From: Tectonostratigraphic terranes of the circum-Pacific region, D.G. Howell (ed.): Circum-Pacific Council for Energy and Mineral Resources, *Earth Science Series Number 1*. 1985

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Age and Tectonics of Plutonic Belts in Accreted Terranes of the Klamath Mountains, California and Oregon

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Klamath Mountains province is a composite of several allochthonous terranes that are tectonic slices of oceanic crust and island arcs ranging from early Paleozoic to Jurassic in age. The primitive nucleus of the province was the lower Paleozoic rocks of the Eastern Klamath terrane, to which the Central Metamorphic terrane was added as a thick underplating during a Devonian subduction event. Other terranes were added sequentially to the enlarged nucleus during Jurassic time.

Granitoid plutonic rocks occur in all the terranes and are subdivided into belts that generally follow the trends of the terranes. The plutonic belts range from Ordovician to Early Cretaceous in age. The plutons of some belts were emplaced before their host terrane became attached to an adjacent terrane. These preamalgamation plutons occur either as parts of ophiolite suites or as parts of comagmatic volcanic-plutonic pairs that formed in island arcs. In contrast, the postamalgamation plutons are significantly younger than their host rocks and are assigned to belts mainly on the basis of their isotopic ages. Some are known to be postamalgamation because they are seen to cross-cut terrane boundaries or because of other regional tectonic considerations. Some plutonic belts are superimposed on older plutonic belts. All the plutonic belts probably intruded before the assembled Klamath terrane (composite) accreted to the North American continent, with the possible exception of the Shasta Bally belt (Early Cretaceous), which may be postaccretion.

Paleontologic evidence suggests that some of the terranes may have originated at great distances from North America. However, paleomagnetic studies on both stratified and plutonic rocks give no clear evidence of significant latitudinal displacement of the terranes, but they do indicate that some terranes have rotated clockwise through large angles relative to stable North America. The data suggest that major rotation began during Late Triassic or Early Jurassic time and that virtually all rotation of the Klamath terrane had ceased by Early Cretaceous time. Nearly all the rotation occurred while the terranes were parts of oceanic plates.

INTRODUCTION

The Klamath Mountains province is part of the mosaic of accreted terranes that make up the western margin of North America from Mexico to Alaska. The province is an arcuate west-facing structure that consists of several individual terranes (Fig. 1), each of which is characterized by its own peculiar combination of lithology, stratigraphy, age, plutonic rocks, and mineral deposits; it was in the southern part of the province that the term "terrane" was first defined and used in its currently accepted tectonic context (Irwin, 1972). All the terranes that constitute the Klamath Mountains are of oceanic rocks; none is continental, except for a few small patches of superjacent strata. Some of the terranes are ophiolitic, consisting partly of oceanic crust and upper mantle; their ophiolitic components are thought to have formed at oceanic spreading centers during Ordovician, Permian, Triassic, and Jurassic time. Most terranes include parts of volcanic island arcs that formed at various times during the Paleozoic and Mesozoic. Some terranes are structurally coherent rocks; others are melange.

The Eastern Klamath terrane is the nucleus of the province. It was a long-standing volcanic arc, built on oceanic crust and upper mantle now represented by the Trinity ophiolite, and shows evidence of intermittent volcanism that ranged from early Paleozoic into Jurassic time (Irwin, 1981). The Central Metamorphic terrane, consisting of the Salmon Hornblende Schist and Abrams Mica Schist, developed along the western edge of the Eastern Klamath terrane during eastward subduction beneath the Trinity ophiolite in Devonian time. No addition of other terranes to the enlarged nucleus seems to have occurred between Devonian and Jurassic time, even though volcanic strata of the Eastern Klamath terrane suggest that subduction events took place during late Paleozoic and early Mesozoic time. The North Fork, Hayfork, Rattlesnake Creek, and Western Jurassic terranes, which sequentially make up the western part of the province, were swept against the Paleozoic nucleus during Jurassic time. The Klamath terrane (composite), which consists of all the terranes that make up the Klamath Mountains province, probably accreted to the North American continent during latest Jurassic or earliest Cretaceous time.

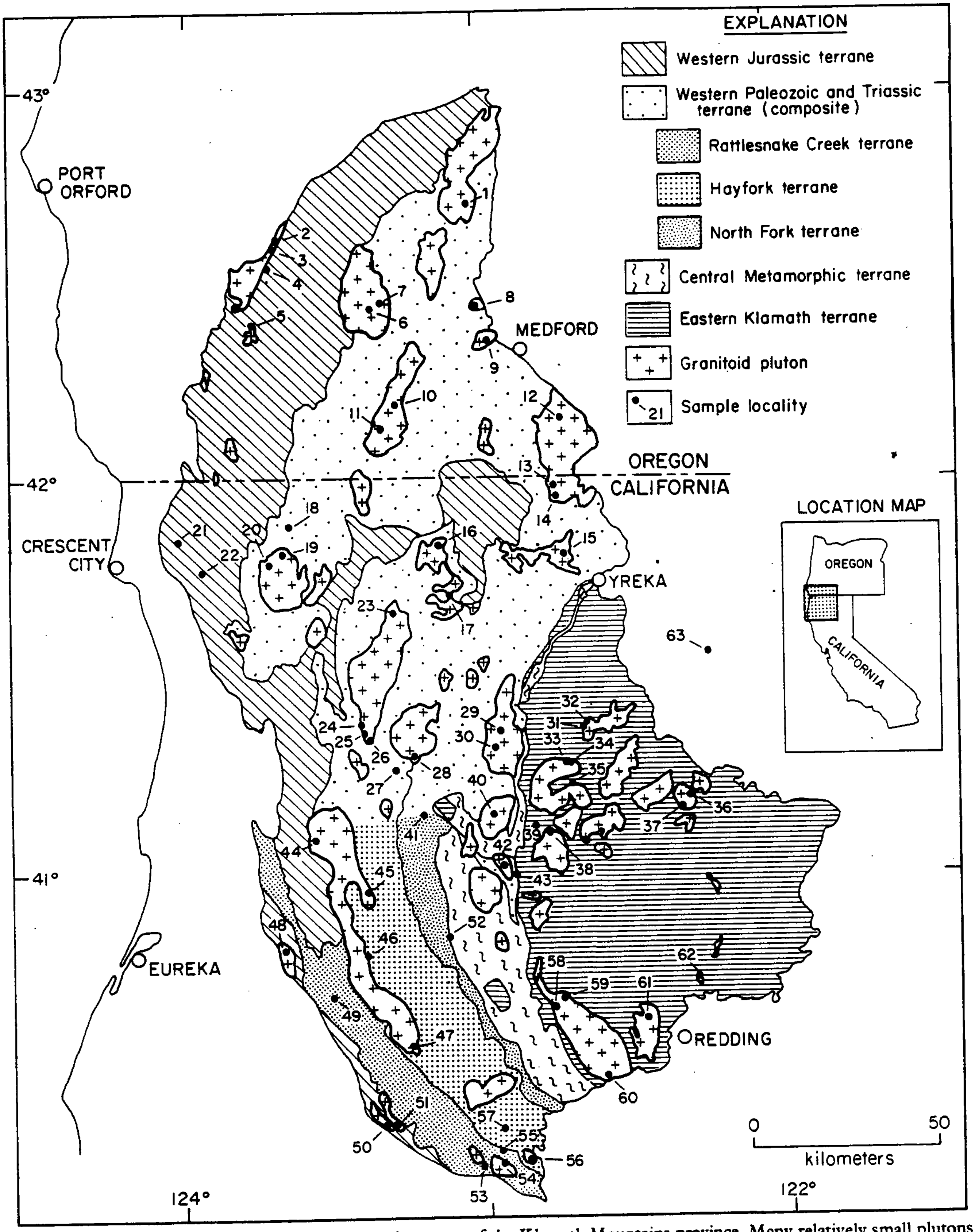

Figure 1—Distribution of granitoid plutons in accreted terranes of the Klamath Mountains province. Many relatively small plutons are not shown. Sample locality numbers correspond to localities listed in Table 1. Geology modified from Smith et al (1982), Wagner and Saucedo (1984), Strand (1962), and others.

DISTRIBUTION OF PLUTONS

Granitoid plutons intrude all the various allochthonous terranes of the Klamath Mountains province (Fig. 1). They are similar in size to most other plutons scattered along the so-called Nevadan orogenic belt that trends northward through the Sierra Nevada, the Klamath Mountains, and into the Ochoco-Blue Mountains region of eastern Oregon, but they are dwarfed by the giant composite Sierra Nevada batholith. Isotopic ages have been measured on many of the plutons of the Klamath Mountains, and these indicate that the plutons are arranged in numerous belts.

The general distribution of plutons in the Klamath Mountains province was well established by 1960 (Wells and Peck, 1961; Irwin, 1960), but the ages of only a few plutons were known. The earliest K-Ar isotopic dating of the plutons was of the Shasta Bally batholith at the south end of the province by Curtis et al (1958), and for many years this was widely cited in regard to the age of the Nevadan orogeny and to the boundary between Jurassic and Cretaceous time. By 1971 the ages of most of the major plutons of the Klamath Mountains had been determined by the K-Ar isotopic method (Davis, 1961; Romey, 1962; Holdaway, 1963; Lanphere et al, 1968; Hotz, 1971). Since 1971 a few other plutons have been dated by the K-Ar method, but most of the recent geochronologic study of the plutons has been through use of the U/Pb method by Mattinson, Saleeby, and Wright (see Table 1). A beltlike pattern of distribution of some of the plutons was recognized by Lanphere et al (1968) on the basis of their K-Ar isotopic dating. This early delineation of plutonic belts, however, has been greatly modified because of additional isotopic age data and an increased understanding of the tectonic development of the Klamath Mountains province.

The distribution of the plutons in the Klamath Mountains is not uniform (Fig. 1). Plutons are most abundant in the Western Paleozoic and Triassic terrane (composite). They are remarkably sparse in the Yreka-Callahan area and much of the area of the Redding section of the Eastern Klamath terrane (Irwin, 1981), especially when the abundance of plutons that intrude the underlying Trinity ophiolite is considered. They are also sparse in the Western Jurassic terrane, including the window of the Condrey Mountain Schist and in the North Fork terrane. Some plutons are strikingly linear, an extreme example being the Ironside Mountain batholith with a length-to-width ratio of approximately 13 to 1; ratios of 2 or 3 to 1 are common. The long axes of the linear plutons tend to be parallel to the regional lithic trends and terrane boundaries. Many of the plutons are entirely within a single terrane, and some of these are truncated by fault boundaries of the terranes. Plutons that are truncated by fault boundaries and plutons that intrude fault boundaries provide important constraints on the ages of the suturing of terranes. Plutons that are not near terrane boundaries at the surface may intrude a structurally lower terrane at depth, but some of these plutons are older than the terrane boundaries and may be truncated by a boundary fault at depth.

The postulated plutonic belts generally follow the trend of the terranes of the province but most are not clearly continuous throughout the length of a given terrane (Fig. 2). The trend of the belts in the northeast part of the Klamath Mountains province is northeast-southwest, virtually at right angles to the northwest-southeast trend in the southwest part of the province. This change in trend is accompanied by other changes in the plutonic belts as well as by major changes in other regional geologic features. These changes occur across a vaguely defined northwest-trending zone that is herein called the Salmon tectonic line because of this parallelism in trend to much of the Salmon River. The Salmon tectonic line divides the Klamath Mountains province into a northeast domain and a southwest domain (Fig. 2). The number of plutonic belts in the northeast domain is nearly double that in the much narrower southwest domain.

AGE OF PLUTONIC BELTS

The plutonic belts range in age from Ordovician to Early Cretaceous. The Paleozoic belts (Alpine gabbro, Skookum Gulch, Mule Mountain, and McCloud belts) are all in the Eastern Klamath terrane, the early nucleus of the province. To the west, the belts are Jurassic and Cretaceous in age and, with some exceptions, are successively younger oceanward. However, the youngest plutonic belt (Shasta Bally) is mainly in the Eastern Klamath terrane and in map pattern (Fig. 2) is partly superimposed on the oldest plutonic belt (Alpine gabbro belt).

The isotopic ages assigned to the plutons are from a combination of K-Ar and U/Pb analyses from various published sources (see Table 1). In some instances a disparity in isotopic age, or a wide range in isotopic ages for a single pluton, results in an equivocal assignment to a specific belt. Many plutons, particularly the smaller ones, are not yet isotopically dated. Because of these shortcomings, the present data are insufficient to define precisely the limits of some of the belts, and therefore the subdivisions must be considered to be provisional. This provisional aspect is most apparent in the Western Paleozoic and Triassic terrane of the northeast domain. There the plutons generally are progressively younger toward the northwest as indicated by the provisional delineation of the Wooley Creek, Greyback, and Grants Pass belts, but it is not clear whether they intruded in a series of successive restricted zones or in a broadly overlapping process. For example, the Grants Pass belt (~140 m.y.) may extend farther southwest to include the Lower Coon Mountain pluton (142 m.y.); and the Cracker Meadow Pluton (136 m.y.), which intrudes the Bear Mountain igneous complex (Snoke et al, 1981) of the Greyback belt, may represent an overlap by the Grants Pass belt. The Gold Hill and Jacksonville plutons, which are seemingly intermediate in age to the plutons of the Grants Pass and Greyback belts, may represent either a northeast extension of the Greyback belt or an overlap by the Grants Pass belt.

Table 1

Map no. (Fig. 1)	Pluton	Lithology	Method	Mineral	Age (m.y.)	Reference
1	White Rock	trondhjemite	K-Ar	B	141	Hotz, 1971
2	Chetco belt	?	K-Ar	H	154	Hotz, 1971
3	Chetco belt	?	K-Ar	H	143	Hotz, 1971
4	Chetco belt	?	K-Ar	H	154	Hotz, 1971
	Chetco belt	?	K-Ar	B	154	Hotz, 1971
5	Chetco belt	?	K-Ar	H	154	Hotz, 1971
6	Grants Pass	qtz-monzonite	K-Ar	H	139	Hotz, 1971
7	Grants Pass	?	U/Pb	Z	139	Saleeby, 1984
8	Gold Hill	granodiorite	K-Ar	H	145	Hotz, 1971
9	Jacksonville	qtz-diorite	K-Ar	H	137	Hotz, 1971
	Jacksonville	qtz-diorite	K-Ar	B	141	Hotz, 1971
10	Greyback	gabbro	K-Ar	H	153	Hotz, 1971
11	Greyback	qtz-diorite	K-Ar	H	153	Hotz, 1971
	Greyback	qtz-diorite	K-Ar	B	141	Hotz, 1971
12	Ashland	granodiorite	K-Ar	H	164	Hotz, 1971
	Ashland	granodiorite	K-Ar	H	170	Hotz, 1971
	Ashland	granodiorite	K-Ar	B	147	Hotz, 1971
13	Ashland	granodiorite	K-Ar	B	151	Lanphere et al, 1968; Hotz, 1971
	Ashland	granodiorite	K-Ar	H	150	Lanphere et al, 1968; Hotz, 1971
14	Ashland	gabbro	K-Ar	B	156	Lanphere et al, 1968; Hotz, 1971
15	Vesa Bluffs	qtz-diorite	K-Ar	B	150	Lanphere et al, 1968
	Vesa Bluffs	qtz-diorite	K-Ar	H	164	Lanphere et al, 1968
16	Slinkard	?	K-Ar	B	151	Lanphere et al, 1968
	Slinkard	?	K-Ar	H	157	Lanphere et al, 1968
17	Slinkard	qtz-diorite	U/Pb	Z	162	Allen et al, 1982
18	Cracker Meadows	granodiorite	K-Ar	B	136	Snoke, 1977
19	Bear Mtn.	gabbro	K-Ar	H	129	Snoke et al, 1981
	Bear Mtn.	hbld-diorite	U/Pb	Z	149	Saleeby et al, 1982
20	Bear Mtn.	monzodiorite	K-Ar	B	146	Snoke et al, 1981
	Bear Mtn.	pyrx-diorite	U/Pb	Z	153	Saleeby et al, 1982
21	Josephine ophiolite	plagiogranite	U/Pb	Z	157	Harper and Saleeby, 1980
22	Lower Coon Mtn. sill	granodiorite	U/Pb	Z	142	Harper and Saleeby, 1980
23	Wooley Creek	qtz-diorite	U/Pb	Z	163	Allen et al, 1982
24	Wooley Creek	granodiorite	U/Pb	Z	163	Allen et al, 1982
25	Wooley Creek	granodiorite	K-Ar	B	158	Lanphere et al, 1968
	Wooley Creek	granodiorite	K-Ar	H	156	Lanphere et al, 1968
26	Wooley Creek	qtz-diorite	K-Ar	B	158	Lanphere et al, 1968
27	Forks of Salmon	diorite	K-Ar	H	171	Lanphere et al, 1968
28	English Peak	granodiorite	K-Ar	H	161	Lanphere et al, 1968
	English Peak	granodiorite	K-Ar	B	159	Lanphere et al, 1968

(continued)

Table 1 (continued)

Map no. (Fig. 1)	Pluton	Lithology	Method	Mineral	Age (m.y.)	Reference
29	Russian Peak	granodiorite	K-Ar	B	147	Romey, 1962; Evernden and Kistler, 1970
30	Russian Peak	granodiorite	K-Ar	B	144	Romey, 1962; Evernden and Kistler, 1970
31	Cobbles in conglomerate	trondhjemite	U/Pb	Z	455	Mattinson and Hopson, 1972
32	Unnamed	gabbro	U/Pb	Z	480	Mattinson and Hopson, 1972
33	"Craggy Peak"	gabbro	K-Ar	H	426	Lanphere et al, 1968
34	"Craggy Peak"	gabbro	K-Ar	H	447	Lanphere et al, 1968
35	"Craggy Peak"	trondhjemite	K-Ar	B	136	Lanphere et al, 1968
36	Castle Crags	granodiorite	K-Ar	B	167	Lanphere et al, 1968
	Castle Crags	granodiorite	K-Ar	H	175	Lanphere et al, 1968
	Castle Crags	granodiorite	K-Ar	B	135	Lanphere et al, 1968
	Castle Crags	granodiorite	K-Ar	B	136	Lanphere et al, 1968
37	Castle Crags	granodiorite	K-Ar	B	162	Lanphere et al, 1968
38	Sugar Pine	qtz-diorite	K-Ar	B	139	Lanphere et al, 1968
	Sugar Pine	qtz-diorite	K-Ar	H	137	Lanphere et al, 1968
39	Unnamed	gabbro	K-Ar	H	340	Lanphere et al, 1968
40	Deadman Peak	qtz-diorite	K-Ar	B	133	Holdaway, 1963; Evernden and Kistler, 1970
41	North Fork ophiolite	plagiogranite	U/Pb	Z	265–310	Ando et al, 1983
42	Caribou Mtn.	trondhjemite	K-Ar	B	133	Davis, 1961; Evernden and Kistler, 1970
43	Horseshoe Lake	diorite	K-Ar	B	133	Davis, 1961
44	Ironside Mtn.	syenodiorite	K-Ar	B	169	Lanphere et al, 1968
45	Denny intrusive unit	?	U/Pb	Z	165	Wright, 1981
46	Ironside Mtn.	syenodiorite	K-Ar	B	171	Lanphere et al, 1968
	Ironside Mtn.	syenodiorite	U/Pb	Z	163	Wright, 1981
47	Ironside Mtn.	diorite	U/Pb	Z	170	Wright, 1981, 1982
48	Ammon Ridge	diorite	K-Ar	?	148	Young, 1978
	Ammon Ridge	diorite	K-Ar	?	152	Young, 1978
49	Saddle Gulch	gabbro	K-Ar	H	189	Lanphere, 1977, personal communication
50	Glen Creek Complex	diorite	U/Pb	Z	144	Wright, 1981; Snoke et al, 1982
	Glen Creek Complex	gabbro	K-Ar	H	151	Irwin et al, 1974
51	Bear Wallow	diorite	U/Pb	Z	193	Wright, 1981
52	East Fork	diorite	K-Ar	B	164	Lanphere, 1983, personal communication
	East Fork	diorite	K-Ar	H	149	Lanphere, 1983, personal communication
53	"WR-1"	qtz-diorite	U/Pb	Z	193	Wright, 1981
54	"PCCK"	qtz-diorite	U/Pb	Z	198	Wright, 1981
55	"Beegum"	qtz-diorite	U/Pb	Z	207	Wright, 1981
56	Walker Point	gabbro	U/Pb	Z	169	Wright, 1981
57	Basin Gulch	diorite	U/Pb	Z	170	Wright, 1981, 1982
58	Shasta Bally	granodiorite	K-Ar	B	135	Lanphere et al, 1968
	Shasta Bally	granodiorite	K-Ar	H	131	Lanphere et al, 1968
59	Shasta Bally	qtz-diorite	K-Ar	B	134	Lanphere et al, 1968

(continued)

Table 1 (continued)

Map no. (Fig. 1)	Pluton	Lithology	Method	Mineral	Age (m.y.)	Reference
	Shasta Bally	qtz-diorite	K-Ar	H	133	Lanphere et al, 1968
	Shasta Bally	qtz-diorite	K-Ar	?	134	Lanphere and Jones, 1978
	Shasta Bally	qtz-diorite	U-Pb	Z	136	Lanphere and Jones, 1978
60	Shasta Bally	qtz-diorite	K-Ar	B	131	Curtis et al, 1958; Evernden and Kistler, 1970
61	Mule Mtn.	qtz-diorite	K-Ar	H	392	Albers et al, 1981
	Mule Mtn.	qtz-diorite	U/Pb	Z	400	Albers et al, 1981
62	Pit River	granodiorite	K-Ar	H	251	Lanphere et al, 1968
	Pit River	granodiorite	K-Ar	H	220	Zeller, 1965
	Pit River	granodiorite	U/Pb	Z	260	Albers, 1982, personal communication
63	Yellow Butte	qtz-monzonite	K-Ar	B	137	Hotz, 1971
	Yellow Butte	qtz-monzonite	K-Ar	H	138	Hotz, 1971

Table 1—List of isotopic ages of plutonic rocks of the Klamath Mountains. The K-Ar ages originally reported have been recalculated, where appropriate, by use of the conversion tables of Dalrymple (1979). Abbreviations used: K-Ar, potassium-argon; U/Pb, uranium/lead; B, biotite; H, hornblende; Z, zircon; m.y., million years.

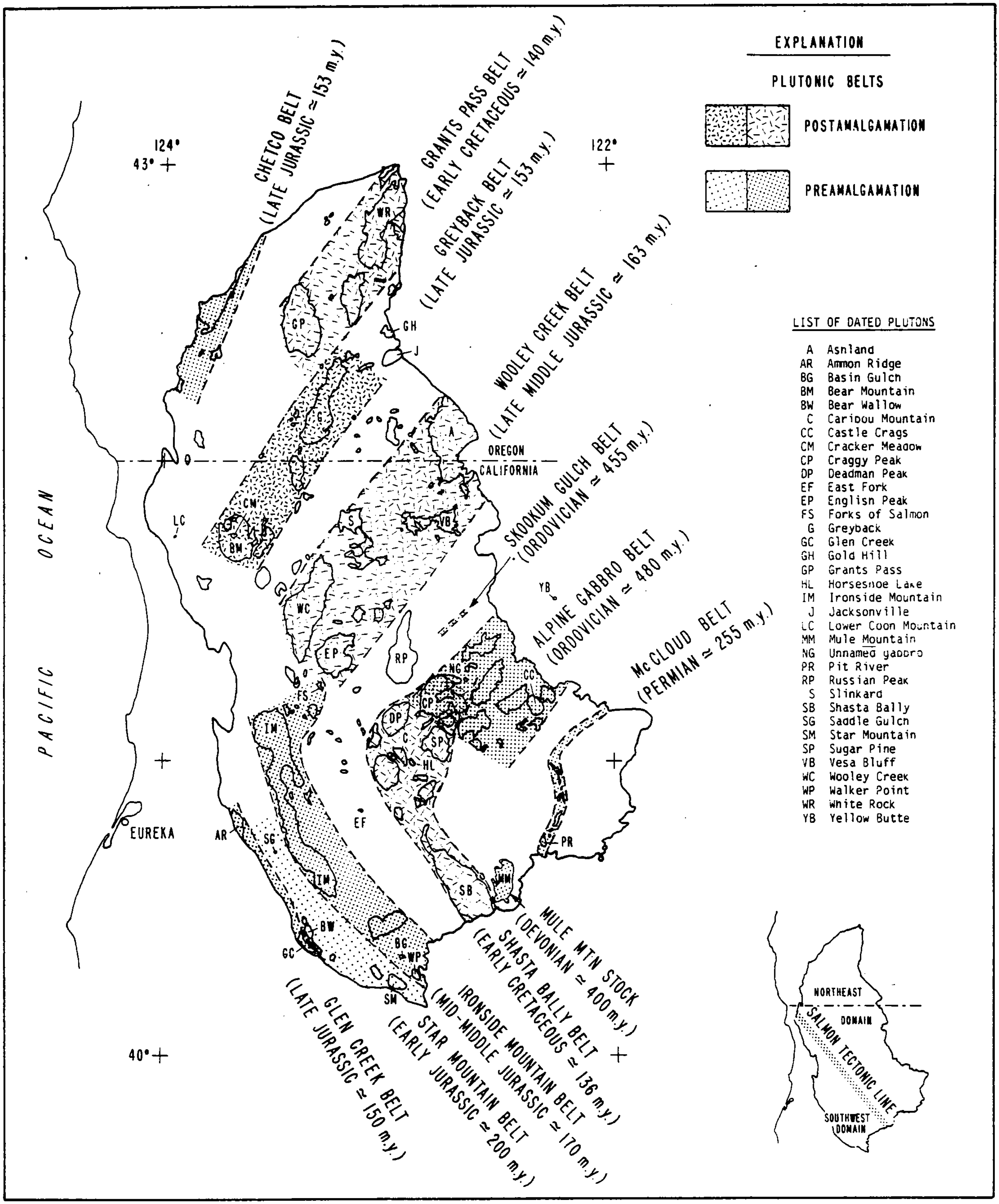

Figure 2—Map of Klamath Mountains province showing outlines of major plutons and the trends of the plutonic belts. Ultramafic ophiolitic rocks are not shown. Letter symbols on map correspond to names in list of dated plutons. The time scale of Harland et al (1982) was used for correlating the isotopic ages with geologic time.

Other plutons that are isotopically dated but not assigned to specific belts include the Russian Peak, East Fork, and Yellow Butte plutons. Neither the Russian Peak nor the East Fork plutons seem to belong to nearby belts, but both plutons are important because they place constraints on the time of suturing of their host terranes. The Russian Peak pluton (144 to 147 m.y.) cross-cuts the sutures between the Central Metamorphic and the Western Paleozoic and Triassic terranes. The East Fork pluton (149 to 164 m.y.) cuts the suture between the Central Metamorphic and North Fork terranes. The Yellow Butte pluton (138 m.y.), which is exposed through a window in Tertiary volcanic rocks of the Cascade Range about 19 km (12 mi) northeast of the Klamath Mountains province, may represent an extension of the Shasta Bally belt.

The Skookum Gulch belt is unusual and may not be a true plutonic belt. It consists of several bodies of silicic plutonic rocks in a matrix of Paleozoic schist and phyllite. The contact relations are not clear, but the plutonic rocks are thought possibly to be large tectonic blocks in a melange rather than local intrusions (Hotz, 1977). The plutonic rocks are tentatively considered early Paleozoic in age because of their similarity to cobbles of isotopically dated trondhjemite (455 m.y.; Mattinson and Hopson, 1972) that occur in a lower Paleozoic conglomerate at nearby Lovers Leap (Potter et al, 1977; Hotz, 1977; Lindsley-Griffin, 1977). The cobbles as well as the plutonic bodies in the Skookum Gulch melange may well have come from the Trinity ophiolite.

PREAMALGAMATION AND POSTAMALGAMATION PLUTONS

As a corollary to the general concepts of plate tectonics and the accretion process, the plutons are categorized as preamalgamation or postamalgamation on the basis of whether they intruded before or after their host terrane was joined to an adjacent terrane.[1] The preamalgamation plutons intrude only a single terrane. The postamalgamation plutons in some instances may intrude a single terrane but in other instances may intrude two or more contiguous terranes.

The preamalgamation plutons of the Klamath Mountains occur in two principal genetic settings: (1) The plutons are part of an ophiolite suite, as exemplified by the early Paleozoic gabbroic plutons that intrude the Trinity ultramafic sheet; and (2) the plutons are similar in age and composition to volcanic strata they intrude, forming comagmatic plutonic-volcanic pairs, and are thought to represent the intrusive phases of volcanic island arcs. The arc-related plutons include the Mule Mountain stock (related to the Devonian Balaklala Rhyolite), plutons of the McCloud belt (related to the Permian Dekkas Andesite), and the Early or Middle Jurassic plutons of the Ironside Mountain belt (related to the Hayfork Bally Meta-andesite). It should be noted that the plutons of the McCloud belt are preamalgamation in the sense that they are genetically related to intermediate-age (Permian) volcanic strata of a long-standing volcanic arc, but they are postamalgamation in relation to the Devonian suturing of the Central Metamorphic terrane to the early part of the Eastern Klamath terrane.

In contrast to the preamalgamation plutons, the postamalgamation plutons are significantly younger than their host rocks and seem to bear no genetic relation to them. They are assigned to belts mainly on the basis of their isotopic ages. These plutons are considered to form postamalgamation belts at places where some of the plutons cross-cut the suture between the host and an adjacent terrane, or where the suture is known to be older than the plutons on the basis of other regional considerations. Postamalgamation plutons seem to be absent southwest of the Shasta Bally belt in the southwest domain except for the small East Fork pluton, whereas belts of post-amalgamation plutons greatly predominate northwest of the Shasta Bally belt in the northeast domain.

The Wooley Creek and Ironside Mountain pluton belts are virtually coincident along trend, but the plutons of the Wooley Creek belt are appreciably less mafic and more quartzose than those of the Ironside Mountain belt. The plutons of both belts intrude presumably correlative volcanogenic strata of the Hayfork terrane (Donato et al, 1981) even though the belts are in separate domains (Fig. 2). The Ironside Mountain batholith is clearly truncated by terrane boundaries (Irwin, 1977). However, because the Wooley Creek, Slinkard, and Vesa Bluffs plutons cross terrane boundaries (Donato et al, 1982; Barnes, 1983; Mortimer, 1984), the plutons of the Wooley Creek belt are postamalgamation even though they appear on average to be only a few million years younger than the preamalgamation plutons of the Ironside Mountain belt (Fig. 3).

The plutons of the Klamath Mountains are grouped in Figure 3 according to the terranes in which they occur and, in most instances, according to the appropriate plutonic belt. The ages of small plagiogranite pods in the Jurassic Josephine ophiolite and the late Paleozoic North Fork ophiolite also are shown. They define the ages of the ophiolites and help to illustrate the time interval between the formation of the ophiolitic base of the terrane and the intrusion of the terrane by younger plutons. In the case of the Josephine ophiolite, the interval is only a few million years, and with the North Fork ophiolite the interval is more than 100 m.y. The time interval between the intrusion by the early Paleozoic plutons of the Alpine gabbro belt and the intrusion by the plutons of the Shasta Bally belt is approximately 300 m.y. This sequential increase in the time intervals between emplacement of the oldest and youngest plutonic rocks of the terranes follows the generally sequential west-east increase in the ages of the oldest rocks of the terranes.

DISPLACEMENT AND ROTATION OF TERRANES

The places of origin of most of the terranes are not known; they could have formed just west of the continental

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[1] In an earlier report (Irwin, 1984), the plutons were categorized as preaccretion and postaccretion plutons, using the term accretion in a general sense, i.e., the joining of one terrane to another, rather than in the restricted sense of Jones et al (1983) that implies the joining of a terrane to a continental margin. For conformity with the terminology of this volume, the term accretion is used in the restricted sense, and the term amalgamation is used to imply the joining of terranes in an oceanic setting.

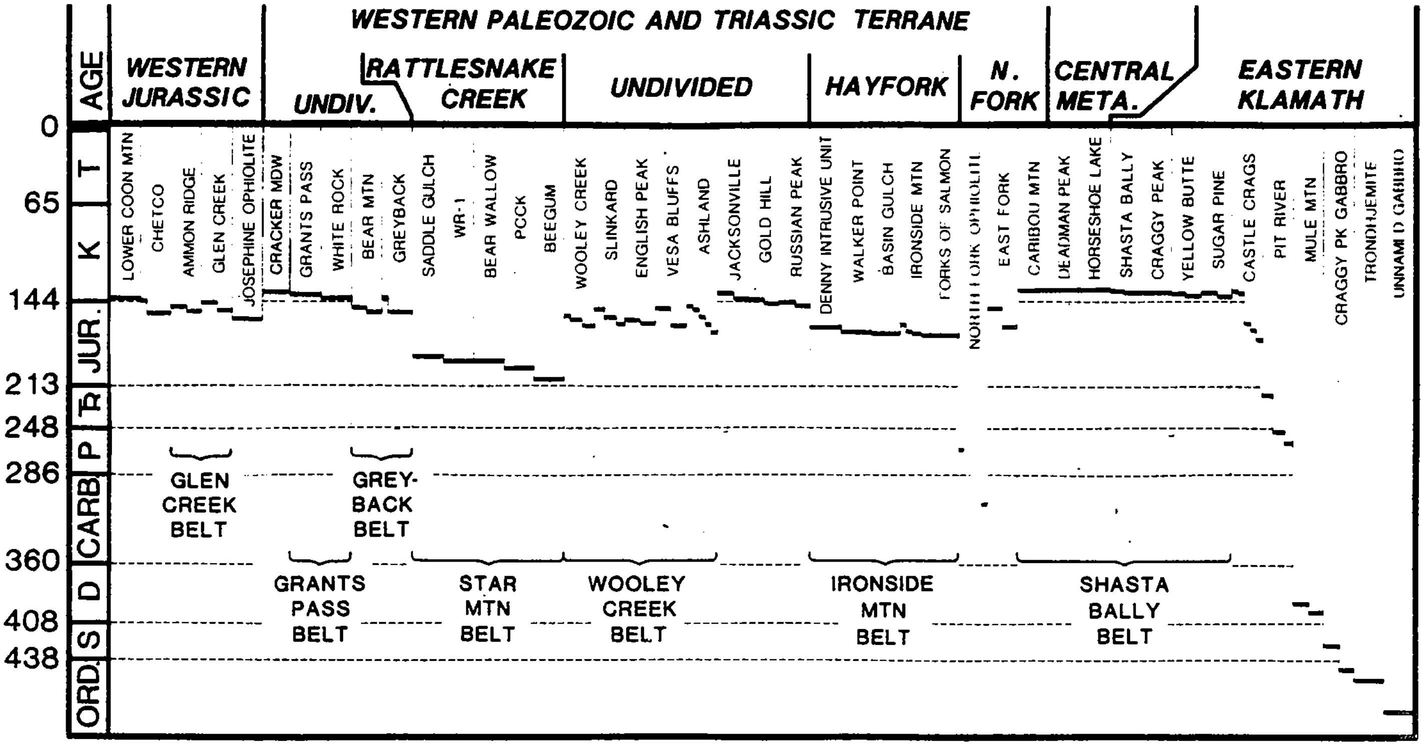

Figure 3—Comparison of ages of plutons of the Klamath Mountains, grouped according to terranes. The time scale is from Harland et al (1982).

margin, not far from their present location in relation to North America, or at some remote location. Paleontologic evidence suggests that some terranes may have traveled great distances to their present sites. For example, pods of Permian limestone in the Western Paleozoic and Triassic terrane northeast of Yreka (Elliott and Bostwick, 1973) and in the Hayfork terrane in the southern part of the province near Wildwood contain a foraminiferal fauna that is foreign to the Western Hemisphere; the fauna closely resembles Tethyan faunas from southern China, Japan, and southeastern Siberia (Nestell et al, 1981). Early Paleozoic shelly faunas in rocks of the Yreka-Callahan area of the Eastern Klamath terrane are of Asiatic-Pacific and European rather than western North American (Great Basin) aspect (Boucot et al, 1973). Triassic ammonities from a locality in the Rattlesnake Creek terrane are not reported elsewhere in North America (Silberling and Irwin, 1962).

Paleomagnetic studies have been made on only a few of the terranes of the Klamath Mountains. These have yielded no clear evidence of significant latitudinal displacements and cannot detect longitudinal displacements. However, the various studies do indicate that the early geographic orientation of the Klamath Mountains terranes differed greatly from their present orientation relative to cratonal North America (Fig. 4). The oldest rocks that have been studied are limestone of the Devonian Kennett Formation at two areas in the Eastern Klamath terrane. In one area the primary magnetism of the Kennett was found to be obscured by a postfolding remagnetism that was interpreted to indicate 70 ± 10° of clockwise rotation relative to stable North America (Achache et al, 1982). Fagin and Gose (1983) measured 116° of clockwise rotation on the Kennett in the other area, 95° on the Mississippian Bragdon Formation, 91° on the Permian McCloud Limestone, and 83° on the Triassic Modin Formation, but these are not clearly measurements of the primary magnetization. Other paleomagnetic studies were on Permian and younger strata along two transects of the Eastern Klamath terrane and on superjacent Cretaceous strata of the Great Valley sequence, and these studies indicate: (1) equal amounts of clockwise rotation of greater than 100° relative to stable North America for the Permian and Triassic rocks, (2) clockwise rotation of about 50° for the Lower and Middle Jurassic rocks, (3) little or no rotation of the Cretaceous superjacent rocks, and (4) no significant latitudinal displacement of any of these rocks (Mankinen and Irwin, 1982; Mankinen et al, 1982; Irwin et al, 1984).

Measurements on five granitoid plutons in the northern part of the Western Paleozoic and Triassic terrane indicate clockwise rotations that range from 53 to 113°, excepting the Ashland pluton that may show small counterclockwise rotation (Schultz, 1983; Schultz and Levi, 1983). All of these plutons are Jurassic with the possible exception of the Grants Pass pluton, which may be early Early Cretaceous in age. Although measurements on plutons are fundamentally difficult to compare with measurements on stratified rocks because the plutons lack an original horizontal reference datum, the rotations indicated for the plutons are generally similar to those for the Jurassic strata of the Eastern Klamath terrane.

Some paleomagnetists have postulated that the large rotations assigned to the Klamath Mountains rocks occurred since Early Cretaceous (Achache et al, 1982) or during Cenozoic time (Fagin and Gose, 1983), and they

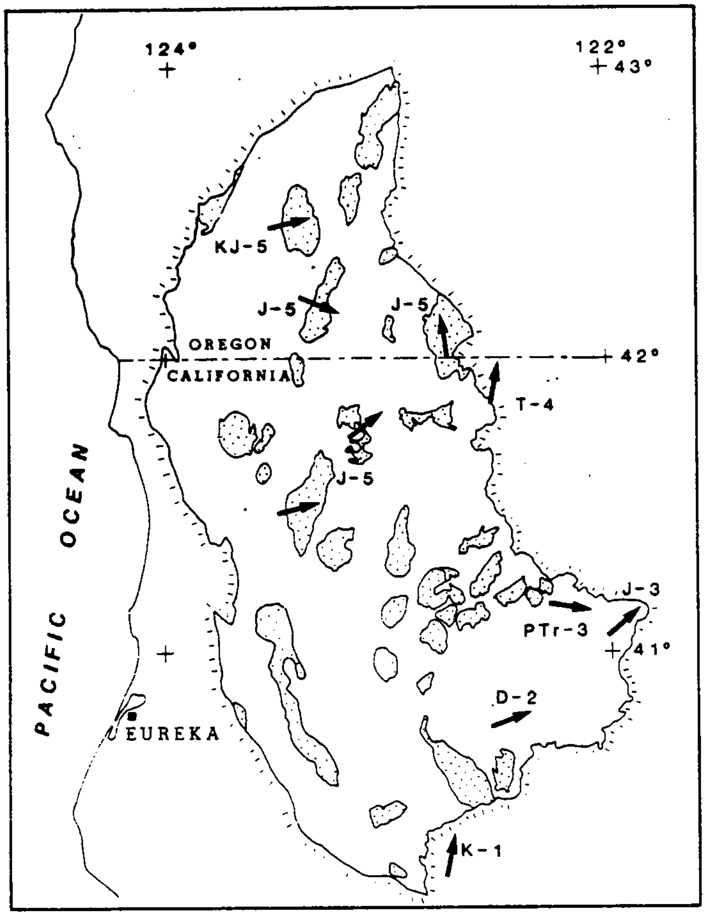

Figure 4—Paleomagnetic measurements of tectonic rotations of Klamath Mountains terranes (slightly modified from Irwin et al, 1984). Azimuth of arrows, measured from north, indicates amount of clockwise rotation of the measured rock unit relative to the expected paleomagnetic direction for a stable North America, except for the Ashland pluton, which may show small counterclockwise rotation. Principal plutons of the province are stippled. Letter symbols denote ages of paleomagnetically sampled rocks units: D = Devonian; PTr = Permian and Triassic; J = Jurassic, KJ = Jurassic or Early Cretaceous; K = Cretaceous; and T = Oligocene. Numbers after letters refer to sources of data: 1, Mankinen and Irwin (1982); 2, Achache et al (1982); 3, Mankinen et al (1982); 4, Craig et al (1981); and 5, Schultz (1983).

suggest that the rotations were contemporaneous with those of Tertiary volcanic rocks of the Oregon Coast Ranges to the north. However, these ideas are incompatible with the small (12°) rotations measured on Lower Cretaceous strata of the Great Valley sequence at the south end of the Klamath Mountains (Mankinen and Irwin, 1982) and on the Tertiary volcanic rocks near the east edge of the Klamath Mountains (Craig et al, 1981). These small rotations measured on the superjacent rocks indicate that most of the rotation of the Klamath basement was pre-Early Cretaceous (pre-Valanginian).

CONCLUSIONS

The relation between the time of rotation of a terrane and the time of accretion to North America is important because it indicates whether the rotation occurred while the terrane was part of an oceanic plate or while part of the North American continent. The results of the paleomagnetic studies on both the plutonic and stratified rocks are compatible with the concept that the Eastern Klamath terrane began major rotation during latest Triassic or earliest Jurassic time and that all elements of the Klamath terrane (composite) had virtually stopped rotating relative to stable North America by Early Cretaceous time. The coincidence of this virtual cessation of rotation with the inception of deposition of the Lower Cretaceous basal strata of Great Valley sequence on Klamath basement is good evidence for the time of completion of the accretion of the Klamath terrane to the North American continent. Nearly all the rotation of the terranes of the Klamath Mountains probably occurred while the terranes were parts of oceanic plates.

The Shasta Bally is the youngest of the plutonic belts, and, although it is shown as postamalgamation on Figure 2, it may possibly be postaccretion. The isotopic age of Shasta Bally batholith (136 m.y.) is remarkably close to the Early Cretaceous (Valanginian) age of the basal strata of the Great Valley sequence that overlap the Klamath terrane. The difference in age between the batholith and the basal strata of the overlap sequence seems unlikely to be more than a few million years. Although paleomagnetic data are not available for the plutons of the Shasta Bally belt, one might speculate that the paleomagnetic orientation of the plutons will be found to differ by no more than a few degrees from that of the overlap sequence and thus may not differ greatly from the orientation of stable North America.

The preamalgamation and postamalgamation pluton belts were captive parts of the tectonically rotating terranes. Paleomagnetic measurements on the plutons and stratified rocks of the northeast domain suggest that the plutonic belts as well as the other components of the terranes must originally have been oriented much differently than now in relation to stable North America; there presently are no paleomagnetic data on the orientation of the plutons of the southwest domain. Much additional data must be obtained before the complex story of plutonism and accretion of the Klamath Mountains can accurately be told. However, in a simple scenario based on the available data the primitive nucleus of the Klamath Mountains province was part of a volcanic island arc that faced southwest during early Paleozoic time. The underplating of the Eastern Klamath terrane by the hornblende and mica schists of the Central Metamorphic terrane was caused by subduction of a northeast-moving plate beneath the arc during Devonian time. Deposition of a thick prism of flyschlike strata (Bragdon Formation) followed during Mississippian time, with volcanism (Baird Formation) becoming important again in Late Mississippian to Early Permian time. The McCloud Limestone represents a reef that formed along the arc during Early Permian time and was partly contemporaneous with the Permian Dekkas Andesite and its comagmatic McCloud pluton belt. The arc continued to face southwest until latest Triassic or earliest Jurassic time and then rotated approximately 50° clockwise to face westward during much of Early to Late Jurassic time. Volcanism and deposition continued in the Eastern Klamath terrane during Early and Middle Jurassic time.

The Western Paleozoic and Triassic and the Western Jurassic terranes sequentially sutured to the western edge of the developing west-facing Klamath terrane during the Middle and Late Jurassic, accompanied by intrusion of plutons. During latest Jurassic and possibly earliest Cretaceous time the arc rotated an additional 50° clockwise to nearly attain its present northwest-facing orientation by the time it accreted to North America.

The number of plutonic belts in a province as small as the Klamath Mountains is remarkably large and may seem to be unique. However, a similar multiplicity of plutonic belts probably will be found in other circum-Pacific borderlands where a long history of accretionary tectonics is preserved.

ACKNOWLEDGMENTS

I am indebted to D. L. Wagner of the California Division of Mines and Geology for generously providing a prepublication copy of a map showing the distribution of plutons in the Weed 2° quadrangle, to M. A. Lanphere for isotopically dating a sample of the East Fork pluton, and to D. C. Ross, T. H. Nilsen, and K. M. Williams of the U.S. Geological Survey for their helpful reviews of the manuscript.

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