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JURASSIC OROGENY IN THE KLAMATH MOUNTAINS: A GEOCHRONOLOGICAL ANALYSIS

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ABSTRACT

The Jurassic growth of Klamath continental crust from oceanic materials has conventionally been considered the result of two discrete orogenies, the "Siskiyou" and "Nevadan". Geochronologic data are now numerous enough to begin to recognize that the metamorphic and deformational episodes are instead a broad continuum of events whose characteristics varied in place and time and were closely linked with areas of active magmatism. Magmatism was widespread at ~200 Ma, and by ~170 Ma, led to the construction of two enormous volcanoplutonic arcs, the Western Hayfork and North Fork-Salmon River. Northwest-southeast extension in the northern Klamaths from 167-155 Ma was coincident with the crystallization of voluminous plutonic and volcanic rocks of the Wooley Creek and Western Klamath suites. Sudden cooling of a large region of the central Klamath Mountains to ~300°C at ~150 Ma may have occurred as the magmatic belt was extinguished by subduction of colder material at deeper structural levels.

INTRODUCTION

The Klamath Mountains provide a well-studied archetype of continental lithosphere constructed largely from oceanic material. Since the inception of the terrane concept in the Klamaths (Irwin, 1972), much debate has centered on whether the terranes are exotic with respect to the rest of western North America or formed more-or-less *in situ* (Davis and others, 1978; Wright, 1982; Gray, 1986). Hamilton (1978) suggested that Jurassic magmatic belts in the Klamaths represent distinct far-traveled arcs, whereas Davis and others (1978) postulated that a single Jurassic arc developed *in situ*. This paper presents preliminary geochronology for Jurassic magmatic and related metamorphic rocks in the central Klamath Mountains that, coupled with extensive earlier geochronologic studies in the western Klamaths (Table 1), reinforces the latter model, and allows a revised tectonic scenario for the Jurassic evolution of the Klamath Mountains.

The overall structure of the Klamath Mountains is a stack of gently east-dipping thrust sheets (Irwin, 1966; Blakely and others, 1985; Mortimer, 1985; Zucca and others, 1986; Fuis and others, 1987). Klamath terranes shown in Figure 1 generally have east-dipping bedding and foliation and west-vergent folds; most are separated by west-directed thrust faults. Terranes related to the main theme of this paper are described below.

The basis for this paper is the radiometric ages listed in Table 1 and Figure 2. All zircon ages summarized here for igneous rocks have been interpreted as crystallization ages. On the other hand, K/Ar and $^{40}Ar/^{39}Ar$ ages generally are minimum ages for the crystallization of plutonic rocks because entrapment of argon in crystals occurs considerably below solidus temperatures. Crystallization times of rapidly cooled hypabyssal and volcanic rocks are more closely reflected in K/Ar and $^{40}Ar/^{39}Ar$ ages—provided that the rocks have not undergone reheating sufficient to liberate argon. Closure temperatures, or the temperature of a mineral at the time represented by its apparent age (Dodson, 1973), are approximately 500–525°C (Harrison, 1981), 400–425°C (summary in Hodges, 1991), and 310–345°C (Harrison and others, 1985), for rapidly cooled hornblende, muscovite, and biotite, respectively. Closure temperatures may be affected by factors such as cooling rate (Dodson, 1973), composition (Harrison and others, 1985; Scaillet and others, 1992), exsolution (Harrison and Fitz Gerald, 1986; Baldwin and others, 1990), alteration (Onstott and Pringle-Goodell, 1988; Baldwin and others, 1990), and grain size (Kelley, 1988). Of potential relevance to this study, exsolution may reduce hornblende closure temperature by more than 100°C (Baldwin and others, 1990). We have not detected exsolution in any Klamath hornblendes studied by back-scattered electron microscopy, but this does not preclude its existence.

Western Klamath Terrane

The western Klamath terrane consists of the Josephine ophiolite, Galice Formation, Rogue Formation, and Chetco complex. The Rogue Formation and Chetco complex are interpreted as a Middle to Late Jurassic (Table 1, c15–c20) immature arc (Garcia, 1979, 1982); plutonic rocks include the

Chetco River complex, Illinois River gabbro, and Rum Creek metagabbro (Saleeby, 1990). The Josephine ophiolite (Harper, 1980) is Middle Jurassic in age (Table 1, c10–c14). It overlies the Rogue/Chetco arc along a regional thrust fault, the Madstone thrust, (Harper and others, 1993) interpreted to have

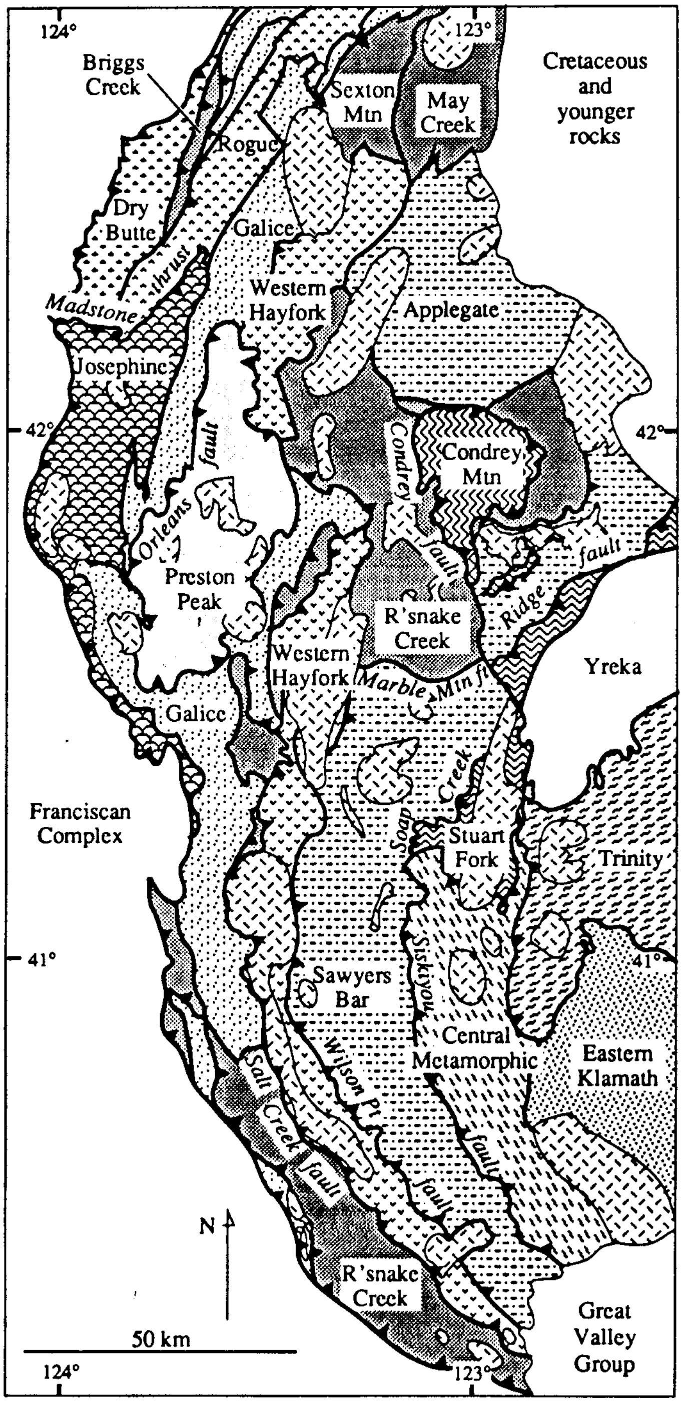


Figure 1. Klamath rock units (after Blake and others, 1982; Smith and others, 1982; Ernst, 1990; Hacker and others, 1993). Plutons discussed in text are shown. Main portions of faults discussed in the text are named with italics; "Marble Mtn ft": Marble Mountains fault. Low-angle faults are shown with teeth, high-angle faults without.

been active during the final stages of arc volcanoplutonism (Harper and others, 1993). The Josephine ophiolite and Rogue/Chetco arc are both depositionally overlain by the Galice Formation (Harper, 1980; Harper and Wright, 1984), which consists of Oxfordian radiolarian chert grading upward into Kimmeridgian flysch (Pessagno and Blome, 1990). The Galice Formation, Rogue Formation, and Josephine ophiolite are all cut by dikes/sills that yield ages as young as ~150 Ma (Table 1, e6–e22). Spinel, staurolite, garnet, and blue-amphibole detritus in the Galice Formation suggests that Galice sediments were derived from sources in more easterly Klamath terranes (Davis and others, 1978; Saleeby and others, 1982). The Galice Formation and depositionally underlying Rogue/Chetco arc and Josephine ophiolite therefore are not far-traveled with respect to the rest of the Klamaths (Davis and others, 1978; cf. Wright and Wyld, 1986).

Preston Peak Ophiolite

The Preston Peak ophiolite comprises greenschist-facies tholeiitic plutons, dikes, breccias and pillowed flows that intrude and unconformably overlie serpentinized ultramafic tectonite with included blocks of amphibolite (Snoke, 1977; Snoke and others, 1981; Saleeby and others, 1982). The ultramafic tectonite, and possibly the amphibolite, are inferred to be part of the Rattlesnake Creek terrane (see below). A late-stage plagiogranite dike in diorite yielded a 164±1 Ma zircon age (Table 1, c21), and chert overlying the flows contains Jurassic radiolarians (Saleeby and others, 1982). One contact-metamorphosed amphibolite block yielded a K/Ar hornblende age of 165±3 Ma (Table 1, c22), whereas amphibolite distant from plutons produced 190 and 193 Ma ages (Table 1, a17–a18). Rocks possibly correlative with the Preston Peak ophiolite (near little Grayback Mountain; Gorman, 1985) contain Jurassic radiolarians (Saleeby and others, 1982) and Late Triassic conodonts (Irwin and others, 1983).

Condrey Mountain Terrane

The Condrey Mountain terrane is in similar structural position to the Western Klamath terrane, but is a transitional greenschist-blueschist facies subduction complex with a greenschist facies overprint (Helper, 1986). The protolith age of part of the Condrey Mountain terrane is bracketed to near 170 Ma by zircon ages (Table 1, b10–b12). Rb/Sr and K/Ar ages indicate that cooling of the Condrey Mountain terrane below ~350°C was delayed until Early Cretaceous time (125–132 Ma; Helper and others, 1989).

Rattlesnake Creek Terrane

The Rattlesnake Creek terrane, high-grade portions of which are also called the

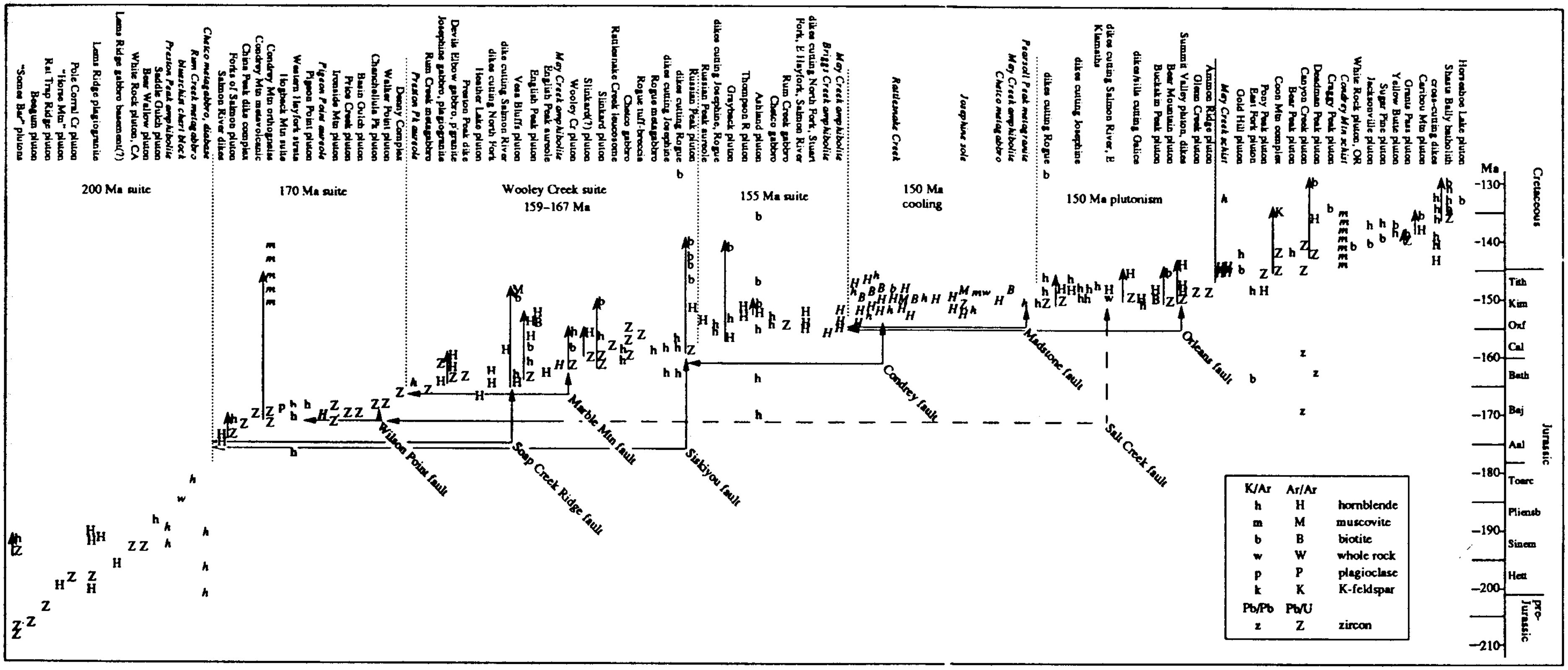


Figure 2. Radiometric ages. Timescale based on Pessagno and Blome (1990) and Hodych and Dunning (1992). Arrows show permissible cooling histories and possible age ranges of motion on faults. Note that the time movement on the Salt Creek fault is poorly constrained. This diagram combines data from many sources and should be treated with caution; for example, some plutons are poorly dated, and K/Ar ages may be unreliable. Italics indicate metamorphic rocks.

Marble Mountain terrane, consists of mafic tectonite and ophiolitic melange overlain by coherent, undeformed volcaniclastic rocks (Wright, 1981; Petersen, 1982; Hill, 1984; Rawson, 1984; Gorman, 1985; Gray, 1985; Wright and Wyld, 1986; Donato, 1987). Irwin (1972) interpreted the Rattlesnake Creek terrane as a dismembered ophiolite.

The melange contains blocks derived from ophiolitic as well as continental sources. Ultramafic blocks retain high-temperature fabrics that predate their incorporation into the melange (Medaris, 1966; Rawson, 1984; Donato, 1987). Mafic blocks within the melange include massive amphibolite (Hill, 1984) and hypabyssal-plutonic complexes, some of which were deformed during crystallization (Klein, 1977; Petersen, 1982). Zircons from plagiogranite cutting one block of dikes at China Peak gave an age of 172±2 Ma (Table 1, b14). Trace elements indicate that mafic igneous rocks in the Rattlesnake terrane have affinities with immature arc and mid-ocean ridge basalts (Fig. 3). Chert blocks in the melange contain radiolarians ranging from Middle Triassic to Early or Middle Jurassic age, and limestone blocks bear Devonian(?) coral to Late Triassic conodonts (Irwin, 1972, 1985b; Irwin and others, 1977, 1982, 1983, 1985; Gray, 1985). The Devonian(?) fossil coral is significant because it is similar to coral found in sedimentary strata in the Eastern Klamaths, and thus ties provenance of the Rattlesnake Creek terrane to the Eastern Klamath terrane (Irwin, 1972).

The coherent volcaniclastic unit overlying the melange contains ~350 m of conglomerate, arenite and tuff deposited subaerially proximal to a volcano (Rawson, 1984; Gray, 1985, 1986). Trace element abundances indicate that the volcano was part of an immature arc (Fig. 3). The relationship between the melange and the coherent volcaniclastic suite is of considerable tectonic import, yet it has not been well documented. Petersen (1982) and Gray (1985) state that the contact is not exposed. Moreover, although plutons ranging in age from 192 to 208 Ma intrude the serpentinite-matrix melange of the Rattlesnake Creek terrane in the Somes Bar area (Gray, 1985), plutons explicitly intruding the volcaniclastic unit in that area have not been dated. A preliminary report by Wright and Wyld (1985) mentioned that plutons as old as 212 Ma do cut volcaniclastic rocks that lie depositionally on melange in the southernmost(?) Klamaths. If depositional on melange, the volcaniclastic rocks must be older than 212 Ma but must also postdate Late Triassic limestone blocks in the melange (Gray, 1986). Early Jurassic radiolarians must have been mixed into the Rattlesnake Creek melange at a later date, otherwise the volcaniclastic rocks would have to postdate them too (Gray, 1985; Wright and Wyld, 1985). Inasmuch as the beginning of the Early Jurassic (201±2 Ma; Hodych and Dunning, 1992) significantly postdates 212 Ma, these reported age relationships are paradoxical.

The Rattlesnake Creek terrane served as rift basement for the Rogue/Chetco arc (Harper and Wright, 1984; Saleeby, 1984), Josephine ophiolite (Wyld and Wright, 1988), Preston Peak ophiolite (Saleeby and others, 1982), and possibly the Western Hayfork (Wright and Fahan, 1988) and Salmon River arcs (see below).

Western Hayfork terrane

The Western Hayfork terrane is a Middle Jurassic (167–177 Ma; Table 1, b1–b7) immature intraoceanic arc that consists of gabbroic to quartz-monzodioritic calc-alkaline plutons intruding >6 km of consanguineous volcaniclastic rocks and depositionally overlying epiclastic rocks (Fig 3; Klein, 1975; Cashman, 1979; Charlton, 1979; Hill, 1984; Rawson, 1984; Wright and Fahan, 1988). Fossils include Silurian coral and Early Permian gastropods in limestone cobbles derived from the McCloud limestone of the Eastern Klamaths, and Triassic or Jurassic radiolarians in chert (Irwin, 1972, 1985b; Fahan, 1982; Irwin and others, 1982; Wright, 1982). The McCloud fauna indicates that the Western Hayfork terrane formed near the eastern Klamaths, and hence is not exotic (Harper and Wright, 1984).

Sawyers Bar terrane

Ernst (1990) and Hacker and others (1993) reported that several Klamath units previously termed terranes, the Eastern Hayfork, Salmon River, and North Fork, are not wholly fault-bounded units, and therefore do not warrant terrane status. In addition, well-bedded, coherent chert formerly included as part of the North Fork unit was given a separate name, the St Claire Creek unit. All four units were grouped as the Sawyers Bar terrane (Ernst, 1990). Hacker and others (1993) provisionally interpreted the Sawyers Bar terrane to represent a volcanoplutonic arc (North Fork and Salmon River units), and associated fore-arc accretionary wedge (Eastern Hayfork unit) and back-arc basin (St Claire Creek unit).

Eastern Hayfork Unit

The Eastern Hayfork unit varies from broken formation to melange and is interpreted to represent an accretionary wedge (Wright, 1981). The non-exotic (plausibly interbedded) component of the Eastern Hayfork includes rocks grading from radiolarian chert to tuff, pillow lava, and quartzose turbidites (Cashman, 1979; Charlton, 1979; Fahan, 1982; Wright, 1982; Hacker and others, 1993). Tuffaceous material and clastic volcanogenic rocks are subordinate to detritus derived from continental or plutonic provenances. Exotic blocks include ultramafic rock, basalt, gabbro, limestone, amphibolite, blueschist, quartzofeldspathic schist, recrystallized chert, and crenulated quartz-mica schist (Cox, 1956; Cashman, 1979; Charlton, 1979; Burton, 1982; Fahan, 1982; Wright, 1982). Cashman and Wright suggested that the metamorphic blocks were derived from the more easterly Stuart Fork and Central Metamorphic terranes; this suggestion has been strengthened by geochronologic work of Goodge and Renne (1991, 1993).

Limestone blocks in the Eastern Hayfork contain Silurian or Devonian through Late Triassic shallow water fossils, including Late Permian Tethyan fusulinids and coral (Irwin, 1972, 1974, 1985b; Cox and Pratt, 1973; Irwin and others, 1977, 1983; Gray, 1986; Miller and Wright, 1987; Stevens and others, 1987, 1991). Eastern Hayfork chert contains Late Permian, Middle Triassic, Late Triassic, and Late Triassic to Early Jurassic radiolarians, and Middle Triassic and Late Triassic conodonts, implying Late Permian to Early Jurassic deposition (Irwin and others, 1982, 1983; Ando and others, 1983; Irwin, 1985b).

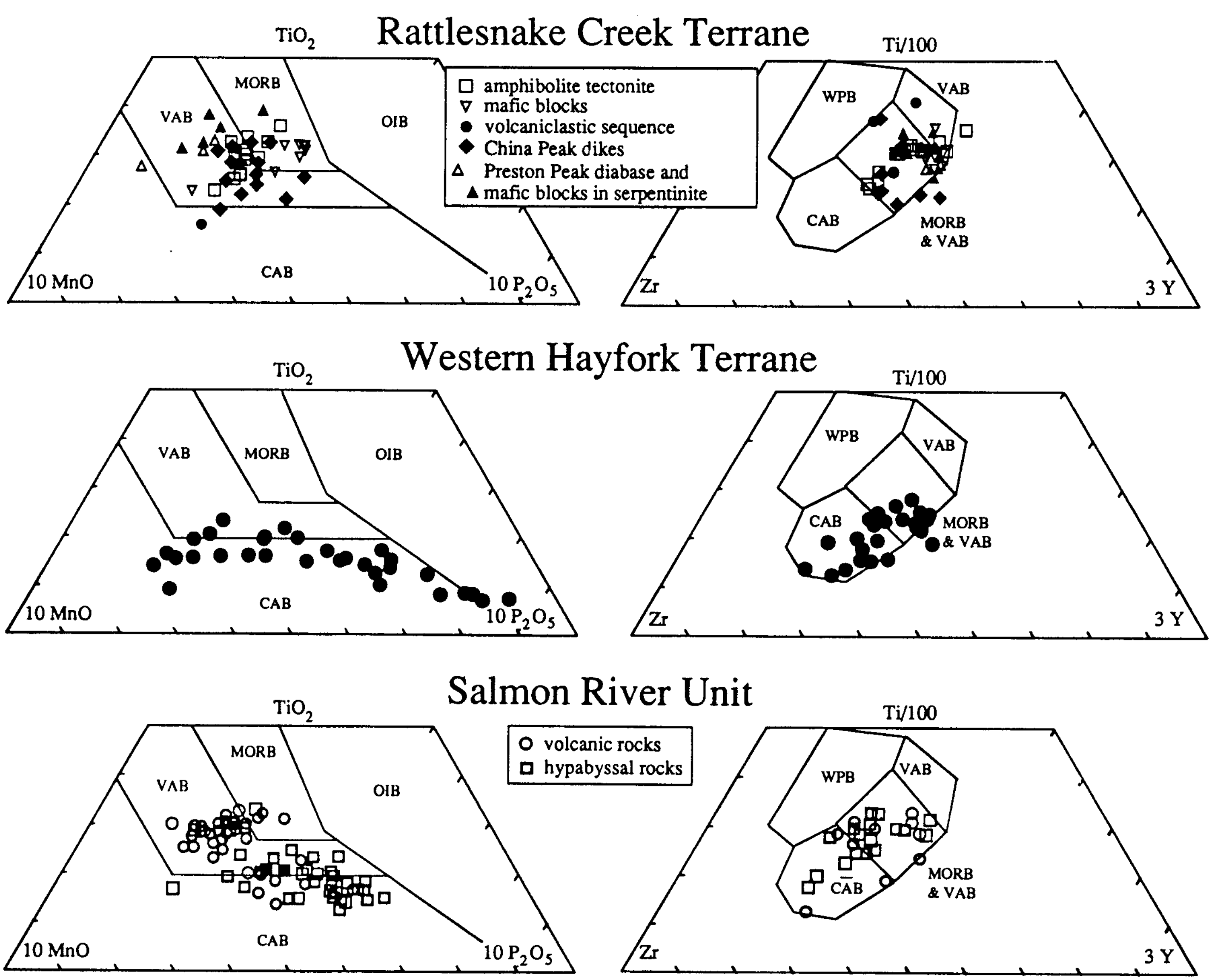


Figure 3. Tectonomagmatic discrimination diagrams after Pearce and Cann (1973) and Mullen (1983). Note that the hypabyssal and volcanic rocks of the Salmon River unit are similar to the Western Hayfork and Rattlesnake Creek terrane, respectively. MORB: mid-ocean ridge basalt; OIB: ocean-island basalt; VAB: intraoceanic arc basalt; CAB: continental arc basalt; WPB: within-plate basalt. Data from Charlton (1979), Wright (1981), Petersen (1982), Hill (1984), Donato (1985), Gorman (1985), Gray (1985), Wyld and Wright (1988), Ernst (1987), Ernst and others (1991), Hacker and others (1993), and Barnes (pers. comm., 1990).

Quartzose blocks contain detrital zircons with Pb/Pb ages of 2.0–2.1 Ga, indicating that some debris was ultimately derived from a mature Precambrian continental source (Miller and Saleeby, 1991). Trace-element abundances of Eastern Hayfork sedimentary rocks suggest that material was also derived from the adjacent North Fork-Salmon River arc (Hacker and others, 1993). The discovery of the same Late Permian Tethyan fossils in the Eastern Klamath terrane and Eastern Hayfork unit (Stevens and others, 1987) implies that the limestone blocks are olistoliths derived from eastern paleo-Pacific seamounts (Miller and Wright, 1987) or from the Eastern Klamath terrane.

Salmon River Unit

The Salmon River unit includes ultramafic rock, gabbro, diabase, and volcanic rock, and was initially interpreted as oceanic crust (Irwin, 1972; Blake and others, 1982; Ando and others, 1983; Mortimer, 1984). Recent field mapping, whole-rock analyses, and mineral analyses provided the basis for Ernst and others (1991) to propose genesis as an immature intraoceanic arc instead. Massive and locally pillowed volcanic rocks with thin volcaniclastic layers contain igneous clinopyroxene, hornblende, and plagioclase, with minor spinel, apatite, and possibly anorthoclase; carbonate and chert are present between pillows (Cox, 1956; Ando, 1979; Mortimer, 1984; Ernst and others, 1991). Metavolcanic rocks have trace element abundances appropriate for immature tholeiitic arc rocks, whereas younger, recrystallized microdioritic dikes and sills tend to be calc-alkaline (Fig. 3; Ernst, 1993).

Fossil ages of interbedded Eastern Hayfork sedimentary rocks suggest that construction of the Salmon River suite began in Permian and extended through Late Triassic time. Plagiogranite within diabase yielded a strongly discordant Pb/U zircon age interpreted to indicate crystallization in the range 265–310 Ma (Pennsylvanian to Permian; Ando and others, 1983). A gabbro body that intrudes the diabase gave a $^{40}Ar/^{39}Ar$ isochron age of 200 Ma on igneous hornblende (Table 1, a9). Two mafic hypabyssal rocks in the Salmon River unit yielded Ar/Ar hornblende ages of ~174 Ma (Table 1, b15–b16). These data are interpreted to indicate the presence of an arc as young as Middle Jurassic built in oceanic basement as old as Permian.

North Fork Unit

The North Fork unit comprises up to 2 km of amygdaloidal volcanic rocks with rare limestone layers and massifs (Ando, 1979; Wright, 1981; Mortimer, 1984). It was initially interpreted as oceanic crust because of its ophiolitic rock types (Irwin, 1972), and has since been suggested to represent a seamount complex (Ando, 1979). Hacker and others (1993) presented an alternative interpretation—that the North Fork is an alkalic part of the Salmon River immature arc. The volcanic rocks are massive to amygdaloidal breccias with angular to subangular clasts, tuffaceous chert, pillowed flows, pillow breccias, and hyaloclastites. Limestone beds or exotic(?) blocks contain fusulinids and foraminifers of Carboniferous to Early Permian age (Irwin, 1972, 1974; Irwin and others, 1977).

The igneous crystallization age of the North Fork volcanics may be as young as 165 Ma, based on Ar/Ar ages obtained on hornblende from two dikes (Table 1, c24–c25). Sedimentary rocks of the Eastern Hayfork unit interbedded with the North Fork range in age from Late Permian to Late Triassic. Late Permian fossils are present in limestone intercalated with the North Fork volcanics, and the interbedded St Claire Creek unit contains Late Permian to Early Jurassic fossils. The oldest pluton intruding the North Fork is the Vesa Bluffs pluton (≥165 Ma Table 1, c9). Thus, eruption is poorly constrained to within Late Permian to Middle Jurassic time.

St Claire Creek Unit

This unit, informally named by Hacker and others (1993), is characterized by chiefly coherent, bedded chert with minor argillite (this study; Ando, 1979; Wright, 1981; Mortimer, 1984) unlike the disrupted, argillite-dominated sequences of the Eastern Hayfork unit. Previously this unit was included as part of the North Fork unit, which it overlies depositionally (Trexler, 1968; Ando and others, 1983); earlier workers postulated that this section represented open-ocean sediments (Davis and others, 1978; Ando, 1979; Wright, 1982). Hacker and others (1993) separated this sediment-dominated unit from the alkalic volcanic rocks of the North Fork unit. The new unit name emphasizes that the Salmon River and North Fork units interfinger and are interbedded with two distinctly different types of sedimentary rock: disrupted chert-argillite of the outboard Eastern Hayfork and coherent well-bedded chert-argillite of the inboard St Claire Creek unit.

St Claire Creek chert contains Late Permian through Early to Middle Jurassic radiolarians, and Middle Permian and Late Triassic conodonts (Irwin and others, 1977, 1982; Lindsley-Griffin and Griffin, 1983; Mortimer, 1984). It includes fragments of plagioclase, quartz, clinopyroxene, brown hornblende, chlorite, muscovite, and carbonaceous material (Cox and Pratt, 1973; Wright, 1981). Sandstone and argillite turbidites interlayered with the chert contain crystals of quartz, plagioclase, rare potassium feldspar, and clasts of argillite, chert, recrystallized chert, mica schist, volcanic rock, and Permian McCloud limestone (Fahan, 1982; Wright, 1982; Gray, 1986). The composition and mineralogy of the detritus indicates that the St Claire Creek unit is native to the Klamaths and was derived from sources similar to those providing sediment to the Eastern Hayfork unit (Wright, 1982).

Stuart Fork Terrane

The Stuart Fork terrane is a subduction complex composed of hemipelagic shale, chert, and basaltic rocks metamorphosed to blueschist facies during Late Triassic time (Hotz, 1977; Hotz and others, 1977; Goodge, 1989). Detrital feldspars in the sedimentary rocks indicate proximity to a craton or magmatic arc. Trace element abundances suggest that the volcanic rocks are back-arc basin basalts (Goodge, 1990).

Eastern Klamath Terrane

The Eastern Klamath terrane contains >10 km of Devonian to Jurassic sedimentary and volcanic strata formed chiefly in an intra-oceanic arc. Rocks of Late Permian and possibly Early Triassic age are absent (Miller and Harwood, 1990). The Pit Formation of Early (Noble and Renne, 1990) to Late Triassic (Albers and Robertson, 1961) age is composed of flows and tuffaceous rocks overlain by shales and chert (Sanborn, 1960; Noble and Renne, 1990). Upper Triassic (Carnian) Hosselkus Limestone and Brock Shale record shallow-water and basinal sedimentation with distal volcanic input (Sanborn, 1960), whereas the Upper Triassic (Rhaetian) Modin Formation records the resumption of influx of proximal volcanic detritus (Miller and Harwood, 1990). An unconformity may (Sanborn, 1960) or may not (Renne and Scott, 1988) be present below pyroclastic beds and minor flows of the Lower Jurassic (Pliensbachian-Sinemurian) Arvison Formation. The Mesozoic section ends with argillite and tuffaceous sandstone of the Lower to Middle (Bajocian-Toarcian) Jurassic Potem Formation (Sanborn, 1960). Faulting and folding in the Eastern Klamath terrane postdated deposition of Bajocian strata and predated ~164–170 Ma plutons (Renne and Scott, 1988).

VOLCANOPLUTONIC AND RELATED METAMORPHIC EVENTS

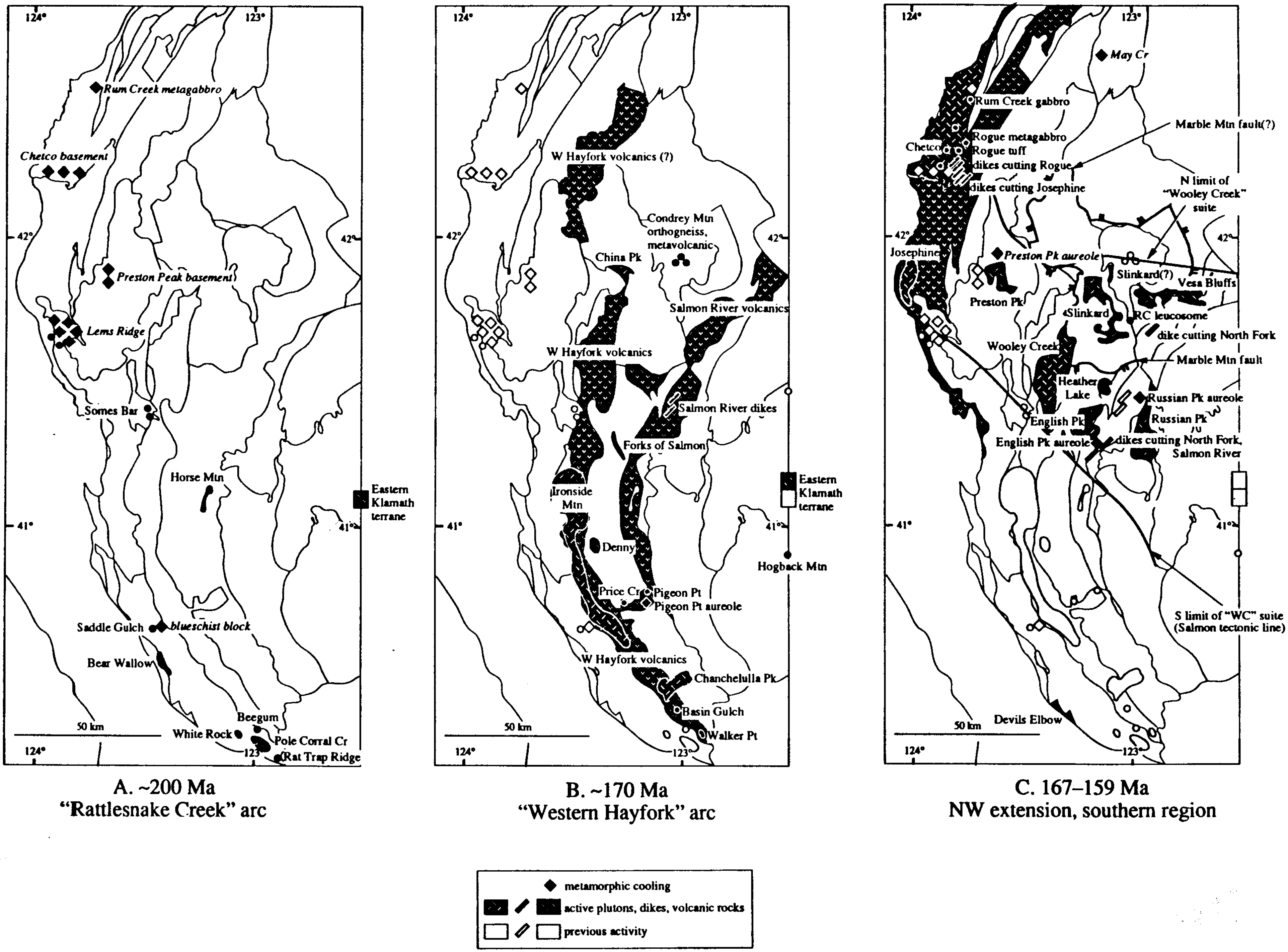
Klamath igneous rocks have been grouped into suites of different age and composition (Irwin, 1985a; Barnes and others, 1992). Figures 2 and 4 divide magmatic and associated metamorphic activity into distinct time frames for ease of discussion.

Earliest Jurassic Events (~200 Ma)

Recognition that volcanoplutonism of earliest Jurassic time (~200 Ma) was widespread in the Klamath Mountains is an important contribution of this paper. Most plutons of this age crop out in the Rattlesnake Creek terrane (Fig. 4a), where they range in zircon age from 192 to 212 Ma—with somewhat younger K/Ar hornblende ages (Table 1, a1–a8). Plutons of probable pre-Middle Jurassic age also crop out in the Salmon River unit of the Sawyers Bar terrane (Cox, 1956; Ando and others, 1983), and one of these bodies at Horse Mountain (Fig. 4a) has been dated as 200 Ma (Table 1, a9). This is significant, for it raises the possibility that plutonic and volcanic rocks in the Salmon River unit might be equivalent to the coherent volcaniclastic section and intruding plutons in the Rattlesnake Creek terrane. Trace-element abundances shown in Figure 3 support this possibility. The Lems Ridge olistostrome, spatially associated with the Josephine ophiolite, also contains gabbro clasts of this age, and may rest depositionally on ~200 Ma basement as well (Table 1, z11–z17; Ohr, 1987; Harper and others, 1993). Roughly 200 Ma metaplutonic rocks in the Rogue/Chetco arc and Preston Peak ophiolite support the presence of Rattlesnake Creek terrane as rift basement to those units as well (Table 1, a17–a22).

Western Hayfork Age Events (177–167 Ma)

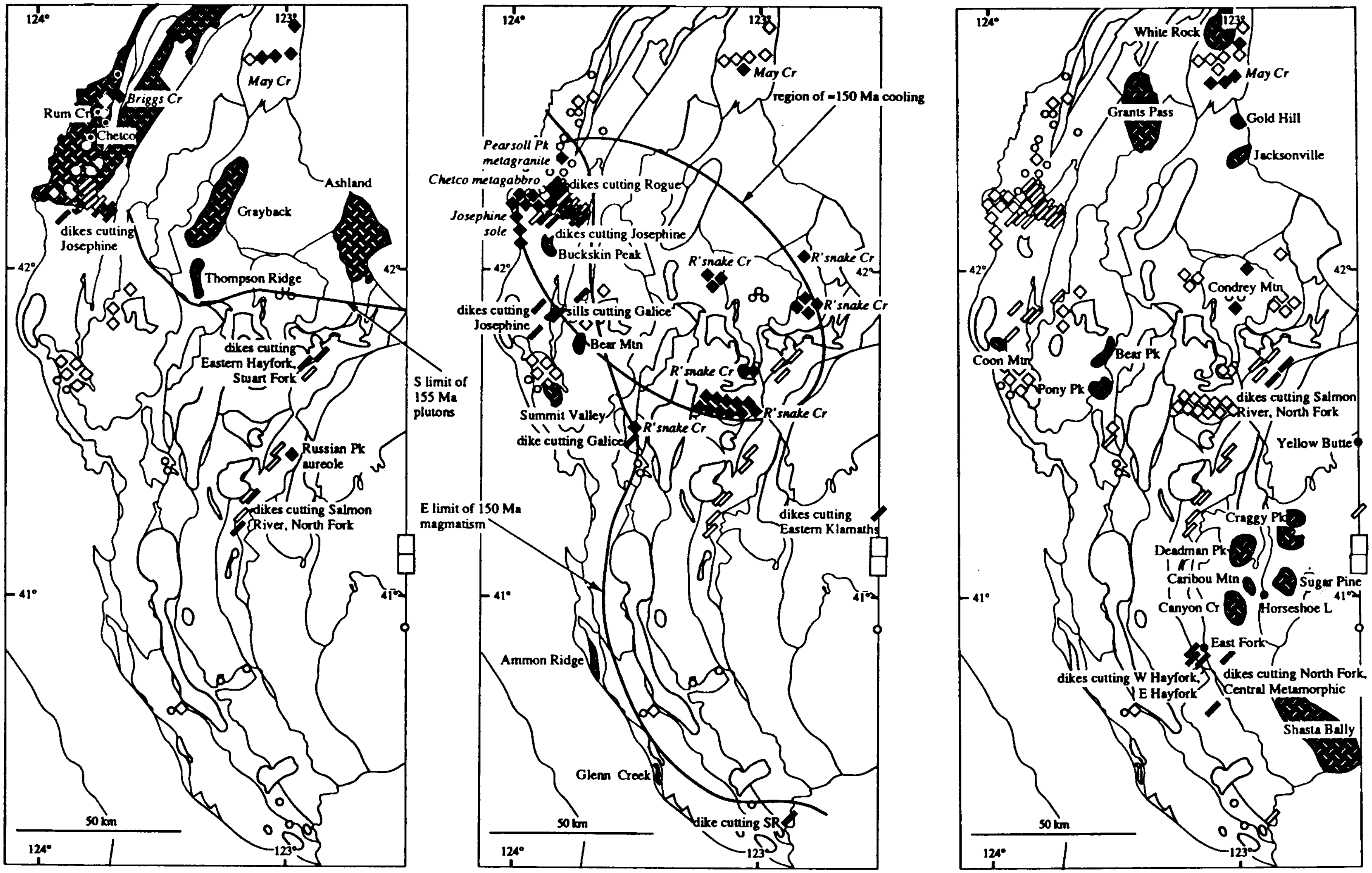
The hallmark volcanoplutonism of early Middle Jurassic age is the Western Hayfork terrane (Fig. 4b). As discussed earlier, plutons in the Western Hayfork terrane proper (the Ironside Mountain suite) yield crystallization ages of 169–171 Ma, and volcaniclastic rocks have K/Ar hornblende ages of 168–177 Ma (Table 1, b1–b7). Plutons of similar composition and age outside the Western Hayfork terrane include the Denny Complex and Forks of Salmon pluton (Table 1, b8–b9). Two dikes within the Salmon River unit also fall in this category (Table 1, b15–b16). This is significant, because hypabyssal and volcanic rocks in the Western Hayfork and Salmon River suites might thus be part of the same volcanoplutonic arc. Figure 3 indicates that hypabyssal rocks in the Salmon River unit are indistinguishable from the Western Hayfork terrane in trace-element abundances. The 172-Ma China Peak dike complex in the older Rattlesnake Creek terrane lies on strike with the Western Hayfork volcanics—although it tends to be more tholeiitic than typical Western Hayfork rocks (Fig. 3). Igneous activity of equivalent age also occurred in the Condrey Mountain and Eastern Klamath terranes (Table 1, b10–b13).



A. ~200 Ma
"Rattlesnake Creek" arc

B. ~170 Ma
"Western Hayfork" arc

C. 167–159 Ma
NW extension, southern region



D. ~155 Ma
NW extension, northern region

E. ~150 Ma
widespread cooling

F. <150 Ma
final stage

Figure 4. Interpretive maps showing intrusion, volcanism, and metamorphism in six stages. Small plutons are shown as circles. Igneous units east of the map area are shown diagramatically at the edge of each panel. Cr: Creek; L: Lake; Pk: Peak; Pt: Point; R: Ridge. Panel B: Only the southern portion of the Western Hayfork volcanic rocks have been dated; the central and northern portions may be of different age. Only dikes have been dated in the Salmon River unit; the volcanic rocks may be older. Panels C and D: Different units within the Rogue/Chetco arc have not been differentiated.

Wooley Creek/Western Klamath Events (167–159 Ma)

The Wooley Creek intrusive suite (Irwin, 1985a; Barnes and others, 1992) constitutes a group of granitic to gabbroic calc-alkaline plutons (Slinkard, Wooley Creek, English Peak, Russian Peak, and Vesa Bluffs) that range in igneous crystallization age from 165–159 Ma (Table 1, c2–c9; Fig. 4c). Coeval volcanic rocks have not been recognized, but may include parts of the Salmon River unit. The Heather Lake pluton's 167-Ma Ar/Ar hornblende age suggests that it too is part of this suite (Table 1, c1). Dikes in the North Fork and Salmon River units also have comparable Ar/Ar hornblende ages (Table 1, c24–c26). Irwin (1985a) included the Ashland pluton in the Wooley Creek suite, but Ar/Ar ages suggest it may be younger. Volcanoplutonism of similar age occurred farther west in the Klamath Mountains, including formation of the Preston Peak and Josephine ophiolites and the Rogue/Chetco arc (Table 1, c10–c22). Igneous activity of this age is restricted to a NW-trending corridor. Plutons and volcanic rocks in the corridor are elongate to the NE and SW, suggesting NW-SE subhorizontal extension. The southern edge of the extended corridor is the Salmon tectonic line of Irwin (1985a, 1989), but a northern, potentially more convoluted, boundary has not been recognized or named. Both boundaries were presumably transfer zones accommodating differential subhorizontal extension, as hypothesized for the Garlock fault in southern California (Davis and Burchfiel, 1973). This hypothesis might be tested by measuring the orientation of comagmatic dikes associated with calc-alkaline plutons in the corridor and by investigating the structure of the Salmon tectonic line.

Late Jurassic Events (~155 Ma)

Plutonic and volcanic rocks of ~155 Ma are also restricted to a particular part of the Klamaths (Fig. 4d). The area is north of slightly older Wooley Creek type events, indicating northward migration of magmatism and continued NW-directed extension. Rocks of this age include the Thompson Ridge pluton, Grayback pluton, Ashland pluton, and Rum Creek metagabbro (Table 1, d1–d3, d13). Hypabyssal rocks of this age intrude the North Fork, Stuart Fork, Eastern Hayfork, Salmon River, Rogue, and Josephine units (Table 1, d5–d13). The 155-Ma magmatism may simply represent a northward shift of the tectonic activity responsible for the Western Klamath/Wooley Creek magmatism.

Latest Jurassic Events (~150 Ma)

Yet another notable change happened in the Klamath Mountains at 152–148 Ma, but in this case, the evidence comes from metamorphic cooling ages as well as from crystallization ages. Igneous bodies of this age are generally restricted to the westernmost Klamaths, and consist exclusively of dikes and small plutons (Table 1, e1–e24; Fig. 4e). Near concordance of crystallization (zircon) and cooling (hornblende and mica) ages indicate rapid cooling of these plutons to ~300°C within 5 m.y. after emplacement (Fig. 2). Metamorphic cooling ages of 148–152 Ma from amphibolite-facies rocks occur in the Josephine sole and throughout the Rattlesnake Creek terrane (Fig. 4e; Table 1, e25–e57). Many hornblende and mica Ar/Ar and K/Ar ages from the Rattlesnake Creek terrane are concordant, suggesting rapid cooling of the metamorphic rocks to ~300°C. K/Ar ages indicate that several plutons of the Wooley Creek suite also cooled through amphibolite-facies conditions at this time (Fig. 2).

Cretaceous Events

Latest Jurassic and earliest Cretaceous time saw a return to widely distributed magmatism (Fig. 4f). Many weakly metamorphosed dikes and plutons of this age intrude the Klamath Mountains (Table 1, f1–f23). This has two significant implications: not only did arc magmatism continue until approximately 135 Ma, but metamorphism of the country rock probably lasted into Early Cretaceous time (see also Harper and others, 1993). Additional evidence for significant heat retention into Cretaceous time comes from the Condrey Mountain terrane (Fig. 1), which yielded muscovite K/Ar ages of 125–143 Ma and Rb-Sr isochron ages of 125–139 Ma (Helper and others, 1989).

DEFORMATION

Intraterrane deformation reveals aspects of the tectonic setting of individual units, whereas interterrane deformation provides information about the large-scale construction of the orogen. The emphasis here is on the latter (Fig. 1). Motion on major faults structurally above the Rattlesnake Creek terrane was Middle Jurassic (or earlier in the eastern Klamaths), whereas movement of faults farther down section (more westerly) was Late Jurassic (Wright and Fahan, 1988; Harper and others, 1993).

Displacement on the Siskiyou fault placed the Central Metamorphic terrane ≥25 km over the Stuart Fork and North Fork units (Davis and others, 1965; Goodge, 1990). Movement postdated deposition of Early to Middle Jurassic chert in the North Fork unit and predated emplacement of the 159-Ma Russian Peak pluton (Table 1, c1; Fig. 2).

Displacement of the Stuart Fork terrane over the Sawyers Bar terrane on the Soap Creek Ridge thrust (Hotz, 1977) exceeds 35 km (Coleman and others, 1988). Movement along this fault predated cooling of the Vesa

Bluffs pluton at 165 Ma (Table 1, c9) and postdated Middle Jurassic chert deposition (Mortimer, 1984) in the footwall (Fig. 2). These constraints, and those for the Siskiyou fault, apply rigorously only to the central Klamaths between about 41°N and 42°N.

Plutons of the Western Hayfork terrane were crystallizing while that unit was thrust beneath the Sawyers Bar terrane along the Wilson Point fault (Wright and Fahan, 1988), effectively constraining the age of faulting to ~170 Ma (Fig. 2); displacement is at least 20 km.

The Salt Creek fault accommodated ~60 km of displacement of the Western Hayfork over the Rattlesnake Creek terrane (Coleman and others, 1988), and postdated crystallization of the 169 Ma Chanchelulla Peak pluton (Table 1, h4; Wright and Fahan, 1988). The cessation of faulting is not unambiguously constrained, but may have been prior to crystallization of the Denny Complex at 167 Ma (Fig 4c; Wright and Fahan, 1988). These constraints, and those for the Wilson Point fault, apply only to the Klamaths south of about 41°N.

The Rattlesnake Creek terrane (including the Preston Peak ophiolite) lies structurally above the Condrey Mountain terrane along the Condrey fault, and on top of the Josephine ophiolite and Galice Formation along the Orleans fault. If the Orleans and Condrey faults are the same structure, modeling of gravity data indicates that the Orleans/Condrey fault dips 10–25° east and has ~100 km of displacement (Jachens and others, 1986). Displacement on the Orleans fault was toward the WNW, occurred prior to crystallization of the 150-Ma Summit Valley pluton (Harper and others, 1990), and must postdate the Kimmeridgian Galice Formation in the footwall. The Condrey fault places high-temperature rocks of the Rattlesnake Creek terrane over low-temperature rocks of the Condrey Mountain terrane. The fault zone preserves a ~1-km-thick inverted metamorphic gradient from greenschist upward into partially melted amphibolite (Medaris, 1966; Barrows, 1969; Burton, 1982). Gravity measurements suggest that the Condrey fault detached the Wooley Creek, Slinkard, and Vesa Bluffs plutons (Barnes, 1982; Barnes and others, 1986; Jachens and others, 1986). Syn-thrusting leucosomes formed at the base of the Rattlesnake Creek terrane during intrusion of the Slinkard pluton; this suggests active faulting at 161 Ma (Saleeby, 1990). Gneissic amphibolite from within the Condrey fault zone yielded an Ar/Ar hornblende cooling age of 152±1 Ma, suggesting that amphibolite-facies metamorphism and coincident thrusting ended by that time (Harper and others, 1993). Widespread hornblende Ar/Ar and scattered mica Ar/Ar ages in the upper plate of the Condrey thrust suggest rapid cooling at ~150 Ma, whereas Rb/Sr and K/Ar ages indicate that the lower plate cooled through similar temperatures ~20 Ma later (Helper and others, 1989). Rapid refrigeration of the upper plate and prolonged cooling of the lower plate may be related to thrusting of the Condrey Mountain terrane beneath the Rattlesnake Creek terrane (Harper and others, 1993).

The Josephine ophiolite was thrust in a NNE direction over the still-active Rogue/Chetco arc on the Madstone thrust between 146 and 152 Ma (Harper and others, 1990, 1993).

Most of the aforementioned faults are demonstrably thrust faults that place higher pressure and temperature rocks over lower pressure and temperature assemblages. Some major faults in the Klamath Mountains, however, may have had normal-sense displacement for at least part of their history. In the Marble Mountains, the typical north-south structural grain of Klamath terranes is broken by an east-west trending contact between amphibolite-facies Rattlesnake Creek terrane to the north and greenschist-facies Sawyers Bar terrane to the south (Donato and others, 1982). We tentatively suggest that this structure, the Marble Mountains fault (Hacker and others, 1992), is a south-dipping normal fault. The Western Hayfork terrane, which is normally present as a thrust sheet between the Rattlesnake Creek and Sawyers Bar terranes, appears to have been excised along this structure; thus ~5 km of structural thickness may have been cut out. In addition to changes in rock type and metamorphic grade, the fault is marked by changes in foliation orientation and Ar/Ar cooling ages. Ar/Ar hornblende, biotite, and muscovite metamorphic ages north of the fault cluster tightly between 148 and 152 Ma (Figs. 2 and 4). South of the structure, Ar/Ar igneous ages range from 175 to 140 Ma, and resetting of Ar isotopes during metamorphism is not apparent. Foliation undergoes a marked change from steep ESE dips south of the fault to gentle and moderate southward or eastward dips to the north (Welsh, 1982; Donato, 1985; Ernst, 1987; Hacker, unpublished data). Rocks on both sides of the fault are intruded by greenschist-facies metatholeiitic dikes (Donato, 1985) that must postdate 150-Ma amphibolite-facies metamorphism. The Marble Mountains fault postdated 172 Ma dikes in the Rattlesnake Creek terrane (Table 1, b14) and predated intrusion of the 161-Ma Wooley Creek batholith (Table 1, c6). If the Western Hayfork terrane was excised along the fault, faulting must also postdate that 167–170 Ma period of magmatism (Fig. 2). The Marble Mountains fault may be exposed in more northerly parts of the Klamath Mountains too (Fig. 4c).

SISKIYOU AND NEVADAN OROGENIES

Lower Cretaceous sedimentary rocks overlying deformed Upper Jurassic rocks led Blackwelder (1914) to suggest that a "Nevadian" orogeny affected the Sierra Nevada and Klamath Mountains. The Nevadan orogeny in the Klamaths involved thrusting along the Madstone and Orleans faults (Harper and others, 1990), deformation of Galice Formation as young as Kimmeridgian, and widespread metamorphism (Donato, 1985; Hill, 1985). The minimum age of the Nevadan orogeny is ~130 Ma, based on undeformed Valanginian sedimentary rocks that overlie metamorphosed units (Hinds, 1934; Sliter and others, 1984; Blake and others, 1985). Hinds (1934) considered all Nevadan activity to postdate the Mariposa Formation in the Sierra Nevada. The Galice Formation, the Klamath equivalent of the Mariposa, is as young as Kimmeridgian (Pessagno and Blome, 1990); this would bracket the age of orogeny as ~155–130 Ma. When isotopic data were first collected (Lanphere and others, 1968), however, it became clear that plutons initially deemed part of the Nevadan orogeny (Hinds, 1934) were as old as Middle Jurassic. Lanphere and others thus pushed the age of the Nevadan orogeny back to Middle Jurassic. Harper and Wright (1984) initially bracketed the age of the Nevadan orogeny between 147 and 150 Ma on the basis of deformed dikes in the Galice Formation as young as 150 Ma, and undeformed plutons as old as 147 Ma. More recently, (Harper and others, 1993) extended the Nevadan orogeny to 135 Ma, based on cooling ages of deformed plutons and dikes.

There is also evidence of metamorphism and deformation in the Klamaths well before the Nevadan orogeny (Wright and Fahan, 1988). Coleman and others (1988) noted that greenschist to amphibolite-facies rocks stretching from the Soap Creek Ridge fault to the Orleans fault appear to be overprinted by aureoles of plutons such as the Wooley Creek, Vesa Bluffs, and Heather Lake, implying that a regional metamorphic event occurred prior to 167 Ma. They named this regional metamorphism the Siskiyou event. The Western Hayfork and Rattlesnake Creek terranes were both affected by Siskiyou metamorphism, thus their 168–170 Ma protolith ages (Table 1, b1–b7, b14) apparently constrain the Siskiyou event to 167–170 Ma. For this reason, K/Ar hornblende ages on amphibolite of ~150 Ma obtained by Lanphere and others (1968) (Table 1, e4–e41) were discounted by Coleman and others (1988) as too young. The large region of 150 Ma cooling ages reviewed in this paper (Table 1, e25–e57) indicate, however, that "Siskiyou" metamorphic rocks remained at amphibolite-facies conditions well into the Late Jurassic—about 10-20 m.y. after crystallization of the supposedly post-metamorphic Wooley Creek plutonic suite. These age relationships between plutons and regional metamorphism and the low to moderate metamorphic pressures (Burton, 1982; Chambers, 1983; Rawson, 1984; Barnes and others, 1986; Lieberman and Rice, 1986; Donato, 1989) substantiate the suggestion that the Siskiyou event occurred within an active magmatic arc (Coleman and others, 1988).

The Siskiyou metamorphic event can no longer be conveniently pigeonholed into a narrow time frame—the advectively supplied heat requisite for metamorphism was probably spatially and temporally variable, as befits igneous activity in an arc. For example, amphibolite-facies metamorphism probably began at 167 Ma around the Heather Lake pluton and perhaps as late as 161 Ma around the Wooley Creek pluton, but the area immediately north of both igneous bodies remained above greenschist facies temperatures until 150 Ma. South of the Salmon tectonic line (Fig. 4c), the Siskiyou event apparently was restricted to the time of Western Hayfork magmatism, or ~167–170 Ma (Wyld and Wright, 1988). North of the Salmon tectonic line, the Siskiyou event lasted longer due to the heat provided by numerous Middle and Late Jurassic plutons. Note that this north-south difference in the Siskiyou event may be due to the exposure of deeper structural levels in the north, rather than to any contrast in magmatic activity.

Thus, at this time, it seems appropriate to abandon attempts to date the "Nevadan" and "Siskiyou" orogenies as though they were distinct thermotectonic events that occurred synchronously throughout the mountain range, and to focus instead on characterizing the ages and other characteristics of the deformation, metamorphism, and volcanoplutonism in different areas. It seems most likely that the "ages" of the Siskiyou and Nevadan orogenies are spatially variable and related to areas of intense plutonism.

REVISED TECTONIC HISTORY

Although Davis and others (1978) cautioned against fitting Klamath terranes into a coherent plate tectonic setting, shortly thereafter Burchfiel and Davis (1981) suggested that the Eastern Hayfork unit formed in an accretionary wedge outboard of the Jura-Triassic volcanoplutonic arc in the eastern Klamaths. Wright (1981) added further the idea that the North Fork unit might represent fore-arc igneous crust and sediments. This tectonic setting has been modified slightly to include the Stuart Fork terrane as a somewhat older subduction complex (Goodge, 1990). Hacker and others (1993) proposed that the North Fork and Salmon River units together represent an immature magmatic arc.

Prior to Triassic time, radiolarians were deposited in the St Claire Creek unit and plagiogranite crystallized in the Salmon River unit or its ophiolitic basement (Sawyers Bar terrane). High-pressure metamorphism occurred in the Stuart Fork terrane at ~219 Ma, and contemporaneously, radiolarians were deposited in the Eastern Hayfork and St Claire Creek units. Melange formation in the Rattlesnake Creek terrane was followed by arc plutonism and volcanism that postdated Late Triassic limestone and predated 212 Ma plutons. The North Fork, Eastern Hayfork, and Western Hayfork units contain similar fossils and epiclastic rocks of similar provenance—a persuasive indication that they are not far traveled (Wright, 1982).

~200 Ma

At roughly 200 Ma (earliest Jurassic time), gabbroic plutons crystallized in the Salmon River and Rattlesnake Creek units coincident with radiolarian deposition in the Eastern Hayfork and St Claire Creek units. The presence of ~200 Ma plutons and associated volcanic rocks in the Rattlesnake Creek and Salmon River units raises the possibility that these now-separated units were once contiguous—or at least tectonically related. The 200-Ma plutons in the Rattlesnake Creek terrane intrude an older basement of serpentinite-matrix melange and volcaniclastic rocks. Coeval plutons in the Salmon River unit intrude diabase rather than melange or volcaniclastic rocks, but serpentinite and mafic volcanic rocks are abundant nearby. Moreover, a Permo-Triassic zircon age obtained from the Salmon River unit (Ando and others, 1983) demonstrates that basement rocks older than 200 Ma are present. If portions of the Rattlesnake Creek and Salmon River units represent a once-coherent, single, ~200 Ma arc, the presence of intervening Late Permian to Late Triassic Eastern Hayfork sedimentary rock mandates significant structural disruption. It is unclear how volcanic rocks of equivalent age in the Eastern Klamath terrane are related to either the Salmon River or Rattlesnake Creek units.

~170 Ma

At 177-169 Ma, the Western Hayfork arc formed; the basement of the Western Hayfork *sensu stricto* may have been the Rattlesnake Creek terrane (Wright and Fahan, 1988). Mafic igneous rocks of this age intrude the Eastern Hayfork, Condrey Mountain, and Rattlesnake Creek units, and may make up a large part of the Salmon River extrusive rocks. Moreover, the last phase of plutonism occurred in the eastern Klamath terrane at this time. The relationship between these three Jura-Triassic magmatic events is a conundrum, although the Middle Jurassic intrusions in the Eastern Klamath terrane do not have arc-like trace-element compositions (Renne and Scott, 1988). The Wilson Point fault was active at this time, and the Salt Creek, Soap Creek Ridge, and Siskiyou faults may have been moving as well.

~167–155 Ma

Rifting within the Rattlesnake Creek terrane led to formation of the Rogue/Chetco arc and the intra-arc Preston Peak and Josephine ophiolites over the interval 165–160 Ma (Harper and Wright, 1984; Wyld and Wright, 1988; Harper and others, 1990; Saleeby, 1990). Contemporaneous with this was emplacement of the Wooley Creek suite and dike intrusion in the Sawyers Bar terrane (Fig. 2). Large-scale NW-SE extension may have been accommodated by normal faults such as the Marble Mountains fault. The zone of magmatic extension is apparently bounded on the south by the Salmon tectonic line—a cryptic, poorly defined feature named by Irwin (1985a). Displacement on this feature should increase from zero at its eastern end to a maximum at its western end, explaining the puzzling nature of the eastern end of the feature noted by Irwin (Irwin, 1989). It is possible that many contractional faults such as Salt Creek, Soap Creek Ridge, Condrey, and Siskiyou faults may have been in motion during this same time frame.

Recorded igneous activity in the Josephine ophiolite ceased, and Galice flysch blanketed the Western Klamath terrane from ~157–150 Ma, during continued activity in the Rogue/Chetco arc. Farther east in the central Klamaths, magmatism (Grayback, Thompson Ridge, Ashland plutons) shifted northward from the region encompassed by the Wooley Creek suite, but covered the same east-west extent.

~150 Ma

Widespread contraction occurred again from about 155 to 146 Ma (Harper and Wright, 1984; Harper and others, 1990). The still active Rogue/Chetco arc was thrust beneath the Josephine ophiolite along the Madstone thrust. The Josephine ophiolite, Galice Formation and Condrey Mountain terrane were telescoped beneath the Rattlesnake Creek along the Condrey fault (Harper and Wright, 1984). The widespread ~150 Ma cooling event may be related to the onset of this thrusting (Harper and others, 1993). Recognition of cooling in the Western Klamath terrane as well as in the Rattlesnake Creek terrane at this time suggests that the Condrey Mountain terrane may have been subducted beneath the Western Klamath terrane.

Cretaceous

Volumetrically minor arc magmatism and minor deformation lasted in the Klamath orogen until 135 Ma, and was followed by exhumation and post-orogenic sedimentation

(Harper and Wright, 1984; Harper and others, 1993).

CONCLUSIONS

Abundant geochronologic information now permits improved recognition of the spatial and temporal ranges of magmatic, metamorphic and deformational events associated with the formation of continental crust in the Klamath Mountains. Widespread magmatism began at ~200 Ma. Two subparallel volcanoplutonic arcs were active around 170 Ma, and although probably related to one another, they are presently separated by an intervening and older accretionary wedge. From 167-159 Ma, alternating extension and contraction occurred along a NW-SE corridor in the northern Klamaths. Still to be determined are details regarding the relation between contraction and extension and the ages and senses of motion on major faults. This same area underwent pronounced cooling at ~150 Ma, perhaps as a result of deeper-level subduction.

The Siskiyou and Nevadan orogenies can no longer be assigned to specific, narrow time windows and may have outlived their usefulness as currently defined. Geochronologic data are now numerous enough to warrant defining the ages and characteristics of specific plutons, deformation fabrics, and metamorphic minerals in individual areas. Assumptions that metamorphism, deformation, and plutonism occur throughout the Klamath orogen within specific time ranges may no longer be valid.

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Table 1. Radiometric ages.

Unit		Age	Intrudes	Reference [original sample number]
Figure 4A				
a1	Saddle Gulch pluton	h 189±6	RC	M.A. Lanphere in Irwin (1985a) [?]
a2	Bear Wallow pluton	Z 193±?	RC	Wright (1981) [BWM]
a3	White Rock pluton (CA)	Z 193±?	RC	Wright (1981) [WR-1]
a4	Pole Corral Cr. pluton	Z 198±?	RC	Wright (1981) [PCCK]
a5	Beegum pluton	Z 207±?	RC	Wright (1981) [Beegum]
a6	Rat Trap Ridge pluton	Z 204±?	RC	Wright (1981) [RT1]
a7	"Somes Bar" pluton	Z 208.1±? 207.3±?	RC	Gray (1985) [OMG-1, DOMG-2]
a7	"	h 191.5±4.5	RC	Gray (1985) [OMG-1]
a8	"Somes Bar" pluton	Z 193.7±?	RC	Gray (1985) [SB-7M?]
a9	"Horse Mtn" pluton	H 200.4±1.4	SR	Hacker and others (1993) [Yr13]
a10	LR gabbro block	H 192±9		Ohr (1987) [LR 10]
a11	LR gabbro block	H 190±9		Ohr (1987) [LR 171]
a12	LR gabbro block	H 191±4		Ohr (1987) [LR 871]
a13	LR gabbro block	H 196±3		Ohr (1987) [LR 1273]
a14	LR gabbro block	H 199±4		Ohr (1987) [LR 1573]
a15	LR volcaniclastic	H 191±5		Ohr (1987) [LR 15]
a16	LR plagiogranite	Z ~198		Ohr (1987) [LR 41]
a17	PP amphibolite	h 193±7		Gorman (1985) [2KL-338]
a18	PP amphibolite	h 190±14		Gorman (1985) [2KL-353]
a19	Rum Creek metagabbro	h 182±12		H.J.B. Dick in Garcia (1982) [?]
a20	metadiabase in Chetco	h 197±5		Dick (1976) [J115-1]
a21	Chetco metagabbro	h 191±7		Dick (1976) [J103-19]
a22	Chetco metagabbro	h 202±17		Dick (1976) [J92-4]
a23	blueschist chert block	w 185±9		Irwin and others (1985b) [?]
Figure 4B				
b1	Walker Point pluton	Z ~169	WH	Wright and Fahan (1988) [WP-1]
b2	Chanchelulla Pk pluton	Z ~169	WH EH	Wright and Fahan (1988) [CP-2]
b3	Basin Gulch pluton	Z ~170	WH	Wright and Fahan (1988) [BG-1]
b4	Price Creek pluton	Z ~170	WH	Wright and Fahan (1988) [89-1]
b5	Ironside Mtn batholith	Z 170±1	WH	Wright and Fahan (1988) [IR-1, 2]
b5	"	b 171±5 169±5	WH	Lanphere and others (1968) [65CLe 29, 65CLe 33]
b6	Pigeon Pt pluton	h 169±1.2 171±1.8	WH	Wright and Fahan (1988) [1058-184, 1058-188]
b6	Pigeon Pt aureole	h 168±3.4	WH	Wright and Fahan (1988) [1058-27]
b7	WH volcaniclastics	h 168±1.9 171±2.0 177±2.8		Wright and Fahan (1988) [16-109, 1058-24, 1058-167]
b8	Denny complex	Z ~167	EH	Wright and Fahan (1988) [DC-1]
b9	Forks of Salmon pluton	Z ~174	EH	Wright and Fahan (1988) [FS-3]
b9	"	h 171±5	EH	Lanphere and others (1968) [65CLe 17]

Table 1 continued.

b10	CMS metagranodiorite	Z 170±1	CMS	Saleeby and Harper (1993) [?]
b11	CMS orthogneiss	Z 172±2 (n=2)	CMS	Helper and others (1989) [?]
b11	"	Rb/Sr 136-165 (n=3)	CMS	Helper and others (1989) [?]
b11	"	m 141-152 (n=5)	CMS	Helper and others (1989) [?]
b12	CMS metavolcanic	Z 170±1	CMS	Helper and others (1989) [?]
b13	Hogback Mtn plutons	p ~169±5 (n=4)	EK	Renne and Scott (1988) [HMS]
b14	"China Pk" dike complex	Z 172±2		J.B. Saleeby in Hill (1985) [?]
b15	Salmon River dike	H 173.2±3.7	SR	B.R. Hacker (unpub. data) [220M]
b16	Salmon River dike	H 174.6±1.3	SR	B.R. Hacker (unpub. data) [190M]
Figure 4C				
c1	Heather Lake pluton	H 167.0±0.6	RC? EH SR	B.R. Hacker (unpub. data) [Yr172]
c2	Russian Pk pluton	Z ~159	NF SR SF	Wright and Fahan (1988) [RP-3, RP-300]
c2	"	H 152.1±0.5	NF SR SF	B.R. Hacker (unpub. data) [542M]
c2	"	b 144±2 147±2	NF SR SF	Evernden and Kistler (1970) [KA955, KA956]
c3	Slinkard pluton	b 151±5	RC	Lanphere and others (1968) [66CLe 25]
c3	"	h 157±5	RC	Lanphere and others (1968) [66CLe 25]
c3	"	Z 161^{+4}_{-2}	RC	Barnes and others (Barnes and others, 1986) [II,III,IV]
c3	*"*	*FTz 91±10*	*RC*	*Lewison (1984) [SL-10]*
c4	Slinkard(?) pluton	H 156.2±0.7	RC	Saleeby and Harper (Saleeby and Harper, 1993) [?]
c4	"	Z 160±2	RC	Saleeby and Harper (Saleeby and Harper, 1993) [?]
c5	RC leucosome	Z 150-162		Saleeby and Harper (1993) [?]
c6	Wooley Creek pluton	h 156±5	WH EH RC	Lanphere and others (1968) [66CLe 21]
c6	"	b 158±5 158±5	WH EH RC	Lanphere and others (1968) [66CLe 20, 66CLe 21]
c6	"	Z 161^{+4}_{-2}	WH EH RC	Barnes and others (Barnes and others, 1986) [V,VI,VIII]
c6	"	Z ≥160	WH EH RC	Wright and Fahan (1988) [WC-2]
c6	*"*	*FTz 91±8, 94±7*	*WH EH RC*	*Lewison (1984) [WC1, WC3z]*
c6	*"*	*FTa 22.2, 20.4±3*	*WH EH RC*	*Lewison (1984) [WC2, WC3a]*
c7	English Peak pluton	Z ≥164	EH NF SR	Wright and Fahan (1988) [EP-1]
c7	"	b 159±5	EH NF SR	Lanphere and others (1968) [66CLe 18]
c7	"	h 161±5	EH NF SR	Lanphere and others (1968) [66CLe 18]
c7	"	H 154.5±1.4	EH NF SR	M.M. Donato and C.G. Barnes (pers. comm., 1992) [EP176B]
c7	"	B 154.3±0.8	EH NF SR	B.R. Hacker (unpub. data) [365M]
c7	"	H 153.3±0.3	EH NF SR	B.R. Hacker (unpub. data) [365M]
c7	"	H 160.4±1.4	EH NF SR	B.R. Hacker (unpub. data) [EP141]
c8	English Peak aureole	H 162.6±1.4	EH NF SR	B.R. Hacker (unpub. data) [506M]
c9	Vesa Bluffs pluton	H 165.1±0.4	RC EH NF SR	B.R. Hacker (unpub. data) [FPV25]
c9	"	M 148.2±0.3	RC EH NF SR	B.R. Hacker (unpub. data) [FPV12]
c9	"	h 164±4	RC EH NF SR	Lanphere and others (1968) [CM 29-60]
c9	"	b 150±5	RC EH NF SR	Lanphere and others (1968) [CM 29-60]
c10	DE plagiogranite	Z 164±1		Wright and Wyld (1986) [DE-1, -2, -3]
c11	DE gabbroic clast	H 160.5±3.0		Harper and others (1993) [OB-1]
c12	DE gabbroic clast	H 164.5±5.2		Harper and others (1993) [OB-4]
c13	JO plagiogranite	Z 162±1		Harper and others (1993) [A88z] Saleeby and others (1982)
c14	JO gabbro	H 165.3±3.5		Harper and others (1993) [KH-6]
c15	Rogue tuff-breccia	Z 157±1.5		Saleeby (1984) Harper and others (1993) [?]
c16	metagabbro in Rogue	h 159±4		Dick (1976) [MGBSCS]
c17	Rum Creek metagabbro	Z 166±2?		Saleeby (1984) Saleeby (1990) [?]
c18	Chetco complex	Z 155-160 (n=5)		J.D. Yule (pers. comm., 1992) [?]
c19	Chetco gabbro	h 161±3		Dick (1976) [J69-3]
c20	Chetco gabbro	h 158±4		Dick (1976) [J94-8]
c21	Preston Peak dike	Z 164±1	RC	Saleeby and others (1982) Saleeby (1990) [PP322]
c22	Preston Peak aureole	h 165±3		Saleeby and others (1982) [PP580]
c23	MC amphibolite	H 162.0±1.4		M.M. Donato (pers. comm., 1992) [MC-154C-86]
c24	dike cutting NF	H 163.8±1.5	NF	Hacker and others (1993) [Yr84]
c25	dike cutting NF	H 164.8±2.2	NF	B.R. Hacker (unpub. data) [601M]
c26	dike cutting SR	H 158.7±5.0	SR	B.R. Hacker (unpub. data) [604M]
c27	dike cutting JO	h 163±5	JO	Dick (1976) [J71-10]
c28	dike cutting JO	h 158±3	JO	Dick (1976) [J47-h]

Table 1 continued.

c29	dike cutting Rogue	h 158±2	R	Dick (1976) [J63-1]
c30	dike cutting Rogue	h 163±5	R	Dick (1976) [J57-6]
c31	dike cutting Rogue	h 157±2	R	Dick (1976) [J57-19]
c31	"	*b 125±2*	*R*	*Dick (1976) [J57-19]*
Figure 4D				
d1	*Ashland pluton*	*h 150±5*	*RC EH NF SR*	*Lanphere and others (1968) [CM77-63]*
d1	"	*b 151±5 136±4*	*RC EH NF SR*	*Lanphere and others (1968) [CM77-63, 26-63]*
d1	"	*h 170±5 164±5*	*RC EH NF SR*	*Hotz (1971) [46?]*
d1	"	*b 147±4*	*RC EH NF SR*	*Hotz (1971) [46?]*
d1	"	h 155±?	RC EH NF SR	P.R. Renne (pers. comm., 1992) [?]
d1	"	b 155±?	RC EH NF SR	P.R. Renne (pers. comm., 1992) [?]
d1	"	H 152.2±1.2	RC EH NF SR	M.M. Donato and C.G. Barnes (pers. comm., 1992) [AP48]
d2	Thompson Ridge pluton	H 153.2±1.2	RC	B.R. Hacker (unpub. data) [TR4]
d2	"	H 153.0±1.0	RC	B.R. Hacker (unpub. data) [TR16]
d3	Grayback pluton	H 157.3±1.4	RC AG	M.M. Donato and C.G. Barnes (pers. comm., 1992) [GM24]
d3	"	*b 141±4*	*RC AG*	*Hotz (1971) [52]*
d3	"	h 153±5 153±5	*RC AG*	Hotz (1971) [51, 52]
d4	Russian Pk aureole	H 154.0±0.8	NF SR	B.R. Hacker (unpub. data) [584M]
d5	dike cutting NF	H 154.2±0.7	NF	Hacker and others (1993) [Yr19]
d6	dike cutting SF	H 155.9±1.6	SF	Hacker and others (1993) [Yr82]
d7	dike cutting EH	H 152.7±0.9	EH	Hacker and others (1993) [Yr61]
d8	dike cutting SR	H 155.5±0.7	SR	Hacker and others (1993) [448M]
d9	dike cutting JO	h 156±3	JO	Dick (1976) [J123-2]
d10	dike cutting JO	h 156±12	JO	Dick (1976) [J137-13]
d11	dike cutting JO	h 154±3	JO	Dick (1976) [J41-d]
d12	dike cutting Rogue	h 154±2	R	Dick (1976) [J61-9]
d13	Rum Creek metagabbro	Z 155±2		Saleeby (1984) [?]
d14	Chetco gabbro	h 154±5		Hotz (1971) [56]
d15	Chetco gabbro(?)	h 155±5 155±5		Hotz (1971) [?]
d16	Chetco gabbro	h 154±5		Hotz (1971) [57]
d17	Briggs Cr amphibolite	H 156.3±0.9		M.M. Donato (pers. comm., 1992) [216-GA-76]
d18	MC amphibolite	h 154±11		Kays and others (1977) [T-112-70]
d19	MC amphibolite	H 154.2±2.1		M.M. Donato (pers. comm., 1992)
d20	MC amphibolite	H 153.3±0.8		M.M. Donato (pers. comm., 1992) [MC-41A-85]
d21	MC amphibolite	H 155.0±9.2		M.M. Donato (pers. comm., 1992) [MC-81A-85]
Figure 4E				
e1	Bear Mountain pluton	Z 149-153	RC PP	Saleeby and others (1982) [PP567, PP572B]
e1	"	b 146±1	RC PP	Snoke and others (1981)
e2	Ammon Ridge pluton	Z 147-151	G	Wright and Fahan (1988) [AR-1]
e3	Glenn Creek pluton	Z 147-151	G	Wright and Fahan (1988) [GC-1]
e4	Summit Valley pluton	H 144.1±0.4	G RC	Harper and others (1993) [SV-1h]
e4	"	Z 150±1	G RC	Harper and others (1993) [4]
e4	Summit V. pluton dike	H 149±4	G RC	Ohr (1987) [LR 82]
e4	"	H 148±1	G RC	Ohr (1987) [D-LRO]
e5	Buckskin Peak pluton	B 148.4±1.2 149.7±1.6	JO	Harper and others (1993) [66]
e5	"	H 148.6±1.5	JO	Harper and others (1993) [66]
e6	sill cutting G	H 150.5±2.0	G	Harper and others (1993) [D24]
e7	sill cutting G	H 146.2±1.0	G	Harper and others (1993) [D26]
e8	sill cutting G	Z 150±2	G	Saleeby and others (1982) [PP582]
e9	dike cutting G	h 151±3	G	Gray (1985) [LDB-9]
e10	dike cutting JO	H 148.9±2.6	JO	Harper and others (1993) [J98-12]
e10	"	*h 146±3*	*JO*	*Dick (1976) [J98-12]*
e11	dike cutting JO	H 148.0±3.0	JO	Harper and others (1993) [J97-6]
e11	"	*h 151±3*	*JO*	*Dick (1976) [J97-6]*
e12	dike cutting JO	h 147±6	JO	Saleeby and others (1982) [K20]
e13	dike cutting JO	Z 151±3	JO	Saleeby and others (1982) [C23]
e14	dike cutting JO	h 150±3	JO	Dick (1976) [J37-H]
e15	dike cutting JO	h 148±2	JO	Dick (1976) [J39-B]
e16	dike cutting JO	h 150±3	JO	Dick (1976) [J45-b]
e17	dike cutting JO	h 148±2	JO	Dick (1976) [J49-j]

Table 1 continued.

e18 dike cutting JO	h 146±2	JO	Dick (1976) [J51-o]
e19 dike cutting Rogue	h 149±2	JO	Dick (1976) [J61-3]
e20 dike cutting Rogue	h 147±3	JO	Dick (1976) [J63-7]
e21 dike cutting Rogue	h 151±2	JO	Dick (1976) [GFCJ]
e21 "	*b 124±2*	*JO*	*Dick (1976) [GFCJ]*
e22 dike cutting Rogue	Z 151±2?	R	Saleeby (1984) Saleeby (1990) [?]
e23 dike cutting SR	H 149.3±1.7	SR	Hacker and others (1993) [Yr2]
e24 dikes cutting EK	w 149±6 (n=6)	EK	Brouxel and others (1989)
e25 JO sole pegmatite	Z 151±1		Harper and others (1993) [5]
e25 "	M 146–150		Harper and others (1993) [J113-7]
e25 "	*m 148±3*		*Dick (1976) [J113-7]*
e26 JO sole metagabbro	H 150.5±1.8		Harper and others (1993) [J89-1]
e26 "	*h 154±3*		*Dick (1976) [J89-1]*
e27 JO sole amphibolite	H 152.8±1.7		Harper and others (1993) [7-15-2k]
e28 JO sole amphibolite	H 151.9±1.8		Harper and others (1993) [7-16-10b]
e29 JO sole pegmatite	m 148±3		Dick (1976) [J82-3]
e30 JO sole amphibolite	h 152±2		Dick (1976) [J87-6]
e31 JO sole amphibolite	w 148±2		Dick (1976) [J113-8]
e32 Chetco metagabbro	H 151.4±4.4		Harper and others (1993) [LCHB]
e32 "	*h 156±3*		*Dick (1976) [LCHB]*
e33 Pearsoll Pk metagranite	m 151±4.5		P.H. Hotz in Ramp (1984) [?]
e34 RC amphibolite	H 152±1		Saleeby and Harper (1993) [CMT-4a]
e35 RC amphibolite	h 148±3		Kays and others (1977) [RdMtAg]
e36 RC amphibolite	H 153.0±2.2		M.M. Donato (pers. comm., 1992) [SV-1-85]
e37 RC amphibolite	H 146.9±2.1		M.M. Donato (pers. comm., 1992) [233-83]
e38 RC amphibolite	H 150.1±4.6		M.M. Donato (pers. comm., 1992) [GF-1-85]
e39 RC amphibolite	H 154.1±3.1		M.M. Donato (pers. comm., 1992) [MMD183-83]
e40 RC amphibolite	h 152±5		Lanphere and others (1968) [CM 3-65]
e41 RC amphibolite	h 150±5		Lanphere and others (1968) [CM 9-65]
e42 RC amphibolite	h 152.9±3.2		Gray (1985) [BM-120?]
e43 RC amphibolite	b 148±5		Welsh (1982)
e44 RC amphibolite	B 150.4±0.4		B.R. Hacker (unpub. data) [Yr131]
e45 RC amphibolite	B 148.8±2.6		B.R. Hacker (unpub. data) [Yr161]
e46 RC amphibolite	M 150.3±0.3		B.R. Hacker (unpub. data) [Yr179]
e47 RC amphibolite	H 147.8±2.3		B.R. Hacker (unpub. data) [Yr121]
e48 RC amphibolite	H 152.5±2.5		B.R. Hacker (unpub. data) [Yr165]
e49 RC amphibolite	H 152.1±4.7		B.R. Hacker (unpub. data) [Yr166]
e50 RC amphibolite	H 149.9±0.4		B.R. Hacker (unpub. data) [Yr151]
e51 RC amphibolite	H 150.3±0.6		B.R. Hacker (unpub. data) [Yr164]
e52 RC amphibolite	H 155–145		B.R. Hacker (unpub. data) [Yr157]
e53 RC amphibolite	H 150.8±0.6		B.R. Hacker (unpub. data) [Yr120]
e54 RC amphibolite	B 149.9±0.2		B.R. Hacker (unpub. data) [Yr154]
e55 RC amphibolite	h 146±?		Welsh (1982)
e56 RC amphibolite	h 148±?		Welsh (1982)
e57 MC amphibolite	B 147.8±0.7		M.M. Donato (pers. comm., 1992) [MC13B-87]
Figure 4F			
f1 White Rock pluton (OR)	b 141±4	MC G	Hotz (1971) [54]
f2 Grants Pass pluton	h 139±4	G AG	Hotz (1971) [53]
f2 "	Z 139±2	G AG	Harper and others (1993) [1]
f3 Gold Hill pluton	b 145±4	AG	Hotz (1971) [49]
f3 "	h 142±4	AG	Hotz (1971) [49]
f4 Jacksonville pluton	b 141±4	AG	Hotz (1971) [48]
f4 "	h 137±4	AG	Hotz (1971) [48]
f5 Bear Peak pluton	h 142±?	RC PP(?)	C.G. Barnes (pers. comm., 1992) [?]
f6 Coon Mtn complex	Z 142±2	JO	Saleeby and others (1982) [J84z]
f6 "	Z 145+1/-2	JO	Harper and others (1993) [2]
f6 "	K 134.9±0.9	JO	Harper and others (1993) [J84z]
f7 Pony Peak pluton	Z 146±3	WH RC	Harper and others (1993) [3]
f7 "	H 148.5±2.0	WH RC	Harper and others (1993) [K85-53]
f7 "	H 147.9±0.1	WH RC	Harper and others (1993) [K85-26]
f8 Yellow Butte pluton	h 138±4	EK	Hotz (1971) [?]
f8 "	b 137±4	EK	Hotz (1971) [?]
f9 Craggy Peak pluton	b 136±4	EK	Lanphere and others (1968) [65CLe 6]
f10 Deadman Peak pluton	Z 141–145	CMT SF	Wright and Fahan (1988) [DP-1]
f10 "	*z 158±6–167±6*	*CMT SF*	*Wright and Fahan (1988) [DP-1]*
f10 "	b 133±?	CMT SF	Evernden and Kistler (1970) [KA957]

Table 1 continued.

f10 "	H 136±2	CMT SF	M.M. Donato and C.G. Barnes (pers. comm., 1992) [DP353]
f11 Caribou Mtn pluton	b 136±?	CMT	Davis and others (1965) [?]
f11 "	H 138±2	CMT	M.M. Donato and C.G. Barnes (pers. comm., 1992) [FPC10]
f12 Sugar Pine pluton	b 139±4	EK	Lanphere and others (1968) [65CLe 8]
f12 "	h 137±4	EK	Lanphere and others (1968) [65CLe 8]
f13 Horseshoe Lake pluton	b 133±1	CMT	Evernden and Kistler (1970) [KA828]
f14 Canyon Creek pluton	*z 159±8 169±9*	*CMT*	*Wright and Fahan (1988) [CC-1]*
f14 "	Z 141-145	CMT SF	Wright and Fahan (1988) [CC-1]
f15 East Fork pluton	h 149±4	NF CMT	M.A. Lanphere in Irwin (1985a) [?]
f15 "	*b 164±5*	*NF CMT*	*M.A. Lanphere in Irwin (1985a) [?]*
f16 Shasta Bally batholith	h 133±4 131±4	EK	Lanphere and others (1968) [65CLe 19, A-5]
f16 "	b 130±4 134±4 135±4	EK	Lanphere and others (1968) [65CLe 1, A-5, "Shasta Bally"]
f16 "	Z 136±2	EK	Lanphere and Jones (1978)
f17 dike cutting NF	h 134±2.1	NF	Wright and Fahan (1988) [1058-158]
f18 dike cutting WH	h 134±1.4	WH	Wright and Fahan (1988) [RCT-0]
f19 dike cutting CMT	h 136±1.5	CMT	Wright and Fahan (1988) [1058-156]
f20 dike cutting EH	h 141±2.0	EH	Wright and Fahan (1988) [1058-86]
f21 dike cutting EH	h 139±1.9	EH	Wright and Fahan (1988) [1058-127]
f22 dike cutting SR	H 142.6±1.7	SR	Hacker and others (1993) [Yr45]
f23 dike cutting NF	H 140.5±1.6	NF	Hacker and others (1993) [Yr52]
f24 MC amphibolite	H 145±7		Donato (1991) [152]
f25 MC amphibolite	H 145±2		Donato (1991) [158]
f26 MC amphibolite	H 145.4±7.3		M.M. Donato (pers. comm., 1992) [MC152-86]
f27 MC amphibolite	H 144.7±2.1		M.M. Donato (pers. comm., 1992) [MC148-80]
f28 MC amphibolite	h 133±3		Kays and others (1977) [T-42-68]
f29 upper CMS	Rb/Sr 134–139 (n=6)		Helper and others (1989) [?]
f29 "	m 135–143 (n=6)		Helper and others (1989) [?]
f30 CMS muscovite schist	m 144±4		Lanphere and others (1968) [CM 120-63]
Ages of Uncertain Significance			
1 dike cutting JO	*k 25±0.5*	*JO*	*Dick (1976) [J123-5]*
2 dike cutting JO	*h 85±1*	*JO*	*Dick (1976) [J52-i]*
3 RC metadacite	*h 102±8*		*Welsh (1982)*
4 RC amphibolite	*h 118±8*		*Welsh (1982)*
5 MC amphibolite	*H 119.6±5.5*		*M.M. Donato (pers. comm., 1992) [MC-126-85]*
6 MC amphibolite	*H 125.4±2.7*		*M.M. Donato (pers. comm., 1992) [MC-157-86]*
7 lower CMS	*Rb/Sr 125-132 (n=5)*		*Helper and others (1989)?]*
7 "	*m 125-134 (n=15)*		*Helper and others (1989)?]*
8 Bear Mountain pluton	*h 129±4*	*RC PP*	*Snoke and others (1981)*
9 dike cutting JO	*h 130±8*	*JO*	*Dick (1976) [J125-1]*
10 RC amphibolite	*h 131±8*		*Kays and others (1977) [KTA-14-71]*
11 JO sole amphibolite	*h 138±5*		*Dick (1976) [J82-7]*
12 "Somes Bar" pluton	*h 142.2±5.8*	*RC*	*Gray (1985) [KR-6]*
13 Chetco quartz diorite	*h 143±4*		*Hotz (1971) [58]*
14 dike cutting JO	*h 171±3*	*JO*	*Dick (1976) [J39-A]*
15 dike cutting JO	*h 171±3*	*JO*	*Dick (1976) [J119-2]*
16 dike cutting JO	*b 91±6*		*Dick (1976) [J119-2]*
17 Castle Crags	*b 162±5 167±5 132±4*	*EK*	*Lanphere and others (1968) [65CLe 1, 65CLe 2, 65CLe 4]*
18 Castle Crags	*h 229±7 175±5*	*EK*	*Lanphere and others (1968) [65CLe 1, 65CLe 4]*
19 Chetco metadiabase	*h 280±15*		*Dick (1976) [J90-7]*
20 Chetco(?) phyllonite	*w 236±5 282±6*		*Dick (1976) [J95-3]*

Quoted uncertainties are ±1σ, except for Pb/U ages, which are ±2σ. Multiple analyses of the same sample or pluton have the same number, "Intrudes" indicates the host rock of plutons, dikes and sills. Italicized ages are not shown in Figure 4.

Z: Pb/U zircon; z: Pb/Pb zircon; h: K/Ar hornblende; b: K/Ar biotite; k: K/Ar K-feldspar; p: K/Ar plagioclase; K: $^{40}Ar/^{39}Ar$ K-feldspar; M: $^{40}Ar/^{39}Ar$ muscovite; H: $^{40}Ar/^{39}Ar$ hornblende; B: $^{40}Ar/^{39}Ar$ biotite; FTz: fission-track zircon; FTa: fission-track apatite.

AG: Applegate terrane; CMS: Condrey Mountain terrane; CMT: central Metamorphic terrane; DE: Devils Elbow remnant of Josephine ophiolite; EH: Eastern Hayfork unit; EK: Eastern Klamath terrane; G: Galice Formation; JO: Josephine ophiolite; LR: Lems Ridge olistostrome; MC: May Creek terrane; NF: North Fork unit; RC: Rattlesnake Creek terrane; SF: Stuart Fork terrane; SR: Salmon River unit; WH: Western Hayfork terrane.

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