TECTONICS, VOL. 14, NO. 3, PAGES 677-703, JUNE 1995

Timescales of orogeny: Jurassic construction of the Klamath Mountains

Bradley R. Hacker,[1] Mary M. Donato,[2] Calvin G. Barnes,[3] M. O. McWilliams,[1] and W. G. Ernst[1]

Abstract. Classical interpretations of orogeny were based on relatively imprecise biostratigraphic and isotopic age determinations that necessitated grouping apparently related features that may in reality have been greatly diachronous. Isotopic age techniques now have the precision required to resolve the timing of orogenic events on a scale much smaller than that of entire mountain belts. Forty–five new $^{40}Ar/^{39}Ar$ ages from the Klamath Mountains illuminate the deformation, metamorphism, magmatism, and sedimentation involved in the Jurassic construction of that orogen, leading to a new level of understanding regarding how preserved orogenic features relate to ancient plate tectonic processes. The new geochronologic relationships show that many Jurassic units of the Klamath Mountains had 200 Ma or older volcanoplutonic basement. Subsequent formation of a large ~170 Ma arc was followed by contractional collapse of the arc. Collision with a spreading ridge may have led to large-scale NW–SE extension in the central and northern Klamaths from 167 to ~155 Ma, coincident with the crystallization of voluminous plutonic and volcanic suites. Marked cooling of a large region of the central Klamath Mountains to below ~350°C at ~150 Ma may have occurred as the igneous belt was extinguished by subduction of colder material at deeper structural levels. These data demonstrate that the Klamath Mountains—and perhaps other similar orogens—were constructed during areally and temporally variant episodes of contraction, extension, and magmatism that do not fit classical definitions of orogeny.

Introduction

Spatial and temporal variations in orogenic features are generally complex because of the wide range of plate interactions and the heterogeneity and anisotropy inherent in lithospheric plates. In spite of the recognized complexity of modern orogens, there has been a tendency to simplify descriptions and evaluations of orogenies. In large part, this simplification has been necessary because isotopic and fossil ages have been imprecise and/or scarce. Isotopic ages are becoming ever more precise and abundant, permitting reevaluation of classical ideas regarding orogenesis.

This paper reconsiders the Jurassic orogenies that built the Klamath Mountains and northern Sierra Nevada of California and Oregon in light of forty five new $^{40}Ar/^{39}Ar$ ages. Three fundamental issues about orogeny in general, and the Klamath Mountains in particular, are addressed: (1) What do orogenic features and their ages tell us about the relations among magmatism, deformation, sedimentation, and metamorphism? (2) What evidence do orogenic features provide for deciphering plate interactions? (3) Are current concepts of orogeny appropriate for resolving the plate tectonic history of convergence zones? The growing abundance and precision of isotopic ages and the detail of geologic mapping make the Klamath Mountains an excellent place to conduct such an analysis, which may serve as a model of mountain-building processes in other orogens built from predominantly oceanic material.

The classic interpretation of Klamath-Sierran mountain building is that the Jurassic Siskiyou and Nevadan orogenies were relatively short events with differentiable deformation, magmatism, sedimentation, and metamorphism. On the contrary, we show that mountain building was spatially and temporally variable, as befits the paleotectonic setting of the Klamath Mountains-Sierra Nevada orogen: an intraoceanic to continental transition where much oceanic lithosphere was subducted beneath accretionary complexes and arc volcanoes.

Nevadan Orogeny

Early geologists [Whitney, 1879; Lawson, 1893] who worked in the Sierra Nevada and Klamath Mountains recognized that undeformed Lower Cretaceous sedimentary rocks unconformably overlying deformed Upper Jurassic Mariposa and Galice Formations indicate that there was a Late Jurassic to Early Cretaceous orogeny. This "Nevadian" orogeny [*Blackwelder,* 1914] was broadly envisioned to have been responsible for much of the deformation and plutonism throughout the orogen. The oldest overlying Lower Cretaceous rocks were subsequently found to be Valanginian [*Hinds,* 1934; *Sliter et al.,* 1984; *Blake et al.,* 1985] and the deformed Galice and Mariposa Formations were dated as Oxfordian–Kimmeridgian [*Taliaferro,* 1942; *Pessagno and Blome,* 1990], bracketing the age of the Nevadan orogeny to between 155 and 130 Ma. But, when isotopic ages were first measured in the

---

[1] Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305-2115
[2] U.S. Geological Survey, Menlo Park, CA 94025
[3] Department of Geosciences, Texas Tech University, Lubbock, TX 79409-1053

Paper number 94TC02454.
0278-7407/95/94TC-02454$10.00

Klamaths by *Lanphere et al.* [1968], it became clear that plutons initially deemed part of the Nevadan orogeny as defined by *Hinds* [1934] were as old as Middle Jurassic. This was the first indication that either (1) the Nevadan orogeny began 10 m.y. earlier than initially thought, or (2) that an important mountain-building event might have predated the Nevadan orogeny by more than 10 m.y. and that the Nevadan orogeny might not be responsible for many orogenic features in the Klamath Mountains and Sierra Nevada. This point was taken up by *Wright and Fahan* [1988], *Coleman et al.* [1988], and *Edelman et al.* [1989b], who discussed the importance of a Middle Jurassic Siskiyou orogeny in the Klamath Mountains and Sierra Nevada.

Inherent in some of the earliest work on the Nevadan orogeny was the assumption that the orogeny occurred over a wide region within a well-defined and narrow time period. *Knopf* [1929, p. 14] stated that "one of the mightiest of physical revolutions, one that caused the folding of the strata of the Sierra Nevada and the subsequent intrusions of immense batholithic masses...ran its course during a fractional part of Late Jurassic time." This line of thought culminated about 10 years ago in very narrowly defined windows for the Nevadan orogeny. *Harper and Wright* [1984] bracketed the Nevadan orogeny in the Klamath Mountains at between 147 and 150 Ma using the ages of undeformed plutons and deformed dikes in the Galice Formation. At the same time, *Schweickert et al.* [1984] used overprinting relationships and isotopic ages to constrain the Nevadan orogeny in the Sierra Nevada to 155 ± 3 Ma. Subsequent isotopic dating has cast doubt upon the applicability of such a narrow time interval. For example, the Yuba Rivers pluton, which was considered by *Schweickert et al.* [1984] to cut Nevadan cleavage, has been shown to have a 159 Ma U/Pb zircon crystallization age [*Edelman et al.*, 1989a]; the so-called Nevadan cleavage in this area is thus Middle Jurassic or older. These issues of timing are not merely semantic, for upon this foundation rest hypotheses for the plate tectonic processes responsible for construction of the Klamaths and Sierra Nevada. For instance, the apparent difference in orogenic age between the two mountain ranges led *Ingersoll and Schweickert* [1986] to propose that a northward migrating microcontinent-arc collision caused the Nevadan orogeny. Evaluation of such hypotheses depends critically on the ages of various orogenic features.

Just as some features initially thought to be part of the Nevadan orogeny have since been shown to be older than the youngest deformed sedimentary rocks (Kimmeridgian), determinations of the end of the orogeny have begun to approach the Valanginian age of overlying, undeformed strata. *Saleeby et al.* [1989a] and *Tobisch et al.* [1989] have shown that cleavage formation and plutonism in the southern Sierra Nevada occurred as late as 138 Ma. *Harper et al.* [1994] have likewise shown that "late phase" Nevadan regional metamorphism and local deformation persisted in the Klamath Mountains until 135 Ma.

Thus one might assume that the terms "Siskiyou orogeny" and "Nevadan orogeny" refer to activity that occurred before or after deposition of the Mariposa and Galice Formations, respectively. As demonstrated in this paper, and recently by *Harper et al.* [1994], such a simple subdivision may no longer be useful. Unless each particular orogenic feature (e.g., pluton, volcanic rock, sedimentary rock, metamorphic rock) is dated, we find that it is difficult to assign it to a particular orogeny—if an orogeny is considered to occur within a discrete time window bounded by anorogenic periods. Some orogenic features clearly owe their existence to processes that began before the onset of the classical Nevadan orogeny and ended after the termination of the Nevadan orogeny. For example, in the Klamath Mountains, emplacement of the Wooley Creek plutonic belt and associated deformation and metamorphism began at 167 Ma, more than 10 m.y. before the Nevadan orogeny began, and yet we show herein that metamorphism (and potentially, deformation) associated with these plutons lasted until ~150 Ma. Other orogenic features developed during deposition of the Mariposa and Galice Formations [*Harper et al.,* 1994]. Rather than attempting to decide whether such an event is "Nevadan" or "Siskiyou," it is more useful to determine the characteristics and precise age of each particular orogenic feature. This leads to a clearer understanding of the causal tectonic processes.

Tectonic Cause of the Nevadan and Siskiyou Orogenies

Plate tectonic explanations for the Nevadan and Siskiyou orogenies are of essentially two types, involving either (1) collision with or subduction of a continental or oceanic fragment or (2) profound changes in plate motion. The collision interpretation is based on apparent differences between the Sierra Nevada and Klamath Mountains in (1) the age of the Nevadan orogeny, (2) the depositional setting of orogenic flysch (Galice and Mariposa Formations), and (3) the apparent lack of a forearc sequence similar to the Great Valley Group outboard of the Klamath Mountains [*Moores,* 1970; *Schweickert and Cowan,* 1975; *Hamilton,* 1978; *Moores and Day,* 1984; *Schweickert et al.,* 1984; *Day et al.,* 1985; *Ingersoll and Schweickert,* 1986]. The plate motion explanation is based on (1) the recognition that many Mesozoic terranes of the Klamath Mountains are interrelated depositionally or magmatically, and are thus interpreted to have formed essentially in situ with respect to the rest of western North America, (2) the apparent continuity in Klamath magmatism from ~177 to ~144 Ma, and (3) the absence of a possible collided arc or microcontinent [*Davis et al.,* 1978; *Wright,* 1982; *Gray,* 1986; *Wright and Fahan,* 1988; *Ernst,* 1990; *Hacker et al.,* 1993]. This issue is far from settled, although data presented here favor the hypothesis of plate motion changes.

The Nevadan and Siskiyou orogenies are often thought of as contractional episodes coincident with arc magmatism, and yet (1) the Klamath volcanoplutonic arcs contain abundant evidence for extension, and (2) most active magmatic arcs are extensional. This mixture of contraction and extension is essential to the formation of continental lithosphere from arcs [*Wright and Fahan,* 1988], and histories of the timing of contraction and extension in the Klamath Mountains have been presented by *Harper and Wright* [1984] and *Hacker and Ernst* [1993].

A corollary to both the collision model of orogeny and the general view of dominant contraction is that the Klamath Mountains are often viewed as the result of progressive accretion of outboard terranes. This paper demonstrates that such a view, while correct overall, is incorrect in detail. Episodic, essentially in situ extension and contraction, rather than accretion, may have built much of the new continental crust. The basis for this intepretation is the new isotopic ages in Table 1, as illustrated in Figures 3 and 4 and the appendix[1], and previously published data of numerous authors listed in Table 1 of *Hacker and Ernst* [1993].

All U/Pb zircon ages summarized here for igneous rocks are interpreted as crystallization ages. K-Ar and ^{40}Ar/^{39}Ar ages reflect the entrapment of Ar during cooling. Closure temperatures, or the temperature of a mineral at the time represented by its apparent age [*Dodson*, 1973], are approximately 450–525°C [*Harrison*, 1981] and <350°C [*Snee et al.*, 1988; *Harrison et al.*, 1985] for rapidly cooled hornblende and mica, respectively. They may be affected by factors such as cooling rate [*Dodson*, 1973], composition [*Harrison et al.*, 1985; *Scaillet et al.*, 1992], exsolution [*Harrison and Fitz Gerald*, 1986; *Baldwin et al.*, 1990], alteration [*Onstott and Pringle-Goodell*, 1988; *Baldwin et al.*, 1990], and grain size [*Kelley*, 1988]. Of potential relevance to this study, exsolution may reduce hornblende closure temperature to ~375°C for cooling rates of 10°C/m.y. [*Baldwin et al.*, 1990]. We have not detected exsolution in any Klamath hornblendes studied by backscattered electron microscopy, but this does not preclude its existence at the submicron scale.

Because Ar closure temperatures are well below solidus temperatures, K-Ar and ^{40}Ar/^{39}Ar ages are minimum ages for the crystallization of igneous rocks. The crystallization age of a rapidly cooled hypabyssal or volcanic rock may be close to its K-Ar or ^{40}Ar/^{39}Ar hornblende age, provided that the rocks have not undergone later heating sufficient to liberate argon. Hornblende ages of more slowly cooled igneous bodies can, of course, differ greatly from the crystallization age. In the absence of zircon ages for a given pluton, we have assumed that available hornblende ages approximate crystallization ages; the reader should remain aware of this assumption, and expect that future zircon ages may revise some of the interpretations presented here.

General Structure of the Klamath Mountains

The overall structure of the Klamath Mountains is a stack of gently east dipping thrust sheets [*Irwin*, 1966; *Blakely et al.*, 1985; *Mortimer*, 1985; *Zucca et al.*, 1986; *Fuis et al.*, 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 central to the main theme of this paper are described below from structurally lowest to highest.

Western Klamath Terrane

The Western Klamath terrane in the study area consists of the Dry Butte, Rogue Valley, Smith River, and Briggs Creek subterranes. The Dry Butte subterrane comprises plutonic rocks of the Chetco complex, Illinois River gabbro complex, and Rum Creek metagabbro [*Saleeby*, 1990]. Lower parts of the Rogue Valley and Smith River subterranes consist of the Rogue Formation and Josephine ophiolite, respectively. The Rogue Formation and Dry Butte subterrane together are interpreted as a Middle to Late Jurassic [*Saleeby*, 1990; *Harper et al.*, 1994] immature arc [*Garcia*, 1979, 1982]. The Middle Jurassic Josephine ophiolite [*Harper*, 1980] (called the Devils Elbow ophiolite remnant in the southernmost Klamath Mountains) has yielded 162 and 164 Ma zircon ages [*Wright and Wyld*, 1986; *Harper et al.*, 1994] and late Callovian radiolarians [*Pessagno and Blome*, 1990]. It overlies the Rogue–Chetco arc along the regionally extensive Madstone thrust fault, interpreted to have been active during the final stages of arc volcanoplutonism [*Harper et al.*, 1994]. The Galice Formation, which consists of 2–4 km of Kimmeridgian flysch, overlies Oxfordian radiolarian chert on top of the Josephine ophiolite and is intercalated with upper levels of the Rogue arc [*Harper*, 1980; *Harper and Wright*, 1984; *Pessagno and Blome*, 1990; *Saleeby*, 1992]. The Galice Formation, Rogue Formation, and Josephine ophiolite are all cut by dikes and sills that yield ages of 146–151 Ma (e6–e22 in Table 1 of *Hacker and Ernst* [1993]). The Galice Formation contains spinel, staurolite, garnet, and blue amphibole detritus probably derived from Klamath terranes farther east, and thus it and the depositionally underlying Rogue–Chetco arc and Josephine ophiolite may not have formed far from the rest of the Klamaths [*Davis et al.*, 1978; *Saleeby et al.*, 1982; *Wright and Wyld*, 1986]; radiolarian assemblages, however, suggest considerable latitudinal transport of the Josephine ophiolite prior to Galice sedimentation [*Pessagno and Blome*, 1990]. The Briggs Creek subterrane consists predominantly of amphibolite interlayered with minor siliceous metasedimentary rocks and serpentinite [*Garcia*, 1982; *Coleman and Lanphere*, 1991]. It has recently been correlated with the Rattlesnake Creek terrane (see below) on the basis of trace element abundances [*Yule and Saleeby*, 1994]. K-Ar cooling age determinations on hornblendes from the Briggs Creek subterrane by previous workers range from 128 to 137 Ma (a summary is given by *Hacker and Ernst* [1993]).

Condrey Mountain Terrane

The Condrey Mountain terrane is a transitional greenschist–blueschist facies volcanic sequence and subduction complex with local greenschist facies overprint [*Helper*, 1986]. The age of part of the protolith of the Condrey Mountain terrane is bracketed at 170–172 Ma by U/Pb zircon ages on metaplutonic rocks [*Helper et al.*,

---

[1] An electronic supplement of this material may be obtained on a diskette or Anonymous FTP from KOSMOS.AGU.ORG (LOGIN to AGU's FTP account using ANONYMOUS as the username and GUEST as the password. Go to the right directory by typing CD APEND. Type LS to see what files are available. Type GET and the name of the file to get it. Finally, type EXIT to leave the system.) (Paper 94YCJ2454, Timescales of orogeny: Jurassic construction of the Klamath Mountains, B.R. Hacker, M.M. Donato, C.G. Barnes, M.O. McWilliams, and W.G. Ernst). Diskette may be ordered from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009; $15.00. Payment must accompany order.

Table 1. Summary of $^{40}Ar/^{39}Ar$ Data

Sample	Mineral	J	Weight, mg	Grain Size, µm	K_2O, wt %	Total Fusion Age, Ma	Isochron Age, Ma	MSWD	Weighted Mean Plateau Age, Ma	T Steps Used, °C	^{39}Ar, %
Stanford University Resistance Furnace											
EK188	hb	0.005323	18.4	250–375	...	156.1 ± 0.5	160.2 ± 0.5	2.0	160.2 ± 0.5	1155–1250	53
FPV25	hb	0.005323	5.7	250–375	0.55	163.6 ± 0.7	165.1 ± 0.4	0.8	165.0 ± 0.3	975–1400	98
FPV12	mu	0.005312	2.7	250–375	...	148.6 ± 0.2	148.2 ± 0.3	1.0	148.5 ± 0.2	800–1200	93
Yr172	hb	0.005401	21.8	400–500	...	166.2 ± 0.7	167.0 ± 0.6	0.1	166.6 ± 0.3	1000–1400	96
542M	hb	0.005418	14.7	200–300	...	150.1 ± 0.8	152.1 ± 0.5	4.8	152.4 ± 0.3	900–1400	99
365M	bi	0.005296	0.9	400	...	155.0 ± 0.2	154.3 ± 0.8	0.6	155.1 ± 0.2	875–1200	*
365M	hb	0.005296	16.7	200–400	...	152.3 ± 0.4	153.3 ± 0.3	0.1	153.2 ± 0.2	all	100
EP141	hb	0.005354	11.9	180–250	...	158.5 ± 0.6	160.4 ± 1.4	0.7	156.6 ± 0.5	975–1400	81
506M	hb	0.005523	9.8	100	...	157.7 ± 4.2	162.6 ± 1.4	0.9	161.5 ± 0.9	all	100
TR16	hb	0.005332	5.9	250–375	0.7	150.7 ± 1.1	153.0 ± 1.0	0.8	154.1 ± 0.5	1000–1400	70
TR4	hb	0.005343	11.2	180–250	...	154.2 ± 2.2	153.2 ± 1.2	0.3	153.9 ± 0.8	all	100
Yr151	bi	0.005474	0.5	100–150	...	149.0 ± 0.4	149.9 ± 0.2	0.5	149.7 ± 0.2	all	100
Yr131	bi	0.005517	1.1	88–106	...	148.8 ± 0.4	150.4 ± 0.4	3.6	150.9 ± 0.2	900–1200	70
Yr179	mu	0.005392	2.3	200–300	...	149.2 ± 0.4	150.7 ± 0.3	1.1	150.5 ± 0.2	875–1200	74
Yr121	hb	0.005463	7.9	88–106	...	142.4 ± 5.8	147.8 ± 2.3	0.9	147.4 ± 1.1	980–1400	89
Yr120	hb	0.005458	7.8	175–200	...	149.2 ± 1.0	150.8 ± 0.6	0.3	150.3 ± 0.3	975–1400	97
Yr165	hb	0.005540	11.3	150–200	...	148.6 ± 1.3	152.5 ± 2.5	0.5	151.8 ± 0.4	1020–1200	71
Yr166	hb	0.005415	6.6	200–300	...	150.4 ± 1.5	152.1 ± 4.7	0.0	153.9 ± 0.4	all	100
Yr154	hb	0.005367	7.5	200	...	149.5 ± 1.0	149.9 ± 0.4	0.8	149.9 ± 0.4	all	100
Yr164	hb	0.005450	20.1	300–400	...	147.2 ± 0.4	150.3 ± 0.6	1.1	150.2 ± 0.4	1050–1400	51
Yr157	hb	0.005426	13.8	700–800	...	148.4 ± 0.8	...	...	...	...	†
584M	hb	0.005509	17.5	300–400	...	152.8 ± 0.4	154.0 ± 0.8	0.6	153.5 ± 0.4	all	100
190M	hb	0.005386	3.2	200–300	...	168.1 ± 5.7	174.6 ± 1.3	1.5	173.0 ± 0.8	all	100
604M	hb	0.005468	7.4	88–106	...	156.0 ± 8.2	158.7 ± 5.0	0.3	159.2 ± 2.8	all	100
601M	hb	0.005545	10.4	100–150	...	157.0 ± 7.0	164.8 ± 2.2	0.7	164.1 ± 1.4	800–1400	95
U.S. Geological Survey Resistance Furnace											
216-GA-76	hb	0.01055	292	50–75	1.15	155.2 ± 1.0	†	†	156.4 ± 0.9	875–1100	94
MMD-233-83	hb	0.00988	240	100–125	1.0	137.6 ± 3.5	†	†	146.9 ± 2.1	900–1000	75
SV-1-85	hb	0.011205	168	100–125	0.3	150.5 ± 1.4	153.0 ± 2.2	1.9	152.0 ± 1.2	all	100
GF-1-85	hb	0.010825	233	150–180	...	148.1 ± 3.6	150.1 ± 4.6	0.8	150.1 ± 4.6	all	100
FPC10	hb	0.010400	1536	180–250	0.3	138.2 ± 1.7	137.9 ± 2.6	0.3	137.6 ± 1.6	all	100
AP48	hb	0.01095	1615	180–250	0.6	150.0 ± 1.6	153.6 ± 1.2	0.2	152.0 ± 1.2	all	100
DP353	hb	0.01080	1432	180–250	0.4	134.9 ± 2.4	137.4 ± 2.8	0.2	135.8 ± 1.9	all	100
GM24	hb	0.01020	1726	180–250	0.5	157.9 ± 1.9	155.8 ± 3.4	0.4	157.3 ± 1.4	750–1400	99
EP176B	hb	0.01063	1331	180–250	0.7	153.5 ± 1.5	154.5 ± 1.4	0.2	153.9 ± 1.2	all	100
MC-41A-85	hb	0.01150	211	180–250	0.5	150.9 ± 1.9	†	†	153.3 ± 0.8	900 only	84
MC-154C-86	hb	0.00895	637	150–180	0.6	150.5 ± 1.9	152.5 ± 3.3	0.6	152.5 ± 1.4	800–1400	99
MC-126-85	hb	0.011347	234	75–150	0.3	145.6 ± 2.5	149.3 ± 6.9‡	0.2‡	151.3 ± 1.6‡	825–1200‡	84‡
MC-157-86	hb	0.01109	219	150–180	0.4	155.2 ± 1.6	153.1 ± 3.3	0.6	151.6 ± 1.2	850–1400	89
MC-81A	hb	0.00914	256	100–125	...	142.6 ± 3.9	155.0 ± 9.2	1.7	154.1 ± 2.1	975–1400	97
MMD-183-83	hb	0.01023	218	100–125	0.2	154.1 ± 3.1	(single-step total fusion)				
MC-152-86	hb	0.01078	163	150–180	0.1	145.4 ± 7.3	(single-step total fusion)				
MC-158-86	hb	0.011175	177	150–180	0.1	144.7 ± 2.1	(single-step total fusion following degas at 750°C)				
U.S. Geological Survey Laser											
MC-13B-87	bi	0.006725	5	180–250	...	147.8 ± 0.7	(single-step total fusion)				

J is the irradiation parameter, MSWD is the mean square weighted deviation [*Wendt and Carl*, 1991] of isochron, isochron and weighted mean plateau ages are based on temperature steps and fraction of ^{39}Ar listed in the last two columns. Mineral abbreviations are hb, hornblende; bi, biotite; mu, muscovite. K_2O is from electron probe analysis.

* Lower temperature steps lost through operator error.

† Disturbed spectrum and/or isochron.

‡ Two discordant steps excluded from indicated range of temperatures.

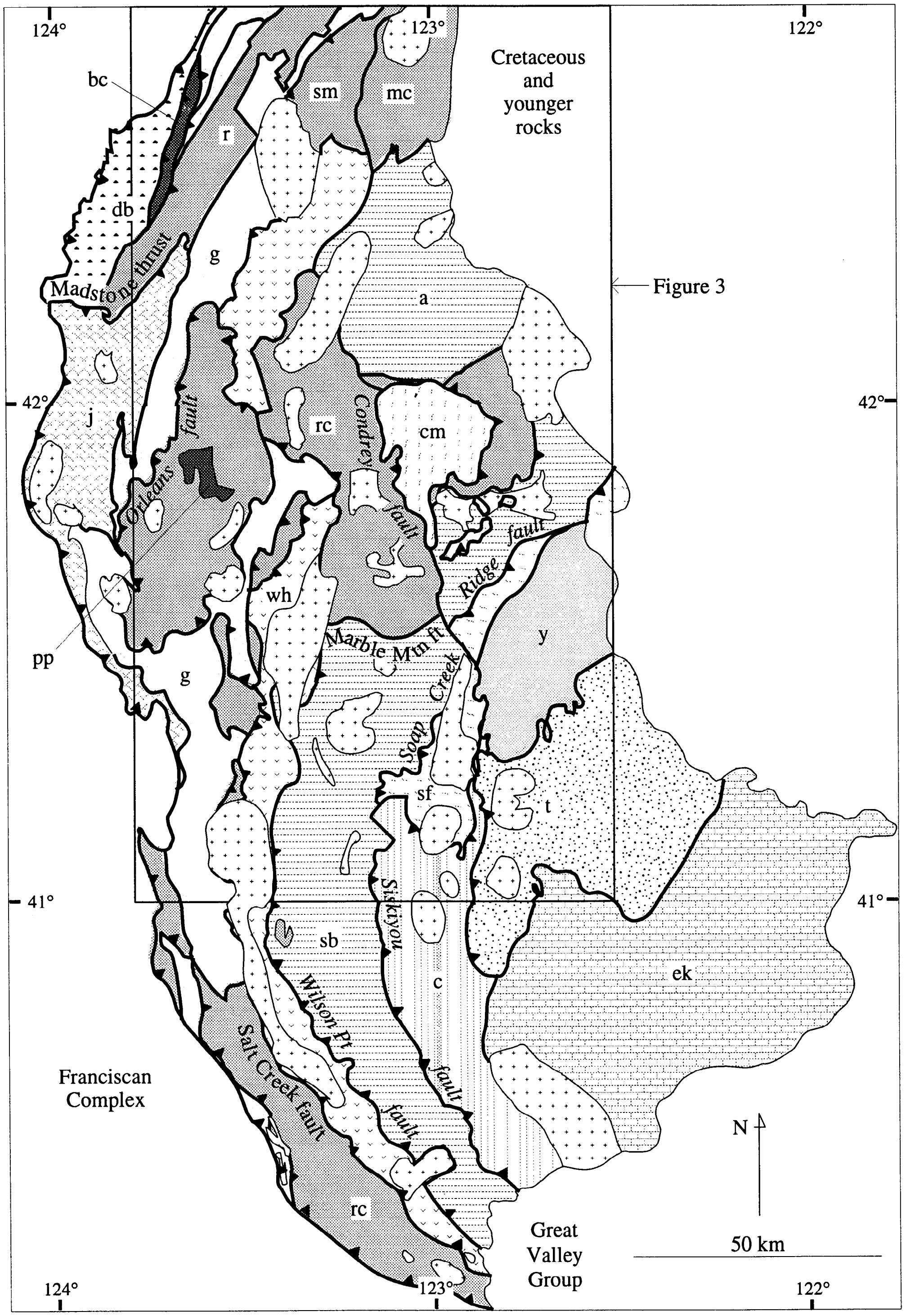

Figure 1. Klamath Mountains rock units [after *Hacker and Ernst*, 1993]. Potentially correlative terranes are shown with identical patterns. Abbreviations are a, Applegate terrane; bc, Briggs Creek subterrane; c, Central Metamorphic terrane; cm, Condrey Mountain terrane; db, Dry Butte subterrane; ek, Eastern Klamath terrane; g, Galice Formation; j, Josephine ophiolite; mc, May Creek terrane; pp, Preston Peak ophiolite; r, Rogue Formation, rc, Rattlesnake Creek terrane; sb, Sawyers Bar terrane; sf, Stuart Fork terrane; sm, Sexton Mountain terrane; t, Trinity terrane; wh, Western Hayfork terrane; y, Yreka terrane; Marble Mtn ft, Marble Mountains fault. The Yreka, Trinity, and Eastern Klamath terranes compose the "eastern Klamaths" referred to in the text, and the Dry Butte, Rogue, Briggs Creek, Josephine, and Galice units make up the western Klamath terrane.

1989; *Saleeby and Harper*, 1993]. Rb/Sr and K-Ar ages indicate that cooling of the deepest levels of the Condrey Mountain terrane below ~350°C was delayed until Early Cretaceous time (125–132 Ma [*Helper et al.*, 1989]). *Saleeby et al.* [1992] suggested that the Condrey Mountain terrane represents subducted Middle Jurassic ocean floor formed during early phases of spreading that produced the Josephine ophiolite, which they suggested may have begun as early as 172 Ma.

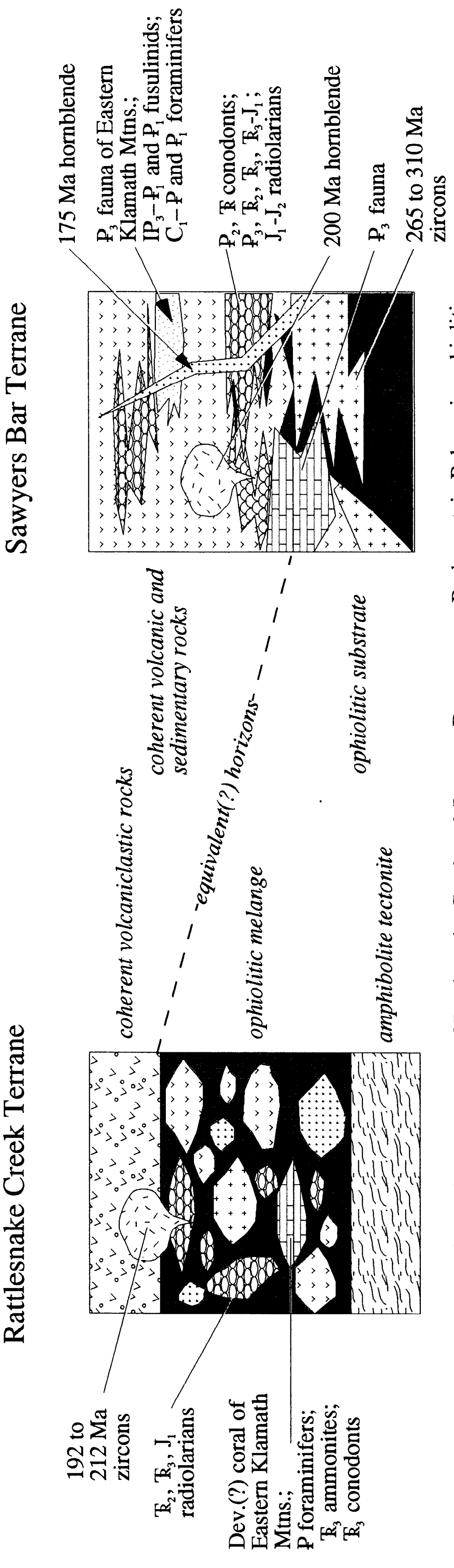

Figure 2. Comparison of Rattlesnake Creek and Sawyers Bar terranes. Both contain Paleozoic ophiolitic basement overlain by Early Jurassic(?) volcanoplutonic centers. Subscripts 1, 2, and 3 to period names refer to Early/Lower, Middle, and Late/Upper, respectively. See references in text.

Rattlesnake Creek Terrane

The Rattlesnake Creek terrane (Figure 2), and high-grade probable correlatives called the Marble Mountain terrane, consist of mafic tectonite and oceanic melange overlain and intruded by a Late Triassic to Early Jurassic tholeiitic to calc-alkalic magmatic arc [*Wright*, 1981; *Petersen*, 1982; *Hill*, 1984; *Rawson*, 1984; *Gorman*, 1985; *Gray*, 1985; *Wright and Wyld*, 1986; *Donato*, 1987; *Wright and Wyld*, 1994]. The melange is dominated by blocks derived from oceanic sources. Mafic blocks within the melange include massive amphibolite and hypabyssal-plutonic complexes, some of which were deformed during crystallization [*Klein*, 1977; *Petersen*, 1982; *Hill*, 1984]. Amphibolite in the Preston Peak area yielded 190 and 193 Ma K-Ar ages [*Gorman*, 1985]. Zircons from plagiogranite cutting a block of dikes at China Peak gave a U/Pb age of 172 ± 2 Ma [*Saleeby and Harper*, 1993]. Trace elements indicate that mafic igneous blocks in the Rattlesnake Creek terrane have a range of affinities, including immature arc, within-plate, and mid-ocean ridge basalts [*Hacker and Ernst*, 1993; *Wright and Wyld*, 1994]; *Wright and Wyld* suggested that the arc blocks were derived from the overlying cover sequence. Chert blocks in the melange contain radiolarians ranging from Middle Triassic to Early or Middle Jurassic age, and limestone blocks bear fossils ranging in age from Devonian(?) coral to Late Triassic conodonts [*Irwin*, 1972; *Irwin et al.*, 1977, 1982; *Smith et al.*, 1982; *Gray*, 1985, 1986]. The Devonian(?) fossil coral is significant because it is similar to corals found in sedimentary strata in the eastern Klamaths, and thus may tie the provenance of the Rattlesnake Creek terrane to the Eastern Klamath terrane [*Irwin*, 1972]; *Wright and Wyld* [1994], however, argue that the absence of terrigenous clastic rocks at deep levels within the melange implies that the terrane was not near a continent prior to the Late Triassic.

The cover sequence probably overlies the melange depositionally [*Wright and Wyld*, 1994]. It contains chert, epiclastic sedimentary rocks, lavas, and tuff deposited proximal to a volcano [*Rawson*, 1984; *Gray*, 1985, 1986; *Wright and Wyld*, 1994]. Trace element abundances suggest that the volcano was part of an immature tholeiitic to more evolved shoshonitic arc [*Hacker and Ernst*, 1993; *Wright and Wyld*, 1994]. A gabbroic to quartz dioritic plutonic suite, believed to be consanguineous with the cover sequence, intrudes the melange and cover sequence and has given U/Pb zircon ages of 193–208 Ma [*Gray*, 1985; *Wright and Wyld*, 1994].

The Rattlesnake Creek terrane served as the basement on which the Rogue–Chetco arc [*Harper and Wright*, 1984;

Saleeby, 1984], Josephine ophiolite [*Wyld and Wright*, 1988], Preston Peak ophiolite [*Saleeby et al.*, 1982], and possibly the Western Hayfork [*Wright and Fahan*, 1988] and Salmon River arcs (see below) formed.

Preston Peak Ophiolite

The Preston Peak ophiolite comprises greenschist facies tholeiitic plutons, dikes, breccias, and pillowed flows that intrude and unconformably overlie tectonized ultramafic rocks and amphibolite of the Rattlesnake Creek terrane [*Snoke*, 1977; *Snoke et al.*, 1981; *Saleeby et al.*, 1982]. A late stage plagiogranite dike in diorite yielded a 164 ± 1 Ma U/Pb zircon age [*Saleeby*, 1990], and chert overlying the flows contains Jurassic radiolarians [*Saleeby et al.*, 1982]. One contact-metamorphosed amphibolite block yielded a K-Ar hornblende age of 165 ± 3 Ma [*Saleeby*, 1982]. Rocks possibly correlative with the Preston Peak ophiolite (near Little Grayback Mountain [*Gorman*, 1985]) contain Jurassic radiolarians [*Saleeby et al.*, 1982] and Late Triassic conodonts [*Irwin et al.*, 1983].

May Creek Terrane

The May Creek terrane comprises a metasedimentary sequence lying structurally above amphibolite facies metaigneous schist and gneiss along a ductile thrust zone that was active during Late Jurassic time [*Donato*, 1992]. The amphibolite may represent a shallow back arc intrusive complex of Jurassic age that was depositional basement for the protolith of the May Creek Schist [*Donato*, 1991]. Two previously reported ^{40}Ar/^{39}Ar hornblende ages from this unit are around 145 Ma [*Donato*, 1991], and several new ^{40}Ar/^{39}Ar age determinations from this unit, reported here (Table 1), are all within a few million years of 150 Ma.

Western Hayfork Terrane

The Western Hayfork terrane is a Middle Jurassic [*Wright and Fahan*, 1988] immature intraoceanic arc that consists of gabbroic to quartz-monzonitic alkali-calcic plutons (Ironside Mountain suite) intruding >6 km of coeval volcaniclastic rocks and depositionally overlying epiclastic rocks [*Klein*, 1977; *Cashman*, 1979; *Charlton*, 1979; *Hill*, 1984; *Rawson*, 1984; *Wright and Fahan*, 1988; C.G. Barnes, unpublished data, 1994]. Fossils include a 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; *Fahan*, 1982; *Irwin et al.*, 1982; *Wright*, 1982; *Irwin*, 1985b]. 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 et al.* [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 terrane was given a separate name, the St Claire Creek unit. All four units were grouped as the Sawyers Bar terrane (Figure 2) [*Ernst*, 1990]. *Hacker et al.* [1993] provisionally interpreted the Sawyers Bar terrane to represent a volcanoplutonic arc (North Fork and Salmon River units), and associated forearc accretionary wedge (Eastern Hayfork unit) and back arc basin (St Claire Creek unit), although such an interpretation warrants further scrutiny focused on biostratigraphy and radiochronology.

Eastern Hayfork unit. The Eastern Hayfork unit ranges from broken formation to melange and is interpreted as an accretionary wedge [*Wright*, 1981]. Nonexotic (i.e., once plausibly interbedded) components include rocks grading from radiolarian chert to tuff, pillow lava, and quartzose turbidites [*Cashman*, 1979; *Charlton*, 1979; *Fahan*, 1982; *Wright*, 1982; *Hacker et al.*, 1993]. Exotic blocks include variably metamorphosed ultramafic rocks, mafic rocks, limestone, and clastic rocks [*Cox*, 1956; *Cashman*, 1979; *Charlton*, 1979; *Burton*, 1982; *Fahan*, 1982; *Wright*, 1982]. Cashman and Wright postulated that some 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* [1993]. Quartzose blocks contain detrital zircons with multigrain Pb/Pb ages of 2.0–2.1 Ga, possibly 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 volcanogenic material was also derived from the adjacent North Fork–Salmon River arc [*Hacker et al.*, 1993].

Limestone blocks in the Eastern Hayfork unit contain Silurian or Devonian through Late Triassic shallow water fossils and Late Permian Tethyan affinity fusulinids and corals, some of which are also found in the Eastern Klamath terrane [*Irwin*, 1972, 1974, 1986; *Cox and Pratt*, 1973; *Irwin et al.*, 1977, 1983; *Gray*, 1986; *Miller and Wright*, 1987; *Stevens et al.*, 1987, 1991]. Some limestone blocks might thus be olistoliths derived from eastern paleo-Pacific seamounts [*Miller and Wright*, 1987] while others might have come from the Eastern Klamath terrane. 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 et al.*, 1982, 1983; *Ando et al.*, 1983; *Irwin*, 1985b].

Salmon River unit. The Salmon River unit includes ultramafic rocks, gabbro, diabase, and volcanic rocks, initially interpreted as remnants of oceanic crust [*Irwin*, 1972; *Blake et al.*, 1982; *Ando et al.*, 1983]. Recent geologic mapping, bulk rock analyses, and mineral analyses provided the basis for *Ernst et al.* [1991] to propose genesis as an immature intraoceanic arc instead. Fossil ages of interbedded Eastern Hayfork sedimentary rocks suggest that construction of the Salmon River unit began in the Permian and extended through Late Triassic or Early Jurassic time. Plagiogranite within diabase yielded a highly discordant U/Pb zircon age interpreted to indicate crystallization in the range 265–310 Ma (Pennsylvanian to Permian) [*Ando et* *al.*, 1983]. A gabbro body that intrudes the diabase gave a ^{40}Ar/^{39}Ar age of 200 Ma from igneous hornblende [*Hacker et al.*, 1993]. Two mafic hypabyssal rocks in the Salmon River unit yielded hornblende ages of ~174 Ma (Table 1). The trace element compositions of these dikes are similar to Salmon River volcanic rocks [*Ernst*, 1993]. These data support the presence of an arc as young as Middle Jurassic built on oceanic basement as old as Permian. It is also possible that the dikes substantially postdate and are unrelated to the volcanic rocks.

North Fork unit. The North Fork unit comprises up to 2 km of amygdaloidal volcanic rocks with rare intercalated limestone massifs [*Ando*, 1979; *Wright*, 1981; *Mortimer*, 1984] that *Hacker et al.* [1993] interpreted as an alkalic part of the Salmon River immature arc. The volcanic rocks are massive breccias with angular to subangular clasts, tuffaceous chert, pillowed flows, pillow breccias, and hyaloclastites. Limestone beds or exotic(?) blocks contain fusulinids and other foraminifers of Carboniferous to Early Permian age [*Irwin*, 1972, 1974; *Irwin et al.*, 1977].

Sedimentary rocks of the Eastern Hayfork unit interbedded with the North Fork unit range in age from Late Permian to Late Triassic or Early Jurassic. Late Permian fossils are present in limestone intercalated with the North Fork volcanic rocks, and the interbedded St Claire Creek unit contains Late Permian to Early Jurassic fossils. The oldest pluton intruding the North Fork unit is the Vesa Bluffs pluton (≥165 Ma; Table 1). Thus, eruption of the North Fork unit is poorly constrained as Late Permian to Early Jurassic.

St Claire Creek unit. This unit, informally named by *Hacker et al.* [1993], is characterized by chiefly coherent, bedded chert with minor argillite [*Ando*, 1979; *Wright*, 1981; *Mortimer*, 1984], unlike the disrupted, argillite-dominated sequences of the Eastern Hayfork unit. It depositionally overlies the North Fork unit [*Trexler*, 1968; *Ando et al.*, 1983], and contains Late Permian through Early to Middle Jurassic radiolarians, and mid-Permian and Late Triassic conodonts [*Irwin et al.*, 1977, 1982; *Lindsley-Griffin and Griffin*, 1983; *Mortimer*, 1984]. The composition and mineralogy of detritus indicate that the St Claire Creek unit 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 volcanic rocks metamorphosed to blueschist facies assemblages during Late Triassic time [*Hotz*, 1977; *Hotz et al.*, 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 more than 10 km of Devonian to Jurassic sedimentary and volcanic strata formed chiefly in an intraoceanic arc. 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 shale and chert [*Sanborn*, 1960; *Noble and Renne*, 1990]. The 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 (Sinemurian to Pliensbachian) Arvison Formation. The Mesozoic section ends with argillite and tuffaceous sandstone of the Lower to Middle (Toarcian–Bajocian) Jurassic Potem Formation [*Sanborn*, 1960]. Faulting and folding in the Eastern Klamath terrane postdated deposition of Bajocian strata and predated ~164 to 170 Ma plutons [*Renne and Scott*, 1988].

New ^{40}Ar/^{39}Ar Ages

Forty-five 40 new ^{40}Ar/^{39}Ar ages have been obtained on Klamath igneous and metamorphic rocks (Table 1; Figures 3 and 4). This section describes the new data, which are then integrated with data from other workers in subsequent sections. For a description of sample preparation and analytical techniques, see the appendix. All ages discussed here are inverse isochron ages, unless stated otherwise. Quoted uncertainties are 1σ standard deviations, including uncertainty in irradiation parameter J.

Plutonic and Hypabyssal Rocks

Numerous plutons and dikes were dated using hornblende or mica separates. Such ages, if accurate, are always younger than the crystallization age because the Ar closure temperatures for hornblende and mica are notably less than solidus temperatures. ^{40}Ar/^{39}Ar ages from igneous rocks that cooled rapidly (typically dikes or stocks) may approximate the crystallization age, whereas ^{40}Ar/^{39}Ar ages from igneous rocks that cooled slowly may differ substantially from the crystallization age.

Samples from seven plutons of the Wooley Creek plutonic belt (Slinkard, Wooley Creek, English Peak, Russian Peak, Vesa Bluffs, Heather Lake, Thompson Ridge; Figure 5c) [*Irwin*, 1985a] were analyzed. Hornblende from the western, gabbroic part of the Vesa Bluffs pluton (sample FPV25) gave an age of 165.1 ± 0.4 Ma. This is one of the oldest hornblende ages obtained for a pluton that is part of the Wooley Creek belt, and is consequently an interesting candidate for zircon dating. In contrast, a muscovite separate from the eastern, two-mica granite part of the pluton (FPV12) yielded an age of 148.2 ± 0.3 Ma. These ages are concordant with earlier K-Ar hornblende and biotite ages of 164 ± 4 and ~150 Ma obtained by *Lanphere et al.* [1968] from the eastern, granitic part of the pluton. Thus both parts of the pluton cooled through hornblende closure temperature at the same time.

The oldest intrusion that is probably part of the Wooley Creek belt is the Heather Lake pluton, for which we obtained a ^{40}Ar/^{39}Ar hornblende age of 167.0 ± 0.6 Ma (sample Yr172). Hornblende from the Russian Peak batholith (542M) gave an age of 152.1 ± 0.5 Ma, intermediate between the U/Pb zircon age of 159 Ma [*Wright and Fahan*, 1988] and K-Ar biotite ages of 140, 143, 144, and 147 Ma [*Davis et al.*, 1965; *Evernden and Kistler*, 1970].

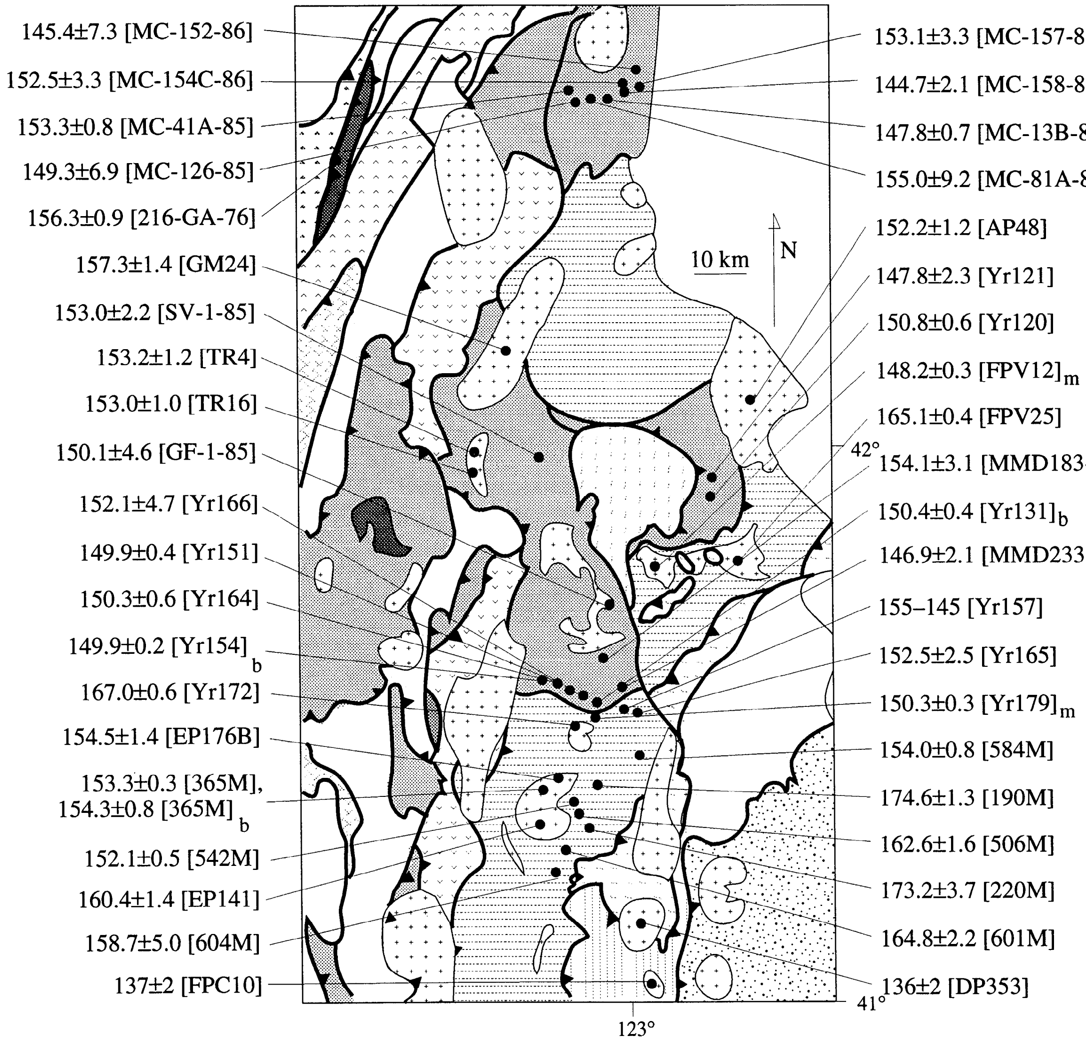

Figure 3. New ^{40}Ar/^{39}Ar ages; all are hornblende, except for biotite and muscovite ages labeled with b and m, respectively. See Figure 1 for location and unit names. For additional ages from this same general area, see *Hacker et al.* [1993].

Our biotite separate from this pluton yielded an uninterpretable hump-shaped spectrum. Hornblende from Salmon River metavolcanic rock (584M) within the contact aureole of the Russian Peak batholith yielded a ^{40}Ar/^{39}Ar age of 154.0 ± 0.8 Ma—slightly, but not significantly, older than hornblende within the batholith, as is appropriate if the aureole cooled before the batholith.

More comprehensive results have been obtained for the English Peak batholith, in which zircon crystallized at or before 164 Ma [*Wright and Fahan*, 1988]. We have measured ^{40}Ar/^{39}Ar ages of 154.3 ± 0.8 Ma on biotite (365M), and 153.3 ± 0.3 (365M), 154.5 ± 1.4 (EP176B), and 160.4 ± 1.4 Ma (EP141) on hornblende. *Lanphere et al.* [1968] previously obtained K-Ar ages of 159 Ma on biotite and 161 Ma on hornblende. This bimodal age distribution, from ~154 to ~160 Ma is interpreted to reflect the polyphase nature of this intrusive body (C.G. Barnes, unpublished data, 1994), but alternatively could result from differences in closure temperature among the minerals studied. Hornblende from Salmon River metavolcanic rock (506M) within the English Peak contact aureole gave an age of 162.6 ± 1.4 Ma—slightly older than hornblende within the pluton, as expected for an aureole rock.

Hornblende from gabbro of the Thompson Ridge pluton yielded an age of 153.2 ± 1.2 Ma (TR4), and hornblende from an appinitelike dike within the same pluton gave a concordant age of 153.0 ± 1.0 Ma (TR16). J. D. Yule (personal communication, 1994), has obtained a concordant U/Pb zircon age on this body of ~162 Ma.

The Castle Crags pluton in the eastern Klamaths has previously yielded such a disparate range of ages as to defy interpretation. *Lanphere et al.* [1968] reported K-Ar ages of 167, 136, and 136 Ma on biotite, and 229, 171, and 162 Ma on hornblende. Our hornblende sample contained two resolvable gas populations: the seven lowest temperature steps suggest an age of approximately 126 Ma, whereas the four highest temperature steps have an age of 160.2 ± 0.5 Ma. Crystallization of the Castle Crags pluton thus predated 160 Ma.

The Ashland and Grayback plutons have magmatic

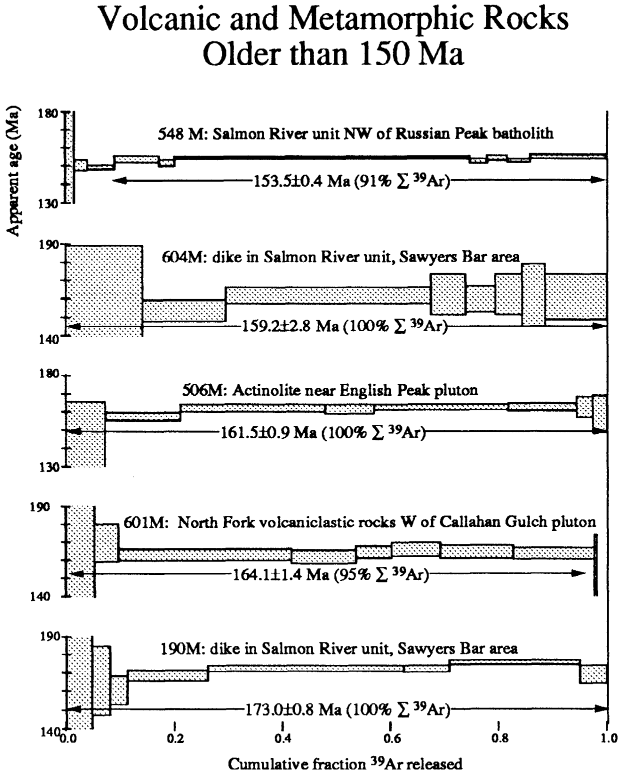

Figure 4. The $^{40}Ar/^{39}Ar$ release spectra of dated samples. All samples are hornblende, except as noted. Rectangles for each step show one standard deviation uncertainties, excluding uncertainty in irradiation parameter *J*. Quoted ages are inverse isochron ages for steps indicated by arrows and include uncertainty in *J*. For tabulated data see the electronic supplement; isochron diagrams, K/Ca spectra, and age spectra may be obtained from the first author.

affinities to the Wooley Creek plutonic belt, but are younger (Figure 5d). Hornblende from the Ashland and Grayback plutons yielded ages of 153.6 ± 1.2 Ma (AP48) and 155.8 ± 3.4 Ma (GM24). Work in progress by J. D. Yule (personal communication, 1994) indicates U/Pb zircon ages for these two plutons of 151–153 Ma and 156–160 Ma, respectively.

An age of 174.6 ± 1.3 Ma was obtained on igneous hornblende (190M) from a dike within the Salmon River unit (Figure 5b). The sample is 7 km from the nearest exposed pluton, matches the age obtained previously for hornblende from a different Salmon River dike [*Hacker et al.*, 1993], and is probably a crystallization age. A weakly metamorphosed dike from the Salmon River unit (604M), also with unaltered igneous hornblende, produced an age of 158.7 ± 5.0 Ma. Like other post-160 Ma dikes dated by *Hacker et al.* [1993], we interpret this dike to postdate formation of the Salmon River unit (Figure 5c).

An enigmatic age of 164.8 ± 2.2 Ma was obtained for hornblende from an alkalic dike (601M) within the North Fork unit west of the Callahan Gulch pluton (Figure 5c). This age matches the only other age obtained for a North Fork dike [*Hacker et al.*, 1993], so it is possible that both samples reflect cooling soon after igneous crystallization. The hornblende of the sample is partly altered to actinolite, however, and the age more plausibly reflects alteration related to intrusion of the Callahan Gulch pluton, which is only 2 km distant—well within the probable thermal aureole of the pluton [*Hacker et al.*, 1992b].

Two of the youngest plutonic hornblende ages in the Klamath Mountains come from the Caribou Mountain and Deadman Peak plutons (Figure 5f). We obtained hornblende ages of 137.9 ± 2.6 Ma (FPC10) and 137.4 ± 2.8 Ma (DP353), respectively for these plutons. Note that the Deadman Peak and the similar Canyon Creek plutons have discordant U/Pb ages of ~144 Ma and Pb/Pb ages of 158–169 Ma [*Wright and Fahan,* 1988]. We suspect that the crystallization ages of these plutons are ~144 Ma, because (1) the $^{40}Ar/^{39}Ar$ and K-Ar ages on the Deadman Peak pluton are ≤138 Ma and (2) these plutons and their neighbors are undeformed, unmetamorphosed, and are enriched in radiogenic Sr and ^{18}O [*Barnes et al.*, 1992c].

Metamorphic Rocks

The remainder of the $^{40}Ar/^{39}Ar$ ages in this study come from amphibolite facies metamorphic rocks. Without exception, samples from the Rattlesnake Creek terrane (sensu lato, Marble Mountain terrane sensu strictu) (Yr151, Yr131, Yr179, Yr121, Yr120, Yr165, Yr166, Yr154, Yr164, Yr157, MMD-183-83, MMD-233-83, SV-1-85, and GF-1-85), which range from metagabbro to pelitic sedimentary rocks, yielded biotite, muscovite, and hornblende ages within the tight range of 148–152 Ma (Figure 5e). In other words, a large area of the Rattlesnake Creek terrane cooled through hornblende and mica closure temperatures at ~150 Ma. Note that the large goodness-of-fit (mean square weighted deviation, MSWD) value for sample Yr179 is produced by a cluster of very radiogenic measurements and does not reflect a complex release spectrum nor analytical error.

One hornblende sample (216-GA-76) from the Briggs Creek subterrane dated previously by the K-Ar method [*Coleman and Lanphere*, 1991] at 137 ± 2.7 Ma yielded a $^{40}Ar/^{39}Ar$ plateau age of ~156 Ma. The reason for this discrepancy is unclear because the total gas age for 216-GA-76 is ~155 Ma, significantly older than 137 Ma. Two other previously reported K-Ar ages from the Briggs Creek subterrane are 131 and 136 Ma [*Coleman and Lanphere*, 1991], and may reflect Ar loss or an analytical problem as well.

Seven hornblende separates (MC-152-86, MC-158-86, MC-126-85, MC-41A-85, MC-154C-86, MC-157-86, and MC-81A-85) from the May Creek terrane gave ages of ~145, ~145, ~149, ~151, ~153, ~153, and ~155 Ma, respectively (Figure 5e). A biotite total fusion age of 148 Ma on another sample (MC-13B-87) falls in the same range. We interpret the ages older than 148 Ma to represent cooling after amphibolite facies metamorphism. The two 145 Ma total fusion ages may be significant underestimates based on the differences in total fusion and isochron ages for the remainder of the samples (Table 1), which were all step heated.

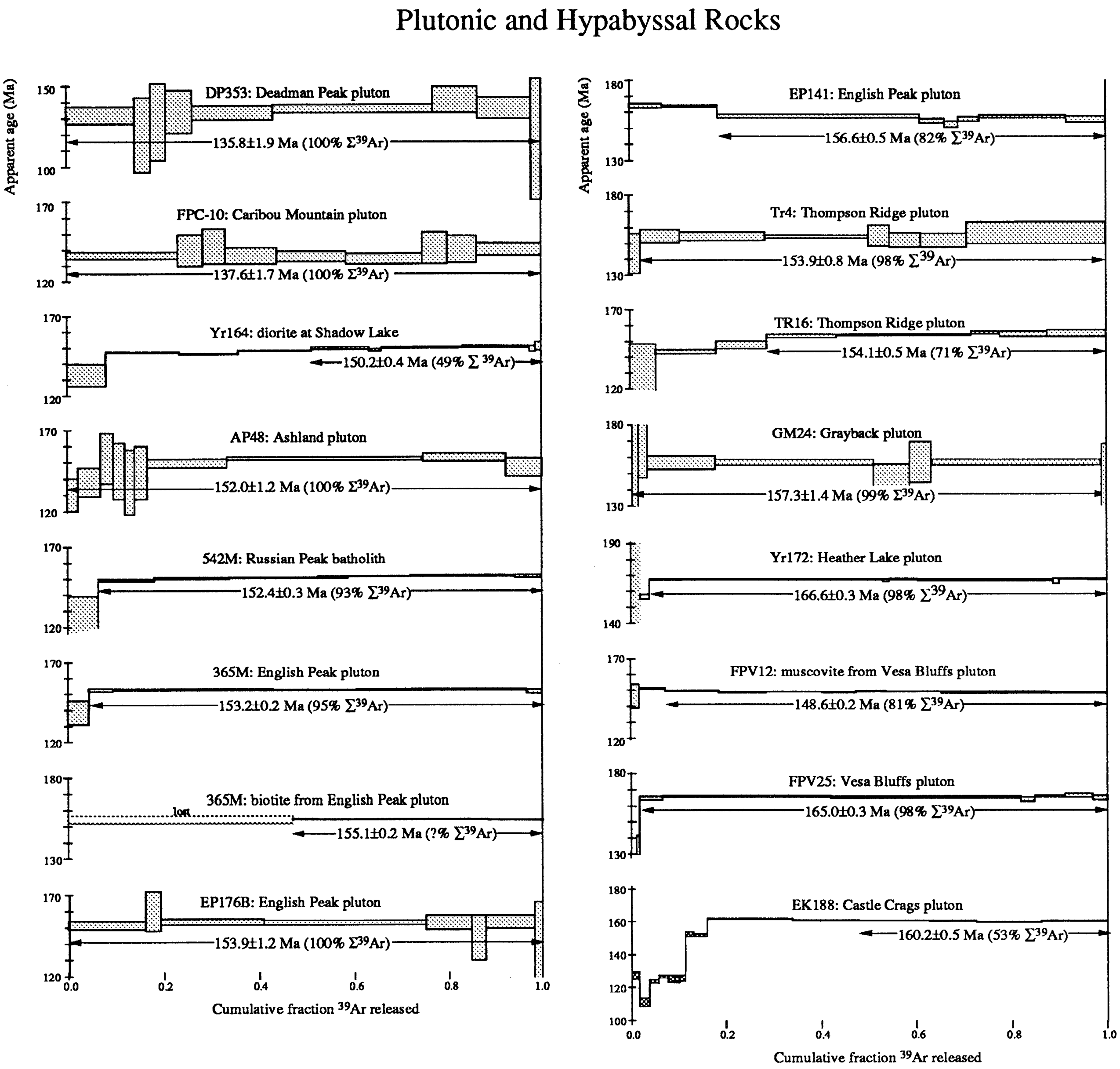

Figure 4. (continued)

Volcanoplutonic and Related Metamorphic Features

The orogenic evolution of Klamath igneous and metamorphic rocks is shown in distinct time frames in Figure 5. The features are described here and interpreted in a later section.

Earliest Jurassic (~200 Ma)

Volcanoplutonism of earliest Jurassic age (~200 Ma) was widespread in the Klamath Mountains [*Hacker et al.*, 1993]. The clearest expression of volcanism is the Arvison Formation of the Eastern Klamath terrane, which includes up to 1200 m of arc-related volcanogenic debris and andesitic flows [*Sanborn*, 1960; *Renne and Scott*, 1988]. The Rattlesnake Creek [*Wright and Wyld*, 1994] and Salmon River units [*Hacker and Ernst*, 1993] may also contain volcanic rocks of this age. Most plutons of this age crop out in the Rattlesnake Creek terrane (Figure 5a), and their U/Pb zircon ages range from 192 to 212 Ma, with somewhat younger K-Ar hornblende ages [*Wright*, 1981; *Gray*, 1985; *Irwin*, 1985a]. Other ~200 Ma ages spread throughout the Klamath Mountains indicate that many terranes may have had Rattlesnake Creek age basement. For example, several plutons of probable pre-Middle Jurassic age (based on field relations) crop out in the Salmon River unit of the Sawyers Bar terrane [*Cox*, 1956; *Ando et al.*, 1983]; igneous hornblende from one of these bodies at Horse Mountain gave a ^{40}Ar/^{39}Ar age of 200 Ma [*Hacker et al.*, 1993]. This raises the possibility that plutonic and volcanic rocks in the Salmon River unit might be equivalent to the cover sequence and crosscutting plutons in the Rattlesnake Creek

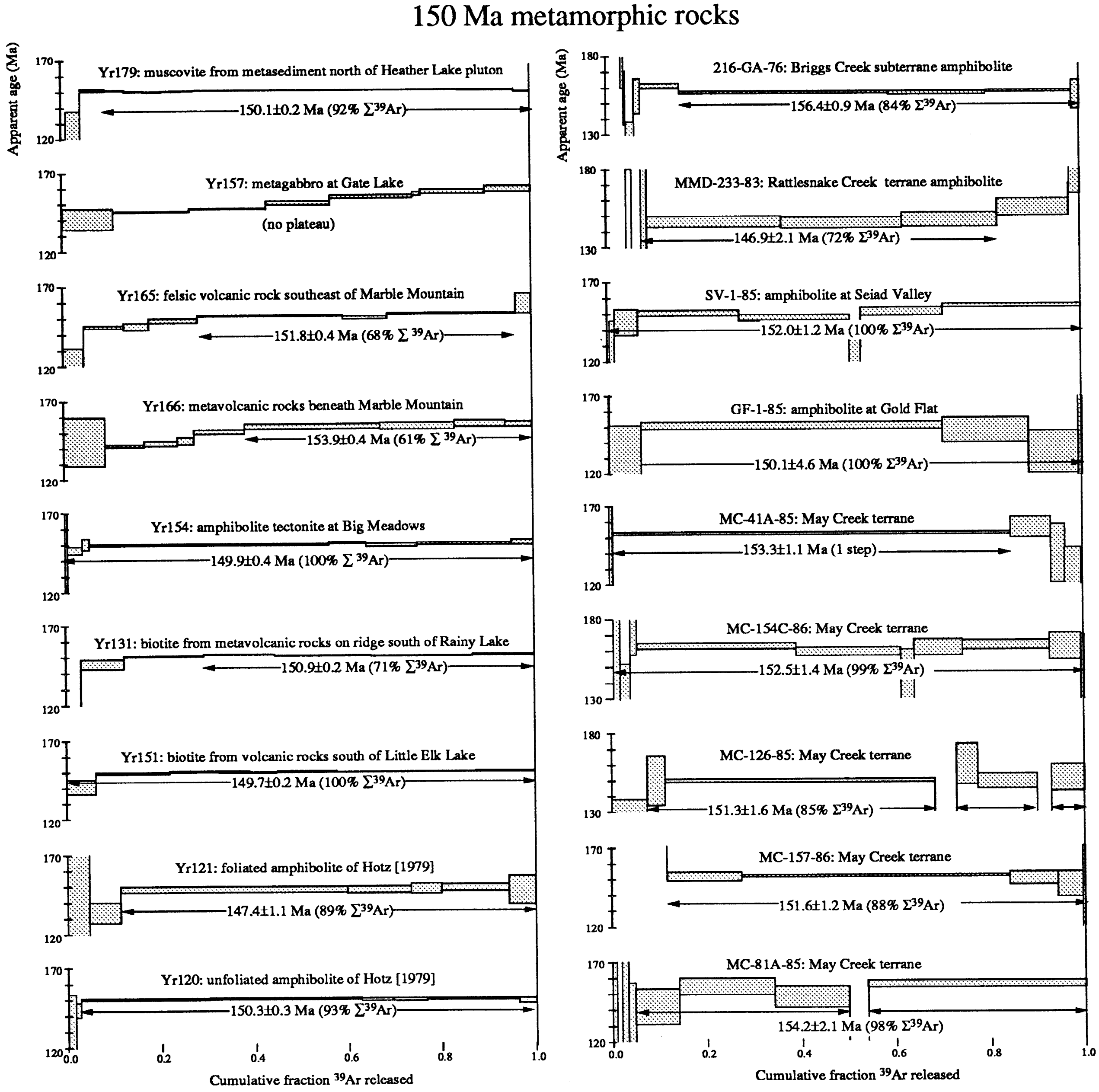

Figure 4. (continued)

terrane (Figure 3); trace element abundances support this possibility [Figure 3 of *Hacker and Ernst*, 1993]. The Lems Ridge olistostrome, spatially associated with the Josephine ophiolite, also contains gabbro clasts with zircons and hornblendes of this age, and may rest depositionally on ~200 Ma basement [*Ohr et al.*, 1986; *Ohr*, 1987; *Harper et al.*, 1994]. Roughly 200 Ma metaplutonic rocks in the Rogue–Chetco arc and Preston Peak ophiolite support the presence of the Rattlesnake Creek terrane as basement to those units as well [*Dick*, 1976; *Gorman*, 1985; *Yule and Saleeby*, 1994]. Thus, 200 Ma igneous rocks are present throughout the western and central Klamaths, suggesting the presence of a widespread earliest Jurassic magmatic event. Following that was an apparent approximately 20 m.y. interregnum in orogenic activity.

Early Middle Jurassic (177–167 Ma)

The hallmark volcanoplutonism of early Middle Jurassic age is the Western Hayfork terrane (Figure 5b) [*Wright and Fahan*, 1988]. Plutons in the Western Hayfork terrane proper (the Ironside Mountain batholith and related bodies) yield crystallization ages of 169–171 Ma, and volcaniclastic rocks have K-Ar hornblende ages of 168–177 Ma [*Wright and Fahan*, 1988]. The alkali-calcic Ironside Mountain batholith is characterized by high K_2O, Rb, Ba, and Sr relative to other Jurassic plutonic rocks in the Klamaths. Sparse Sr and O isotopic data [*Masi et al.*, 1981; C.G. Barnes and R.W. Kistler, unpublished data, 1994) suggest that the batholithic magmas did not interact with radiogenic crust. Plutons of similar composition and age outside the Western

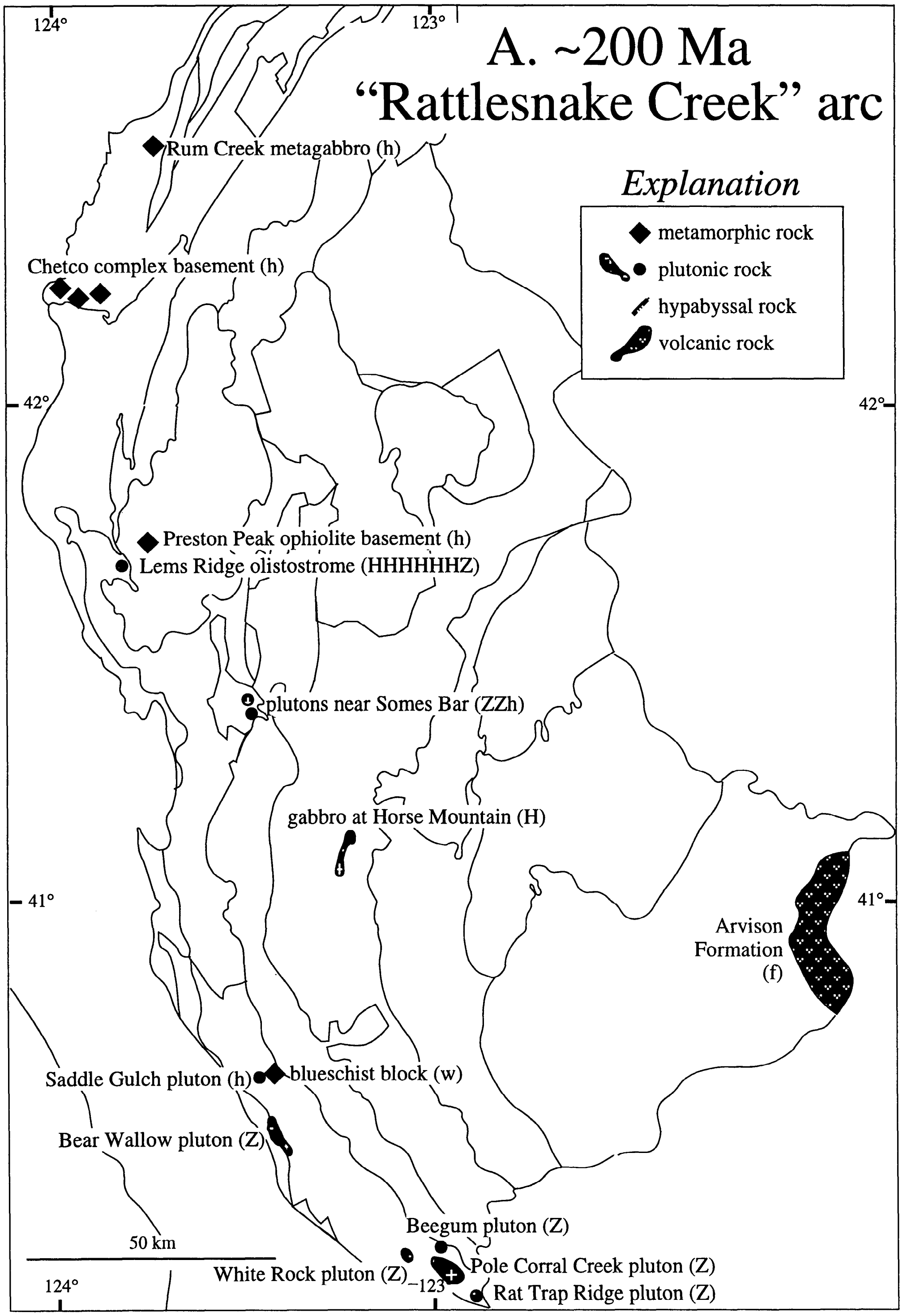

Figure 5. Interpretive maps showing intrusion, volcanism, and metamorphism in six stages. Letters in parentheses indicate dating method: Z, U/Pb zircon; H, ^{40}Ar/^{39}Ar hornblende; M, ^{40}Ar/^{39}Ar muscovite; B, ^{40}Ar/^{39}Ar biotite; h, K-Ar hornblende; m, K-Ar muscovite; b, K-Ar biotite; p, K-Ar plagioclase; w, K-Ar whole rock; f, fossil. After its initial appearance in black, each feature is shaded in subsequent panels. Small plutons are shown as circles. In Figure 5b, only the southern part of the Western Hayfork terrane volcanic rocks have been dated; the central and northern parts may be of different age. In Figures 5c and 5d, different units within the Rogue/Chetco arc have not been differentiated. In Figure 5e, medium shading shows plutons cooling through hornblende and mica closure to Ar. Data used to compile this figure are from this paper or summarized by *Hacker and Ernst* [1993].

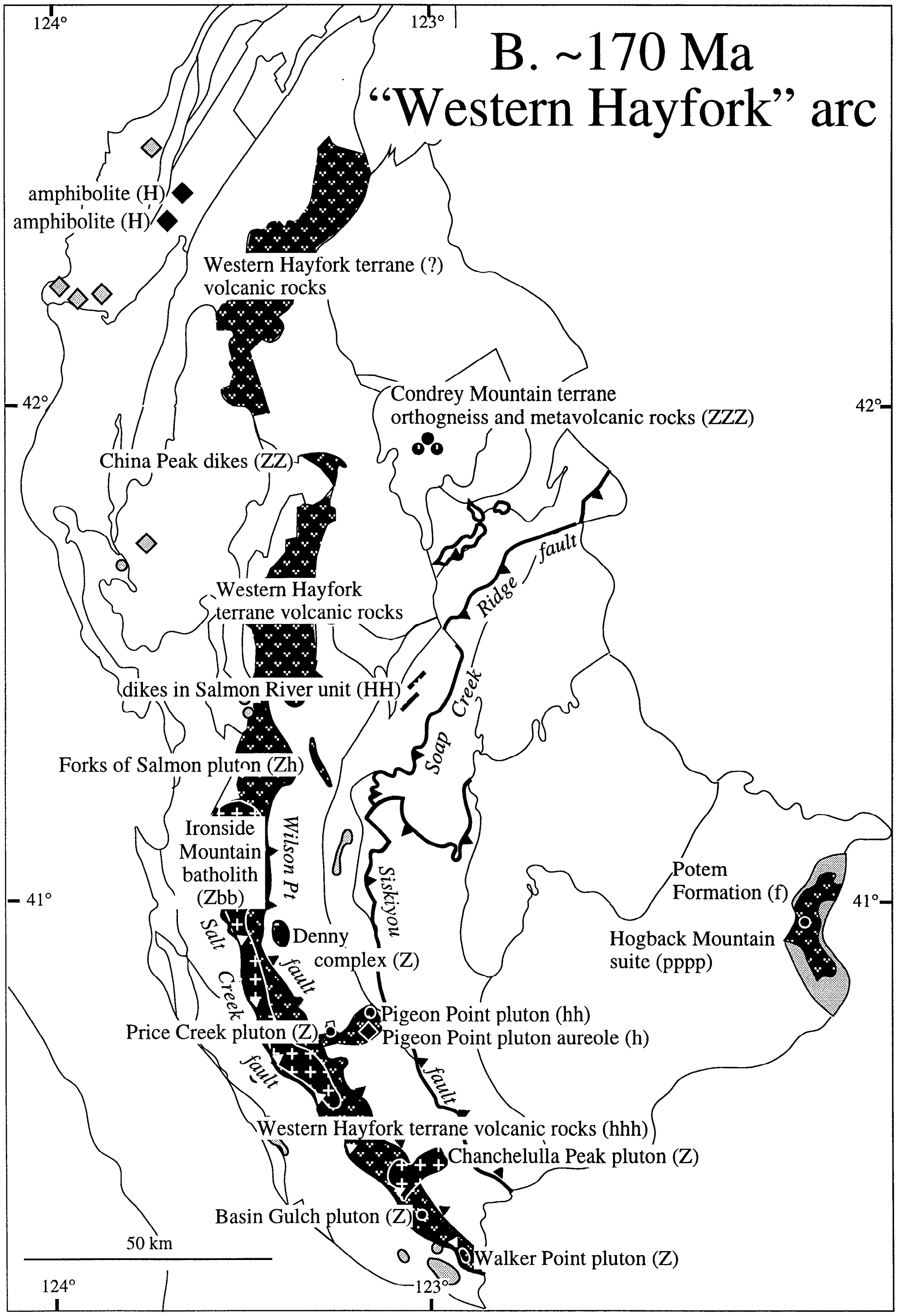

Figure 5. (continued)

Hayfork terrane include the Denny Complex, Forks of Salmon pluton [*Wright and Fahan*, 1988], and the Hogback Mountain suite in the Eastern Klamaths [*Renne and Scott*, 1988]. Two dikes within the Salmon River unit also fall in this age range. This is important because hypabyssal rocks in the Salmon River unit might be related to Western Hayfork magmatism [*Hacker and Ernst*, 1993]. The 172 Ma China Peak dike complex has previously been mapped as part of the Rattlesnake Creek terrane [*Saleeby and Harper*, 1993], but is more likely related to Western Hayfork magmatism. It lies on strike with the Western Hayfork volcanic rocks and has similar trace element abun-

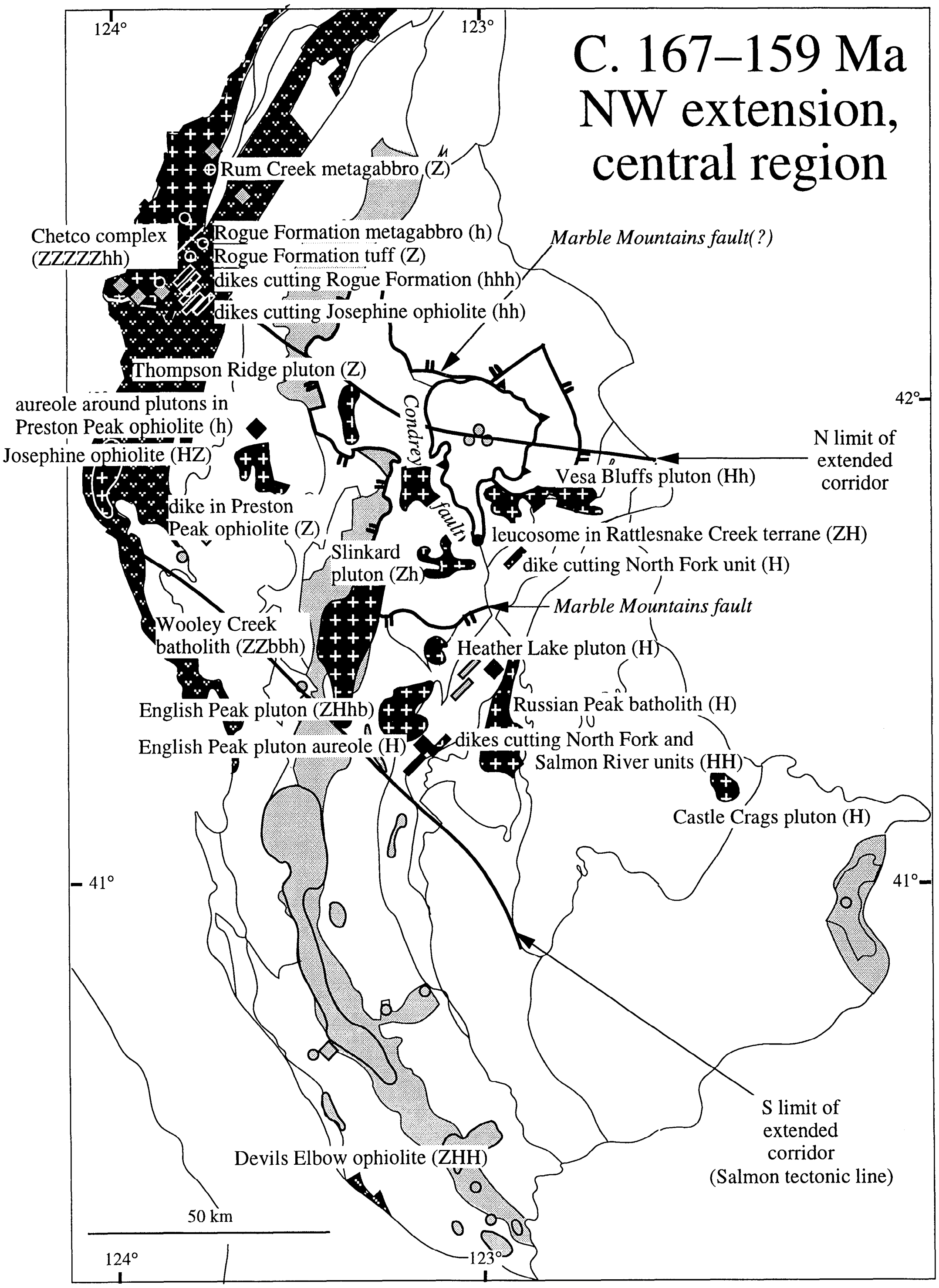

Figure 5. (continued)

dances—although it tends toward more tholeiitic composition than typical Western Hayfork rocks [*Hacker and Ernst*, 1993]. Igneous activity of equivalent age also occurred in the Condrey Mountain [*Helper et al.*, 1989; *Saleeby and Harper*, 1993] and Eastern Klamath terranes (Figure 5b). The Eastern Klamath terrane includes the Potem Formation, more than 1000 m of calcareous argillite and volcanogenic sandstone [*Sanborn*, 1960], and the Hogback Mountain suite of Fe-Ti-rich intrusions that reportedly lack arc compositional affinities [*Renne and Scott*, 1988]. Aside from contact metamorphic rocks reported by *Wright and Fahan* [1988], the only metamorphic ages in the 177–167 Ma range are 169.6±0.7 Ma and 173.1±0.6 Ma ages on hornblende from amphibolite that forms basement to the Rogue Formation [J. D. Yule and B. R. Hacker, unpublished data, 1994].

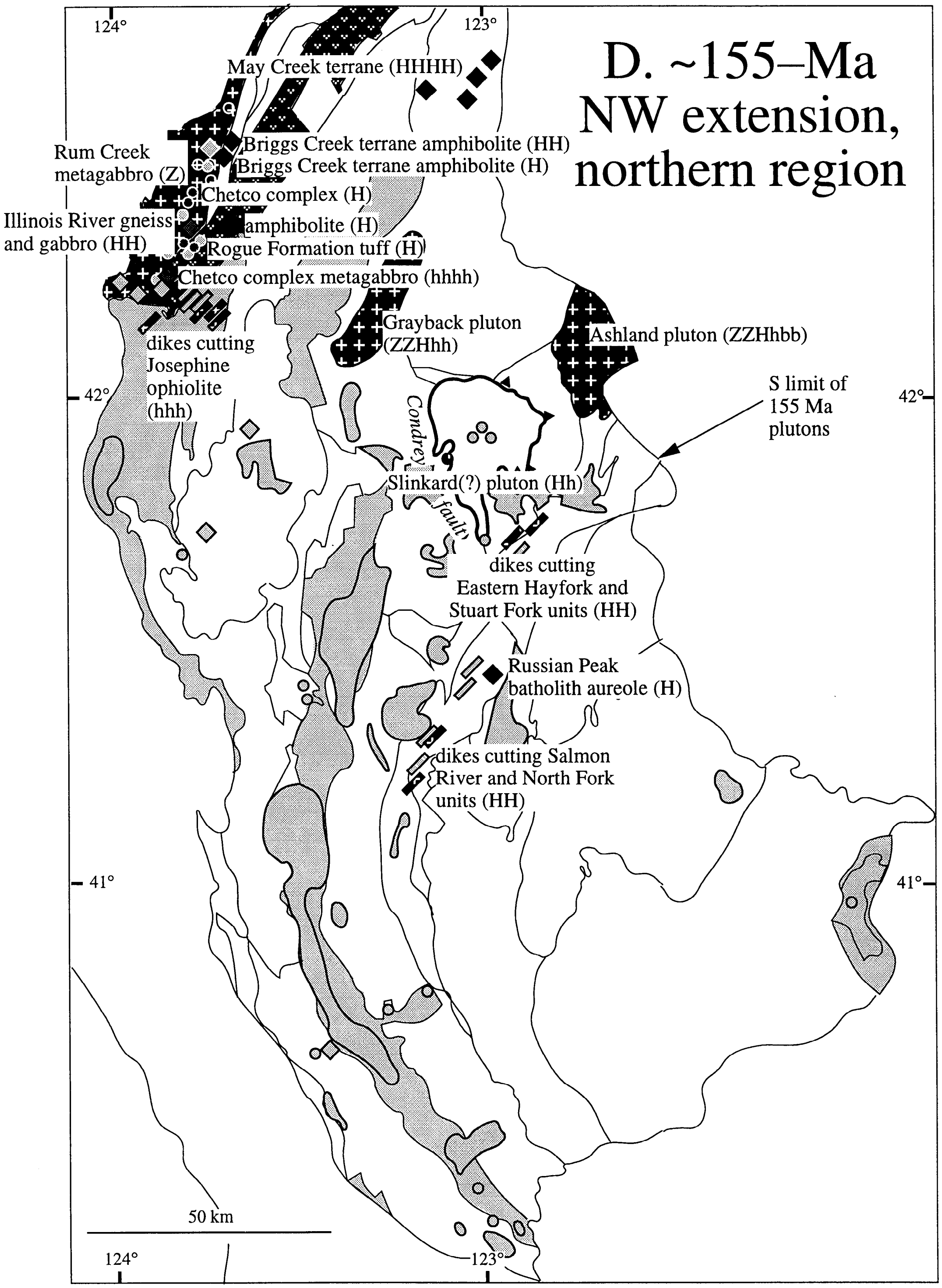

Figure 5. (continued)

Late Middle Jurassic (167–159 Ma)

The Wooley Creek plutonic belt [*Irwin*, 1985a; *Barnes et al.*, 1992c] constitutes a group of granitic to gabbroic calc-alkaline to calcic plutons (Slinkard, Thompson Ridge, and Vesa Bluffs plutons and the English Peak, Wooley Creek, and Russian Peak batholiths; Figure 5c) that range in igneous crystallization (U/Pb zircon) age from 165 to 159 Ma [*Barnes et al.*, 1986a, b; *Wright and Fahan*, 1988]. Coeval volcanic rocks have not been recognized, but may include the youngest parts of the Salmon River unit [*Hacker*, 1993]. Field and geochemical evidence shows that the mafic to intermediate parts of these plutons were open to influx of basaltic magmas at and below the level of intru-

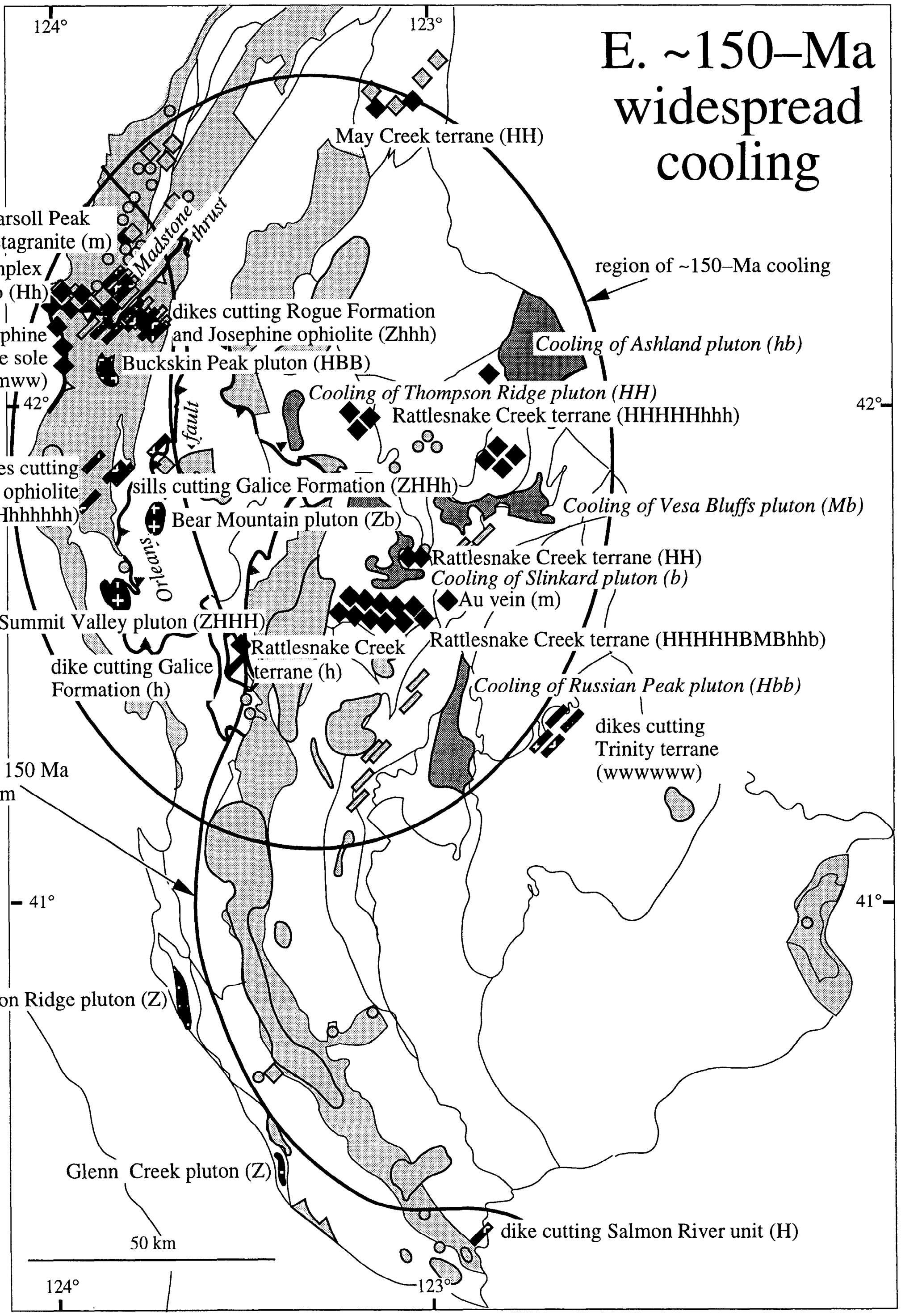

Figure 5. (continued)

sion [*Barnes et al.*, 1986a]. Initial $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values for the belt indicate that even the most mafic magmas assimilated deep-seated crustal rocks or mixed with crustal melts prior to final emplacement [*Barnes et al.*, 1992c]. Two-mica granites in the Slinkard and Vesa Bluffs plutons and late stage hornblende-biotite granite in the Wooley Creek batholith [*Hotz*, 1971; *Barnes et al.*, 1986a] are probably representative of crustal melts, and their compositions suggest a graywacke-like source.

The Heather Lake pluton yielded a 167 Ma $^{40}Ar/^{39}Ar$ hornblende age (Figure 5c; Table 1), suggesting that it too is part of this suite. Dikes in the North Fork and Salmon

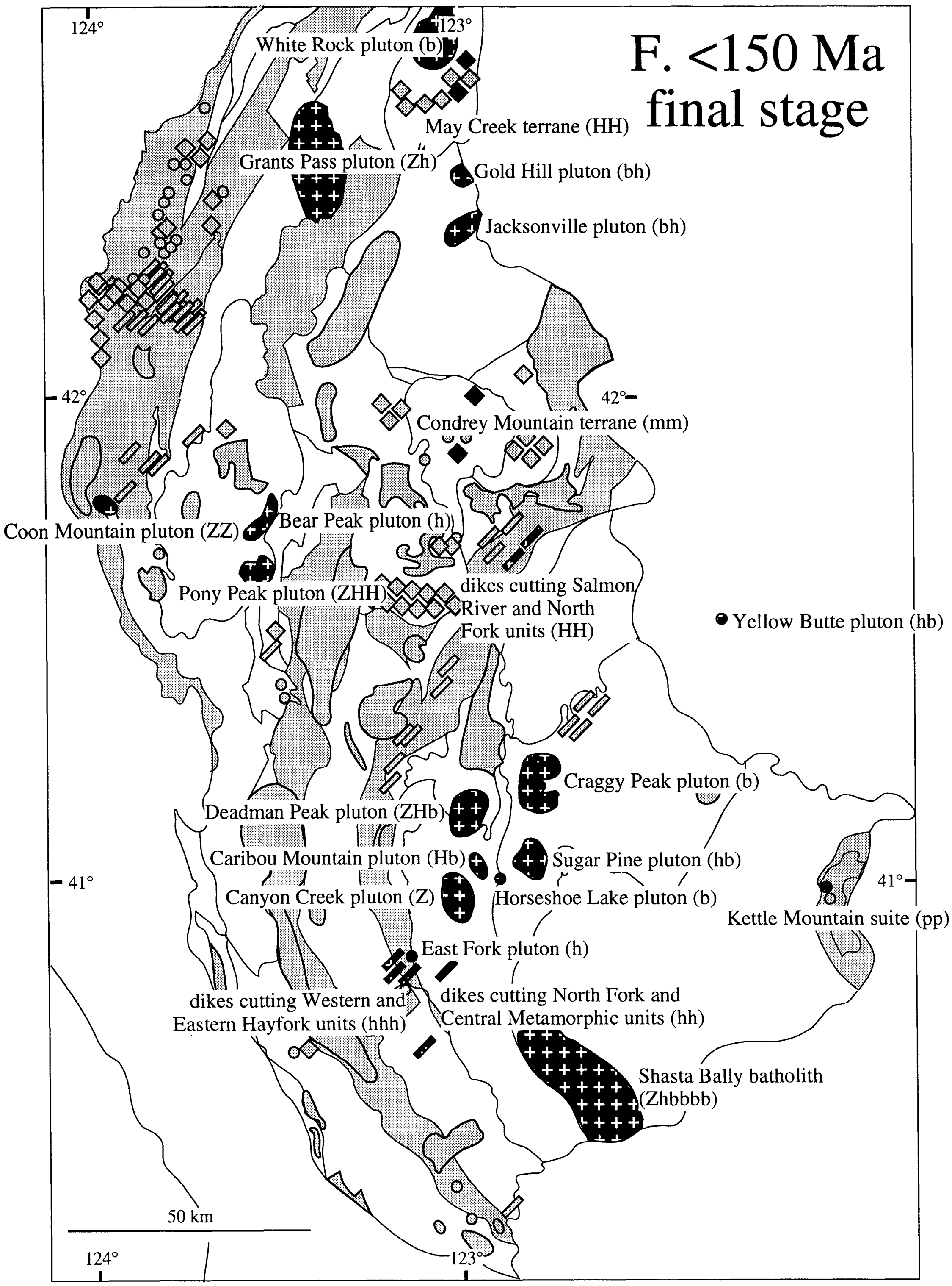

Figure 5. (continued)

River units also have comparable ^{40}Ar/^{39}Ar ages (Table 1 of *Hacker and Ernst* [1993]). *Irwin* [1985a] included the Ashland pluton (Figure 5d) in the Wooley Creek belt, but its ^{40}Ar/^{39}Ar hornblende age of 153.6 Ma suggests that its crystallization postdated 159 Ma. Volcanoplutonism of similar age occurred farther east and west in the Klamath Mountains, including formation of the Castle Crags pluton, Preston Peak ophiolite, Josephine ophiolite, and Rogue–Chetco arc. Igneous features of this age in the central Klamaths are restricted to a NW trending corridor, either because magmatic activity was limited to this zone or because coeval igneous features north and south of the corridor are not exposed (Figure 5c).

Late Jurassic (~155 Ma)

Plutonic and volcanic rocks of ~155 Ma age are also restricted to a particular part of the Klamaths (Figure 5d). The area is north of the slightly older Wooley Creek belt. Rocks of this age include the Grayback pluton, Ashland pluton, and the Rum Creek metagabbro (s1, d3, and d13 of Table 1 of *Hacker and Ernst* [1993]). The Grayback and Ashland plutons are generally similar to the Wooley Creek belt, display open system characteristics, and have field and isotopic evidence for interaction with deep-seated crustal melts [*Barnes et al.*, 1992a]. Hypabyssal rocks of this age intrude the North Fork unit, Stuart Fork terrane, Eastern Hayfork unit, Salmon River unit, and Josephine ophiolite (d5–d12 of Table 1 of *Hacker and Ernst* [1993]). Another six $^{40}Ar/^{39}Ar$ hornblende ages from this extended corridor—Rogue Formation tuff (153.4±0.6 Ma), Chetco complex metagabbro (155.3±0.5 Ma), Briggs Creek subterrane (156.8±0.5 and 157.9±0.5 Ma), and Illinois River gabbro complex (156.3±0.6 and 156.0±0.5 Ma) (J. D. Yule and B. R. Hacker, unpublished data, 1994)—lend further support to a northward migration of magmatism.

Latest Jurassic (~150 Ma)

Yet another notable change occurred in the Klamath Mountains at 152–148 Ma, but in this case, the evidence comes from cooling ages as well as from crystallization ages. Igneous bodies of this age (e1–e24 of Table 1 of *Hacker and Ernst* [1993]) are generally restricted to the westernmost Klamaths, and consist exclusively of dikes and small, calc-alkaline to calcic plutons (Figure 5e). Zircon, hornblende, and biotite ages indicate cooling of the Bear Mountain, Summit Valley, and Buckskin Peak plutons to <350°C within 5 m.y. after emplacement [*Snoke et al.*, 1981; *Saleeby et al.*, 1982; *Harper et al.*, 1994]. Metamorphic cooling ages in the 148–152 Ma range have been reported from amphibolite facies rocks in the sole of the Josephine ophiolite and at more than two dozen localities throughout the Rattlesnake Creek and May Creek terranes (Figure 5e; e25–e58 of Table 1 of *Hacker and Ernst* [1993]). Moreover, many of the hornblende and mica $^{40}Ar/^{39}Ar$ and K-Ar ages from the Rattlesnake Creek terrane are concordant, suggesting rapid cooling to <350°C. Hornblende and mica ages indicate that five Klamath plutons (four of which ring the Condrey Mountain terrane) also cooled through amphibolite-facies conditions at this time, even though their igneous crystallization ages are ~9–15 m.y. older (medium shading in Figure 5e). For example, the Russian Peak pluton has a U/Pb zircon age of ~159 Ma [*Wright and Fahan*, 1988], a $^{40}Ar/^{39}Ar$ hornblende age of 152.1±0.5 Ma (this paper), and biotite K-Ar ages of 147±2 and 144±2 Ma [*Evernden and Kistler*, 1970].

Latest Jurassic and Earliest Cretaceous

Latest Jurassic and earliest Cretaceous time saw a return to widely distributed magmatism (Figure 5f). Many weakly metamorphosed dikes and plutons of this age intrude the Klamath Mountains (f1–f23 of Table 1 of *Hacker and Ernst* [1993]). *Barnes et al.* [1992c] presented trace element and isotopic data which showed that trondhjemitic Lower Cretaceous plutons (White Rock, Caribou Mountain, Canyon Creek, Sugar Pine, and Craggy Peak) were derived by melting of an amphibolite facies crustal source and generally were not contaminated by metasedimentary rocks (see also *Arth and Hanson* [1972]). Other Cretaceous plutons in the Klamaths (e.g., Grants Pass, Jacksonville, Pony Peak, and Gold Hill plutons) are more potassic than the trondhjemites, and have high $\delta^{18}O$ and low initial $^{87}Sr/^{86}Sr$ [*Barnes et al.*, 1992b, 1992c]. The isotopic data and the presence of inherited Proterozoic zircon in the Grants Pass [*Saleeby*, 1984], Coon Mountain, and Pony Peak [*Harper et al.*, 1994] plutons suggest that these magmas assimilated young metasedimentary crustal rocks prior to or during emplacement.

Deformational Features

The characteristics and ages of deformation on a regional scale in the Klamaths are less well known than volcanoplutonic and metamorphic features. Faults of regional extent and displacement are shown in Figures 1 and 5.

Displacement on the Siskiyou fault (Figure 5b) placed the Central Metamorphic terrane ≥25 km over the Stuart Fork terrane, St Claire Creek, and North Fork units [*Davis et al.*, 1965; *Goodge*, 1990]. Movement postdated deposition of Lower to Middle Jurassic radiolarians in the St Claire Creek unit and predated emplacement of the 159 Ma Russian Peak batholith [*Wright and Fahan*, 1988].

The Stuart Fork terrane was thrust more than 35 km over the Sawyers Bar terrane along the Soap Creek Ridge thrust (Figure 5b) [*Hotz*, 1977; *Coleman et al.*, 1988]. Movement predated cooling of the Vesa Bluffs pluton at 165 Ma (Table 1) and postdated Middle Jurassic radiolarian deposition [*Mortimer*, 1984] in the footwall.

Plutons of the Western Hayfork terrane were crystallizing while that terrane was thrust beneath the Sawyers Bar terrane at least 20 km along the Wilson Point fault, effectively constraining the age of faulting to ~170 Ma (Figure 5b) [*Wright and Fahan*, 1988]. The northward extension of the Wilson Point thrust is cut by the Wooley Creek batholith, which places an age limit of ~161 Ma on movement in the central Klamaths. The Salt Creek fault (Figure 5b) accommodated ~60 km of displacement of the Western Hayfork terrane over the Rattlesnake Creek terrane [*Coleman et al.*, 1988] after crystallization of the 169 Ma Chanchelulla Peak pluton [*Wright and Fahan*, 1988]; faulting may have ended prior to 165 Ma if the foliation within the Rattlesnake Creek terrane truncated by the Vesa Bluffs plutons is related to motion along this fault [*Wright and Wyld*, 1994] (Figure 5b).

The Rattlesnake Creek terrane lies structurally above the Condrey Mountain terrane along the Condrey fault (Figure 5d), and on top of the Josephine ophiolite and Galice Formation along the Orleans fault (Figure 5e). 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 et al.*, 1986]. Displacement on the Orleans fault was toward the WNW, occurred prior to crystallization of the 150 Ma Summit Valley pluton (Figure 5e) [*Harper et al.*, 1994], and must postdate the Oxfordian–Kimmeridgian Galice Formation in the footwall. The Condrey fault places high-temperature metamorphic 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 batholith, and the Slinkard, Ashland, and Vesa Bluffs plutons [*Barnes*, 1982; *Mortimer*, 1984; *Barnes et al.*, 1986a; *Jachens et al.*, 1986]. A synthrusting leucosome within the Condrey fault zone at the base of the Rattlesnake Creek terrane has given a U/Pb age of 157±1 Ma, and nearby gneissic amphibolite yielded a ^{40}Ar/^{39}Ar hornblende age of 152 ± 1 Ma, suggesting that amphibolite facies metamorphism and coincident thrusting ended by that time [*Saleeby and Harper*, 1993]. Widespread hornblende and scattered mica ^{40}Ar/^{39}Ar ages in the upper plate of the Condrey thrust support rapid cooling at ~150 Ma, whereas Rb/Sr and K-Ar ages indicate that the deeper levels of the lower plate cooled through similar temperatures ~20 m.y. later [*Helper et al.*, 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 et al.*, 1994].

The Josephine ophiolite was thrust NNE over the still active Rogue–Chetco arc on the Madstone thrust (Figure 5e) between 155 and 150 Ma [*Harper et al.*, 1994]. This deformation also produced slaty cleavage in the Galice Formation, coeval with deposition [*Harper et al.*, 1994].

Most of the aforementioned faults are demonstrably thrusts that place higher-pressure rocks over lower-pressure assemblages. Some major faults in the Klamath Mountains, however, probably 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 the amphibolite facies Rattlesnake Creek terrane to the north and greenschist facies Sawyers Bar terrane to the south [*Donato et al.*, 1982]. We tentatively suggest that this structure, the Marble Mountains fault (Figure 5c), is a south dipping normal fault [*Hacker et al.*, 1992a]. *Saleeby* [1990] also noted that this structure might have undergone low-angle normal movement. 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 a change in the orientation of foliation. Foliation undergoes a marked change from steep ESE dips south of the fault to gentle and moderate southward or eastward dips north of the fault [*Welsh*, 1982; *Donato*, 1985; *Ernst*, 1987; B.R. Hacker, unpublished data, 1992]. 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 [*Saleeby and Harper*, 1993] and predated intrusion of the 161 Ma Wooley Creek batholith [*Barnes et al.*, 1986a]. If the Western Hayfork terrane was excised along this structure, faulting must also postdate that 167 to 170 Ma period of magmatism (Fig. 5c). Faults analogous to the Marble Mountains fault may also be exposed in more northerly parts of the Klamath Mountains.

Intepretation of Klamath Orogenic Features

Much of the Klamath orogen was built during Jurassic time. *Burchfiel and Davis* [1981] suggested that the Eastern Hayfork unit formed in an accretionary wedge outboard of the Jurassic–Triassic volcanoplutonic arc in the eastern Klamaths. *Wright* [1981] added 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 et al.* [1993] proposed that the North Fork and Salmon River units together represent an immature magmatic arc.

Activity at ~200 Ma

At roughly 200 Ma (earliest Jurassic time), a magmatic arc was built in the Rattlesnake Creek terrane [*Wright and Wyld*, 1994]; a similar arc edifice may have formed in the Salmon River unit [*Hacker et al.*, 1993]. The presence of ~200 Ma plutons and associated volcanic rocks in the Rattlesnake Creek terrane and Salmon River unit raises the possibility that these now separated rock sequences were once contiguous—or at least tectonically related (Figure 3). 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 (200 Ma ^{40}Ar/^{39}Ar hornblende age) diabase rather than melange or volcaniclastic rocks, but serpentinite and mafic volcanic rocks are abundant nearby. Moreover, a Permian to Triassic U/Pb zircon age demonstrates that basement rocks older than 200 Ma are present within the Salmon River unit [*Ando et al.*, 1983]. If parts of the Rattlesnake Creek and Salmon River units represent a once coherent, single ~200 Ma arc, the presence of intervening Upper Permian to Upper Triassic Eastern Hayfork sedimentary rocks mandates significant structural disruption. The probability that the Rattlesnake Creek terrane is exotic with respect to the rest of the Klamaths is reduced if portions of the Rattlesnake Creek terrane and the Salmon River unit are related. These units have not been investigated in sufficient detail to evaluate this suggestion fully, however, and their similarities may be more apparent than real. There are also volcanic rocks of earliest Jurassic age in the Eastern Klamath terrane (Arvison Formation), but it is unclear how or if they are related to either the Salmon River unit or the Rattlesnake Creek terrane.

Paleomagnetic data suggest that at about 200 Ma (the J1 apparent polar wander cusp), North American plate motion underwent a marked change to more northward movement [*May and Butler*, 1986]. It is possible that the 200 Ma volcanoplutonic suite is related to this tectonic event. Until more information regarding 200 Ma metamorphism, sedimentation, and deformation is obtained, this earliest Jurassic orogeny will remain an enigma.

Activity at ~170 Ma

Construction of a volcanoplutonic arc, followed by regional contraction and associated metamorphism of Middle Jurassic age, has been called the Siskiyou orogeny [*Coleman et al.*, 1988; *Wright and Fahan*, 1988]. No changes in plate motion or collisions have been identified as possible causes of this activity, although *Saleeby* [1992] suggested collision of the Insular superterrane (now in Canada) as a possibility.

At 177–169 Ma, the Western Hayfork arc formed; the basement of the Western Hayfork arc sensu stricto may have been the Rattlesnake Creek terrane (Figure 5b) [*Wright and Fahan*, 1988]. Igneous rocks of this age intrude the Eastern Hayfork unit, the Condrey Mountain and Rattlesnake Creek terranes, and the Salmon River unit. Moreover, the last phase of volcanism in the Eastern Klamath terrane (Potem Formation) occurred at this time. The relationship between these ~170 Ma magmatic belts is poorly understood, although they apparently all formed in proximity to one another [*Wright and Fahan*, 1988].

The abundance of volcanoplutonic arc rocks and the presence of dikes (China Peak area and Salmon River unit) suggest that deformation during magmatism was dominated by extension. Shortly thereafter, during the 170 to 165 Ma interval, units throughout the Klamath Mountains were telescoped together coincident with crystallization of 170 to 167 Ma plutons [*Renne and Scott*, 1988; *Wright and Fahan*, 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. *Barnes et al.* [1992c] interpreted this telescoping event to have emplaced at a deep structural level the metasedimentary crustal rocks which subsequently gave rise to granitic melts that formed the Wooley Creek and Grayback belts.

The only bona fide pre-167–Ma metamorphic cooling ages in the Klamath Mountains come from the aureole surrounding the deformed pluton at Pigeon Point [*Wright and Fahan*, 1988], and from amphibolite beneath the Rogue Formation (J. D. Yule and B. R. Hacker, unpublished data, 1994). The rest of the metamorphic rocks traditionally assigned to "Siskiyou" metamorphism have subsequently yielded considerably younger ages. *Coleman et al.* [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 plutonic bodies such as the Wooley Creek batholith, Vesa Bluffs pluton, and Heather Lake pluton, 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 to 170 Ma protolith ages [*Wright and Fahan*, 1988; *Saleeby and Harper*, 1993] apparently constrain the Siskiyou event to 167–170 Ma. For this reason, K-Ar hornblende ages from amphibolite of ~150 Ma [*Lanphere et al.*, 1968] were discounted by *Coleman et al.* [1988] as too young. The large region of ~150 Ma cooling ages reviewed here indicates, however, that "Siskiyou" metamorphic rocks remained in excess of 350°C well into the Late Jurassic—about 10–15 m.y. after igneous crystallization of the supposedly postmetamorphic Wooley Creek belt. These age relationships between plutons and regional metamorphism and the low to moderate metamorphic pressures [*Burton*, 1982; *Chambers*, 1983; *Rawson*, 1984; *Barnes et al.*, 1986b; *Lieberman and Rice*, 1986; *Donato*, 1989] substantiate the suggestion that the Siskiyou event occurred within an active magmatic arc [*Coleman et al.*, 1988]. Thus, the type "Siskiyou" metamorphism in the central Klamaths cannot be related confidently to Middle Jurassic events.

Activity at ~167 to 155 Ma

Between the time frames conventionally assigned to the Siskiyou and Nevadan orogenies, some of the most voluminous Klamath magmatism and, we infer, concomitant widespread extension, occurred (Figure 5c). Rifting within the Rattlesnake Creek terrane led to formation of the Rogue–Chetco arc, the Preston Peak ophiolite, and the Josephine ophiolite over the interval 165–160 Ma [*Harper and Wright*, 1984; *Wyld and Wright*, 1988; *Harper et al.*, 1990; *Saleeby*, 1990]. The Wooley Creek belt formed coevally and was followed within ~5 m.y. by the Grayback and Ashland plutons farther north. Dikes intruded the Sawyers Bar, Eastern Hayfork, North Fork, and Stuart Fork terranes throughout this interval. Except for the Josephine ophiolite, these features crop out within a NW trending corridor in the central Klamaths. The Russian Peak batholith, Wooley Creek batholith, and Grayback pluton are elongate to the NE and SW, suggesting that they were emplaced during NW–SE subhorizontal extension. Dike orientations within the Josephine ophiolite [*Harper*, 1982] and Sawyers Bar terrane [*Ernst*, 1993] suggest N–S and NNE extension, respectively. A N–S trending dike swarm related to the 157 Ma Grayback pluton cuts earlier, post-Western Hayfork north–south normal faults [*Barnes et al.*, 1993]. Evidence for open system magmatism and abundant influx of basaltic melts in the Wooley Creek belt and 155 Ma suites is also consistent with an extensional environment. Large-scale NW–SE extension may have been accommodated by normal faults such as the Marble Mountains fault. It is possible that many contractional faults such as the Salt Creek, Soap Creek Ridge, Condrey, and Siskiyou faults were in motion during this same time frame—either coincident with extension in nearby areas or in alternating phases.

We equate the southern edge of the extended corridor with the Salmon tectonic line of *Irwin* [1985a, 1989], but a northern, potentially more convoluted, boundary has not been recognized. 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. Displacement on the Salmon tectonic line should increase from zero at its eastern end to a maximum at its western end, explaining the puzzling disappearance of its eastern end noted by *Irwin* [1989]. The Forks of Salmon pluton, which predates this phase of extension, may owe its unusual sigmoidal shape to strike-slip motion along the Salmon tectonic line. Construction of this wide belt of volcanoplutonism could be related to transform tectonism behind a subduction zone [*Harper et al.*, 1985; *Saleeby et al.*, 1992].

Igneous activity recorded by the Josephine ophiolite ceased, and flysch of the Galice Formation blanketed the Western Klamath terrane from ~157 to 150 Ma during continued activity in the Rogue–Chetco arc. Farther east in the central Klamaths, magmatism (Grayback and Ashland plutons) shifted northward from the region encompassed by the Wooley Creek belt, but covered the same east–west extent. The northward propagation in rifting may be related to the collision of a spreading ridge with the continental margin as proposed by *Murchey and Blake* [1993].

Activity at ~150 Ma

Paleomagnetic data suggest that North American plate motion underwent another marked change at about 150 Ma (J2 apparent polar wander cusp) [*May et al.*, 1989]. Deposition of Galice Formation flysch ceased, and structures and metamorphism characteristic of the Nevadan orogeny developed (Figure 5e).

The major structural expression of the Nevadan orogeny was thrust faulting from 155 to 150 Ma along the Madstone and Orleans faults [*Harper et al.*, 1990], but deformation of the Galice Formation and retrograde metamorphic assemblages formed in terranes farther east have also been attributed to the Nevadan orogeny [*Donato*, 1985; *Hill*, 1985]. The Josephine ophiolite was thrust in a NNE direction (present coordinates) over the still active Rogue–Chetco arc on the Madstone thrust between 146 and 152 Ma [*Harper et al.*, 1990, 1994]. *Cashman* [1988] and *Harper* [1992] also reported strain measurements in the Galice Formation suggesting orogen-parallel stretching at this time. The final motion of the Rattlesnake Creek terrane, the Wooley Creek batholith, the Slinkard pluton, and the Vesa Bluffs pluton WNW over the Condrey Mountain terrane along the Condrey fault occurred by 152–150 Ma [*Saleeby and Harper*, 1993]. The ^{40}Ar/^{39}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 deeper part of the lower plate cooled through similar temperatures ~20 m.y. later [*Helper et al.*, 1989]. Rapid refrigeration of the upper plate may be related to thrusting of the cooler Condrey Mountain terrane beneath the Rattlesnake Creek terrane [*Harper et al.*, 1994].

Latest Jurassic and Earliest Cretaceous Activity

Volumetrically minor arclike magmatism and minor deformation lasted in the Klamath orogen until 135 Ma (Figure 5f) [*Harper and Wright*, 1984]. This has two significant implications: Not only did arc magmatism continue until approximately 135 Ma, but metamorphism of the country rock apparently lasted into Early Cretaceous time. Additional evidence for significant heat retention into Cretaceous time comes from the Condrey Mountain terrane, which yielded muscovite K-Ar ages of 125–143 Ma and Rb-Sr isochron ages of 125–139 Ma [*Helper et al.*, 1989]. Although mafic and intermediate parts of the Grants Pass, Gold Hill, Jacksonville, and Shasta Bally plutons display trace element evidence of arc activity (C.G. Barnes, unpublished data, 1993], their small volumes and nonsystematic spatial distribution may indicate emplacement in a transpressional/transtensional environment. If so, the arc signature is probably due to tapping of source mantle and crust that had inherited the characteristics of an arc source earlier in the development of the province. *Harper et al.* [1994] suggested that Mesozoic orogenesis in the Klamaths was terminated by a final extensional episode between 135 and ~130 Ma.

Coeval Orogenic Activity in the Sierra Nevada

The orogenic features recognized in the Klamath Mountains have clear parallels in the Sierra Nevada and perhaps elsewhere in the Jurassic arc of the North American Cordillera. This concordance suggests that the causative plate tectonic processes had orogen-wide effects.

Roughly 200 Ma mafic arc complexes are found the length of the Sierra Nevada metamorphic belt, typically in more westerly outcrops—including the Slate Creek and Smartville complexes and the Peñon Blanco Formation [*Saleeby*, 1982; *Edelman et al.*, 1989a, b; *Edelman and Sharp,* 1989; *Saleeby et al.*, 1989b]. The Sierra Nevada also contains a signature of post-200 Ma, pre-176 Ma deformation and metamorphism [*Edelman et al.*, 1989a, b; *Edelman and Sharp,* 1989; *Hacker*, 1993] not recognized in the Klamath Mountains.

Similar to the Klamaths, the Sierra Nevada contains widespread ~170 Ma plutons [*Hacker*, 1993] and indications of pre-165 Ma thrusting [*Renne and Turrin*, 1987; *Edelman et al.*, 1989a, b; *Edelman and Sharp*, 1989]. Igneous activity and associated extension in the 167 to 155 Ma time frame occurred throughout the Sierra Nevada, including the Smartville complex, Folsom dike swarm, and Sonora dike swarm [*Schweickert et al.*, 1988; *Edelman et al.*, 1989a, b; *Edelman and Sharp,* 1989; *Saleeby et al.*, 1989b]. Motion along parts of the extensive Foothills fault system, often considered a major feature of the Nevadan orogeny, occurred prior to 159 Ma [*Day et al.*, 1985; *Edelman et al.*, 1989a; *Hacker*, 1993].

As in the Klamaths, dike intrusion occurred as late as 148 Ma in the Independence dike swarm and the Owen Mountain dike swarm-shear zone [*Chen and Moore*, 1979; *Wolf and Saleeby*, 1992]. The north-south orientation of these dikes suggests east-west extension. Like the Klamath Mountains, structures in the Foothills terrane support oblique convergence at 150 Ma [*Paterson et al.*, 1989]. Unlike the Klamaths, igneous activity that began in Early Cretaceous time continued until the Late Cretaceous in the Sierra Nevada [*Stern et al.*, 1981].

Conclusions

Current concepts of Klamath orogenies must be revised in light of the growing body of more precise radiometrically derived chronology. Pigeonholing specific orogenic features into particular orogenies does not address the fundamental issue of what tectonic activity caused the orogeny. It is better to characterize each orogenic feature and its age and try to relate each to coeval features. For example, the "170 Ma" Siskiyou metamorphic event can no longer be conveniently restricted to a narrow time frame unless its scope is redefined. Amphibolite facies metamorphism probably began near 167 Ma around the Heather Lake pluton and perhaps as late as 161 Ma around the Wooley Creek batholith, but the area immediately north of both igneous bodies remained above greenschist facies temperatures until 150 Ma, well within the conventional age range of the Nevadan orogeny.

Orogenies in the Klamath Mountains and Sierra Nevada are often thought of as the result of collision [e.g., *Ingersoll and Schweickert*, 1986]. The Klamath Mountains do not contain direct evidence of successive outboard accretion of volcanoplutonic arcs, but rather reflect repeated formation and collapse of arcs essentially in situ. These alternating periods of contraction and extension [*Wright and Fahan*, 1988] (probably with considerable margin-parallel translation as well) are fundamental to the growth of Klamath-type orogens.

Tectonic plates are large features and undergo relatively constant motions for extended time periods. This leads naturally to the assumption that a span of several tens of millions of years might witness a single, short orogenic event that affects a large area within an orogen. The large geochronologic, petrologic, and structural database for the Klamath Mountains mandates considerable revision of this view. Widespread magmatism began at ~200 Ma, and these rocks subsequently formed the basement for younger intrusive episodes. Two now subparallel volcanoplutonic belts were active at around ~170 Ma, and although probably related to one another, they are presently separated by an older or coeval accretionary wedge. Understanding the plate tectonic processes responsible for these ~200 and 170 Ma rocks will require identification and analysis of associated metamorphic and sedimentary rocks. From 167 to ~155 Ma, alternating extension and contraction occurred along a NW–SE corridor in the northern Klamaths, perhaps because of oblique ridge collision. Still to be determined are details regarding the relation between contraction and extension, the ages and senses of motion on major faults, and the plate tectonic processes responsible. This same area underwent pronounced cooling at ~150 Ma, possibly as a result of deeper-level subduction.

Tobisch et al. [1989], *Saleeby et al.* [1989a], and *Paterson et al.* [1991] have reached similar conclusions by documenting diachronous plutonism, metamorphism, and deformation in domains of the southern Sierra Nevada metamorphic belt. They noted that the long-held assumption of contemporaneous cleavage and fold formation during the Nevadan orogeny is at odds with the long-lived nature of modern arc systems. A similar conclusion holds for the Jurassic of the Klamath Mountains.

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 sufficient to begin considering the ages and characteristics of specific plutons, deformation fabrics, and metamorphic minerals in individual areas, rather than assuming that such events occurred throughout the orogen within specific time ranges. Perhaps the principal insight to be gained is that instead of speaking of the Jurassic rocks of the Klamath Mountains as being the end product of two orogenies, we can now recognize spatially and temporally variable igneous activity, metamorphism, and deformation, and migration of thermal events along the strike of the orogen.

Many outstanding questions still remain. What happened in the Klamath Mountains between ~200 Ma and ~170 Ma, an interval for which there is no record of orogenic activity? What are the implications of the ~200 Ma and ~170 Ma volcanoplutonic arcs that are now recognized to be widespread features? What plate tectonic processes caused the orogenic signatures we observe? How do the orogenic features in the Klamath Mountains and Sierra Nevada differ and what do these differences tell us? Answers require much further work, and yet the existing Klamath database provides a firm foundation for progress.

Acknowledgments. Our synthesis relies heavily upon the earlier work of many other geologists cited in Table 1 of *Hacker and Ernst* [1993], and we encourage the interested reader to read those papers. We have benefited from reviews by Dave Harwood, Mark Helper, Bonnie Murchey, and, particularly, Greg Harper. This work was supported by Department of Energy grants DE-FGO3-90ER14154 and 8802-121 and NSF grants EAR 8720141 and EAR 9117103.

References

Albers, J.P., and J.F. Robertson, Geology and ore deposits of East Shasta copper-zinc district, Shasta County, California, *U. S. Geol. Surv. Prof. Pap., 338*, 107 pp., 1961.

Ando, C.J., Structural and petrologic analysis of the North Fork terrane central Klamath Mountains, California, Ph.D. dissertation, 197 pp., Univ. of South. Calif., Los Angeles, 1979.

Ando, C.J., W.P. Irwin, D.L. Jones, and J.B. Saleeby, The ophiolitic North Fork terrane in the Salmon River region, central Klamath Mountains, California, *Geol. Soc. Am. Bull., 94*, 236-252, 1983.

Arth, J.G., and G.N. Hanson, Quartz diorites derived by partial melting of eclogite or amphibolite at mantle depths, *Contrib. Mineral. Petrol., 37*, 161–174, 1972.

Baldwin, S.L., T.M. Harrison, and J.D. Fitz Gerald, Diffusion of ^{40}Ar in metamorphic hornblende, *Contrib. Mineral. Petrol., 105*, 691–703, 1990.

Barnes, C.G., Geology and petrology of the Wooley Creek batholith Klamath Mountains, northern California, Ph.D. dissertation, 213 pp., Univ. of Ore., Eugene, 1982.

Barnes, C.G., C.M. Allen, and J.B. Saleeby, Open- and closed-system characteristics of a tilted plutonic system, Klamath Mountains, California, *J. Geophys. Res., 91*, 6073-6090, 1986a.

Barnes, C.G., J.M. Rice, and R.F. Gribble, Tilted plutons in the Klamath Mountains of California and Oregon, *J. Geophys. Res., 91*, 6059-6071, 1986b.

Barnes, C.G., K. Johnson, M.A. Barnes, T. Prestvik, and R.W. Kistler, The Grayback pluton: Magmatism in a Jurassic back-arc environment, Klamath Mountains, Oregon, *Trans. R. Soc. Edinburgh Earth Sci., 83*, 485, 1992a.

Barnes, C.G., H.R. Karlsson, K. Johnson, and

R.W. Kistler, Isotopic variation of pre- and post-Nevadan plutons (Middle Jurassic–Early Cretaceous) Klamath Mountains, *Geol. Soc. Am. Abstr. Programs, 24*, 6, 1992b.

Barnes, C.G., S.W. Petersen, R.W. Kistler, T. Prestvik, and B. Sundvoll, Tectonic implications of isotopic variation among Jurassic and Early Cretaceous plutons, Klamath Mountains, *Geol. Soc. Am. Bull., 104*, 117–126, 1992c.

Barnes, C.G., M.M. Donato, and S.L. Tomlinson, Correlation of the Applegate Group in the Oregon Klamath Mountains with terranes of the western Paleozoic and Triassic belt in California, *Geol. Soc. Am. Abstr. Programs, 25*, 6, 1993.

Barrows, A.G., Geology of the Hamburg-McGuffy Creek area, Siskiyou County, California, and petrology of the Tom Martin ultramafic complex, Ph.D. dissertation, 301 pp., Univ. of California, Los Angeles, 1969.

Blackwelder, E., A summary of the orogenic epochs in the geologic history of North America, *J. Geol., 22*, 633–654, 1914.

Blake, M.C., D.G. Howell, and D.L. Jones, Preliminary tectonostratigraphic terrane map of California, U. S. Geol. Surv., *Open File Rep.*, 82-593, 1982.

Blake, M.C., D.C. Engebretson, A.S. Jayko, and D.L. Jones, Tectonostratigraphic terranes in southwest Oregon, in *Tectonostratigraphic Terranes of the Circum-Pacific Region*, Earth Sci. Ser., edited by D.G. Howell, pp. 147–157, Circum-Pacific Council for Energy and Mineral Resources, Houston Tex., 1985.

Blakely, R.J., R.C. Jachens, R.W. Simpson, and R.W. Couch, Tectonic setting of the southern Cascade Range as interpreted from its magnetic and gravity fields, *Geol. Soc. Am. Bull., 96*, 43-48, 1985.

Burchfiel, B.C., and G.A. Davis, Triassic and Jurassic tectonic evolution of the Klamath Mts-Sierra Nevada geologic terrane, in *The Geotectonic Development of California*, edited by W.G. Ernst, pp. 50–70, Prentice-Hall, Englewood Cliffs, N.J., 1981.

Burton, W.C., Geology of the Scott Bar Mountains, northern California, M.S. thesis, 120 pp., Univ. of Ore., Eugene, 1982.

Cashman, P.H., Geology of the Forks of Salmon area, Klamath Mountains, California, Ph.D. dissertation, 212 pp., Univ. of South. Calif., Los Angeles, 1979.

Cashman, S.M., Finite-strain patterns of Nevadan deformation, western Klamath Mountains, California, *Geology, 16*, 839–843, 1988.

Chambers, J.M., The geology and structural petrology of ultramafic and associated rocks in the northeast Marble Mountain wilderness, Klamath Mountains, northern California, M.S. thesis, 149 pp., Univ. of Ore., Eugene, 1983.

Charlton, D.W., Geology of part of the Ironside Mountain quadrangle, northern California Klamath Mountains, Ph.D. dissertation, 542 pp., Univ. Calif., Santa Barbara, 1979.

Chen, J.H., and J.G. Moore, Late Jurassic Independence dike swarm in eastern California, *Geology, 7*, 129–133, 1979.

Coleman, R.G., and M. Lanphere, The Briggs Creek amphibolite, Klamath Mountains, Oregon: Its origin and dispersal, *N. Z. J. Geol. Geophys., 34*, 271–284, 1991.

Coleman, R.G., C.E. Manning, M.M. Donato, N. Mortimer, and L.B. Hill, Tectonic and regional metamorphic framework of the Klamath Mountains and adjacent Coast Ranges, California and Oregon, in *Metamorphism and Crustal Evolution of the Western United States, Rubey vol VII*, edited by W.G. Ernst, pp. 1061-1097, Prentice-Hall, Englewood Cliffs, N.J., 1988.

Cox, D.P., Geology of the Helena Quadrangle, Trinity County, California, Ph.D. dissertation, 123 pp., Stanford Univ., Stanford, Calif., 1956.

Cox, D.P., and W.P. Pratt, Submarine chert-argillite slide-breccia of Paleozoic age in the southern Klamath Mountains, California, *Geol. Soc. Am. Bull., 84*, 1423-1438, 1973.

Davis, G.A., and B.C. Burchfiel, Garlock fault; An intracontinental transform structure, South. Calif., *Geol. Soc. Am. Bull., 84*, 1407–1422, 1973.

Davis, G.A., M.J. Holdaway, P.W. Lipman, and W.D. Romey, Structure, metamorphism, and plutonism in the south-central Klamath Mountains, California, *Geol. Soc. Am. Bull., 76*, 933–966, 1965.

Davis, G.A., J.W.H. Monger, and B.C. Burchfiel, Mesozoic construction of the Cordilleran "collage," central British Columbia to central California, in *Mesozoic Paleogeography of the Western United States*, edited by D.G. Howell and K.A. McDougall, pp. 1–32, Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, Calif., 1978.

Day, H.W., E.M. Moores, and A.C. Tuminas, Structure and tectonics of the northern Sierra Nevada, *Geol. Soc. Am. Bull., 96*, 436–450, 1985.

Dick, H.J.B., The origin and emplacement of the Josephine peridotite of southwestern Oregon, Ph.D. dissertation, 409 pp., Yale Univ., New Haven, Conn., 1976.

Dodson, M.H., Closure temperature in cooling geochronological and petrological systems, *Contrib. Mineral. Petrol., 40*, 259–274, 1973.

Donato, M.M., Metamorphic and structural evolution of an ophiolitic tectonic melange, Marble Mountains, northern California, Ph.D. dissertation, 257 pp., Stanford Univ., Stanford, Calif., 1985.

Donato, M.M., Evolution of an ophiolitic tectonic mélange, Marble Mountains, northern California Klamath Mountains, *Geol. Soc. Am. Bull., 98*, 448–464, 1987.

Donato, M.M., Metamorphism of an ophiolitic tectonic melange, Marble Mountains, northern California Klamath Mountains, USA, *J. Metamorph. Geol., 7*, 515-528, 1989.

Donato, M.M., Geochemical recognition of a captured back-arc basin metabasaltic complex, southwestern Oregon, *J. Geol., 99*, 711–728, 1991.

Donato, M.M., A newly recognized ductile shear zone in the northern Klamath Mountains, Oregon, *U.S. Geol. Surv. Bull., 2028*, 1992.

Donato, M.M., C.G. Barnes, R.G. Coleman, W.G. Ernst, and M.A. Kays, Geologic map of the Marble Mountain wilderness area, Siskiyou County, California, scale 1:48,000, *U. S. Geol. Surv., Misc. Field Stud. Map, MF-1452A*, 1982.

Edelman, S.H., and W.D. Sharp, Terranes, early faults, and pre-Late Jurassic amalgamation of the western Sierra Nevada metamorphic belt, California, *Geol. Soc. Am. Bull., 101*, 1420–1433, 1989.

Edelman, S.H., H.W. Day, and M.E. Bickford, Implications of U-Pb zircon ages for tectonic settings of the Smartville and Slate Creek complex, northern Sierra Nevada, *Geology, 17*, 1032–1035, 1989a.

Edelman, S.H., H.W. Day, E.M. Moores, S.M. Zigan, T.P. Murphy, and B.R. Hacker, Structure across a Mesozoic ocean-continent suture zone in the northern Sierra Nevada, California, *Spec. Pap. Geol. Soc. Am. 224*, 56, 1989b.

Ernst, W.G., Mafic meta-igneous arc rocks of apparent komatiitic affinities, Sawyers Bar area, central Klamath Mountains, northern California, *Spec. Publ. Geochem. Soc., 1*, 191-208, 1987.

Ernst, W.G., Accretionary terrane in the Sawyers Bar area of the western Triassic and Paleozoic belt, central Klamath Mountains, northern California, in Paleozoic and Early Mesozoic Paleogeographic Relations; Sierra Nevada, Klamath Mountains, and Related Terranes, edited by D.S. Harwood and M.M. Miller, *Spec. Pap. Geol. Soc. Am., 255*, 297–305, 1990.

Ernst, W.G., Chemically distinct mafic dike/sill sequences of contrasting age ranges, Sawyers Bar area, central Klamath Mountains, northern California, *J. Petrol.*, 1993.

Ernst, W.G., B.R. Hacker, M.D. Barton, and G. Sen, Occurrence, geochemistry and igneous petrogenesis of magnesian metavolcanic rocks from the WTrPz belt, central Klamath Mountains, northern California, *Geol. Soc. Am. Bull., 103*, 56–72, 1991.

Evernden, J.F., and R.W. Kistler, Chronology of emplacement of Mesozoic batholithic complexes in California and western Nevada, *U. S. Geol. Surv. Prof. Pap., 623*, 42 pp., 1970.

Fahan, M.R., Geology and geochronology of part of the Hayfork terrane, Klamath Mountains, northern California, M.S. thesis, 127 pp., Univ. Calif., Berkeley, 1982.

Fuis, G.S., J.J. Zucca, W.D. Mooney, and B. Milkereit, A geologic interpretation of seismic-refraction results in northeastern California, *Geol. Soc. Am. Bull., 98*, 53-56, 1987.

Garcia, M.O., Petrology of the Rogue and Galice Formation, Klamath Mountains, Oregon; Identification of a Jurassic island-arc sequence, *J. Geol., 86*, 29–41, 1979.

Garcia, M.O., Petrology of the Rogue River island-arc complex, southwest Oregon, *Am. J. Sci., 282*, 783–807, 1982.

Goodge, J.W., Polyphase metamorphic evolution of a Late Triassic subduction complex, Klamath Mountains, northern California, *Am. J. Sci., 289*, 874-943, 1989.

Goodge, J.W., Tectonic evolution of a coherent Late Triassic subduction complex, Stuart Fork terrane, Klamath Mountains, northern California, *Geol. Soc. Am. Bull., 102*, 86-101, 1990.

Goodge, J.W., and P.R. Renne, Mid-Paleozoic olistoliths in eastern Hayfork terrane mélange, Klamath Mountains: Implications for late Paleozoic-early Mesozoic Cordilleran forearc development, *Tectonics, 12*, 279–289, 1993.

Gorman, C.M., Geology, geochemistry and geochronology of the Rattlesnake Creek terrane, west-central Klamath Mountains, California, M.S. thesis, 111 pp., Univ. of Utah, Salt Lake City, 1985.

Gray, G.G., Structural, geochronologic, and depositional history of the western Klamath Mountains, California and Oregon: Implications for the early to middle Mesozoic tectonic evolution of the western North American Cordillera, Ph.D. dissertation, 161 pp., Univ. of Tex. at Austin, 1985.

Gray, G.G., Native terranes of the central Klamath Mountains, *Tectonics, 5*, 1043–1053, 1986.

Hacker, B.R., Evolution of the northern Sierra Nevada metamorphic belt: petrological, structural, and Ar/Ar constraints, *Geol. Soc. Am. Bull., 105*, 637–656, 1993.

Hacker, B.R., and W.G. Ernst, Jurassic orogeny in the Klamath Mountains: A geochronological approach, in *Mesozoic Paleogeography of the Western United States*, edited by D.G. Howell and K.A. McDougall, pp. 37-60, Society of Economic Paleontologists and

Mineralogists, Pacific Section, Los Angeles, Calif., 1978.

Hacker, B.R., M.M. Donato, and W.G. Ernst, Jurassic synmagmatic normal fault in the central Klamath Mountains, *Geol. Soc. Am. Abstr. Programs, 24*, 29, 1992a.

Hacker, B.R., W.G. Ernst, and M.D. Barton, Metamorphism, geochemistry, and origin of magnesian volcanic rocks, Klamath Mountains, California, *J. Metamorph. Geol., 10*, 55–69, 1992b.

Hacker, B.R., W.G. Ernst, and M.O. McWilliams, Genesis and evolution of a Permian–Jurassic magmatic arc/accretionary wedge, and reevaluation of terranes in the central Klamath Mountains, *Tectonics, 12*, 387–409, 1993.

Hamilton, W., Mesozoic tectonics of the western United States, in *Mesozoic Paleogeography of the Western United States*, edited by D.G. Howell and K.A. McDougall, pp. 33–70, Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, Calif., 1978.

Harper, G.D., The Josephine ophiolite—Remains of a Late Jurassic marginal basin in northwestern California, *Geology, 8*, 333-337, 1980.

Harper, G.D., Evidence for large-scale rotations at spreading centers from the Josephine ophiolite, *Tectonophysics, 82*, 25–44, 1982.

Harper, G.D., Contrasting thrust directions along the roof and basal thrusts of the Josephine-Galice Subterrane, western Klamath Mountains, *Geol. Soc. Am. Abstr. Programs, 24*, 31, 1992.

Harper, G.D., J.B. Saleeby, and E.A.S. Norman, Geometry and tectonic setting of sea-floor spreading for the Josephine ophiolite, and implications for Jurassic accretionary events along the California margin, in *Tectonostratigraphic Terranes of the Circum-Pacific Region*, Earth Sci. Ser., edited by D.G. Howell, pp. 239–257, Circum-Pacific Council for Energy and Mineral Resources, Houston Tex., 1985.

Harper, G.D., and J.E. Wright, Middle to Late Jurassic tectonic evolution of the Klamath Mountains, California-Oregon, *Tectonics, 3*, 759–772, 1984.

Harper, G.D., K. Grady, and J. Wakabayashi, A structural study of a metamorphic sole beneath the Josephine ophiolite, western Klamath terrane, California-Oregon, in Paleozoic and Early Mesozoic Paleogeographic Relations; Sierra Nevada, Klamath Mountains, and Related Terranes, edited by D.S. Harwood and M.M. Miller, *Spec. Pap. Geol. Soc. Am., 255*, 379–396, 1990.

Harper, G.D., J.B. Saleeby, and M. Heizler, Formation and emplacement of the Josephine ophiolite and the Nevadan orogeny in the Klamath Mountains, California-Oregon: U/Pb zircon and ^{40}Ar/^{39}Ar geochronology, *J. Geophys. Res., 99*, 4293–4321, 1994.

Harrison, T.M., Diffusion of ^{40}Ar in hornblende, *Contrib. Mineral. Petrol., 78*, 324-331, 1981.

Harrison, T.M., and J.D. Fitz Gerald, Exsolution in hornblende and its consequences for ^{40}Ar/^{39}Ar age spectra and closure temperature, *Geochimica Cosmochimica et Acta, 50*, 247-253, 1986.

Harrison, T.M., I. Duncan, and I. McDougall, Diffusion of ^{40}Ar in biotite: Temperature, pressure, and compositional effects, *Geochimica Cosmochimica et Acta, 49*, 2461-2468, 1985.

Helper, M.A., Deformation and high P/T metamorphism in the central part of the Condrey Mountain window, north-central Klamath Mountains, California and Oregon, *Mem. Geol. Soc. Am., 164*, 125–141, 1986.

Helper, M.A., N.W. Walker, and D.W. McDowell, Early Cretaceous metamorphic ages and Middle Jurassic U-Pb zircon ages for the Condrey Mountain schist, Klamath Mountains, NW Calif. and SW Oregon, *Geol. Soc. Am. Abstr. Programs, 21*, 92, 1989.

Hill, L.B., A tectonic and metamorphic history of the north-central Klamath Mountains, California, Ph.D. dissertation, 248 pp., Stanford Univ., Stanford, Calif., 1984.

Hill, L.B., Metamorphic, deformational, and temporal constraints on terrane assembly, northern Klamath Mountains, California, in *Tectonostratigraphic Terranes of the Circum-Pacific Region*, Earth Sci. Ser., edited by D.G. Howell, pp. 173–186, Circum-Pacific Council for Energy and Mineral Resources, Houston Tex., 1985.

Hinds, N.E.A., The Jurassic age of the last granitoid intrusives in the Klamath Mountains and Sierra Nevada, California, *Am. J. Sci., 227*, 182–192, 1934.

Hotz, P.E., Plutonic rocks of the Klamath Mountains, California and Oregon, *U. S. Geol. Surv. Prof. Pap., 684B*, B1-B20, 1971.

Hotz, P.E., Geology of the Yreka quadrangle, Siskiyou County, California, *U. S. Geol. Surv. Bull., 1436*, 72 pp., 1977.

Hotz, P.E., Regional metamorphism in the Condrey Mountain quadrangle, north-central Klamath Mountains, California, *U. S. Geol. Surv. Prof. Pap., 1086*, 1979.

Hotz, P.E., M.A. Lanphere, and D.A. Swanson, Triassic blueschist from northern California and north-central Oregon, *Geology, 5*, 659-663, 1977.

Ingersoll, R.V., and R.A. Schweickert, A plate-tectonic model for Late Jurassic ophiolite genesis, Nevadan orogeny and forearc initiation, northern California, *Tectonics, 5*, 901-912, 1986.

Irwin, W.P., Geology of the Klamath Mountains province, *Bull. Calif. Div. Mines Geol., 190*, 17–36, 1966.

Irwin, W.P., Terranes of the western Paleozoic and Triassic belt in the southern Klamath Mountains, California, *U.S. Geol. Surv. Prof. Pap., 800C*, C101-C111, 1972.

Irwin, W.P., Reconnaissance geologic map of the Hayfork Quadrangle, Trinity County, California, scale 1:62,500, *U.S. Geol. Surv. Misc. Field Invest., MF-576*, 1974.

Irwin, W.P., Age and tectonics of plutonic belts in accreted terranes of the Klamath Mountains, California and Oregon, in *Tectonostratigraphic Terranes of the Circum-Pacific Region*, Earth Sci. Ser., edited by D.G. Howell, pp. 187–199, Circum-Pacific Council for Energy and Mineral Resources, Houston Tex., 1985a.

Irwin, W.P., Reconnaissance geologic map of the Hyampom Quadrangle, Trinity County, California, scale 1:62,500, *U. S. Geol. Surv., Misc. Field Map, MF-1809*, 1985b.

Irwin, W.P., Cryptic tectonic domains of the Klamath Mountains, California and Oregon, *Eng.Geol., 27*, 433–448, 1989.

Irwin, W.P., D.L. Jones, and E.A. Pessagno, Significance of Mesozoic radiolarians from the pre-Nevadan rocks of the southern Klamath Mountains, California, *Geology, 5*, 557-562, 1977.

Irwin, W.P., D.L. Jones, and C.D. Blome, Map showing radiolarian localities in the western Paleozoic and Triassic belt, Klamath Mountains, California, scale 1:250,000, *U.S. Geol. Surv., Misc. Field Map, MF-1399*, 1982.

Irwin, W.P., B.R. Wardlaw, and T.A. Kaplan, Conodonts of the western Paleozoic and Triassic belt, Klamath Mountains, California and Oregon, *J. Paleont, 57*, 1030–1039, 1983.

Jachens, R.C., C.G. Barnes, and M.M. Donato, Subsurface configuration of the Orleans fault: Implications for deformation in the western Klamath Mountains, California, *Geol. Soc. Am. Bull., 97*, 388-395, 1986.

Kelley, S., The relationship between K-Ar mineral ages, mica grainsizes and movement on the Moine Thrust Zone, NW Highlands, Scotland, *J. Geol. Soc. London, 145*, 1–10, 1988.

Klein, C.W., Thrust plates of the north-central Klamath Mountains near Happy Camp, California, *Spec. Rep. Calif. Div. Mines Geol., 129*, 23–26, 1977.

Knopf, A., The Mother Lode system of California, *U. S. Geol. Surv. Prof. Pap., 157*, 88 pp., 1929.

Lanphere, M.A., W.P. Irwin, and P.E. Hotz, Isotopic age of the Nevadan orogeny and older plutonic and metamorphic events in the Klamath Mountains, California, *Geol. Soc. Am. Bull., 79*, 1027-1052, 1968.

Lawson, A.C., The Cordilleran Mesozoic revolution, *J. Geol., 1*, 579–586, 1893.

Lieberman, J.E., and J.M. Rice, Petrology of marble and peridotite in the Seiad ultramafic complex, northern California, USA, *J. Metamorph. Geol., 4*, 179-199, 1986.

Lindsley-Griffin, N., and J.R. Griffin, The Trinity terrane: An early Paleozoic microplate assemblage, in *Pre-Jurassic Rocks in Western North American Suspect Terranes*, edited by C.H. Stevens, 63–75, Society of Economic Paleontologists and Mineralogists, Tulsa, Okla., 1983.

Masi, U., J.R. O'Neil, and R.W. Kistler, Stable isotope systematics in Mesozoic granites of central and northern California and southwestern Oregon, *Contrib. Mineral. Petrol., 76*, 116–126, 1981.

May, S.R., and R.F. Butler, North American Jurassic apparent polar wander: implications for plate motion, paleogeography and Cordilleran tectonics, *J. Geophys. Res., 91*, 11519–11544, 1986.

May, S.R., M.E. Beck Jr., and R.F. Butler, North American apparent polar wander, plate motion, and left oblique convergence: Late Jurassic-Early Cretaceous orogenic consequences, *Tectonics, 8*, 443–451, 1989.

Medaris, L.G., Geology of the Seiad Valley area, Siskiyou County, California, and petrology of the Seiad ultramafic body, Ph.D. dissertation, 333 pp., Univ. Calif., Los Angeles, 1966.

Miller, M.M., and D.S. Harwood, Paleogeographic setting of upper Paleozoic rocks in the northern Sierra and eastern Klamath terranes, northern California, in Paleozoic and Early Mesozoic Paleogeographic Relations; Sierra Nevada, Klamath Mountains, and Related Terranes, edited by D.S. Harwood and M.M. Miller, *Spec. Pap. Geol. Soc. Am., 255*, 175–192, 1990.

Miller, M.M., and J.B. Saleeby, Permian and Triassic paleogeography of the Eastern Klamath arc and Eastern Hayfork subduction complex, Klamath Mountains, California. in *Paleozoic Paleogeography of the Western United States-II:*, vol. 67, edited by J.D. Cooper and C.H. Stevens, pp. 643–652, Society of Econonic Paleontologists and Mineralogists, Pacific Section, Los Angeles, Calif., 1991.

Miller, M.M., and J.E. Wright, Paleogeographic implications of Permian Tethyan corals from the Klamath Mountains, California, *Geology, 15*, 266–269, 1987.

Moores, E.M., Ultramafics and orogeny, with models for the U.S. Cordillera and the Tethys, *Nature, 228*, 837–842, 1970.

Moores, E.M., and H.W. Day, Overthrust model for the Sierra Nevada, *Geology, 12*, 416–419, 1984.

Mortimer, N., Petrology and structure of Permian to Jurassic rocks near Yreka, Klamath Mountains, California, Ph.D. dissertation, 83 pp., Stanford Univ., Stanford, Calif., 1984.

Mortimer, N., Structural and metamorphic aspects of Middle Jurassic terrane juxtaposition, northeastern Klamath Mountains, California, in *Tectonostratigraphic Terranes of the Circum-Pacific Region*, Earth Sci. Ser., edited by D.G. Howell, pp. 201–214, Circum-Pacific Council for Energy and Mineral Resources, Houston Tex., 1985.

Murchey, B.L., and J. M.C. Blake, Evidence for subduction of a major ocean plate along the California margin during the Middle to early Late Jurassic, in *Mesozoic Paleogeography of the Western United States,* vol. II, edited by G. Dunne and K. McDougall, pp. 1–18, Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, Calif., 1993.

Noble, P., and P. Renne, Paleoenvironmental and biostratigraphic significance of siliceous microfossils of the Permian-Triassic Redding section, eastern Klamath Mountains, California, *Mar. Micropaleontol., 15*, 379-391, 1990.

Ohr, M., Geology, geochemistry, and geochronology of the Lems Ridge olistostrome, Klamath Mountains, California, M.S. thesis, 278 pp., State Univ. of N.Y. at Albany, 1987.

Ohr, M., G.D. Harper, and J.E. Wright, Fracture zone origin of the Lems Ridge olistostrome, NW California, Klamath Mountains (abstract), *Eos Trans. AGU, 67*, 1210, 1986.

Onstott, T.C., and L. Pringle-Goodell, The influence of microstructures on the relationship between argon retentivity and chemical composition of hornblende, *Geochimica Cosmochimica et Acta, 52*, 2167–2168, 1988.

Paterson, S.R., O.T. Tobisch, and T. Bhattacharyya, Regional, structural and strain analyses of terranes in the western metamorphic belt, central Sierra Nevada, California, *J. Struct. Geol., 11*, 255–273, 1989.

Paterson, S.R., O.T. Tobisch, and R.H. Vernon, Emplacement and deformation of granitoids during volcanic arc construction in the Foothills terrane, central Sierra Nevada, California, *Tectonophysics, 191*, 89–110, 1991.

Pessagno, E.A., and C.D. Blome, Implications of new Jurassic stratigraphic, geochronometric, and paleolatitudinal data from the western Klamath terrane (Smith River and Rogue Valley subterranes), *Geology, 18*, 665–668, 1990.

Petersen, S.W., Geology and petrology around Titus Ridge, north-central Klamath Mountains, California, M.S. thesis, 73 pp., Univ. of Ore., Eugene, 1982.

Rawson, S.A., Regional metamorphism of rodingites and related rocks from the north-central Klamath Mountains, California, Ph.D. dissertation, 235 pp., Univ. of Ore., Eugene, 1984.

Renne, P.R., and G.R. Scott, Structural chronology, oroclinal deformation, and tectonic evolution of the southeastern Klamath Mountains, California, *Tectonics, 7*, 1223-1242, 1988.

Renne, P.R., and B.D. Turrin, Constraints on timing of deformation in the Benton Range, southeastern California, and implications to Nevadan orogenesis, *Geology, 15*, 1031–1034, 1987.

Saleeby, J.B., Polygenetic ophiolite belt of the California Sierra Nevada: Geochronological and tectonostratigraphic development, *J. Geophys. Res., 87*, 1803–1824, 1982.

Saleeby, J.B., Pb/U zircon ages from the Rogue River area, western Jurassic belt, Klamath Mountains, Oregon, *Geol. Soc. Am. Abstr. Programs, 16*, 331, 1984.

Saleeby, J.B., Geochronological and tectonostratigraphic framework of Sierran-Klamath ophiolitic assemblages, in Paleozoic and Early Mesozoic Paleogeographic Relations; Sierra Nevada, Klamath Mountains, and Related Terranes, edited by D.S. Harwood and M.M. Miller, *Spec. Pap. Geol. Soc. Am., 255*, 93–114, 1990.

Saleeby, J.B., Petrotectonic and paleogeographic settings of U.S. Cordilleran ophiolites, In *The Cordilleran Orogen: Conterminous U.S.., Decade of N. Am. Geol.*, vol G3, edited by B.C. Burchfiel, P.W. Lipman, and M.L. Zoback, pp. 653–682, Geological Society of America, Boulder, Colo., 1992.

Saleeby, J.B., and G.D. Harper, Tectonic relations between the Galice Formation and the schists of Condrey Mountain, Klamath Mountains, northern California, n *Mesozoic Paleogeography of the Western United States,* vol. II, edited by G. Dunne and K. McDougall, pp. 61–80, Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, Calif., 1993.

Saleeby, J.B., G.D. Harper, A.W. Snoke, and W.D. Sharp, Time relations and structural-stratigraphic patterns in ophiolite accretion, west central Klamath Mountains, California, *J. Geophys. Res., 87*, 3831-3848, 1982.

Saleeby, J.B., E.E. Geary, S.R. Paterson, and O.T. Tobisch, Isotopic systematics of Pb/U (zircon) and ^{40}Ar/^{39}Ar (biotite-hornblende) from rocks of the central Foothills terrane, Sierra Nevada, California, *Geol. Soc. Am. Bull., 101*, 1481–1492, 1989a.

Saleeby, J.B., H.F. Shaw, S. Niemeyer, and E.M. Moores, U/Pb, Sm/Nd, and Rb/Sr geochronological and isotopic study of northern Sierra Nevada ophiolitic assemblage, California, *Contrib. Mineral. Petrol., 102*, 205–220, 1989b.

Saleeby, J.B., C. Busby-Spera, J.S. Oldow, G.C. Dunne, J.E. Wright, D.S. Cowan, N.W. Walker, and R.W. Allmendinger, Early Mesozoic tectonic evolution of the western U.S. Cordillera, In *The Cordilleran Orogen: Conterminous U.S.., Decade of N. Am. Geol.*, vol G3, edited by B.C. Burchfiel, P.W. Lipman, and M.L. Zoback, pp. 107–168, Geological Society of America, Boulder, Colo., 1992.

Sanborn, A.F., Geology and paleontology of the southwest quarter of the Big Bend Quadrangle Shasta County, California, *Spec. Rep. Calif. Div. Mines Geol., 63*, 26 pp, 1960.

Scaillet, S., G. Feraud, M. Ballevre, and M. Amouric, Mg/Fe and [(Mg,Fe)Si-Al2] compositional control on argon behaviour in high-pressure white micas: A ^{40}Ar/^{39}Ar continuous laser-probe study from the Dora-Maira nappe of the internal western Alps, Italy, *Geochimica Cosmochimica et Acta, 56*, 2851–2872, 1992.

Schweickert, R.A., and D.S. Cowan, Early Mesozoic tectonic evolution of the western Sierra Nevada, California, *Geol. Soc. Am. Bull., 86*, 1329–1336, 1975.

Schweickert, R.A., N.L. Bogen, G.H. Girty, R.E. Hanson, and C. Merguerian, Timing and structural expression of the Nevadan orogeny, Sierra Nevada, California, *Geol. Soc. Am. Bull., 95*, 967–979, 1984.

Schweickert, R.A., C. Merguerian, and N.L. Bogen, Deformational and metamorphic history of Paleozoic and Mesozoic basement terranes in the western Sierra Nevada metamorphic belt, in *Metamorphism and Crustal Evolution of the Western United States, Rubey vol VII,* edited by W.G. Ernst, pp. 789–822, Prentice-Hall, Englewood Cliffs, N.J., 1988.

Sliter, W.V., D.L. Jones, and C.K. Throckmorton, Age and correlation of the Cretaceous Hornbrook Formation, in *Geology of the Upper Cretaceous Hornbrook Formation, Oregon and California*, edited by T.H. Nilsen, pp. 89–98, Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, Calif., 1984.

Smith, J.G., N.J. Page, M.G. Johnson, B.C. Moring, and F. Gray, Preliminary geologic map of the Medford 1° x 2° quadrangle, Oregon and California, scale 1:250,000, U.S. Geol. Surv., *Open-File Rep., 82-955*, 1982.

Snee, L.W., J.F. Sutter, and W.C. Kelly, Thermochronology of economic mineral deposits: Dating the stages of mineralization at Panasqueira, Portugal, by high-precision ^{40}Ar/^{39}Ar age spectrum techniques on muscovite, *Econ. Geol., 83*, 335–354, 1988.

Snoke, A.W., A thrust plate of ophiolitic rocks in the Preston Peak area, Klamath Mountains, California, *Geol. Soc. Am. Bull., 88*, 1641–1659, 1977.

Snoke, A.W., J.E. Quick, and H.R. Bowman, Bear Mountain igneous complex, Klamath Mountains, California, *J. Petrol., 22*, 501–522, 1981.

Stern, T.W., P.C. Bateman, B.A. Morgan, M.F. Newell, and D.L. Peck, Isotopic U-Pb ages of zircon from the granitoids of the central Sierra Nevada, California, *U.S. Geol. Surv. Prof. Paper, 1185*, 17 pp., 1981.

Stevens, C.H., M.M. Miller, and M.K. Nestell, A new Permian Waagenophyllid coral from the Klamath Mountains, California, *J. Paleont, 61*, 690-699, 1987.

Stevens, C.H., M.D. Luken, and M.K. Nestell, The Upper Permian fusulinids Reichelina and Parareichelina in northern California: Evidence for long-distance tectonic transport, In *Paleozoic Paleogeography of the Western United States-II*, edited by J.D. Cooper and C.H. Stevens, Pacific section Society of Economic Paleontologists and Mineralogists, pp. 635-642, 1991.

Taliaferro, N.L., Geologic history and correlation of the Jurassic of southwestern Oregon and California, *Geol. Soc. Am. Bull., 53*, 71–112, 1942.

Tobisch, O.T., S.R. Paterson, J.B. Saleeby, and E.E. Geary, Nature and timing of deformation in the Foothills terrane, central Sierra Nevada, California: Its bearing on orogenesis, *Geol. Soc. Am. Bull., 101*, 401–413, 1989.

Trexler, D.T., Geology of the northwest quarter of the Cecilville quadrangle, Siskiyou County, California, M.S. thesis, 133 pp., Univ. of South. Calif., Los Angeles, 1968.

Welsh, J.L., Structure, petrology, and metamorphism of the Marble Mountains area, Siskiyou County, California, Ph.D. dissertation, 250 pp., Univ. of Wisconsin, Madison, 1982.

Wendt, I., and C. Carl, The statistical distribution of the mean squared weighted deviation, *Chemical Geology, 86*, 275–285, 1991.

Whitney, J.D., The auriferous gravels of the Sierra Nevada of California, Mem. *6*, Harvard Mus. Comp. Zool., Cambridge, Mass., 1879.

Wolf, M.B., and J.B. Saleeby, Jurassic Cordilleran dike swarm-shear zones: Implications for the Nevadan orogeny and

North American plate motion, *Geology, 20*, 745–748, 1992.

Wright, J.E., Geology and U-Pb geochronology of the western Paleozoic and Triassic subprovince, Klamath Mountains, northern California, Ph.D. dissertation, 300 pp., Univ. Calif., Santa Barbara, 1981.

Wright, J.E., Permian-Triassic accretionary subduction complex, southwestern Klamath Mountains, northern California, *J. Geophys. Res., 87*, 3805-3818, 1982.

Wright, J.E., and M.R. Fahan, An expanded view of Jurassic orogenesis in the western US Cordillera: Middle Jurassic (pre-Nevadan) regional metamorphism and thrust faulting within an active arc environment, *Geol. Soc. Am. Bull., 100*, 859-876, 1988.

Wright, J.E., and S.J. Wyld, Significance of xenocrystic Precambrian zircon contained within the southern continuation of the Josephine ophiolite: Devils Elbow ophiolite remnant, Klamath Mountains, northern California, *Geology, 14*, 671–674, 1986.

Wright, J.E., and S.J. Wyld, The Rattlesnake Creek terrane, Klamath Mountains, California: an early Mesozoic volcanic arc and its basement of tectonically disrupted oceanic crust, *Geol. Soc. Am. Bull., 106*, 1033-1056, 1994.

Wyld, S.J., and J.R. Wright, The Devils Elbow ophiolite remnant and overlying Galice Formation: New constraints on the Middle to Late Jurassic evolution of the Klamath Mountains, *Geol. Soc. Am. Bull., 100*, 29–44, 1988.

Yule, J.D., and J.B. Saleeby, Geochemistry of Rattlesnake Creek terrane fragments contained within the Western Jurassic belt, Oregon Klamath Mountains, *Geol. Soc. Am. Abstr. Programs, 26*, 106–107, 1994.

Zucca, J.J., G.S. Fuis, B. Milkereit, W.D. Mooney, and R.D. Catchings, Crustal structure of northeastern California, *J. Geophys. Res., 91*, 7359-7382, 1986.

C. G. Barnes, Department of Geosciences, Texas Tech University, Lubbock, TX 79409-1053. (gical@ttacs1.ttu.edu)

M. M. Donato, U.S. Geological Survey, 345 Middlefield Road, MS 910, Menlo Park, CA 94025. (mdonato@mojave.wr.usgs.gov)

W. G. Ernst, B. R. Hacker, and M. O. McWilliams, Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305-2115. (ernst@pangea.stanford.edu, hacker@pangea.stanford.edu, and mac@pangea.stanford.edu)

(Received March 14, 1994;
revised August 8, 1994;
accepted September 6, 1994.)