast orientation of the migmatitic amphibolite enclaves; the wrapping of magmatic fabric around the enclaves; and the septa-like nature of extensive, albeit discontinuous, enclaves separating intrusive units. This interpretation is consistent with the observation that, near contacts with metasedimentary host rocks, metasedimentary enclaves are completely surrounded by the host pluton. However, the in situ screen hypothesis is not consistent with the lack of mafic volcaniclastic rocks in the aureole. In the classic case of in situ screen formation (e.g., Pitcher, 1970; Pitcher and Berger, 1972), a ghost stratigraphy defined by enclaves is in geologic continuity with rock units and contacts in the aureole. Thus, in the Bear Peak intrusive complex, development of in situ screens is only viable if one assumes that a package of volcaniclastic rocks in the Rattlesnake Creek terrane was completely engulfed by magma.

Hypothesis 2 involves entrainment and upward transport of mafic rocks torn from magmatic conduit(s). Regional geologic relationships suggest that such rocks would be from either the Galice Formation or Josephine ophiolite. However, the Galice Formation in the area around the Bear Peak intrusive complex lacks volcaniclastic rocks, and such rocks are essentially absent in the Josephine ophiolite (Harper, 1984, 2003; Harper et al., 1994). Moreover, the probable low viscosity and yield strength of parental Bear Peak magmas make entrainment and upward transport of amphibolitic rafts of the dimensions observed unlikely.

The stoping hypothesis (3) requires that the cover sequence of the Rattlesnake Creek terrane consisted, in part, of volcaniclastic rocks similar to the sequence exposed southeast of the complex. Had significant stoping of the typical Rattlesnake Creek terrane cover sequence occurred, one might expect a greater proportion of metasedimentary enclaves in the pluton, as well as randomly oriented enclaves. The paucity of metasedimentary enclaves could result from a cover (roof) sequence that was chiefly volcaniclastic rocks or from complete melting and incorporation of metasedimentary enclaves into the host magma. This latter idea is unlikely, owing to the quartz-rich, and therefore refractory, nature of many of the host rocks. Finally, the present orientation of the enclaves may be related to post-stoping rotation by late-stage magmatic deformation, which is consistent with the orientation of magmatic foliations, subparallel to the orientation of the enclave blocks.

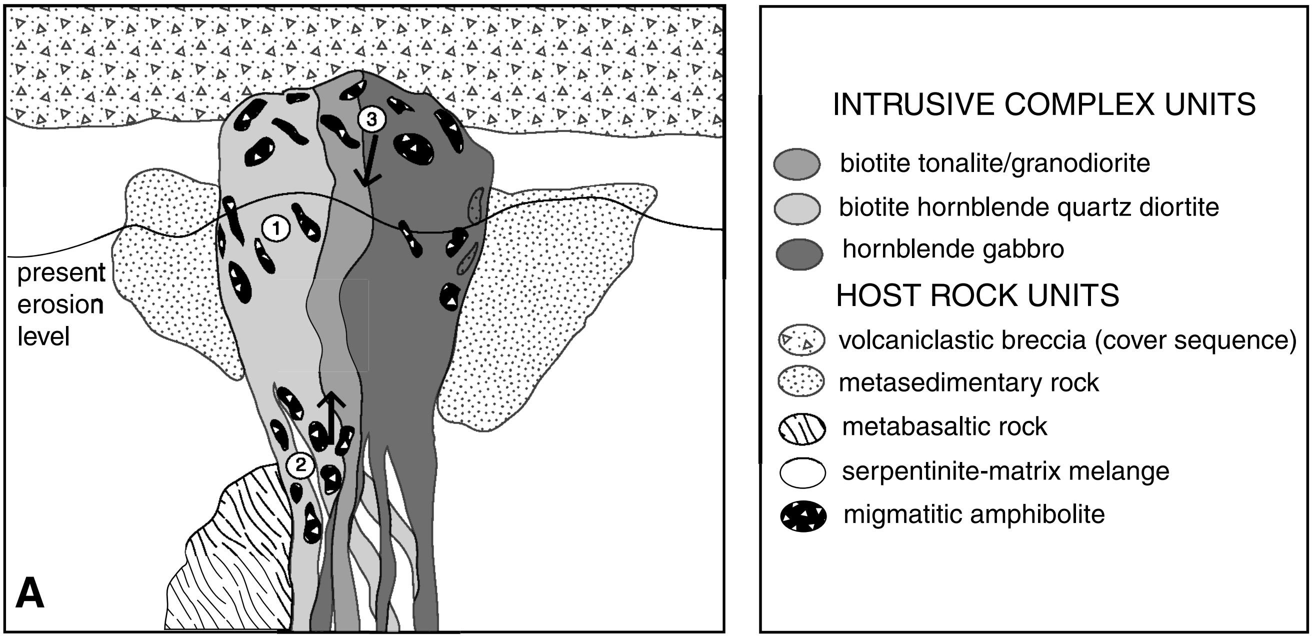
We conclude that the heterogeneity of the enclaves, their textural characteristics, their subparallel orientations, and the presence of similar protolith rocks within a few km of the pluton are consistent with the development of in situ screens and/or stoping.

Interpretation of Geochemical Data

Major, trace, and REE abundances (Tables 1 and 2, Figs. 7 and 8) suggest that the Bear Peak intrusive complex had at least two types of mafic parental magma that resulted in three of the plutonic units: (1) ultramafic-mafic rocks, (2) hornblende gabbro, and (3) biotite-hornblende quartz diorite.

A basaltic parental magma is probable for the ultramafic-mafic rocks, based on development of magnesian olivine (Fo_{85}–Fo_{75}), diopsidic augite, Fe-Cr spinel, and calcic plagioclase (~An_{65}). Most samples of this unit are probably cumulate, which would explain their high CaO and MgO and low Al_2O_3. Accumulation of olivine ± augite ± hornblende is consistent with the high Cr and Ni contents, as is the concave-downward REE pattern (Fig. 9, sample 1188). Early stability of clinopyroxene without plagioclase plus the abundance of cumulate hornblende indicate that the parental magma was H_2O-rich. This property in turn suggests that this MgO- and H_2O-rich parental magma had a source in a mantle wedge above a subducting slab.

The gabbroic unit probably also had basaltic parental magmas, which is supported by the overlap in compositions of fine-



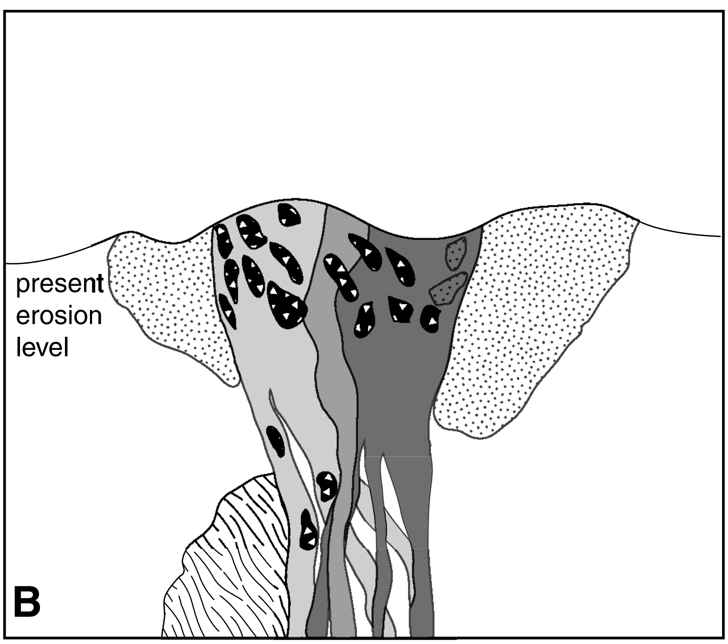


Figure 11. Schematic illustration of three possible hypotheses for the occurrence of enclaves of migmatitic amphibolite in the Bear Peak intrusive complex. (A) Illustration representing the Bear Peak intrusive complex during emplacement. Hypothesis 1 proposes that the Bear Peak intrusive complex intruded as sheets of magma that coalesced and surrounded screens of metavolcaniclastic rock that in turn led to in situ dehydration-melting of hornblende. Hypothesis 2 proposes the entrainment of amphibolitic to metabasaltic host-rock xenoliths (i.e., enclaves) ripped from a deep conduit. Hypothesis 3 proposes metavolcaniclastic rocks from the cover sequence of the Rattlesnake Creek terrane (Bear Peak intrusive complex roof rocks) were stoped into the intrusive complex and subsequently sank and rotated to their present level and position. Arrows near hypotheses 2 and 3 indicate the inferred direction of transport for the host-rock enclaves. See text for discussion of the three hypotheses. (B) Illustration representing Bear Peak intrusive complex at its current level of erosion.

grained basaltic dikes and the gabbroic unit (Figs. 7 and 8). The parental magmas to the gabbroic rocks were probably also H_2O-rich, which would explain the early stability of hornblende, the presence of hornblende phenocrysts locally, the extremely variable grain sizes (fine-grained to pegmatitic), and the presence of plagioclase-rich dikelets and veinlets (thought to represent low-temperature melt fractions). Together, the coherent compositional trends shown by the ultramafic-mafic and gabbroic units (Figs. 7 and 8) are consistent with a single parental magma type for both. Such a model has been proposed for similar rocks in the region (Bear Mountain intrusive complex: Snoke et al., 1981; Barnes et al., this volume, Chapter 17) and elsewhere (DeBari, 1997).

The nature of magmas parental to the quartz dioritic unit is less certain. Their phase assembly is consistent with evolved basaltic or andesitic magmas. On the basis of Al_2O_3 and MgO variation (Fig. 8), we surmise that plagioclase was an early stable phase in the parental magmas (along with hornblende), which in turn suggests crystallization from H_2O-bearing magmas, but ones with less H_2O than magmas parental to the ultramafic-mafic and gabbroic units. In a companion paper, Barnes et al. (this volume, Chapter 17) further investigated the origin of these magmas. They concluded that the parental magmas arose by partial melting of a hydrated mantle wedge and then evolved by fractional crystallization prior to emplacement in the Bear Peak intrusive complex.

Several of the tonalitic and granodioritic rocks have distinctive features, such as relatively high Mg/(Mg + Fe), high Sr values (>700 ppm), large Sr/Y and Ba/Y ratios, and reverse J-shaped REE patterns (Figs. 7–9). Such features are characteristic of partial melting of metabasic rocks in which amphibole ± garnet are residual phases (e.g., Martin, 1987; Drummond and Defant, 1990; Beard and Lofgren, 1991; Rapp et al., 1991; Rushmer, 1991; Wolf and Wyllie, 1994; Barnes et al., 1996; Wyllie et al., 1997). Although it is tempting to relate the tonalitic and granodioritic magmas to partial melting of migmatitic enclaves, we view this possibility as unlikely for at least two reasons. First, the chemistry of the tonalitic and granodioritic rocks indicates residual garnet in the source, yet the migmatitic enclaves lack garnet. Second, the dated granodiorite sample contains inherited zircon that is virtually identical to detrital zircon in the Galice Formation (Miller and Saleeby, 1995; Miller et al., 2003; Allen and Barnes, this volume). This observation requires that the magma parental to the dated sample, and presumably to other tonalite-granodiorite samples, assimilated Galice Formation metasedimentary rocks, and therefore originated well below the level of emplacement.

One of the characteristic features of the Bear Peak intrusive complex is the presence of partly disrupted synplutonic mafic dikes. Their crosscutting relationships, fragmentation and incorporation into host units, and formation of adjacent mafic magmatic enclaves are typical of mechanical mingling while the host magmas were still hot. Moreover, the presence of dispersed mafic magmatic enclaves suggests that mingling also occurred below the level of emplacement.

The synplutonic dikes appear to be compositionally similar to the MgO-rich gabbroic unit (Tables 1 and 2, Figs. 7–9). That these dikes intrude all stages of the Bear Peak intrusive complex indicates that the MgO-rich parental magma type was being generated in the underlying mantle wedge throughout the history of the Bear Peak intrusive complex.

CONCLUSIONS

The 144-Ma Bear Peak intrusive complex is a composite plutonic suite that ranges in composition from ultramafic to silicic, indicative of the extended compositional range characteristic of some oceanic-arc plutonic suites (e.g., Snoke et al., 2001). Contact-metamorphic assemblages and Al-in-hornblende barometry indicate crystallization at 3.5–4.7 kb, thus implying a mesozonal emplacement (12–20 km). Contact-metamorphic temperatures of 650–770 °C suggest high magmatic temperatures or significant flow of magma past the host rocks.

The intrusive complex grew by the multistage emplacement of magmas, commonly as dikes and large-scale, sheetlike bodies. This process is evident in the early development of the Bear Peak intrusive complex, as manifested by the intrusion of multiple gabbroic to dioritic dikes in the central (structurally low) ultramafic-mafic complex. The piecemeal growth of the Bear Peak intrusive complex continued throughout its development, as indicated by the presence of synplutonic mafic dikes and mafic magmatic enclaves in the major intrusive units of the complex. However, some space for the magmas also was made by stoping, as indicated by enclaves and screens of migmatitic amphibolite and xenoliths of quartzofeldspathic and ultramafic rocks. The in situ partial melting of metabasic and quartzofeldspathic rocks indicate the high temperatures of the intruded magmas of the Bear Peak intrusive complex, and this conclusion is also consistent with the estimated contact-metamorphic temperatures. Thus, the distribution of xenoliths and wall-rock screens as well as the mineralogical and textural heterogeneity of the intrusive plutonic rocks are the key field relations that suggest that the gabbroic to dioritic to tonalitic units of the Bear Peak intrusive complex were chiefly emplaced as multiple magmatic sheets. These sheets eventually coalesced into distinct, mappable plutonic rock units.

Geochemical features of the earliest two stages and the synplutonic dikes show that MgO- and H_2O-rich basaltic magma was present in the system from its inception to its end. Such magmas probably originated in the underlying mantle wedge, and some must have ponded in the crust. Such ponded magmas may have given rise to the MgO-poor parent for the quartz diorite unit. Furthermore, ponding in, and assimilation of, the underlying Galice Formation could explain the evolved nature of, and inherited zircon in, the late-stage tonalites and granodiorites. With evidence for a mantle source, deep-crustal ponding, mid-crustal interaction and assimilation, and upper-crustal stoping, the Bear Peak intrusive complex is a clear manifestation of a crustal magma column and cannot be viewed as a small, isolated pluton.

ACKNOWLEDGMENTS

This research was funded by National Science Foundation grant EAR-9902807 to AWS and EAR-9902912 to CGB. The Gregg Ranch Foundation also partially supported the fieldwork of RRM. Discussions in the field and office with J.C. Bushey were helpful in interpreting the evolution of the Bear Peak intrusive complex. The help and advice of Susan Swapp in obtaining and interpreting mineral analyses with the University of Wyoming, Laramie, automated JEOL JXA-8900 electron probe microanalyzer are greatly appreciated. Drew S. Coleman and Susan M. DeBari provided us with many comments and suggestions that were helpful in preparing the final version of this chapter.

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Manuscript Accepted by the Society 10 January 2006

Printed in the USA