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The development of tectonic concepts for the Klamath Mountains province, California and Oregon

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ABSTRACT

The Klamath Mountains province of northwestern California and southwestern Oregon is a classic example of a mountain belt that developed by the tectonic accretion of rock assemblages of oceanic affinity during progressive crustal growth along an active continental margin. Consequently, the Klamath Mountains province has served as an important model for the definition and application of the terrane concept as applied to the evolution of Phanerozoic orogenic belts. Early regional studies divided the Klamath Mountains province into four arcuate lithic belts of contrasting age (from east to west): the eastern Klamath, central metamorphic, western Paleozoic and Triassic, and western Jurassic belts. The lithic belts are bounded by regional thrust faults that commonly include ophiolitic assemblages in the hanging-wall block. The age of thrusting is a complex problem because of structural overprinting, but generally the age of regional thrust faulting is older in eastern parts of the province and younger to the west. The lithic belts were subsequently subdivided into many tectonostratigraphic terranes, and these lithotectonic units are always fault-bounded. Few of the regional faults are fossil subduction zones, but multiple episodes of high pressure–low temperature (blueschist-facies) metamorphism are recognized in the Klamath Mountains province. The tectonostratigraphic terranes of the Klamath Mountains province are intruded by many composite, mafic to felsic, arc-related plutons, some of which reach batholithic dimensions. Many of these plutonic bodies were emplaced during the Jurassic; however, radiometric dates ranging from Neoproterozoic through Early Cretaceous have been determined from (meta)plutonic rocks of the Klamath Mountains province. The orogenic evolution of the province apparently involved the alternation of contraction and extension, as exemplified by the Jurassic history of the province. Widespread Middle Jurassic plutonism and metamorphism is associated with a poorly understood contractional history followed by the development of the Preston Peak–Josephine ophiolite and Upper Jurassic Galice Formation in a probable transtensional inter-arc basin. During the Late Jurassic Nevadan orogeny, this basin collapsed, and rocks of the Galice Formation were thrust beneath the Rattlesnake Creek terrane along the Orleans fault. During this regional deformation, the

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Galice Formation experienced polyphase deformation and was metamorphosed under lower greenschist-facies conditions. Immediately following thrusting, the hanging-wall and footwall blocks of the Orleans fault were intruded by a suite of composite, mafic to felsic plutons (i.e., western Klamath plutonic suite) that have oceanic-arc geochemical and isotopic characteristics, indicating a subduction-zone petrogenesis for the magmas. The western boundary of the Klamath Mountains province is a regional thrust fault that emplaced the rocks of the province above Early Cretaceous blueschist-facies rocks (South Fork Mountain Schist) of the Franciscan Complex. Neogene structural doming is manifested in the north-central Klamath Mountains by the Condrey Mountain window, which exposes the high pressure–low temperature Condrey Mountain Schist framed by chiefly amphibolite-facies metamorphic rocks of the Rattlesnake Creek terrane.

Keywords: Klamath Mountains, northwestern California, southwestern Oregon, history of geology, thrust faults, ophiolite, igneous and metamorphic rocks, Jurassic orogenies, tectonostratigraphic terranes, Tethyan fauna, blueschist-facies metamorphism, intraoceanic arcs, accretionary subduction complexes, continental growth, accretionary orogen, Neogene structural dome

INTRODUCTION

The Klamath Mountains province of northwestern California and southwestern Oregon is the largest exposure of pre-Tertiary rocks between the northern Sierra Nevada and North Cascade core of Washington State (Figs. 1 and 2). Furthermore, the Klamath Mountains province is an archetypal example of a mountain belt developed by the progressive tectonic accretion of oceanic rocks (Figs. 3 and 4). Perhaps because the Klamath Mountains province is part of a megabelt of accreted terranes that stretches from Alaska through Mexico and beyond (Dickinson, 2004; Monger et al., 2005; Snoke, 2005) the size of the Klamath Mountains province sensu stricto is commonly overlooked, but its area is comparable to that of the Western Alps of Europe (Fig. 5).

The Klamath Mountains province is bounded on the west by the eastward-dipping Coast Range thrust or equivalent fault, beneath which lies the Franciscan Complex (Fig. 3). The geologic character of the eastern margin of the Klamath Mountains province is variable, and rocks of the province may extend to the east in the subsurface (Fuis et al., 1987). Immediately north and south of the California-Oregon border, rocks of the Klamath Mountains province are unconformably overlain by sedimentary rocks of the Cretaceous Hornbrook Formation (Nilsen, 1984) that in turn are overlain by Tertiary volcanic and volcanogenic rocks of the Western Cascade Group. As the eastern margin is traced south, Tertiary rocks overlie the Klamath Mountains province, with no exposed Cretaceous rocks. Far to the south, fossiliferous Cretaceous sedimentary rocks of the Great Valley sequence unconformably overlie the rocks of the Klamath Mountains province (including the Early Cretaceous Shasta Bally batholith); this locality at the south end of the Klamath Mountains province (Blake et al., 1999) is historically important in the development of the Lower Cretaceous timescale (e.g., Curtis et al., 1958). In Oregon, the northeastern margin of the Klamath Mountains province is generally faulted, with Tertiary rocks juxtaposed against various rock units of the Klamath Mountains province.

The fundamental structural character of the Klamath Mountains province is a system of fault-bounded, imbricated plates of oceanic-affinity rocks that dip eastward in a regional sense but are locally folded and cut by younger, high-angle faults. This imbricated pattern of lithotectonic units is interpreted as a manifestation of progressive accretion of oceanic rocks along an active continental margin during early Paleozoic through Late Jurassic time. If the tectonic accretion history of the adjacent northern California Coast Ranges is considered, the exposed accretionary history spans into the middle Cenozoic, and active tectonic accretion is ongoing along the Pacific margin in the form of the Cascadia subduction zone. The ages of the lithotectonic units range from Neoproterozoic remnants in the eastern Klamath Mountains (Mankinen et al., 2002; Lindsley-Griffin et al., 2003, this volume) to Upper Jurassic in the western Klamath Mountains (Diller, 1903; Irwin, 1960, 1994). The age of the lithotectonic units generally decreases to the west as well as structurally downward. Consequently, many workers have viewed the Klamath Mountains province as an excellent example of thin-skinned accretionary tectonics in which successive arc-related lithotectonic units were accreted by thrust-fault imbrication with older, inboard, amalgamated terranes (Davis, 1968; Snoke, 1977; Saleeby et al., 1982; Wright, 1982; Harper and Wright, 1984; Wright and Fahan, 1988).

The fault-bounded, lithotectonic units are intruded by many plutons that range in age from early Paleozoic to Early Cretaceous, in size from stocks to batholiths, and in composition from ultramafic to silicic. Besides petrogenetic signifi-

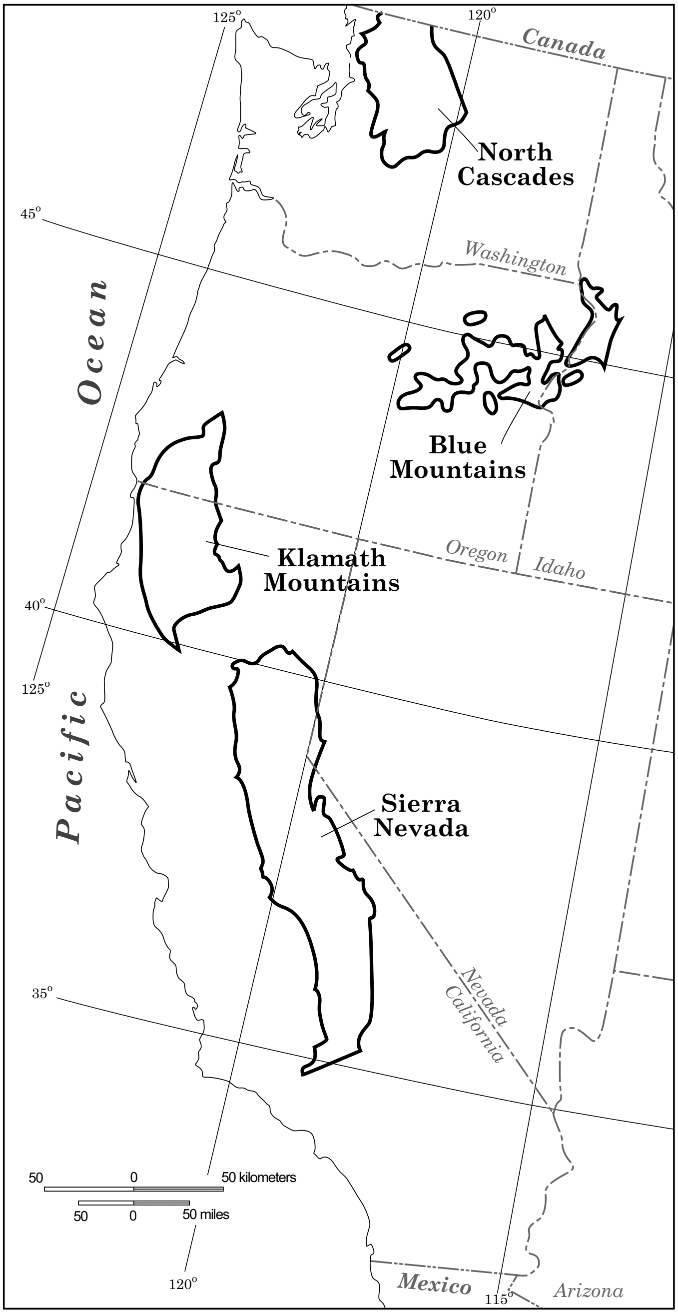


Figure 1. Geologic sketch map of a part of the western North American Cordillera showing the position of the Klamath Mountains province with respect to the Sierra Nevada (central California), Blue Mountains (northeast Oregon), and North Cascades (north-central Washington State). Adapted from King (1967, 1970).

cance, the plutons are important in regard to bracketing the age of deformation in the Klamath Mountains province (Lanphere et al., 1968; Davis et al., 1978; Wright and Fahan, 1988). Some plutons, such as the ca. 139-Ma Grants Pass pluton (Fig. 6), are classic examples of post-thrusting (postkinematic) emplacement because they intruded and metamorphosed both the hanging-wall and footwall blocks on either side of a regional thrust fault (Orleans fault in this example). Other plutonic complexes (ca. 162-Ma Wooley Creek batholith and comagmatic Slinkard pluton) are apparently "rootless" in that they occur in the hanging wall of a regional thrust plate with a displacement history younger than the emplacement/crystallization ages of the intrusive plutonic bodies (Barnes et al., 1986). The relationship among deformation, magmatism, and metamorphism through time during the evolution of the Klamath Mountains province is fundamental to understanding basic orogenic processes along an active continental margin. Furthermore, the Klamath Mountains province provides an excellent opportunity to better understand the accretion and growth of continental lithosphere as well as its modification during progressive orogenesis.

SOME EARLY GEOLOGIC OBSERVATIONS AND CONTRIBUTIONS

Among the first geologists to explore the Klamath Mountains province were those associated with J.D. Whitney's Geological Survey of California. Although their specific comments on the geology of the Klamath Mountains province were minor compared to their more detailed exploration of the adjacent Cascade Range (e.g., environs surrounding Mount Shasta and Lassen Peak), in 1863 William H. Brewer and Clarence King made a rapid reconnaissance geologic traverse from Yreka to Crescent City at the Pacific coast (Whitney, 1865, p. 356–363). The extensive geologic mapping of J.S. Diller (Fig. 7) of the U.S. Geological Survey (USGS) represented the first systematic exploration of the Klamath Mountains province. Diller's many publications on the Klamath Mountains province as well as the adjacent Oregon Coast Ranges had a profound influence on all subsequent studies, and some of his basic conclusions are still accepted today (e.g., correlation of the Upper Jurassic Galice Formation with the Mariposa Formation of the western Sierra Nevada [see MacDonald et al., this volume; Gray, this volume], recognition of important high-level erosion surfaces in the Klamath Mountains and adjacent Coast Ranges [Diller, 1902; see Aalto, this volume]). Furthermore, Diller established a stratigraphic framework for the eastern Klamath Mountains (Diller, 1906), where a coherent stratigraphy ranges from mid-Paleozoic to mid-Jurassic time and is now recognized as one of the longest-lived oceanic-arc sequences in the western North American Cordillera (Lapierre et al., 1985, 1987; Miller, 1989; Charvet et al., 1990; Miller and Harwood, 1990; Dickinson, 2000). When J.S. Diller retired from the USGS on December 31, 1923, at the age of 73, he had studied large portions of the Klamath Mountains province and Coast Ranges of northwestern California and southwestern Oregon as well as completed important studies on Crater Lake, Mount Shasta, and Lassen Peak. His contributions to the geologic mapping of the region include the following USGS folios: Roseberg (no. 49, 1898), Coos Bay

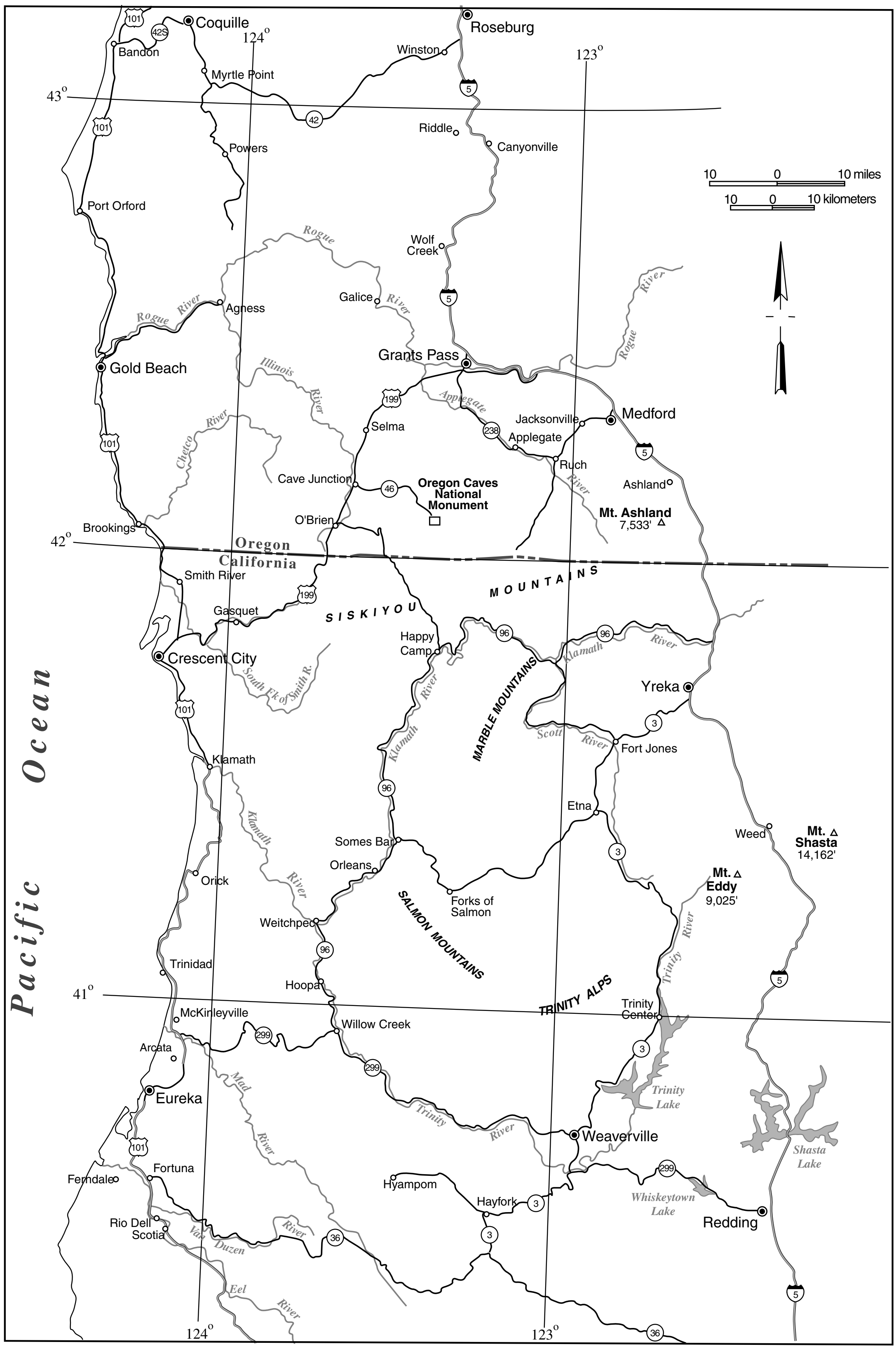


Figure 2. Map of the Klamath Mountains province showing geographic localities cited in the text.

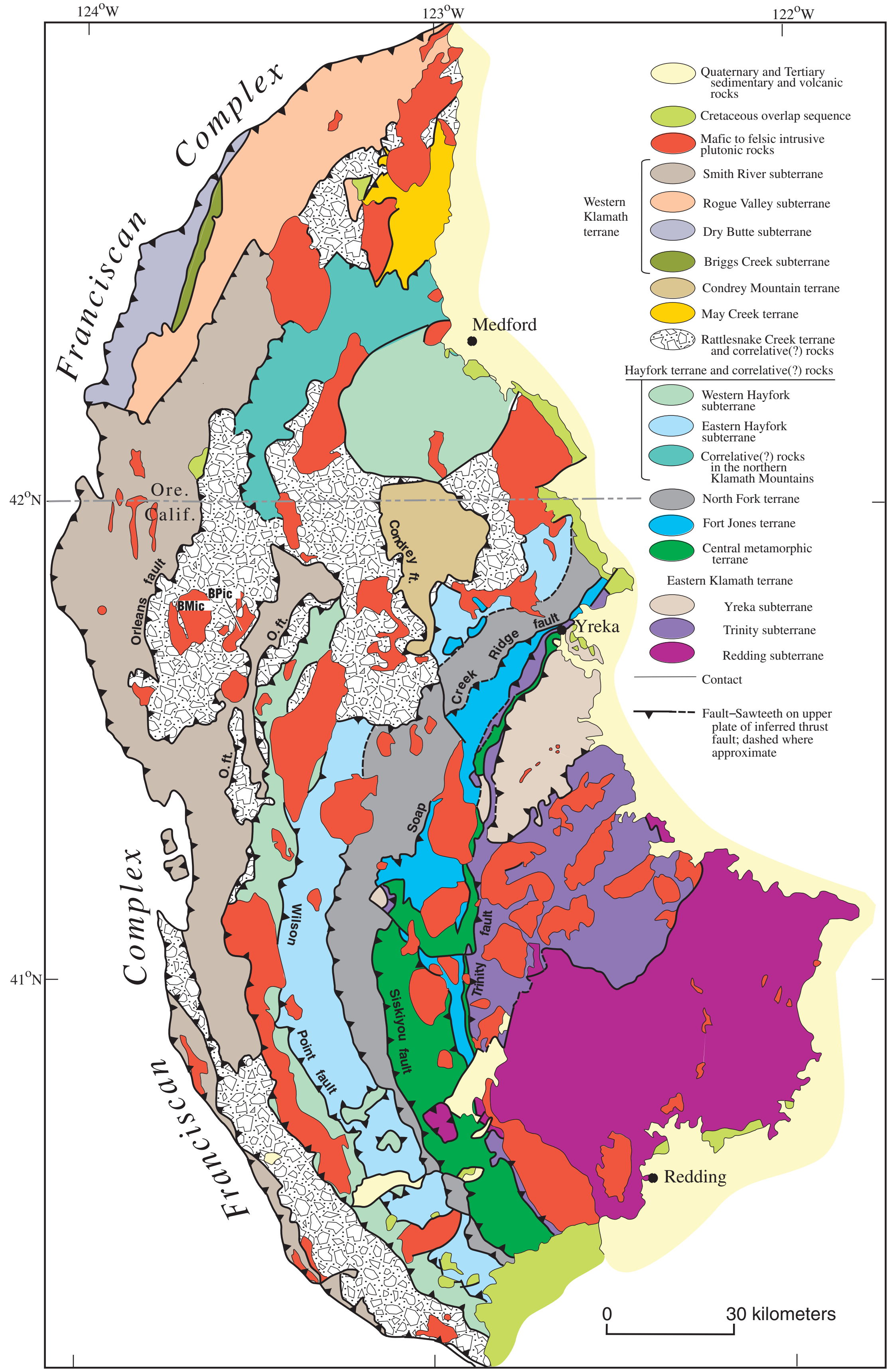


Figure 3. Geologic sketch map of the tectonostratigraphic terranes of the Klamath Mountains province, California and Oregon. BMic—Bear Mountain intrusive complex; BPic—Bear Peak intrusive complex; O. ft.—Orleans fault. Modified from Irwin (1994).

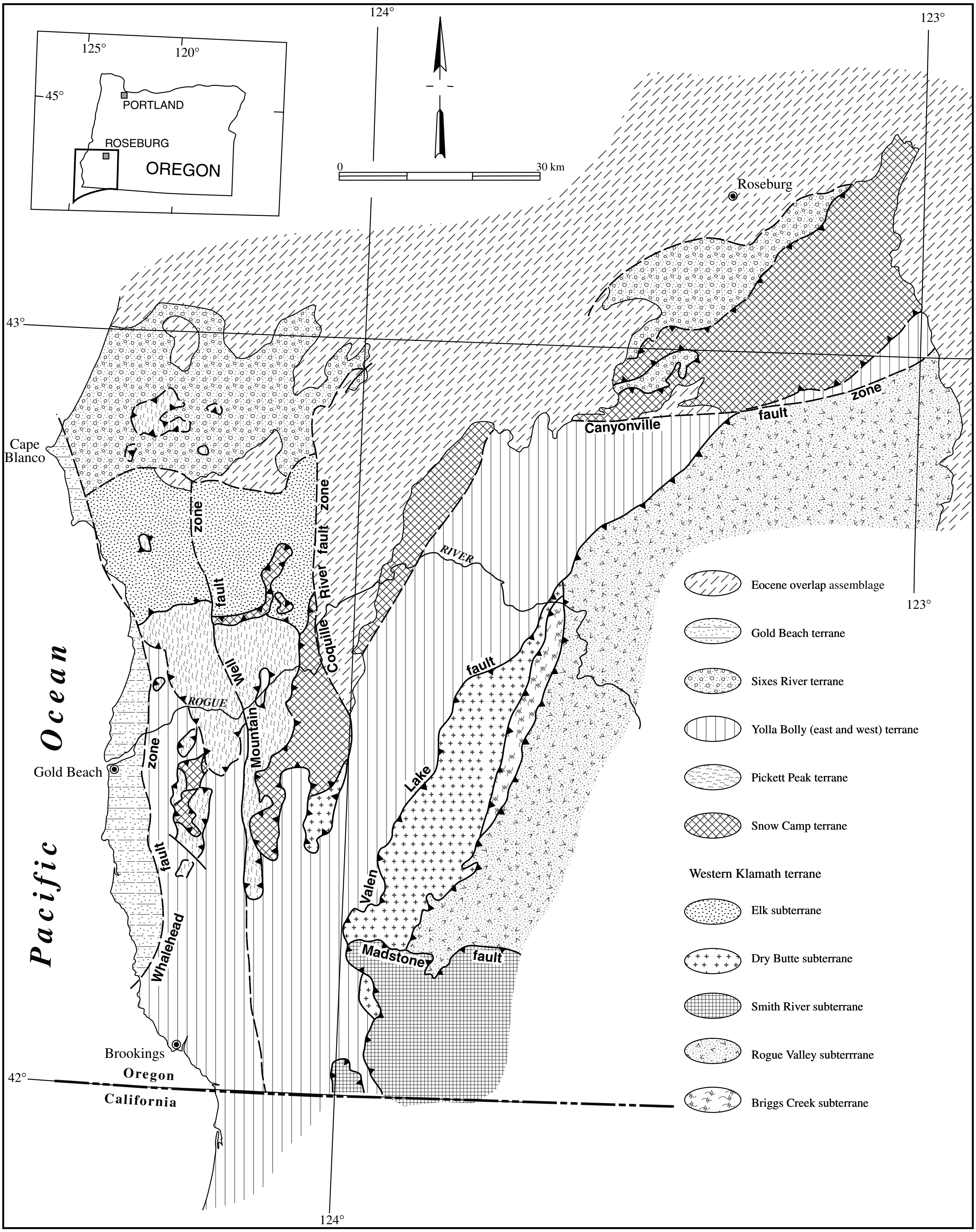


Figure 4. Geologic sketch map of the tectonostratigraphic terranes in southwestern Oregon. After Blake et al. (1985).

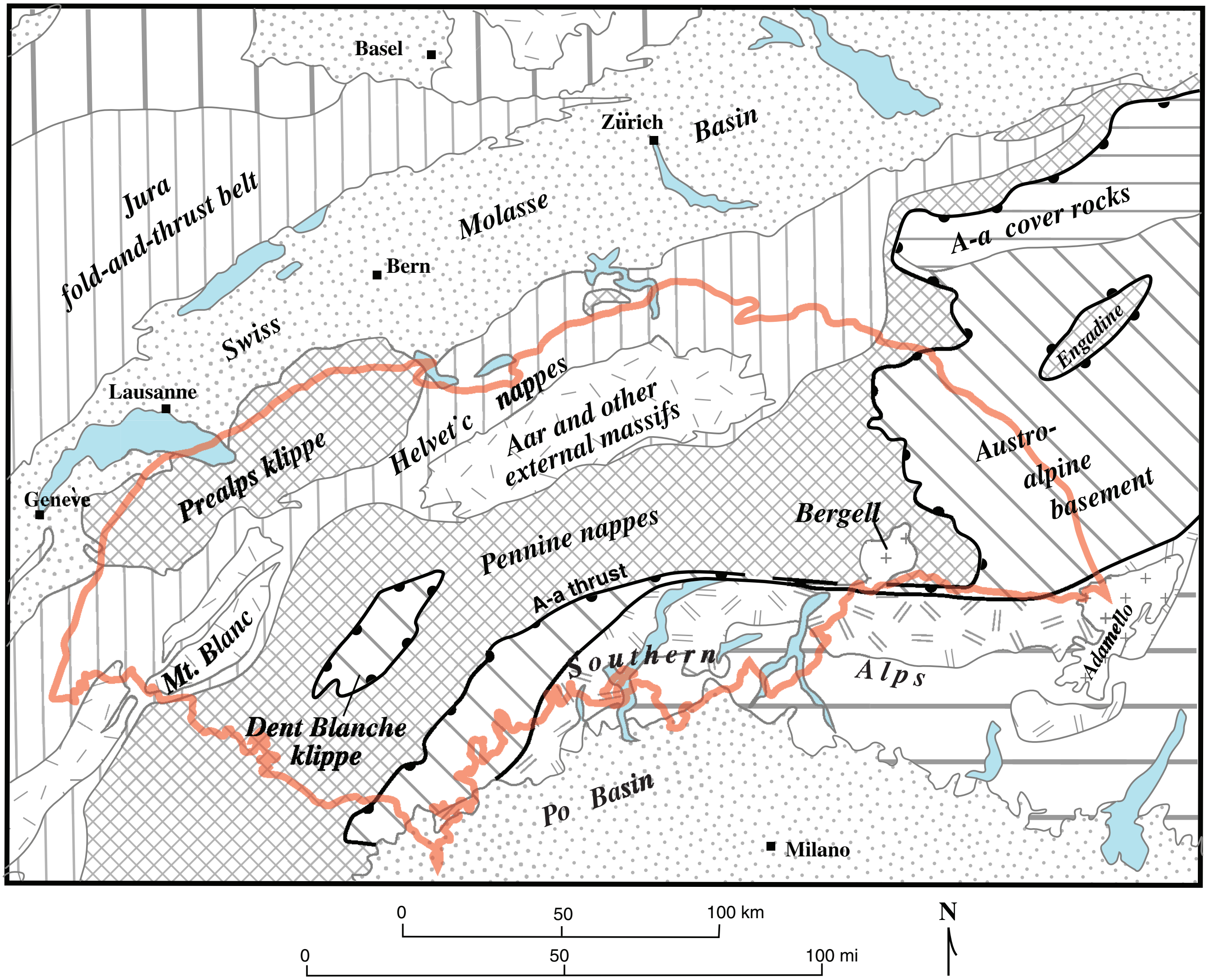


Figure 5. Comparison of the Klamath Mountains province (outlined in red and turned sideways such that north is to the right) with the Western Alps of Europe (inspired by a comment made by W.P. Irwin to AWS). A-a—Austro-alpine. Geology of the Western Alps modified from Ramsay (1991); outline of the Klamath Mountains province from Irwin (1994).

(no. 73, 1901), Port Orford (no. 89, 1903), Redding (no. 138, 1906), and Riddle (no. 218, 1924).

An important contemporary of Diller's was Oscar H. Hershey (Fig. 8), a consulting geologist, who was an associate of Andrew C. Lawson, professor of geology at the University of California–Berkeley. After Hershey's death in 1939, Lawson (1941) wrote the "Memorial to Oscar H. Hershey" that was published in the *Proceedings of the Geological Society of America for 1940*. Hershey, born in 1874 in Pennsylvania, was not formally trained in geology or any of the sciences but was a careful observer as well as a diligent reader. He was also fond of walking and made numerous excursions throughout Illinois and neighboring states after his family moved to Freeport, Illinois, in 1891. In his early twenties, Hershey began to write papers on the physiography and geology of Illinois. Eventually, after geologic excursions in the Ozark Mountains and Panama, he settled in California and began extensive field studies of the Klamath Mountains. During 1901–1906, fifteen of his papers on aspects of the geology of the Klamath Mountains were published in various periodicals on geology. His last paper on the Klamath Mountains, a one-page note with a geologic sketch map of Del Norte County, was published in 1911, but this short contribution showed the approximate position of the Orleans fault, now known to be a fundamental structural feature in the western Klam-

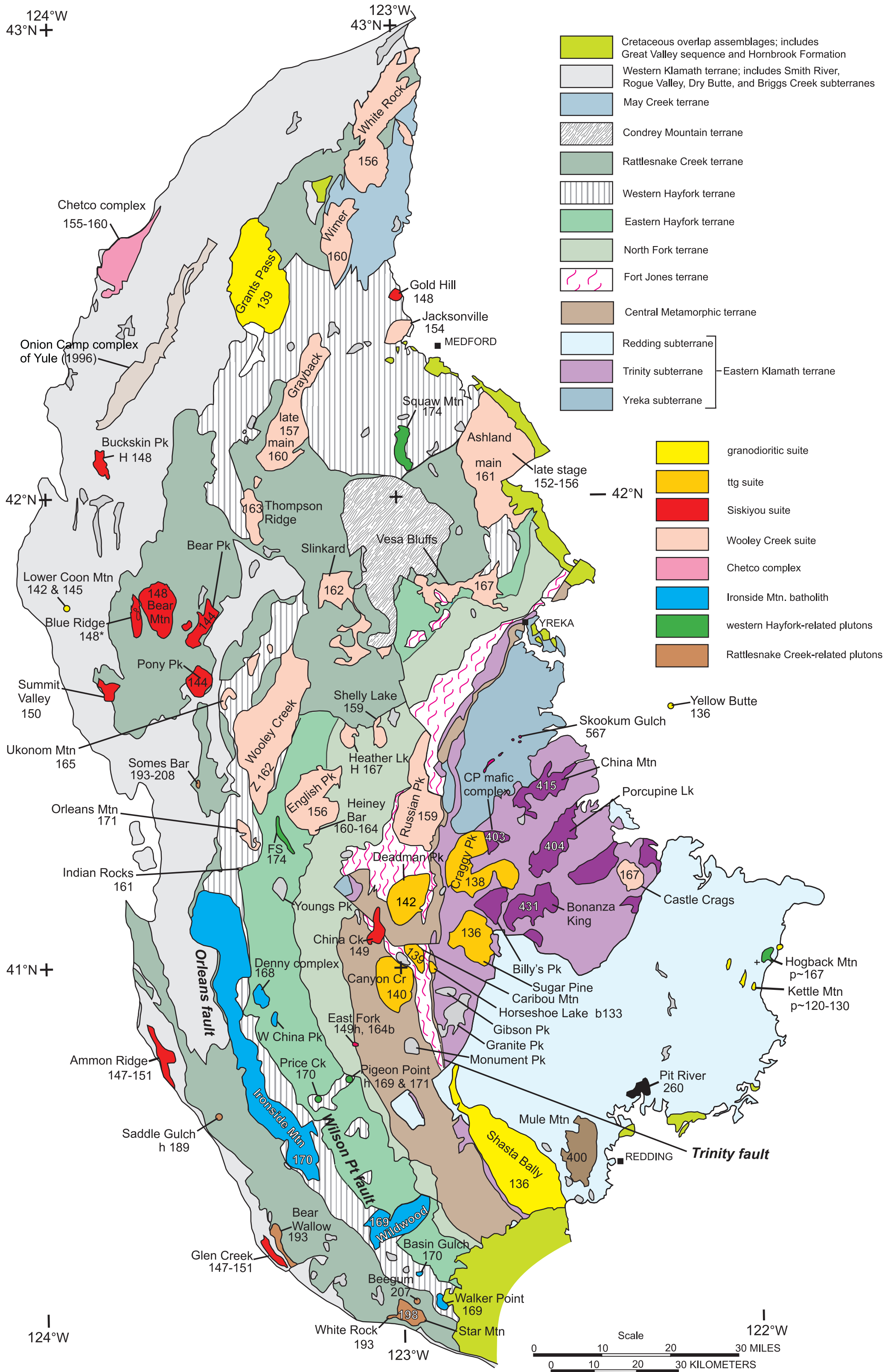


Figure 6. Geologic map of the Klamath Mountains province after Irwin and Wooden (1999) showing principal tectonostratigraphic terranes and plutons color coded according to age group. In the key, "ttg suite" refers to Early Cretaceous tonalite-trondhjemite-granodiorite plutons. Numbers associated with each pluton are ages in Ma. Ages were determined by U-Pb (zircon) unless noted: t indicates U-Pb on titanite, h and b indicate K-Ar ages on hornblende and biotite, respectively, and H and p indicate $^{40}Ar/^{39}Ar$ ages or hornblende and plagioclase, respectively. Data are from Allen and Barnes (this volume), Chamberlain et al. (this volume), and sources summarized in Irwin and Wooden (1999). The age of the Blue Ridge pluton is a minimum age determined on the basis of a cross-cutting tonalitic pluton (Chamberlain et al., this volume). Ck—Creek; CP—Craggy Peak; FS—forks of Salmon pluton; Lk—Lake; Pk—Peak.

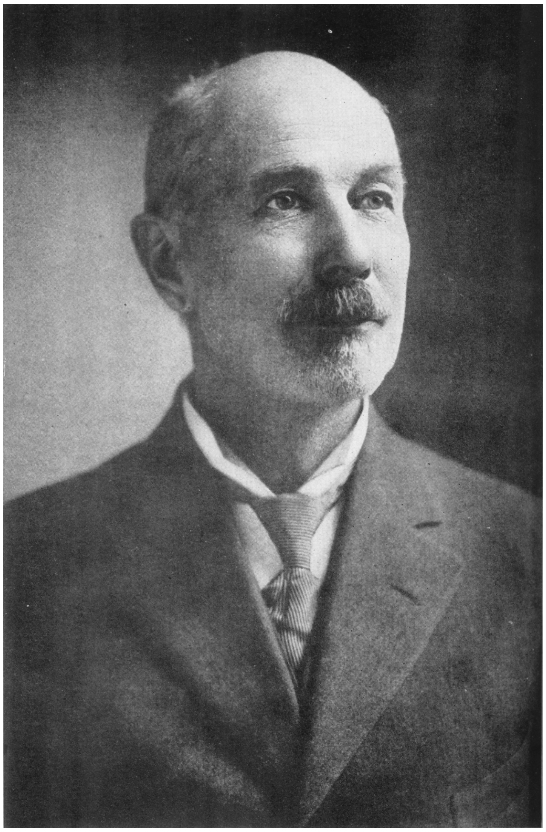


Figure 7. J.S. Diller (1850–1928). See Collier (1929).

ath Mountains (see below for a more extensive discussion of the Orleans fault). An early synthesis of the Klamath Mountains province was Hershey's (1901) article titled "Metamorphic formations of northwestern California," published in *The American Geologist.* In this classic paper, Hershey classified the pre-Cretaceous rocks of the Klamath Mountains into "seven great formations" (exclusive of the intrusive granitic rocks) and provided the first detailed descriptions of the "Abrams Mica Schist" and "Salmon Hornblende Schist" (see additional discussions later in this chapter).

RECOGNITION OF THE LITHIC BELTS

As outlined above, early studies in the Klamath Mountains province by Diller and Hershey as well as the work of N.E.A. Hinds in the southern Klamath Mountains (1932, 1933, 1935) and F.G. Wells and associates in the Oregon Klamath Mountains (F.G. Wells et al., 1940, 1949; Wells and Walker, 1953; Wells, 1956) provided much stratigraphic and structural data regarding the geologic evolution of this complex, remote, and rugged terrane. Some of these geologic studies, especially those carried out by members of the USGS, were related to the assessment of various mineral commodities, for example, gold, chromite, copper, and manganese. Nevertheless, no regional synthesis of the Klamath Mountains province existed, and Irwin's (1960) *Geologic reconnaissance of the northern California Coast Ranges and Klamath Mountains, California,* published as California Division of Mines Bulletin 179, represented an enormous advancement in understanding the fundamental relationships between the Klamath Mountains and Coast Ranges as well as among the diverse group of rocks of contrasting age, deformational history, and metamorphism that constitute the Klamath Mountains province (Fig. 9). This survey was based on a compilation of all previous geologic studies but also involved numerous reconnaissance traverses in key areas throughout the California Klamath Mountains.

An important concept that Irwin (1960) introduced in his synthesis of the California Klamath Mountains and adjacent northern Coast Ranges was the recognition of distinct lithic belts within these geologic provinces (Fig. 10). Within the Klamath Mountains province, Irwin (1960) designated four lithic belts from east to west: (1) eastern Paleozoic belt, (2) central metamorphic belt, (3) western Paleozoic and Triassic belt, and (4) western Jurassic belt. The delineation of these belts was based on a combination of the available age data (especially fossil material) and lithology. The eastern Paleozoic belt is the most fossiliferous, with numerous fossil localities that span a considerable part of the Paleozoic and Mesozoic. Fossil localities in the western Jurassic belt are sparse and the collections small; but

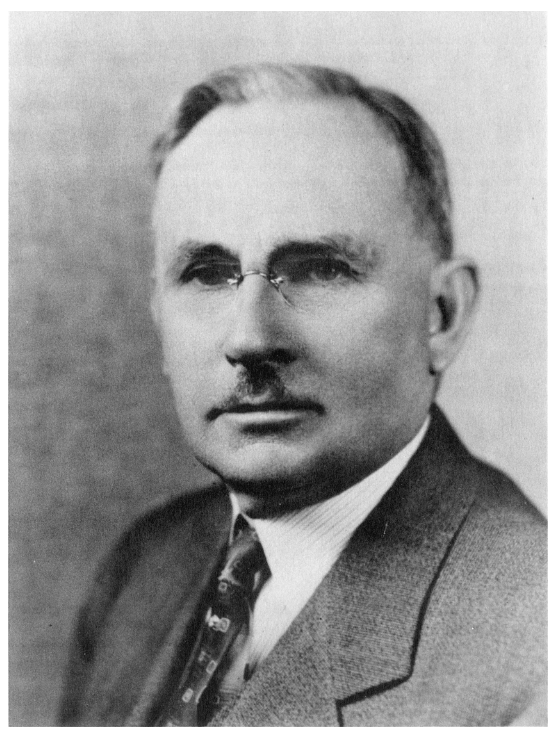


Figure 8. Oscar H. Hershey (1874–1939). See Lawson (1941).

Figure 9. W.P. Irwin and D.B. Tatlock with a map compilation of the geology of the northern Coast Ranges and Klamath Mountains, California, prepared for a presentation (Irwin and Tatlock, 1955) at the Geological Society of America Cordilleran Section Meeting in Berkeley, California (April 28–30, 1955). This early report formed much of the basis for *California Division of Mines Bulletin 179* published in 1960. Photograph taken at the USGS offices in Menlo Park, California, in 1955.

the age of these rocks, including the Galice Formation of Diller (1907), is well known, based on the scattered occurrences of Late Oxfordian to middle Kimmeridgian *Buchia concentrica* (Sowerby) (Imlay, 1959). The original definition of the western Paleozoic and Triassic belt (Irwin, 1960) was chiefly based on locally common fossil occurrences in the southern Klamath Mountains. The fossils indicated a great range in ages, from Devonian through Triassic. More recently, Early and Middle Jurassic radiolarians were also reported from these rocks (see Irwin et al., 1977, 1978, 1982; Blome and Irwin, 1983; Irwin and Blome, on the CD-ROM accompanying this volume and in the GSA Data Repository[1]), and it is clear that the Paleozoic fossils are predominantly found in tectonic or olistostromal blocks in mélange (e.g., Goodge and Renne, 1993).

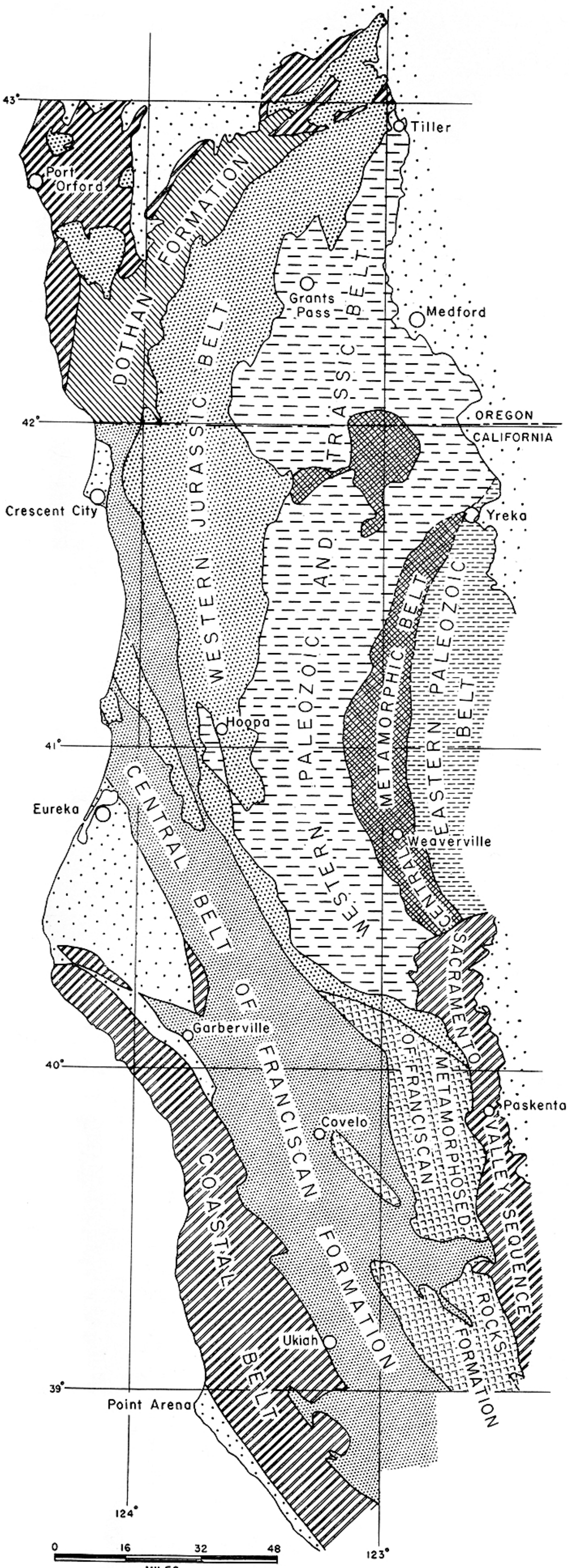
No fossil localities occur in the central metamorphic belt; in fact, some early workers considered these chiefly amphibolite-facies rocks as possibly Precambrian in age (e.g., Hershey, 1901, p. 243–245; Hinds, 1933, p. 84), whereas Irwin (1960, his plate 1) labeled them as "pre-Silurian." Irwin (1960) also included various schists exposed in the environs of Condrey Mountain (north-central Klamath Mountains) as part of the central metamorphic belt (Fig. 10). Subsequently Hotz (1967, 1979), and more recently Helper (1986), Helper et al. (1989), and Saleeby and Harper (1993) have demonstrated that the Condrey Mountain Schist is unrelated to—and significantly younger than—the rocks of the central metamorphic belt.

Davis and Lipman (1962) significantly revised the structural sequence and consequently the stratigraphic nomenclature of Irwin's (1960) central metamorphic belt by abandoning the name "Abrams Mica Schist" (Hershey, 1901) and redefining these rocks as two distinct metasedimentary units: Stuart Fork and Grouse Ridge Formations, separated by the mafic metavolcanic Salmon Formation ("Salmon Hornblende Schist" of Hershey, 1901). According to the structural interpretation of Davis and Lipman (1962), the Stuart Fork Formation is structurally below the Salmon Formation, and these contrasting metamorphic units are separated by a folded, regional thrust fault (i.e., Siskiyou thrust zone of Davis, 1968). The formal stratigraphic nomenclatural status of the Grouse Ridge Formation remains controversial, and Lanphere and Irwin (1987) argued that the name "Abrams Schist" should be retained for the amphibolite-facies, chiefly metasedimentary unit (i.e., the Grouse Ridge Formation of Davis and Lipman, 1962) that overlies the "Salmon Schist."

Goodge (1989a,b, 1995) studied the Stuart Fork Formation in detail, employing modern structural analysis and thermobarometry; he recognized that this unit was deformed and metamorphosed under high pressure–low temperature metamorphic conditions ($P > 6$–11 kb and $T = 250$–400 °C; Goodge, 1995), most likely related to subduction in an accretionary complex. K-Ar radiometric dating reported by Hotz et al. (1977) from the Stuart Fork Formation near Yreka, California, indicated a Late Triassic age (ca. 220 Ma) for the blueschist-facies metamorphism, significantly younger than the Devonian age (ca. 380 Ma) based on Rb-Sr and K-Ar radiometric dating reported by Lanphere et al. (1968) on rocks and minerals from the "Abrams Mica Schist" and "Salmon Hornblende Schist."

In the pamphlet that accommodated the *Preliminary geologic map of the Kerby quadrangle, Oregon* (1948, scale 1:96,000), Wells et al. (1949, p. 3) defined the Triassic(?) Applegate Group as: "A thick assemblage of metamorphosed volcanic rocks with lens-shaped interbeds of argillite, chert, quartzite, conglomerate, and marble." The Applegate Group has since been shown to consist primarily of rocks that may be correlated to terranes recognized in the southern Klamath Mountains province and potentially to the May Creek Schist and related rocks (see below). Many of the rocks of the classic

[1]GSA Data Repository item 2006196, Fossil localities of Rattlesnake Creek, western and eastern Hayfork, and North Fork terranes of the Klamath Mountains, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.



Applegate Group of Wells et al. (1949) are lithologically identical to the western Hayfork terrane of Wright (1982) and contain igneous and detrital (igneous) hornblende grains with identical $^{40}Ar/^{39}Ar$ ages (Donato et al., 1996).

Southeast of the Wimer pluton (Fig. 6), the "Applegate Group" is thrusted above medium- to high-grade semipelitic schist and amphibolitic metabasite (Donato, 1991a,b), collectively referred to as the "May Creek terrane" (Silberling et al., 1987; Irwin, 1994). The amphibolitic unit lacks a formal name; the metasedimentary rocks are called the "May Creek Schist" (Donato, 1991a,b; also see Kays, 1968, 1970, 1995). Donato (1992) described the boundary between the May Creek Schist and structurally underlying amphibolitic unit as an 800- to 1500-m-thick ductile shear zone. Surprisingly, this shear zone is one of the few tectonic boundaries in the Klamath Mountains province that has been studied in detail in regard to its kinematic evolution based on mesoscopic and microscopic structural features. Within the metasedimentary rocks of the hanging-wall plate (i.e., May Creek Schist), Donato (1992) recognized S-C fabrics and asymmetric porphyroclasts and determined quartz [c]-axes patterns in twelve oriented samples. All these data indicate northwest-directed (N38–45°W) thrusting of the May Creek Schist above the amphibolitic unit. However, the age of this thrusting cannot be Nevadan (i.e., Late Jurassic; see later section on Jurassic orogenies for additional discussion), as initially speculated by Donato (1992), because the mapped thrust-fault zone is intruded by the ca. 160-Ma Wimer pluton (Donato, 1991b; Yule, 1996). This ductile shear zone is thus a contractional structural feature that must predate the Late Jurassic. Furthermore, the protolith age of the May Creek terrane is unknown, and its relationship with adjacent tectonostratigraphic terranes of the Klamath Mountains province is everywhere tectonic (fault-bounded) (Silberling et al., 1987; Irwin, 1994; Fig. 3).

SIGNIFICANCE OF ALPINE-TYPE ULTRAMAFIC ROCKS AND THE OPHIOLITE CONCEPT

The recognition that bodies of peridotite-dunite, serpentinite and/or metaserpentinite occur in belts in many orogens on Earth was well known in the early part of the twentieth century (Hess, 1955). The Australian geologist W.N. Benson (1926) referred to such ultramafic rocks in orogenic belts as "alpine-type" ultramafic rocks and inferred an intrusive mode of emplacement. Many subsequent writers delineated the differences between alpine-type ultramafic rocks and stratiform ultramafic complexes, such as the Stillwater Complex, Montana (e.g., see Thayer, 1960, for a comparison). Nevertheless, Robert S. Dietz's (1963) speculative suggestion that alpine-type serpentinites were a slice of oceanic crust tectonically emplaced into

Figure 10. Distribution of lithic belts of the Klamath Mountains province. After Irwin (1960, his fig. 3).

an orogenic belt initiated significant rethinking of the tectonic significance of the so-called "alpine-type" ultramafic rocks. The Dutch geologist W.P. de Roever (1957) had made a similar suggestion about the significance of alpine-type ultramafic rocks in orogens, but his essay was written in German, published in *Geologische Rundschau,* and apparently largely unnoticed by English-speaking geologists. The seminal paper by Harry H. Hess (1962) titled "History of ocean basins" had previously argued that oceanic crust consisted chiefly of serpentinized peridotite (see fig. 7 *in* Hess 1962) and thus also set the stage for Dietz's interpretation of alpine-type ultramafic rocks as tectonic slices of oceanic crust in an orogen.

In this light, the Klamath Mountains played a key role in understanding the tectonic significance of ultramafic belts in orogens. Beginning before World War II and continuing throughout the war years and into the early 1950s, economic geologists, especially members of the USGS, mapped and studied the many chromite deposits associated with the alpine-type ultramafic rocks of the Klamath Mountains (e.g., Rynearson and Smith, 1940; Wells et al., 1946; Wells and Cater, 1950). These early studies were important in determining the broad distribution of the ultramafic rocks in this mountain belt; in many cases, these geologists recognized that mafic rocks (e.g., gabbro, diabase) were associated with these ultramafic rocks. The concept that the ultramafic rocks were part of an intrusive body pervaded the thinking of virtually all geologists who studied such orogenic ultramafic rocks throughout the 1950s and into the early 1960s. The recognition that regional sheets of ultramafic and related rocks (Irwin and Lipman, 1962; Lipman, 1964) occurred along the boundaries of the lithic belts defined by Irwin (1960) eventually stimulated a significant shift in thinking regarding the emplacement of alpine-type ultramafic rocks in the Klamath Mountains province and elsewhere. In contrast to the ruling hypothesis that alpine-type ultramafic rocks were intrusive bodies, Irwin (1964) argued that they were part of the hanging wall of regional-scale allochthons that occurred as imbricated thrust sheets throughout the Klamath Mountains province.

The first publication that specifically used the term "ophiolite" to describe an ultramafic-mafic complex in California was an abstract written by Stephen P. Bezore (1969) in regard to an ophiolitic sequence exposed in the northern California Coast Ranges near Saint Helena. In this abstract, Bezore described a pseudostratiform sequence of ultramafic-mafic rocks that ranged from (1) a basal peridotite unit through (2) an intermixed zone of ultramafic and gabbroic rocks to (3) massive gabbro and in turn overlain by (4) diabase breccia. The basal contact with the Franciscan Complex was interpreted as a tectonic boundary, manifested by a zone of mélange, whereas the contact with the overlying Knoxville Formation was interpreted as a depositional contact. This early description of an ophiolitic sequence quickly led to the recognition of similar sequences at many localities within the California Coast Ranges (Bailey et al., 1970), and these ophiolitic sequences were in general referred to as the "Coast Range ophiolite." In the adjacent Klamath Mountains, Snoke (1971) recognized an ophiolitic sequence in the Preston Peak area that had originally been included in Irwin's (1960) "western Paleozoic and Triassic belt." During the late 1970s and early 1980s, numerous detailed studies of ophiolitic suites from the Klamath Mountains province were published (e.g., Lindsley-Griffin, 1977; Snoke, 1977; Snoke et al., 1977; Harper, 1980, 1984; Quick, 1981, Ando et al., 1983). Many of these ophiolitic sequences were subsequently radiometrically dated (summarized in Saleeby, 1990) and/or their age was established by radiolarians from sedimentary rocks that form interpillow sediment or rest in depositional contact immediately above the lavas (e.g., Pessagno and Blome, 1990; Pessagno et al., 2000).

Of all the ophiolites exposed in the Klamath Mountains province, the Josephine ophiolite is the best-documented sequence because of the many studies by Gregory D. Harper and coworkers (e.g., Harper, 1980, 1984, 2003; Harper and Wright, 1984; Harper et al., 1985, 1988, 1990, 1994; Saleeby and Harper, 1993). Other workers have also made significant contributions on the petrogenesis, deformation features and mechanisms, and microfabric of the ultramafic rocks forming the basal unit of the Josephine ophiolite (Loney and Himmelberg, 1976; Dick, 1977; Evans, 1987; Kelemen and Dick, 1995). A probable continuation of the Josephine ophiolite (i.e., Devils Elbow ophiolite remnant) has been recognized in the southernmost Klamath Mountains (Wright and Wyld, 1986; Wyld and Wright, 1988). Plagiogranite from the Josephine ophiolite yielded a U-Pb zircon age of 163 ± 5 Ma (table 2, sample 6 *in* Harper et al., 1994), whereas Wright and Wyld (1986, their table 1, fig. 3) reported a U-Pb zircon age of 164 ± 1 Ma from the Devils Elbow ophiolitic remnant in the southern Klamath Mountains.

The Josephine ophiolite (Harper, 1984) is an "ideal ophiolite" in the sense that it corresponds closely to the classic definition of ophiolite as published in *Geotimes* (Anonymous, 1972) after the first Penrose Field Conference on ophiolites and has been commonly cited in ophiolite literature for the past thirty or more years. As pointed out by some recent ophiolite workers (e.g., Dilek, 2003), this classic definition, established in the early days of the application of the plate tectonic paradigm to orogenic belts, is too confining in its emphasis on a pseudostratigraphic character, and many ophiolitic assemblages are more complex than the definition admits (e.g., ophiolitic mélange—see Gansser, 1974) or are polygenetic (Saleeby, 1982). Nevertheless, the Josephine ophiolite fits the classic definition as well as any ophiolite in the Klamath Mountains. An important aspect of the Josephine ophiolite is that its early history is exceptionally well preserved along its margins, even though the Josephine ophiolite and the marginal "rift facies" were involved in regional contraction manifested by the Late Jurassic Nevadan orogeny (see detailed discussion later in this chapter). The rift facies of the Josephine ophiolite was originally identified along the eastern margin of the Late Jurassic basin that is floored by the Josephine ophiolite. In the Preston Peak area, Snoke (1977) described a mafic complex associated with the Preston Peak ophiolite. This mafic complex consists of many small intrusive bodies of metadiabase and/or metagabbro as well as numerous metadiabase dikes (i.e., a mafic dike swarm). Saleeby and Harper (1993, their table 1, sample 3) reported a U-Pb zircon age of 164 ± 4 Ma on a quartz diorite dike, a scarce member of the mafic complex of the Preston Peak ophiolite, indicating that the dike swarm was similar in age or slightly older than the Josephine ophiolite (ca. 164–162 Ma). Yule et al. (1992) and Yule and Saleeby (1993) argued that mafic dikes intrusive into the Rattlesnake Creek terrane on the west side of the western Jurassic belt (i.e., part of the Onion Camp complex; Yule, 1996) are a remnant of the rifted *western* margin of the basin (also see Yule et al., this volume) and consequently equivalent to the mafic complex of the Preston Peak ophiolite of the eastern margin of the basin. If this interpretation is correct, the Josephine ophiolite and its rifted margins represent the most complete ophiolitic sequence in North America. A somewhat similar scenario has been proposed for the development of the Rocas Verdes ophiolites of southernmost South America (Stern and De Wit, 2003, and references therein) but in this setting, the rifting occurred within continental crust rather than in an older ensimatic terrane (i.e., Rattlesnake Creek terrane).

The tectonic setting of the rifting associated with the development of the Josephine ophiolite is still uncertain. Recently, Harper (2003) interpreted the development of the Josephine ophiolite as a propagating rift analogous to the rifting that formed the modern Lau Basin of the western Pacific Ocean (see his fig. 9). However, previously, Harper et al. (1985) argued that the rifting associated with the development of the Josephine ophiolite developed during regional, oblique extension associated with a broad zone of concurrent strike-slip faulting and extension (intra-arc transform fault), as presently manifested in the Andaman Sea north of Sumatra.

Another ophiolitic assemblage that has a long history of study by various workers is the Trinity ultramafic-mafic complex (Trinity subterrane of Irwin, 1994) exposed in the eastern Klamath Mountains (Lipman, 1964; Lindsley-Griffin, 1977, 1983; Quick, 1981; Boudier et al., 1989; Lindsley-Griffin and Griffin, 1991; Wallin and Metcalf, 1998; Metcalf et al., 2000; Mankinen et al., 2002). This suite of ultramafic and mafic rocks is the oldest ophiolitic assemblage in the Klamath Mountains province but is also a polygenetic suite of rocks that has yielded a broad range of ages—from Neoproterozoic through Early Devonian (Mattinson and Hopson, 1972; Jacobsen et al., 1984; Wallin and Metcalf, 1998; Metcalf et al., 2000; Mankinen et al., 2002; Lindsley-Griffin et al., 2003). Multiple hypotheses have been advanced for this assemblage; the most recent interpretation is that it is a supra-subduction ophiolite formed during forearc rifting in an incipient intraoceanic arc (Wallin and Metcalf, 1998; Metcalf et al., 2000). A Sm-Nd mineral isochron of 472 ± 32 Ma on plagioclase peridotite (Jacobsen et al., 1984) is interpreted to date the lithospheric emplacement of the Trinity peridotite. This peridotite massif was subsequently intruded by a suite of gabbroic plutons that range in age from Early Silurian to Early Devonian (431–404 Ma) (Wallin and Metcalf, 1998). Wallin and Metcalf (1998) and Metcalf et al. (2000) argued that the Early Devonian Copley Greenstone and Balaklala Rhyolite of the Redding section may be a downfaulted or erosional remnant of the volcanic carapace related to these Siluro-Devonian plutonic rocks (see their figs. 7 and 12, respectively). Wallin and Metcalf (1998) and Metcalf et al. (2000) also argued that the Trinity ultramafic-mafic complex was part of a west-facing intraoceanic arc system, with the Central Metamorphic terrane interpreted as a remnant of underthrusted oceanic lithosphere. Dickinson (2000) proposed an opposite subduction-zone geometry for these terranes, in which the Trinity ultramafic-mafic complex was part of an east-facing subduction system that migrated southeastward during slab rollback. The Late Devonian volcanic assemblages of the northern Sierra Nevada are interpreted as younger manifestations of this southeast-facing island-arc system.

Perhaps the most enigmatic ophiolitic assemblage in the Klamath Mountains province is the Rattlesnake Creek terrane (Irwin, 1972; Petersen, 1982; Rawson and Petersen, 1982; Hill, 1984; Gorman, 1985; Gray, 1985; Donato, 1987, 1989; Wright and Wyld, 1994). The Rattlesnake Creek terrane is best known in the southern Klamath Mountains, where Irwin (1972) originally delineated it as a mappable subdivision of his "western Paleozoic and Triassic belt." Irwin (1972) recognized the ophiolitic nature of this heterogeneous assemblage of rocks as well as its overall mélange structural character. Wright and Wyld (1994) demonstrated the polygenetic evolution of this terrane. They recognized that the Rattlesnake Creek terrane consists of a widespread basement of ophiolitic mélange overlain locally by various "cover sequences," which exhibit characteristics of an oceanic-arc regime. Furthermore, Wright and Wyld (1994) argued that the ophiolitic mélange developed in a fracture zone (i.e., oceanic transform fault zone) that predates the Late Triassic. The first cover sequence is interpreted to be an intraoceanic Late Triassic–Early Jurassic arc tied to eastward-dipping subduction zone(s) developed over the fracture-zone mélange (see their fig. 10). During the Middle Jurassic, the Rattlesnake Creek terrane apparently served as ensimatic basement for a second oceanic-arc cover sequence referred to as the "western Hayfork terrane" (Wright, 1982; Wright and Fahan, 1988; Donato et al., 1996). During regional Middle Jurassic contraction (prior to ca. 170 Ma), this oceanic-arc system collapsed, and the eastern Hayfork terrane (part of a long-lived accretionary subduction complex; see Wright, 1982) was thrust on top of the western Hayfork terrane along the Wilson Point fault (Fig. 3). In turn, the western Hayfork terrane was apparently thrust (i.e., Salt Creek thrust) on top of the Rattlesnake Creek terrane (fig. 10 *in* Wright and Wyld, 1994). The Wilson Point thrust is intruded by the ca. 170-Ma Ironside Mountain batholith (Barnes et al., this volume, Chapter 10) and thus is a manifestation of regional contraction in the Klamath Mountains province associated with a cryptic Middle Jurassic orogenic history (see later section on Jurassic orogenies).

In the north-central Klamath Mountains, rocks correlated with the Rattlesnake Creek terrane (Marble Mountain terrane of Blake et al., 1982) become progressively metamorphosed from greenschist facies to locally as high-grade as granulite facies (Barrows, 1969; Medaris, 1975; Rawson and Petersen, 1982; Donato, 1987, 1989; Coleman et al., 1988). The highest metamorphic grade equivalents of the Rattlesnake Creek terrane frame the Condrey Mountain window, a Neogene structural dome (Mortimer and Coleman, 1985) that exposes the high pressure–low temperature Condrey Mountain Schist (Hotz, 1967, 1979; Helper, 1986). The high-grade rocks of the Rattlesnake Creek terrane are penetrated by numerous late Middle Jurassic plutonic complexes, but the Condrey Mountain Schist is *not* intruded by plutonic rocks of this age. The correlation of the high-grade rocks of the western Paleozoic and Triassic belt with the Rattlesnake Creek terrane and the abundance of large, penecontemporaneous plutons (e.g., Hacker et al., 1995) suggest that the anomalous high-grade metamorphism of the Rattlesnake Creek terrane may be a manifestation of late Middle Jurassic regional contact metamorphism. In this interpretation, intrusive arc magmas play a fundamental role in the advection of heat into the Rattlesnake Creek terrane in the north-central part of the Klamath Mountains province. Such a simple model to explain the increase in metamorphic grade of the Rattlesnake Creek terrane is complicated by the recognition that regional thrusting predated emplacement of the Middle Jurassic plutons (Donato et al., 1982), and the regional metamorphism apparently involved an increase in pressure as well as temperature (Medaris, 1975; Grover, 1984; Lieberman and Rice, 1986). The evolution of the Rattlesnake Creek ophiolitic mélange and its progressive metamorphism to upper amphibolite-facies conditions and locally even higher metamorphic grade is still a major unsolved problem in the Klamath Mountains province (see section on important problems for future study).

RECOGNITION OF REGIONAL THRUST FAULTS

An analysis of each individual thrust-fault system in the Klamath Mountains province is beyond the scope of this summary, and in some cases, the data are insufficient to attempt such an analysis. However, the Orleans fault, originally recognized and named by Hershey (1906, 1911) has been studied in many places along its trace throughout the western Klamath Mountains (Klein, 1977; Snoke, 1977; Petersen, 1982; Hill, 1984; Gorman, 1985; Gray, 1985; Jachens et al., 1986; Cashman, 1988; Saleeby and Harper, 1993; Gray, this volume). A synthesis of these data thus serves as a useful introduction to the complexity of the thrust-fault systems of the Klamath Mountains province. Along the Klamath River from near Happy Camp to Orleans, California (Fig. 2), the Orleans fault is exposed in the canyon walls. It forms an erosional re-entrant through the hanging-wall upper plate near Happy Camp (Klein, 1977; Petersen, 1982; Fig. 3) and underlies a large klippe of hanging-wall rocks north of Orleans (Gray, 1985). The rocks of the hanging wall consist of the Rattlesnake Creek terrane, western Hayfork terrane, and various intrusive plutonic rocks, whereas the footwall rocks are the Upper Jurassic Galice Formation of the Smith River subterrane (i.e., a subdivision of the western Klamath terrane). Near Happy Camp, the rocks of the Rattlesnake Creek terrane (Lower Triassic to Early Jurassic and older[?]) reach amphibolite-facies metamorphic conditions (Petersen, 1982; Hill, 1984; Donato, 1987, 1989; Coleman et al., 1988), whereas the footwall rocks are lower greenschist facies but penetratively strained to Textural Zone 2 or 2+ (Gray, 1985, this volume; Cashman, 1988). Thus the Orleans fault emplaced older rocks onto younger rocks and, at least locally, high-grade metamorphic rocks onto lower-grade metamorphic rocks. These hanging-wall–footwall relationships indicate a contractional fault system.

A gravity survey (Jachens et al., 1986) was carried out to determine the subsurface extent of the Orleans fault in the west-central Klamath Mountains. These data support the interpretation that the Orleans fault is an original low-angle regional thrust fault that has been subsequently folded by broad, kilometer-scale upright folds. Furthermore, a suite of Late Jurassic plutons (western Klamath suite; see Barnes et al., this volume, Chapter 17) locally intrude rocks of both the hanging wall and footwall of the Orleans fault. These field relationships therefore provide tight age constraints on the developmental history of this regional thrust system (Harper et al., 1994). The plutons range in age from ca. 151 to 144 Ma, whereas detritial zircon grains as young as ca. 153 Ma have been identified in metagraywackes from the Upper Jurassic Galice Formation (Miller et al., 2003). The data therefore constrain the movement history of the Orleans fault as between 151 and 153 Ma and support long-standing interpretations that this structural feature is part of the classic Late Jurassic Nevadan orogeny (see section on Jurassic orogenies for a complete discussion). The regional thrust faulting manifested by the Orleans fault and development of penetrative cleavage in the Upper Jurassic Galice Formation are the quintessential structural elements of the Nevadan orogeny in the Klamath Mountains province.

The significance of the regional Orleans thrust system in regard to the overall Late Jurassic plate tectonic framework of western North America remains a fundamental tectonic question. The lack of high pressure–low temperature metamorphism associated with the Upper Jurassic Galice Formation argues against a fossil subduction-zone interpretation for this fault system, which can be traced for the length of the Klamath Mountains province (Fig. 3). It could be an intraplate fault that is a manifestation of outboard Late Jurassic subduction (Davis et al., 1978). Late Jurassic blueschist- and amphibolite-facies rocks occur as tectonic blocks in some mélanges of the Franciscan Complex (Coleman and Lanphere, 1971), and the Late Jurassic plutons of the western Klamath suite have arc geochemical characteristics (Barnes et al., this volume, Chapter 17). These geologic features suggest that subduction was ongoing along the margin of western North America during the Late Jurassic (ca. 150 Ma). The presence of rift facies of the Josephine ophiolite on both the east and west margins of the Late Jurassic Josephine ophiolite basin (i.e., depocenter for the Upper Jurassic Galice Formation) is perhaps the most definitive geologic relationship that eliminates the Orleans fault as a direct manifestation of subduction-zone underthrusting. The Orleans fault, therefore, is a contractional fault system that has been localized along the eastern flank of the Josephine marginal rift basin. This fault system has led to significant underthrusting of the Smith River subterrane beneath the Rattlesnake Creek terrane and other terranes situated to the east. The estimated 100 km of contraction accommodated by this structure (Jachens et al., 1986) is quite considerable but still is far shy of the thousands of kilometers associated with fossil subduction-zone systems.

Older thrust faults occur in the hanging-wall plate of the Orleans fault, but their ages are not well constrained. For example, Barnes et al. (1986) argued that the thrust-fault system that frames the Condrey Mountain window (Fig. 3) is younger than ca. 162 Ma. This interpretation is based on the U-Pb radiometric age of the Slinkard pluton that occurs in the hanging-wall plate of this low-angle fault system but also contains a high-temperature foliation subparallel to the fault. This fault system, which emplaced high-grade metamorphic rocks of the Rattlesnake Creek terrane (Marble Mountain terrane of Blake et al., 1982; also see Donato et al., 1982; Donato, 1987, 1989; Coleman et al., 1988) above the greenschist-blueschist Condrey Mountain terrane, is chiefly exposed because of Neogene doming in this part of the Klamath Mountains province (Mortimer and Coleman, 1985). Neither this fault system nor the Condrey Mountain Schist has been identified farther to the west, suggesting that the Orleans fault truncated the older thrust-fault system (fig. 2 *in* Saleeby and Harper, 1993) during the Nevadan orogeny.

The ages of thrust faults exposed farther to the east of the Orleans fault are even more broadly constrained and are commonly only bracketed by the youngest rocks involved in thrusting and the oldest pluton that intruded both the hanging-wall and footwall plates of these thrust faults (Davis et al., 1978; fig. 9 *in* Wright and Fahan, 1988). An important exception is the Trinity thrust (Fig. 3), which has been interpreted as a high-temperature shear zone that formed during the emplacement of the Trinity peridotite (Peacock and Norris, 1989). Devonian (ca. 380 Ma) Rb-Sr radiometric dates from minerals and rocks of the underlying Grouse Ridge Formation of the Central Metamorphic terrane are commonly interpreted as dating the emplacement of the Trinity peridotite.

One final topic related to the character of the thrust faults of the Klamath Mountains province concerns the various faults that bound several terranes, which Irwin (1972) included as part of his western Paleozoic and Triassic belt. These tectonostratigraphic terranes are the Fort Jones, North Fork, and eastern Hayfork terranes (Fig. 3). Each terrane is bounded by an eastward-dipping regional thrust fault. The Fort Jones terrane includes ca. 220-Ma blueschist-facies rocks (Hotz et al., 1977; Goodge, 1989a,b), the North Fork terrane is ophiolitic (Ando et al., 1983), and the eastern Hayfork is a mélange containing Tethyan fauna (Irwin and Galanis, 1976; Nestell et al., 1981; Miller, 1987; Miller and Wright, 1987). One possible interpretation of these three terranes is that they make up an accretionary subduction complex that began to evolve in Late Triassic time and continued into Middle Jurassic time (Wright, 1982; Dickinson, 2000). Jurassic radiolarians have been recovered from both the North Fork and eastern Hayfork terranes (Irwin et al., 1977, 1978, 1982; Blome and Irwin, 1983; Irwin and Blome, on the CD-ROM accompanying this volume and in the GSA Data Repository [see footnote 1]).

TECTONOSTRATIGRAPHIC TERRANE CONCEPT

An early application of plate tectonic theory to the North American Cordilleran orogen—and in particular, the Klamath Mountains and northern California Coast Ranges—was Warren Hamilton's (1969) classic paper titled "Mesozoic California and the underflow of Pacific mantle." In this important synthesis of California geology, Hamilton established the framework for a complete reevaluation of the geology of the Klamath Mountains and environs. In particular, he recognized the importance of distinct tectonic assemblages of rocks, such as island arcs and accretionary prisms and associated mélanges.

Although Hamilton (1969) did not employ the term "terrane" to describe his various tectonic assemblages in the California Coast Ranges, Klamath Mountains, and western Sierra Nevada, he clearly analyzed the geologic evolution of these provinces in terms of distinct lithotectonic units. W.P. Irwin (1972) introduced the term "terrane" into modern geologic literature and first delineated a group of distinct "terranes" in the southern Klamath Mountains to better understand the heterogeneous and complex "western Paleozoic and Triassic belt" of his earlier synthesis. Irwin (1972) recognized three distinct terranes (from east to west): North Fork, Hayfork, and Rattlesnake Creek terranes (Fig. 11). Irwin (1972, p. C103) stated the following regarding his use of the term "terrane": "refers to an association of geologic features, such as stratigraphic formations, intrusive rocks, mineral deposits, and tectonic history, some or all of which lend a distinguishing character to a particular tract of rocks and which differ from those of an adjacent terrane."

Subsequently, Wright (1982) recognized that the Hayfork terrane of Irwin (1972) was composite in lithology, age, and inferred tectonic setting. He subdivided the original Hayfork terrane into the eastern and western Hayfork terranes. The former consists chiefly of tectonic mélange and broken formation; Wright (1982) interpreted it as part of a Permo–Triassic accretionary subduction complex. The latter consists chiefly of volcaniclastic deposits, which were dated as Middle Jurassic (177–168 Ma), based on conventional K-Ar hornblende dates (table 5 *in* Wright and Fahan, 1988). Wright (1982) interpreted this terrane as deposited in an intraoceanic-arc setting.

Although the published record clearly indicates that Irwin's (1972) recognition of terranes in the southern Klamath Moun-

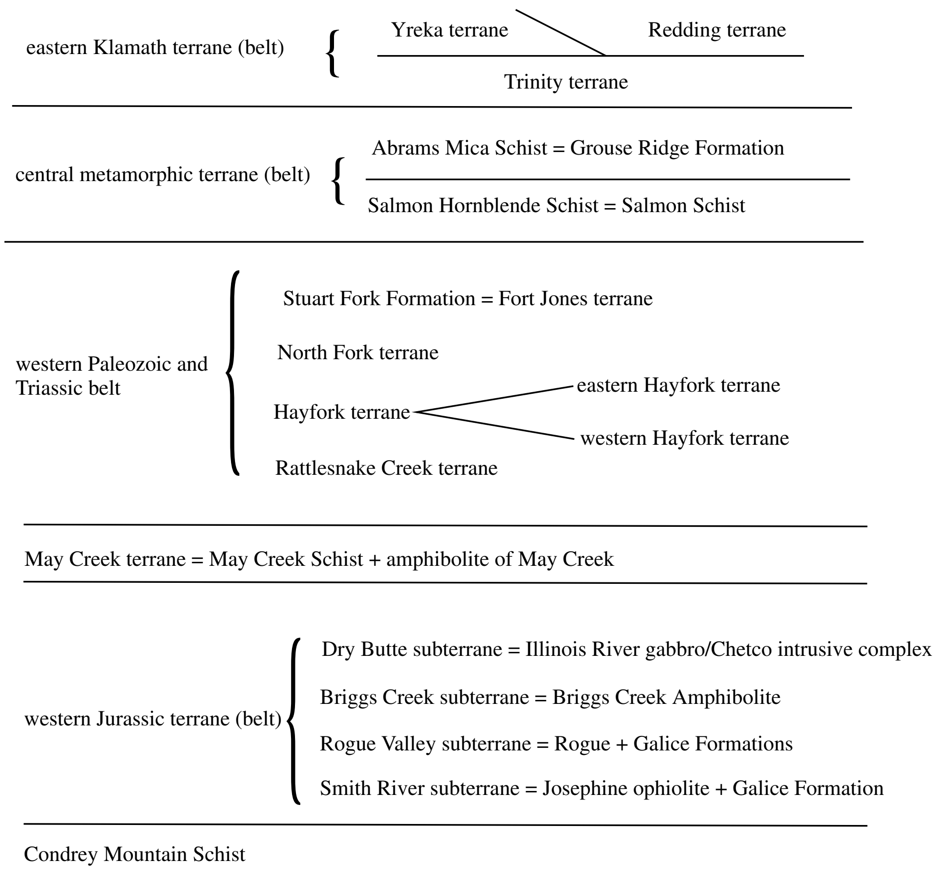


Figure 11. A comparison of lithic belts as defined by Irwin (1960) and subsequent terrane nomenclature (see text for pertinent references) for the Klamath Mountains province.

tains was fundamental in analyzing the tectonic development of that mountain belt, the concept of terrane analysis as applied to orogens in general was not widely used by the geologic community until the 1980s. In this light, the paper by Peter J. Coney, David L. Jones, and James W.H. Monger, published in 1980 in *Nature* is commonly recognized as the most significant contribution to interpretation of the North American Cordillera as a collage of allochthonous terranes. Gradually the term "terrane" was modified into the more descriptive term "tectonostratigraphic terrane." In a book on the terranes of the circum-Pacific region, Howell et al. (1985, p. 4) defined "tectonostratigraphic terrane" as "a fault-bounded package of rocks of regional extent characterized by a geologic history which differs from that of neighboring terranes."

Gray (1986) introduced the term "native terrane" for tectonostratigraphic terranes that have specific geologic and paleontological ties to western North America, and he used several tectonostratigraphic terranes of the Klamath Mountains as examples, specifically, the terranes of Irwin's (1960) "western Paleozoic and Triassic belt" (Fig. 10). This term has been partially supplanted by the term "pericratonic terrane," defined as a terrane that formed near a craton (i.e., North America), based on facies or clastic component provenance (e.g., Monger and Nokleberg, 1996). Furthermore, a growing body of geochemical and isotopic studies indicate a Precambrian (cratonic) input into some accreted tectonostratigraphic terranes along the length of the Cordillera (Centeno-Garcia et al., 1993; Patchett and Gehrels, 1998; Unterschutz et al., 2002; Frost et al., this volume). In the Klamath Mountains province, Nd isotope data for argillaceous rocks from the Rattlesnake Creek terrane and Upper Jurassic Galice Formation of the western Klamath terrane indicate a significant input of Precambrian debris during deposition of portions of these accreted terranes (Frost et al., this volume). Detritial zircon studies from upper Paleozoic strata of the eastern Klamath terrane (Miller and Saleeby, 1991; Gehrels and Miller, 2000) and Upper Jurassic Galice Formation (Miller and Saleeby, 1995) also indicate the input of Precambrian zircon grains during deposition. Likewise, xenocrystic Paleoproterozoic (ca. 1.7 Ga) zircon grains have been recognized in the Upper Jurassic Devils Elbow ophiolite remnant of the southern Klamath Mountains (Wright and Wyld, 1986).

The North Fork terrane provides an informative example of another possible native or pericratonic terrane. Wright (1982) showed that (meta)sedimentary rocks of the North Fork and eastern Hayfork terranes were similar in lithologic character and age and showed evidence of craton-derived (hemipelagic) sedimentary provenance. He suggested that the two units were part of what is now referred to as a supra-subduction-zone complex in which the coeval arc lay in what is now the eastern Klamath belt (Redding section). On the basis of detailed mapping, geochemical, and geochronological studies in the central Klamath Mountains province, Ernst (1999) supported the supra-subduction- zone interpretation. However, Ernst and his coworkers found that North Fork metabasaltic rocks in the Sawyers Bar area consisted of island-arc basalt (IAB) and ocean island basalt (OIB), which in turn suggest that the North Fork terrane was at least in part an arc terrane. On the basis of OIB geochemistry, Mortimer (1985) correlated similar metabasaltic rocks in the Yreka area with the North Fork terrane. In this volume, Scherer et al. present new geochemical data for North Fork mafic metavolcanic rocks from the southern Klamath Mountains province. They found OIB-type basalts, as seen elsewhere in the terrane, but also mid-ocean ridge basalts (MORB). The presence of MORB in the southern North Fork terrane may not be consistent with a pericratonic origin and was interpreted by Scherer et al. (this volume) to indicate a distal tectonic setting. It is presently unclear whether the North Fork terrane represents oceanic crust whose petrologic character changed dramatically along strike, or whether the North Fork terrane in the southern Klamath Mountains province is a distinct tectonic fragment compared to the more northern parts of the terrane.

Since the advent of the terrane concept in the interpretation of orogenic belts, paleontological data have played an important role in recognizing the potential exotic nature of a specific terrane. In the Klamath Mountains province, the recognition of Tethyan fauna in several terranes was considered especially significant (Irwin, 1972). Permian limestones containing verbeekinid fusulinids have played a key role in understanding the distribution of Tethyan fauna in the western North American Cordillera (Monger and Ross, 1971). Two fragmentary, subparallel belts of tectonostratigraphic terranes containing contrasting Permian fauna have been recognized along the length of the western North American Cordillera and designated the McCloud and Cache Creek belts (Miller, 1987). The Cache Creek belt lies generally west of the McCloud belt, and blueschist-facies metamorphic rocks are commonly an element in the former (Hotz et al., 1977). The presence of blueschist-facies rocks and the commonly chaotic nature of the terranes that are part of the Cache Creek belt have led to an interpretation of these terranes as components of an accretionary complex developed during subduction. The presence of Early and Middle Jurassic radiolarians (e.g., Irwin et al., 1977, 1978, 1982; Blome and Irwin, 1983) in some of the terranes of the Cache Creek belt indicate that the development of the accretionary complex continued nto the early Mesozoic. In the Klamath Mountains province, the tectonostratigraphic terranes that have been classified as part of the Cache Creek belt are the Fort Jones and eastern Hayfork terranes. To the northeast, in the Blue Mountains province, the Baker terrane (Silberling et al., 1987) is part of the Cache Creek belt; to the south, the Calaveras Complex (Schweickert et al., 1977) is also interpreted as belonging to the Cache Creek belt (Miller, 1987), although no fossils of Tethyan affinity have ever been recovered from this rock assemblage.

IMPORTANCE OF PLUTONIC STUDIES

The geologic map that Irwin (1960) compiled to accompany his geologic reconnaissance of the California Klamath Mountains and adjacent northern Coast Ranges clearly demonstrated that distinct plutons, some of batholithic dimensions, intruded all the lithic belts of the Klamath Mountains. In contrast, except for the so-called "alpine-type ultramafic rocks," such plutonic rocks do not occur in the northern California Coast Ranges. When Irwin's map was published (1960), none of the intrusive plutonic complexes in the Klamath Mountains province had been studied in detail, although Curtis et al. (1958) had dated hornblende and biotite from the Shasta Bally pluton using the K-Ar method. This early interest in the Shasta Bally pluton arose because it is depositionally overlain by fossiliferous, Lower Cretaceous sedimentary rocks of the Great Valley sequence, which places a maximum absolute age on these rocks.

Early, detailed petrologic studies of Klamath Mountains province plutons focused on well-exposed intrusions in the Trinity Alps region (south-central Klamath Mountains province). These studies are exemplified by the work of Davis (1963) and Lipman (1963), who showed that individual plutons consist of distinct, mappable intrusive units and that magma emplacement styles ranged from forceful emplacement to stoping. These observations were emphasized in the compilation study of the Trinity Alps region (Davis et al., 1965) that showed pluton distribution, structural character, and contact relations. Davis et al. (1965) also showed that many plutons truncated regional tectonic boundaries, which emphasized the need for dating individual intrusive events. Another important observation from these early studies was the abundance of tonalitic to trondhjemitic rocks in the Trinity Alps region and the similarity of Klamath tonalitic plutons with those of the western Sierra Nevada Metamorphic belt (e.g., Hietanen, 1951, 1976; Compton, 1955; Clark, 1964, 1976; also see Irwin, 2003, on the CD-ROM accompanying this volume and the GSA Data Repository,[2] and Day and Bickford, 2004, for more recent summaries). In the Klamath Mountains province, this sequence of primarily tonalitic to trondhjemitic plutons spans a narrow range of geologic time (ca. 142–136 Ma; Allen and Barnes, this vol-

[2]GSA Data Repository item 2006197, Correlation of the Klamath Mountains and Sierra Nevada, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

ume) and is related to partial melting of deep-seated metabasic rocks (Barnes et al., 1996). As discussed below and in Allen and Barnes (this volume), other plutonic suites in the Klamath Mountains province display distinct compositional and petrogenetic features.

Few geochronological data were available prior to the study by Lanphere et al. (1968). They reported K-Ar and Rb-Sr ages of plutonic and metamorphic rocks from the California Klamath Mountains province and showed that pluton ages ranged from at least as old as Silurian to as young as Cretaceous. On the basis of ages and petrographic and chemical compositions, they recognized three distinct plutonic belts, which represent the foundation of modern views of plutonic suites in the province. These results were expanded to include the entire Klamath Mountains province by Hotz (1971), who enlarged the coverage of K-Ar ages and presented a large petrographic and geochemical dataset. Hotz (1971) recognized the predominantly calcic to calc-alkalic nature of most of the plutons, which was consistent with their position west of Moore's (1959) "quartz diorite line." However, Lanphere et al. (1968) and Hotz (1971) also recognized the potassic nature of a distinct group of plutons associated with the Ironside Mountain batholith—compositions that are otherwise absent west of the quartz diorite line (see Barnes et al., this volume, Chapter 10). At this time, four plutonic belts were recognized: southwestern Ironside Mountain belt (pyroxene-rich mildly to strongly potassic plutons), "northern plutonic area" (diverse calcic to calc-alkalic plutons), Trinity Mountains belt (tonalitic and trondhjemitic plutons), and the eastern belt (diverse plutons, some of which had Triassic and Silurian K-Ar ages; Fig. 6).

Published accounts of Klamath Mountains province plutons languished until 1980. With the appearance of field and geochemical results from the Castle Crags pluton (Vennum, 1980), Bear Mountain intrusive complex (Snoke et al., 1981), and Wooley Creek batholith (Barnes, 1983) and the isotopic data of Masi et al. (1981), studies of Klamath plutons entered the modern era. These petrologic and geochemical studies were accompanied by the rapid growth and refinement of the geochronological database, in which U-Pb (zircon) ages supplanted K-Ar and Rb-Sr data, and the renewed recognition of the importance of "pinning plutons" with regard to tectonic history. Irwin (1985) published a synthesis of the geochronological and tectonic data, in which he recognized eleven plutonic belts and distinguished between pre- and post-amalgamation plutons. This synthesis was necessarily preliminary because many plutons lacked reliable U-Pb (zircon) ages. It was revisited in 1999 (Irwin and Wooden, 1999) with a greatly expanded geochronological dataset. At this writing, only a handful of plutons in the Klamath Mountains province lack radiometric age information.

The ages of plutonic rocks in the Klamath Mountains province were nowhere more important than for those that intrude the terranes of the eastern Klamath Mountains. The K-Ar dating (summarized in Hotz, 1971) indicated the possible presence of Silurian and Cretaceous plutons and Mattinson and Hopson (1972) reported U-Pb (zircon) ages of ca. 455 Ma from trondhjemitic boulders in a conglomerate and ca. 480 Ma from a gabbroic body along the northern margin of the Trinity peridotite. The Paleozoic ages, bimodal nature (gabbro and trondhjemite), and common mafic dike swarms (Petersen et al., 1991; Wallin and Metcalf, 1998) led some workers (e.g., Brouxel and Lapierre, 1988; Brouxel et al., 1988) to propose a genetic relationship between the Trinity peridotite and Paleozoic plutons. However, Wallin and coworkers (Wallin et al., 1995; Wallin and Metcalf, 1998) showed that Paleozoic plutons in the eastern Klamath Mountains are primarily Silurian and early Devonian and therefore younger than the Trinity peridotite. Detailed geochemical study of these plutonic systems led these workers (Wallin and Metcalf, 1998; Metcalf et al., 2000) to suggest that the Silurian–Devonian plutons formed in an oceanic, protoarc setting. Wallin et al. (1995) also dated a Neoproterozoic metagabbro in tectonic contact with the Trinity peridotite, one indication of the complexity and polygenetic nature of the Trinity terrane.

As isotopic and trace-element data for Jurassic and Early Cretaceous plutons increased (e.g., Masi et al., 1981; Barnes et al., 1990, 1992; Gribble et al., 1990), it was possible to refine the compositional distinctions recognized by Lanphere et al. (1968) and Hotz (1971). Barnes et al. (1992) showed that isotopic distinctions between plutonic suites may be related to their age and tectonic history. This concept is further refined in this volume (Allen and Barnes; Barnes et al., this volume, Chapter 10, Chapter 17). In these contributions, plutonic subdivisions are recognized on the basis of age; Nd, Sr, and oxygen isotope ratios; rare-earth element patterns; inferred source regions; and petrogenetic processes. Specifically, these data show that (1) most plutons show evidence for intense and complex interaction between mantle-derived magmas and crustal rocks (or magmas), (2) crustal melting was widespread during at least some Mesozoic igneous episodes, (3) changes in magmatic compositions were related to discrete tectonic events (thrust faulting) ± thermal maturation history, and (4) many plutons contain zircons inherited from their source region(s) or incorporated as xenocrysts during ascent (see section on problems for future research).

Many plutons in the Klamath Mountains province still lack detailed petrogenetic study (e.g., Chetco Complex, Grants Pass, Gold Hill, Vesa Bluffs, Sugarpine, Canyon Creek, Shasta Bally, and Wildwood plutons). This omission is unfortunate, for reasons cited above and because these plutons are excellent examples of precursor activity to the giant pulses of Cretaceous magmatism in the Sierra Nevada and Idaho batholiths. Moreover, because Klamath plutons typically lack the deformation and thermal alteration commonly associated with Sierran Cretaceous activity, they preserve mineral assemblages conducive to detailed analysis of *P, T,* and compositional variations (e.g., Barnes, 1987; Cotkin and Medaris, 1993).

IMPORTANCE OF METAMORPHIC STUDIES

The central metamorphic belt of Irwin (1960), now referred to as the "Central Metamorphic terrane" (see Irwin, 1994), occurs as a fault-bounded slice of upper greenschist- to amphibolite-facies metavolcanic and metasedimentary rocks in the eastern part of the Klamath Mountains (Fig. 3). This terrane is bound by the Trinity thrust system on the east and Siskiyou thrust of Davis (1968) on the west. The hanging wall of the Trinity thrust is the ophiolitic Trinity ultramafic-mafic complex, discussed earlier in this chapter. The footwall of the Siskiyou thrust is referred to as the North Fork terrane (Irwin, 1972) (Fig. 3). The Stuart Fork Formation of Davis and Lipman (1962) (discussed below as an example of high pressure–low temperature metamorphism in the Klamath Mountains province) is locally sandwiched between the Siskiyou and Soap Creek Ridge faults (Fig. 3). The Stuart Fork Formation is now considered part of the Fort Jones terrane (Irwin, 1994). The Stuart Fork Formation is commonly interpreted as part of an early Mesozoic accretionary subduction complex (Wright, 1982; Goodge, 1989a; Dickinson, 2000).

As previously discussed in this chapter, the protolith age of the Central Metamorphic terrane is uncertain, and unit nomenclature (i.e., Abrams Mica Schist versus Grouse Ridge Formation) and the structural (stratigraphic) sequence in this belt (terrane) have been controversial. Clearly, a significant aspect of this terrane is its high-grade metamorphic character compared to the surrounding terranes (Hershey, 1901; Hinds, 1932, 1933). Moreover, the grade of metamorphism across the terrane decreases from amphibolite facies adjacent to the Trinity thrust (and peridotite) through albite-epidote amphibolite facies to upper greenschist facies near the structural base of the terrane (Davis et al., 1965). This inverted metamorphic gradient was interpreted to result from emplacement of the Trinity peridotite (Peacock and Norris, 1989), perhaps during intraoceanic thrusting (Boudier et al., 1982). Such gradients are commonly associated with metamorphic soles that form during emplacement of ophiolitic allochthons, such as the Bay of Islands ophiolite of Newfoundland (Malpas, 1979) or the Semail ophiolite of Oman (Searle and Malpas, 1980; Searle and Cox, 1999). The Devonian Rb-Sr isochron age reported by Lanphere et al. (1968) and Hotz (1977) is consistent with this interpretation, such that the Central Metamorphic terrane has been thought to represent oceanic rocks accreted to the eastern Klamath terrane during mid-Paleozoic subduction. Barrow and Metcalf (this volume) illustrate the MORB-like character of Salmon Schist metabasites, which supports an oceanic origin for the terrane.

However, $^{40}Ar/^{39}Ar$ cooling ages of hornblende from the Salmon Schist (Barrow and Metcalf, this volume) are Early Permian (ca. 274 Ma). These cooling ages and the observation that the temperature of the Trinity peridotite was below amphibolite-facies conditions at the time of faulting complicate the simple picture of the Central Metamorphic terrane as oceanic crust subducted during development of the Silurian–Devonian proto-arc plutons. Barrow and Metcalf (this volume) suggest that the cold-over-hot geometry of the Trinity fault (cold Trinity peridotite over hot Salmon Schist) may indicate that the final motion on the fault was normal sense. This suggestion does not negate the idea that the Central Metamorphic terrane represents oceanic crust subducted (underthrust) during Silurian–Devonian time, but it does require later normal reactivation of a cold Trinity fault system.

The Central Metamorphic terrane is not the only fault-bounded slice of high-grade metamorphic rocks associated with an ophiolitic assemblage in the Klamath Mountains province. A distinct dynamothermal metamorphic sole also has been documented along part of the western margin of the Josephine ophiolite, near Vulcan Peak, Oregon (Harper et al., 1990). The development of this metamorphic sole is atypical of the emplacement history described for the Bay of Islands (Newfoundland) or Semail (Oman) ophiolitic allochthons in that the Josephine ophiolite was apparently emplaced by the underthrusting of an active magmatic arc (Harper et al., 1996).

High-grade tectonic inclusions with K-Ar and $^{40}Ar/^{39}Ar$ ages of ca. 190 Ma are well known from the Rattlesnake Creek terrane (Snoke, 1977; Gorman, 1985; Wright and Wyld, 1994). Other allochthonous fragments of high-grade metamorphic rocks include the Briggs Creek amphibolite of Garcia (1979) (or Briggs Creek subterrane of Blake, 1984; Blake et al., 1985) and Big Craggies amphibolite exposed in southwestern Oregon (Coleman, 1972).

As previously noted, parts of the Rattlesnake Creek terrane are metamorphosed to amphibolite facies or locally even to granulite facies (e.g., Barrows, 1969; Medaris, 1975). Such rocks are widespread in the Marble Mountains area and along the Siskiyou Divide (north of Seiad Valley, California), and some workers once referred to these high-grade rocks as the "Marble Mountain terrane" (Blake et al., 1982; see discussion by Donato, 1987, 1989) in California and, in Oregon, the mélange of Dutchman Peak and rocks of Seiad Valley (Smith et al., 1982). For simplicity, most recent compilations of the Klamath Mountains province (e.g., Irwin, 1994) consider these rocks as part of the Rattlesnake Creek terrane (also see Donato et al., 1996). Radiometric ages of these high-grade rocks are in the 153–146 Ma range (see summaries in Hacker and Ernst, 1993, and Hacker et al., 1995). These ages are enigmatic because the high-grade Rattlesnake Creek terrane rocks are intruded by plutons as old as the Slinkard and Grayback plutons, with U-Pb (zircon) ages of ca. 162–161 Ma and $^{40}Ar/^{39}Ar$ cooling ages of ca. 167–148 Ma (Hacker and Ernst, 1993; Hacker et al., 1995).

Another area of anomalously high metamorphic grade occurs in the northernmost Klamath Mountains of Oregon and was originally called the "May Creek formation" in Diller and Kay (1924). These rocks are now referred to as the "May Creek terrane" (Silberling et al., 1987; Irwin, 1994), although they may simply be a high-grade area within the Rattlesnake Creek terrane. Detailed studies of the May Creek terrane are few, but Kays (1968, 1970, 1995) and Donato (1991a,b) have documented metamorphic grade variations and structural style in these rocks. Donato (1991b, 1992) recognized an important high-temperature ductile shear zone (i.e., low-angle thrust-fault zone) in the May Creek terrane where the May Creek Schist is thrusted on top of an unnamed amphibolite unit. This ductile thrust zone is intruded by the ca. 160-Ma Wimer pluton (Donato, 1991b, 1992; Yule, 1996), and consequently, the age of metamorphism and ductile faulting within the May Creek terrane is apparently late Middle Jurassic or older. Thus the May Creek terrane is an example of high-grade metamorphism and contractional deformation that predate the Late Jurassic Nevadan orogeny and is another manifestation of the enigmatic Middle Jurassic orogenic history of the Klamath Mountains province.

One of the most interesting and tectonically significant aspects of the metamorphic history of the Klamath Mountains province is that at least three distinct high pressure–low temperature (HP–LT) metamorphic events have been recognized in the province. Furthermore, a fourth episode of Early Cretaceous HP–LT metamorphism (Lanphere et al., 1978) is well known in the Pickett Peak terrane, part of the Franciscan Complex, immediately west of the Klamath Mountains province. The oldest episode of HP–LT metamorphism is in the eastern Klamath Mountains, and it is manifested as the schist of Skookum Gulch metamorphosed under blueschist-facies conditions (T = 275 °C and P = 7.0 kb; Cotkin, 1987) in the Late Ordovician (Cotkin et al., 1992). Lawsonite + glaucophane schist is interlayered with other schists and dolomitic marble. The glaucophane schist is well foliated and consists of lawsonite porphyroblasts set in a fine-grained matrix of Na-amphibole, chlorite, quartz, albite, and calcite (Cotkin, 1987). The schist of Skookum Gulch is the only early Paleozoic blueschist locality in western North America (Patrick and Day, 1995) and apparently formed in an accretionary prism during Late Ordovician subduction (Cotkin, 1992). However, the tectonic relationships of these early Paleozoic blueschist-facies rocks with other early Paleozoic elements of the western North American Cordillera are vague and potentially suggest an initial origin outside the Cordilleran realm for the schist of Skookum Gulch and perhaps other rock units of the Yreka terrane (Harms et al., 2003; Wright and Wyld, 2003). The Stuart Fork terrane (Goodge, 1989a,b) or Fort Jones terrane (Irwin, 1994) includes Late Triassic (ca. 220 Ma) blueschist-facies rocks, whereas the metamorphic age of the HP–LT metamorphic rocks exposed in the Condrey Mountain window apparently spans from Late Jurassic into mid-Cretaceous time (Helper, 1986, personal commun. 2005; Helper et al., 1989; Hacker et al., 1995). The Condrey Mountain Schist thus may be a composite unit, reflecting accretion (i.e., tectonic underplating) of progressively younger oceanic rocks.

The last topic that we discuss in regard to metamorphic studies in the Klamath Mountains province is the metamorphic evolution of schists that occur immediately west of the province and are part of the Pickett Peak terrane (Blake, 1984; Blake et al., 1985), the easternmost terrane in the Coast Ranges. In California, the Pickett Peak terrane consists of the South Fork Mountain Schist (Blake et al., 1967) and Valentine Spring Formation (Worrall, 1981), whereas in southwestern Oregon, this terrane consists of the Colebrooke Schist (Coleman, 1972) and an underlying serpentinite-matrix mélange that locally contains tectonic blocks of high-grade blueschist- and amphibolite-facies rocks. We include a brief discussion of these low-grade schists in this synthesis of the Klamath Mountains province, because their HP–LT metamorphism has been commonly interpreted as forming when the Klamath Mountains province allochthon was juxtaposed above the rocks of the Coast Ranges (Blake et al., 1967; Lanphere et al., 1978). Furthermore, these rocks represent the fourth episode of HP–LT metamorphism developed in association with the Klamath Mountains province, and their overall character is reminiscent of other, pelitic to wacke, schist units in the Klamath Mountains province (e.g., Condrey Mountain Schist). The South Fork Mountain and Colebrooke Schists are Textural Zone 3 (Blake et al., 1967) quartz–albite–white mica–chlorite ± lawsonite schists (metagraywacke protolith), whereas associated metabasalts (Chinquapin Metabasalt Member of the South Fork Mountain Schist) consist chiefly of the assemblage albite–chlorite–actinolite–epidote but also include blue-amphibole-bearing varieties. Although available geochronological data are not conclusive, the South Fork Mountain Schist was probably metamorphosed in the Early Cretaceous (ca. 125 Ma) (Lanphere et al., 1978). A similar age of metamorphism is also probable for the Colebrooke Schist in southwestern Oregon (Coleman, 1972). An interesting complication concerning metamorphism in the Franciscan Complex (which includes the Pickett Peak terrane) is the ca. 150-Ma age for the high-grade amphibolite-, eclogite-, and blueschist-facies blocks in mélange of the Franciscan Complex (Coleman and Lanphere, 1971). This apparent age of subduction-zone metamorphism is synchronous with the emplacement of the Orleans (thrust) fault in the adjacent Klamath Mountains province as well as the classic Nevadan orogeny (see below for a full discussion of this Late Jurassic orogeny).

JURASSIC OROGENIES

The Nevadian (later modified to "Nevadan," see Hinds, 1932, p. 378, 1935, p. 331–333) orogeny was defined by Blackwelder (1914, p. 643–645) as a Middle to Late Jurassic orogenic event that affected much of the western margin of the North American Cordillera. His type locality was the Sierra Nevada, but Blackwelder envisioned that Nevadan orogenic effects could be traced from the Alaska Range to Baja California and western Mexico. In California, Taliaferro (1942) recognized that two events were commonly included in the Nevadan orogeny: severe folding of bedding and widespread plutonic intrusion. However, he argued that these orogenic effects were separated in time and a distinction should be made between them. Based on field relations between folded Jurassic strata of the western

Sierra Nevada and intrusive plutonic rocks, Taliaferro (1942) concluded that the folding had occurred prior to the last, widespread intrusion of granitic rocks of the Sierra Nevada batholith. Furthermore, he proposed that the early phase of the Nevadan orogeny (folding and thrusting) could be tightly bracketed as post-late Oxfordian–early Kimmeridgian (age of the Mariposa Formation as well as the Galice Formation of the Klamath Mountains) but prior to the Tithonian (age of the Knoxville Formation; i.e., basal unit of the Great Valley sequence). These geologic field relationships indicated that the "restricted Nevadan orogeny" was Late Jurassic in age. Subsequently, radiometric dating demonstrated that the widespread plutonism of the Sierra Nevada batholith was Late Cretaceous in age (Evernden et al., 1957; Curtis et al., 1958; Evernden and Kistler, 1970), and this magmatism was not considered part of the Nevadan orogeny. Curtis et al. (1958) suggested that the widespread granitic plutonism of the Sierra Nevada and Salinian block (i.e., Santa Lucia Range, Gabilan Range, etc.) be referred to as the "Santa Lucian orogeny," but this name never took hold in the literature of California geology.

The restricted definition of the Nevadan orogeny, as proposed by Taliaferro (1942), has been widely used in the Klamath Mountains and western Sierra Nevada to interpret important regional orogenic features in these mountain belts (e.g., Lanphere et al., 1968; Schweickert and Cowan, 1975; Snoke, 1977; Davis et al., 1978; Saleeby et al., 1982; Harper and Wright, 1984; Schweickert et al., 1984). However, as detailed geologic mapping was coordinated with radiometric dating (especially U-Pb zircon dating), it also became clear that important orogenic events had occurred prior to the Late Jurassic Nevadan orogeny (e.g., Lanphere et al., 1968). In a paper that greatly expanded the U-Pb zircon geochronological database for the southern Klamath Mountains, Wright and Fahan (1988) argued that Middle Jurassic orogenic events, including regional thrusting, folding, and metamorphism, were widely developed during ca. 169–161 Ma. Geologic mapping and metamorphic studies by Coleman et al. (1988) further documented the importance of Middle Jurassic orogenic events in the north-central Klamath Mountains, and these workers referred to this orogenic episode as the "Siskiyou event," subsequently modified to "Siskiyou orogeny" (e.g., Hacker et al., 1995). However, as cited above, Hacker et al. (1995) showed that rocks considered the high-grade manifestations of the Siskiyou orogeny (i.e., high-grade rocks of the Rattlesnake Creek terrane) had ^{40}Ar/^{39}Ar cooling temperatures younger than cooling temperatures of plutons intruded during and/or after the regional high-grade metamorphic event. Furthermore, in many cases, these late Middle Jurassic plutons also imposed distinct mineralogical and/or textural effects of contact metamorphism on the adjacent Rattlesnake Creek terrane host rocks. Hacker et al. (1995) also noted the similarity in these cooling ages (152–148 Ma) with the approximate ages of Nevadan thrusting. This similarity suggests either that: (1) high-grade Rattlesnake Creek terrane did not cool below the ^{40}Ar hornblende closure temperature until it was refrigerated by Nevadan thrusting, or (2) the high-grade metamorphic rocks of the Rattlesnake Creek terrane were reheated after peak metamorphic conditions and after emplacement of large, late Middle Jurassic plutons. The fact that the plutons have older cooling ages, and that ca. 150-Ma resetting of magmatic hornblendes in the western Hayfork terrane has not been observed, makes possibility (1) problematic, and possibility (2) highly unlikely.

In summary, it is apparent that some orogenic events in the Klamath Mountains province, such as the "restricted Nevadan orogeny" encompass a specific set of structural, metamorphic, and magmatic events. However, it is also apparent that such orogenic events as the Siskiyou orogeny may be difficult to characterize, particularly in the absence of a well-defined and/or readily characterized thermal or tectonic signature. It is entirely possible that other high-grade metamorphic events in the Klamath Mountains province—specifically, metamorphism of the May Creek Schist and related amphibolites (Kays, 1970; Donato, 1991a,b, 1992) and the Central Metamorphic terrane (Davis et al., 1965; Lanphere et al., 1968; Peacock and Norris, 1989; Barrow and Metcalf, this volume)—have similarly complex thermal and tectonic histories.

IMPORTANT PROBLEMS FOR FUTURE STUDY

The following are important questions and possibly new directions that need to be addressed in future geologic studies in the Klamath Mountains province:

1. What were the facing directions of the oceanic arcs that form various terranes in the Klamath Mountains province? How can the polarity of these arcs be determined and tested through geologic and geochemical data?
2. What was the provenance of clastic metasedimentary rocks in various Klamath Mountains province terranes? New, albeit scant, isotopic data (e.g., Frost et al., this volume) suggest that even "oceanic" terranes contain cratonic sedimentary components. What is the importance and/or the volume of these cratonic materials, and what do these data tell us about the paleotectonic setting of various terranes and their subsequent translation (e.g., Wyld and Wright, 2001)? What can be learned from detailed study of detrital zircon in metasandstones as well as hemipelagic and pelagic units? Nearly every terrane in the Klamath Mountains province contains such rocks; they may reveal significant changes in sediment sources that can be correlated to tectonic history.
3. How did the crust of the Klamath Mountains province respond to contractional deformation? Evidence for ~8-kb differentiation of late Middle Jurassic magmas suggests thick crust, at least some time during amalgamation and accretion of the terranes of the Klamath Mountains province. Was thick crust ephemeral, followed quickly by exhumation and/or tectonic erosion?

4. Does evidence for thickened crust (i.e., thrust faulting: Donato et al., 1982; Donato, 1992) during late(?) Middle Jurassic time relate to the high-grade parts of the Rattlesnake Creek terrane? Is it possible that these high-grade zones were widespread in the deep crust but only locally preserved by syn- or post-Nevadan exhumation in the region around the Condrey Mountain dome? An associated conundrum with the high-grade rocks of the Rattlesnake Creek terrane is the range of $^{40}Ar/^{39}Ar$ ages available from these rocks. Although these high-grade rocks are widely intruded by late to post-synkinematic late Middle Jurassic plutons, the metamorphic rocks invariably yield significantly younger $^{40}Ar/^{39}Ar$ ages that must reflect a complex cooling history subsequent to both regional metamorphism and pluton emplacement.
5. Recent recognition of the importance of inherited/assimilated zircons in many Klamath plutons (Harper et al., 1994; Allen and Barnes, this volume; Chamberlain et al., this volume) and the correlation of zircon inheritance with isotopic systematics suggest that these plutons may be sensitive probes of the crust through which they passed. Will application of detailed, modern isotopic and dating methods to plutons from distinct tectonic panels provide a record of changes in crustal and mantle architecture through time?
6. What can modern geomorphologic and geochronological methods tell us about the Neogene and Quaternary history of the Klamath Mountains province, and particularly about landform development and the high-standing, deeply incised nature of the Klamath Mountains province?

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