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Metamorphism in Allochthonous and Autochthonous Terranes of the Western United States [and Discussion]

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Metamorphism in allochthonous and autochthonous terranes of the western United States

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The haphazard accretion of exotic terranes during continental reassembly results in a crustal college typified by genetically unrelated lithotectonic belts. Profound chronologic, lithologic, geochemical, and metamorphic breaks characterize such suture zones. However, post-metamorphic differential vertical uplift and erosion can generate a marked discontinuity in grade within a single lithotectonic entity, and in contrast, post-amalgamation recrystallization of an exotic terrane assembly can produce an isofacial metamorphic overprint. Thus the tectonic context of metamorphic mineral parageneses must be interpreted with caution.

In spite of the presence of allochthonous terranes, the western U.S. Cordillera in general is characterized by gradual sectorial enlargements towards the modern edge of the continent, by coherent, broadly continuous isotopic or geochemical provinces, and by systematic oceanward decreases in the metamorphic intensities of the constituent lithic assemblages, both within a belt, and across a series of belts. These relationships hold over a wide range of scales, from that of a physiographic province to that of a quadrangle-sized area. Examples described include chronologic, isotopic, igneous and metamorphic belts of (1) the entire western conterminous U.S. Cordillera, (2) the Phanerozoic Sierran–Klamath basement terrane assembly, and (3) the Great Valley and Franciscan sedimentary couplet derived from the late Mesozoic Sierra Nevada–Klamath arc. For these cases, systematic recrystallization–deformation trends and nearly *in situ* growth of sialic crust are evident. Mapped metamorphic and structural discontinuities reflect dislocations involving spatially associated, co-evolving continental lithotectonic units, and, except for far-travelled oceanic fragments, do not imply wholesale juxtaposition of exotic, genetically unrelated terranes.

Introduction

Differential plate-tectonic motions profoundly affect P–T evolution of the continental crust, and constituent metamorphic assemblages (Miyashiro 1973). Constructional stages are typified by head-on and oblique convergent plate motions, resulting in paired orogenic belts. These comprise: firstly, the development of broad inboard, low P/T, high heat-flow recrystallization régimes characterized by the addition of primary calc-alkaline igneous arc rocks, and the anatectic, metamorphic, and sedimentary reworking of preexisting materials; and secondly, the formation of narrow outboard metamorphic belts of high P/T, low heat-flow subduction complexes which include the suturing of far-travelled oceanic assemblages (with or without island arcs) and allochthonous microcontinental fragments, and are characterized by a lack of coeval calc-alkaline igneous activity. Young paired belts provide a characteristic pattern which documents the nature of geologically recent continental accretion. Episodic rifting and strike–slip faulting, which attend divergent and transform plate motions, modify and obscure the record of sialic growth. Remnants of old metamorphic belts are scattered piecemeal, and annealed or recrystallized by later thermotectonic events. Extension and transform motions thereby rearrange previously produced terranes, but do not increase the aggregate mass of the sialic crust. Of course, these processes do result in the enlargement of acceptor assemblies at the expense of donor continents.

Experimental phase relations for synthetic and natural rock and mineral systems, taken together with $^{18}O/^{16}O$ and D/H isotopic geothermometers and diverse mineralogic thermobarometers, allow the erection of a metamorphic-facies grid (see, for example, Ernst 1976; Liou *et al.* 1985). The thermal structures of divergent and convergent plate boundaries have been modelled numerically by many workers (e.g. Oxburgh & Turcotte 1971). Combining mineralogic P–T grids with computed temperature-depth arrangements, the geologic disposition of metamorphic facies for divergent and convergent lithospheric plate junctions have been approximated (Ernst 1976; Zen 1988). The very high heat-flow régime characterized by an oceanic spreading system accounts for a telescoped metamorphic zonation, and relatively shallow-level development of high-rank hornfels beneath the ridge. In contrast, the more complex convergent plate-tectonic setting is characterized by a broad, relatively high heat-flow environment in the magmatic arc, reflected in a crude bilaterally symmetric upwarp of the metamorphic-facies assemblages, in the anatexis of basal portions of thick, 'juicy' continental crust, and in a spectacular downward, asymmetric projection of relatively high P/T phase compatibilities in the subduction zone.

Crustal metamorphic environments and geochemical signatures of igneous rocks derived from the mantle and/or the deep crust, combined with regional and local structural–geologic and lithologic–tectonic age relationships, provide constraints regarding the complex interplay of processes attending continental accretion. Isotopic data suggest that for the conterminous western U.S. Cordillera, the bulk of sialic material was added northwest and, especially, south of the Archaean shield during early and mid-Proterozoic time, whereas late Proterozoic–Phanerozoic growth occurred predominantly along the western margin of the North American craton. Continental enlargement by igneous processes was accompanied by the development of successively younger metamorphic belts. Geologic relations of the Franciscan, Great Valley, and Sierra Nevada–Klamath lithotectonic triad provide a well-preserved example of Phanerozoic continental growth and concomittant metamorphism; it provides a possible analogue for older, inboard lithotectonic complexes. New maps of portions of the central Klamath Mountains and the eastern California Coast Ranges reveal small-scale details of the Mesozoic, nearly in-place accretion of the studied areas. Insight regarding crustal growth and recrystallization may be obtained through an integration of the information obtained from investigations at several scales such as these.

The relationship between metamorphic facies assemblages and terrane accretion is not always straightforward. In favourable cases, pronounced contrasts in grade occur across terrane boundaries, reflecting the post-metamorphic juxtaposition of genetically unrelated lithotectonic units. However, within a single terrane, differential uplift across a late fault can result in the surface exposure of a marked discontinuity in metamorphic grade. On the other hand, post-accretionary recrystallization of an exotic terrane assembly can produce a homogeneous, monotonic metamorphic zonation. Clearly, unambiguous tectonic interpretation of metamorphic belts requires the existence of important chronologic and structural constraints.

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Archaean to Cenozoic tectonometamorphic belts of the western conterminous U.S.

Regional metamorphism

Maps summarizing the predominant mineral facies and times of metamorphism in the western Cordillera are presented as figures 1 and 2, respectively. Compilations are based on relationships described by many workers (e.g. Ernst 1988). Although the Mesozoic history of the continental margin is reasonably well known, younger metamorphic tracts are still largely buried. In contrast, pre-Mesozoic belts have been deeply eroded, or overprinted and dislocated by later dynamothermal or tectonic processes, thus are imperfectly preserved. Mesozoic belts

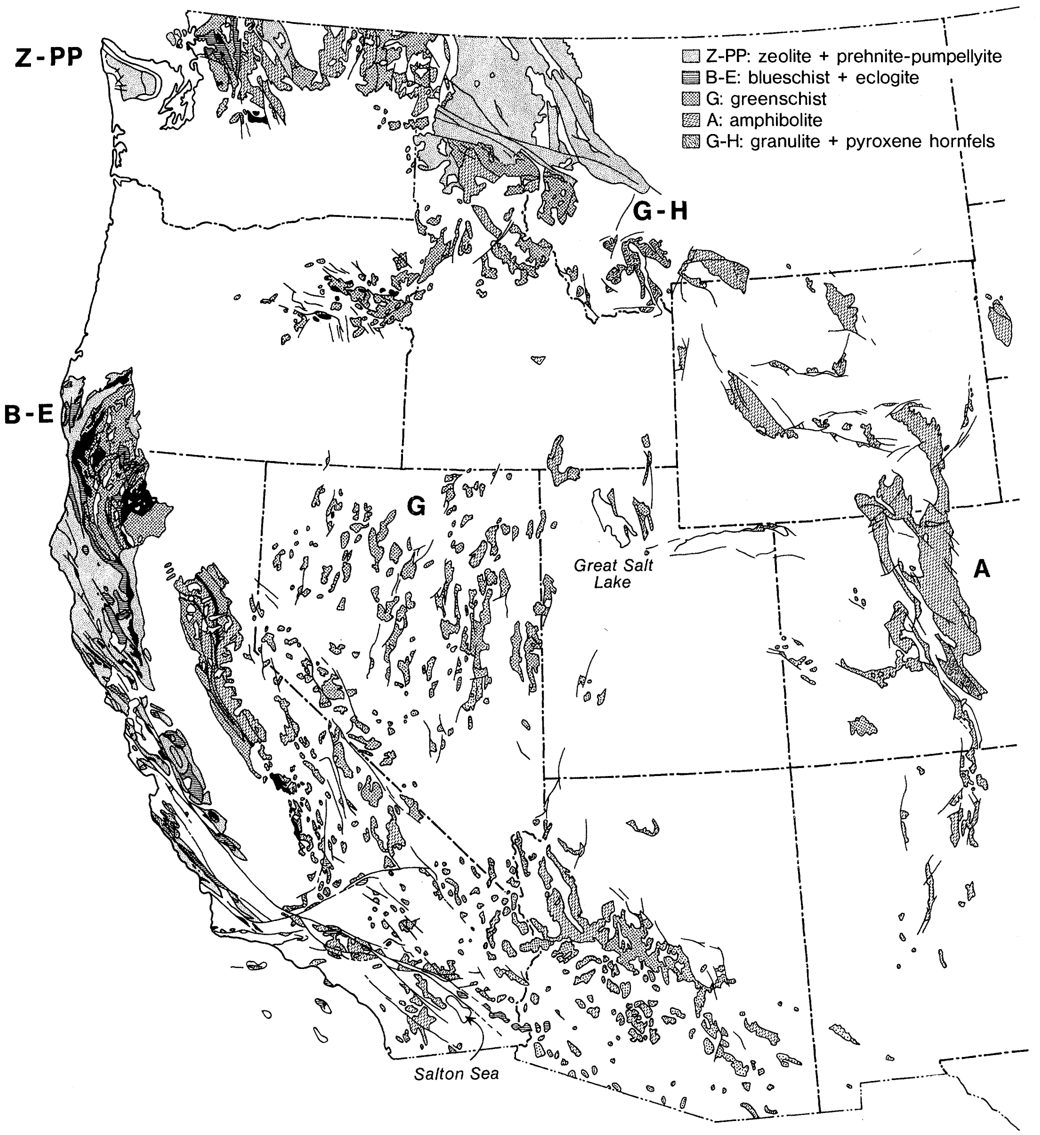

Figure 1. Generalized areal disposition of metamorphic belts of the western conterminous U.S., based on regional summary contributions in Ernst (1988); serpentinized peridotites shown in black. The dominant regional metamorphic facies assemblages are presented, irrespective of age. Relict earlier assemblages, and incipient later parageneses are not shown. Some metamorphic facies are combined, as shown in the legend.

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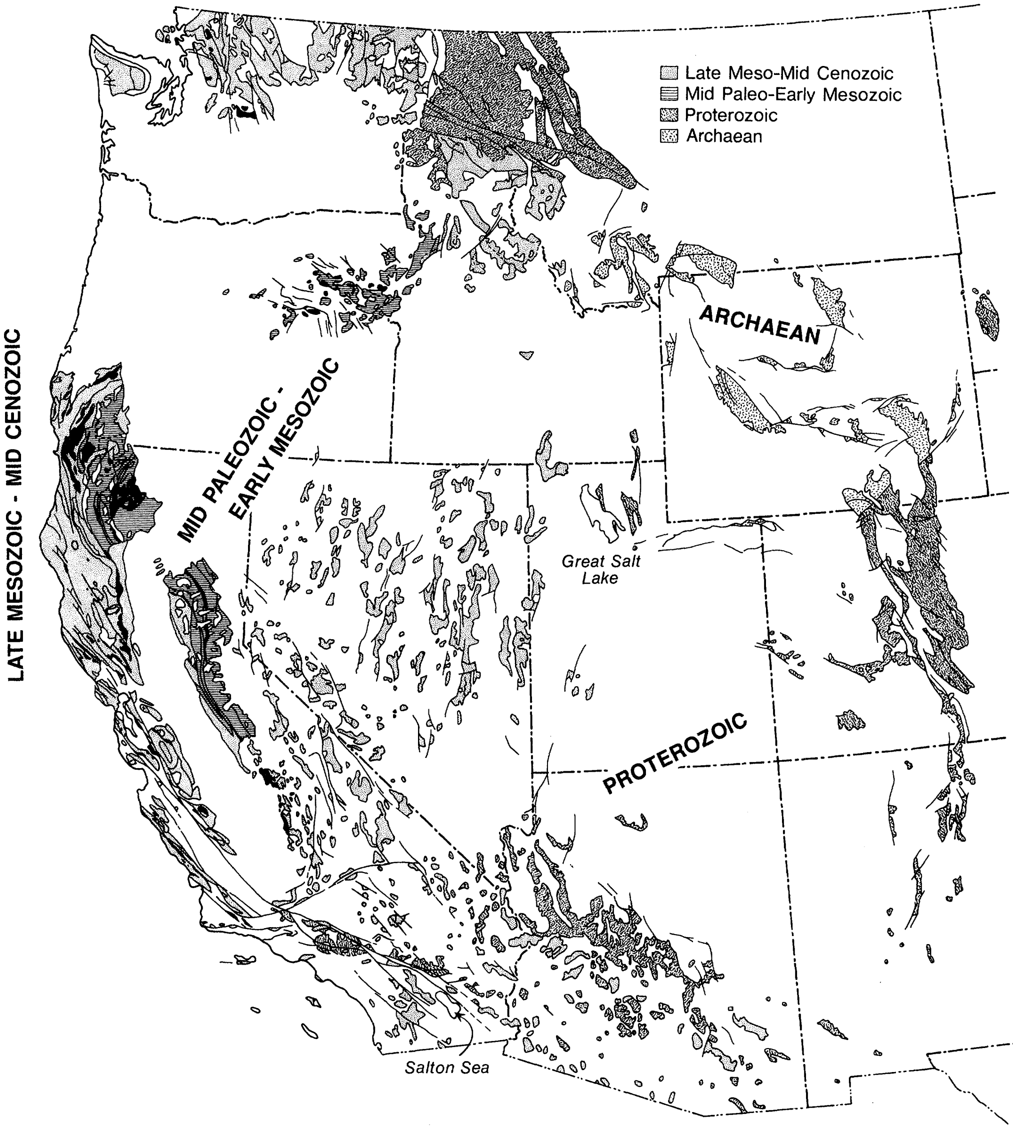

FIGURE 2. Approximate ages of principal recrystallization events characteristic of the dominant metamorphic assemblages (see figure 1), for metamorphic belts of the western conterminous U.S., based on regional summary contributions in Ernst (1988); serpentinized peridotites shown in black. Traces of earlier events, and later, feeble overprintings are not shown. Ages of metamorphism are combined, as shown in the inset.

apparently represent the optimum stage of preservation and exposure for deciphering petrogenetic evolution of the western U.S.

Archaean metamorphism, of which chiefly high-T, low- to moderate-P amphibolite and granulite facies assemblages are preserved, typifies the basement of Wyoming and adjacent parts of Idaho, Utah, Montana and South Dakota. Orogenic activity ceased by late Archaean time, and much of the ancient crust was not influenced significantly by later dynamothermal metamorphism. Weak recrystallization characterizes the upper Proterozoic passive-margin section northwest of the Wyoming nucleus. Intermediate-P amphibolite-type parageneses developed in mid-Proterozoic accretionary sialic crust to the south in Colorado, Utah and New Mexico. A regional transition links greenschists in southeastern Arizona to low-P amphibolites

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and low-rank granulites in western Arizona. In southeastern California, Proterozoic high-rank, low-P amphibolites are scattered along the San Andreas transform system. To the northwest in California, and in east-central Oregon and northwestern Washington, segments of once more continuous metamorphic belts reflect Ordovician through Cretaceous recrystallization events; sutures within these vestiges of palaeo-Pacific convergent margins are marked by tectonized meta-ophiolites, mantle fragments, and rare allochthonous microcontinental scraps. Oceanward subduction-zone, high-P, non-volcanic metamorphic belts are juxtaposed against landward, high-T, continental-margin, calc-alkaline batholithic realms and pre-existing metamorphic wall rocks.

Westward from the North American platform, lithotectonic belts have been overprinted by late Jurassic–Cretaceous and early-mid Cenozoic intracontinental polymetamorphism accompanying widespread intermediate and silicic igneous activity. Mobilization of inboard, high-rank core complexes (Coney 1980; Armstrong 1982) and broad-scale development of greenschist and low-P amphibolite facies assemblages in the Great Basin, Mojave–Sonoran Desert, and the Sierra Nevada–Peninsular Ranges occurred at this time. Greater depths of emplacement are recorded in country rocks surrounding and north of the Idaho batholith, where high-P amphibolites of late Cretaceous metamorphic age are exposed. Outboard towards the modern North American margin in western California and northwestern Washington, accretionary prisms containing oceanic as well as terrigenous materials have been subjected to zeolite to blueschist facies metamorphism during late Triassic and younger suturing against the continent.

Metamorphic terranes are successively younger from the Wyoming nucleus toward the Pacific Basin and the Gulf of Mexico. Where detailed lithotectonic relationships are available within a province (e.g. Cheyenne belt, Colorado-New Mexico, northwestern Washington, Klamaths, Sierra Nevada, California Coast Ranges), formational ages of original rock assemblages and times of recrystallization decrease seaward. The observed temporal sequence is compatible with nearly *in situ* growth, but would be coincidental if exotic slices of older and younger oceanic and microcontinental terranes had been stranded haphazardly at the accreting western margin of North America.

Paired metamorphic belts of the Cordillera are well preserved only in younger Phanerozoic sections bordering the Pacific Ocean. Inland, recrystallized terranes of diverse ages exhibit lithologic assemblages produced mainly in continental-margin and island-arc settings. Blueschist belts and extensive tracts of peridotite are lacking; if such associations were formed in early Palaeozoic and older plate-tectonic environments of the western U.S., they must have been selectively destroyed by subsequent thermotectonic events or transported away along margin-parallel shear zones.

Isotopic data

Tectonometamorphic trends in the western Cordillera are clearest for the Phanerozoic complexes. Summary of the isotopic data for sialic igneous rocks helps to illuminate the more obscure crustal growth and petrogenesis of less well-preserved Precambrian metamorphic belts. Melts derived from partial fusion of deep-crustal and upper-mantle source materials provide geochemical constraints on the nature of the basement. Mesozoic and Cenozoic magmatic rocks reflect a continental lithosphere typified by discrete Pb and Nd isotopic provinces (Zartman 1974; Farmer & DePaolo 1983; Wooden *et al.* 1988); these igneous units exhibit variable contributions from mantle and crustal protoliths. The age of separation of the continental crust from an evolving mantle reservoir, as indicated by Precambrian Pb and Nd model and crystallization ages, monotonically decreases from the Archaean Wyoming province through the early Proterozoic central Great Basin and Mojave Desert to the mid-Proterozoic Sonoran Desert (Bennett & DePaolo 1987). Within the Mesozoic calc-alkaline belts, a systematic oceanward decrease in the degree of continental involvement, as expressed by decreasing $^{87}Sr:^{86}Sr$ initial ratios, and increasing ϵ_{Nd} values for volcanics and plutonics, is well documented (Kistler & Peterman 1978; DePaolo 1981; Condie 1986; Farmer & DePaolo 1983; Bickford 1988).

Accretion and accompanying recrystallization of the western U.S. continental crust occurred principally during three major intervals, through the primary formation of calc-alkaline batholiths and superjacent volcanogenic arcs: (1) the later Archaean (2.5–3.3 Ga), when the continental nucleus was assembled; (2) the early and mid-Proterozoic (1.4–2.3, chiefly 1.7–1.9 Ga), when most of the sialic basement was generated progressively southward; and (3) the

FIGURE 3. Isotopic provinces of the western conterminous U.S. based on Nd-depleted model mantle ages (Farmer & DePaolo 1983; Farmer 1988; Bennett & DePaolo 1987), and $^{87}Sr:^{86}Sr$ (= 0.706 and 0.704) initial ratio limits in Mesozoic and Cenozoic granitoids (Armstrong *et al.* 1977; Kistler & Peterman 1978). Mid-Proterozoic and older basement lies inboard of the 0.706 line. Lead isotopic provinces (Zartman 1974) exhibit analogous areal dispositions.

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Phanerozoic, when the continent grew westward. The age of separation from the mantle of materials constituting the Precambrian basement gradually decreases from the Wyoming province (greater than 2.6 Ga), through the central Great Basin and Mojave Desert (2.0–2.3 Ga) and the Colorado Plateau (1.8–2.0 Ga), to the Sonoran Desert (1.7–1.8 Ga), and the mid-continent granite-rhyolite belt (less than 1.4 Ga). Igneous crystallization ages and times of metamorphism mirror these trends.

Geochemical–radiometric provinces are shown in figure 3. Isotopically distinct belts border the Archaean craton, and exhibit overall Proterozoic and Phanerozoic enlargements towards the modern continental margins. Relationships hold for model mantle separation ages as well as times of igneous crustal formation. Lithotectonic belts apparently developed asymmetrically and episodically rather than concentrically and continuously, indicating sequential lateral growth rather than continuous circumferential enlargement. They evidently mark the sites of subduction zones and landward arcs. Truncations of these belts suggest the episodic rifting and removal of gradually accreted segments of the North American continental crust (Burchfiel & Davis 1975).

Broad trends typifying Precambrian crustal evolution and coeval metamorphism are compatible with overall growth of the western Cordillera mainly by the generation and telescoping of new continental crust surmounting convergent plate junctions, with the incorporation of variable amounts of recycled sialic material, and by the random accretion of exotic, mainly oceanic terranes of unrelated geochemistry. Because of the observed systematic decrease in igneous and metamorphic ages, and coherence of isotopic data for the belts proceeding outward from the Wyoming craton (greater than 2.6 Ga), it is evident that addition of far-travelled microcontinental terranes consisting of sialic basement detectably older than the developing margin did not characterize growth of the western conterminous U.S. Possible exceptions to this generalization include: the Salinian granitic salient west of the San Andreas fault (Hill & Dibblee 1953; Page 1982); easternmost California, where a westward step in the $^{87}Sr:^{86}Sr$ initial ratio offsetting the late Precambrian continental margin may mark a faulted terrane boundary (Kistler & Peterman 1978); and the Yellow Aster Complex (Misch 1966) of the northwestern Cascades, a small, outboard fragment of old sialic crust.

Sierra Nevada–Klamath basement complex

The Sierra Nevada appears to represent the southeastern continuation of the Klamath province (Davis 1969; Day *et al.* 1988). The Klamaths consist of metamorphosed country rocks intruded by isolated, pre-Cretaceous calc-alkaline plutons, whereas the Sierra Nevada consists principally of coalescing, Jurassic–Cretaceous batholithic units, separated incompletely by thin metamorphic septa. The northwestern foothills belt is the only major segment of Sierran wall rocks preserved adjacent to the plutonic series, although isolated roof pendants occur throughout the range. Compared with the Klamaths, the Sierra Nevada may represent a deeper level of crustal exposure, especially at its southern extremity where high-rank amphibolitic or low-rank granulitic meta-igneous rocks are exposed beneath the batholith (Sams & Saleeby 1988). The dispositions of metamorphic belts and lithotectonic terranes of northern and central California are presented in figures 4 and 5, respectively.

Sutures bounding individual Sierran and Klamath metamorphic belts are marked by

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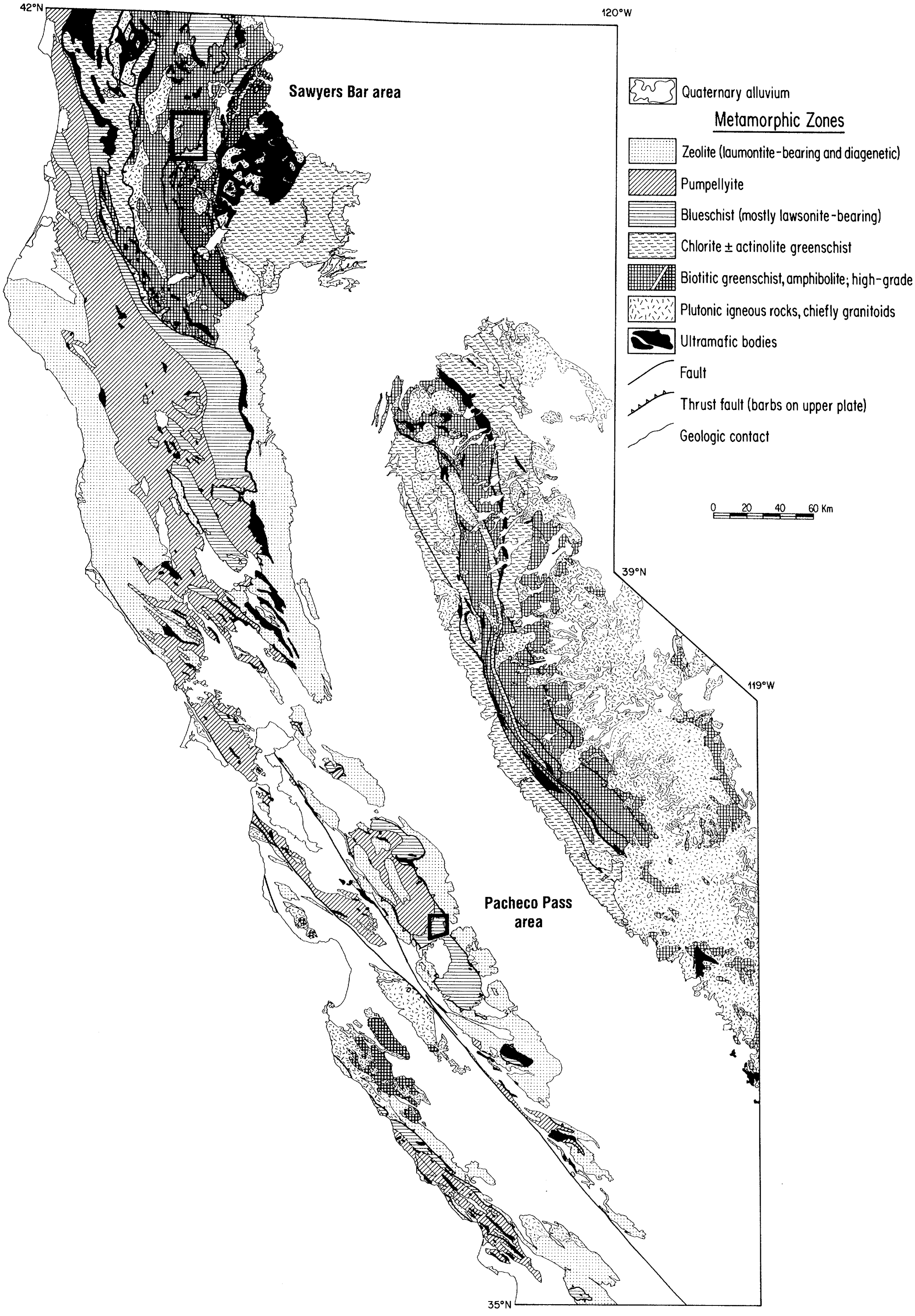

FIGURE 4. Metamorphic zonations developed in lithotectonic belts of northern and central California, based on the geologic map of California (Jennings 1977), and generalized by Ernst (1983) from numerous literature sources. High-grade metamorphic rocks are present, especially in Sierran roof pendants, in the Klamath central metamorphic belt, and in the Salinian terrane. Locations of the Sawyers Bar area (figure 6) and the Pacheco Pass area (figure 8) are indicated.

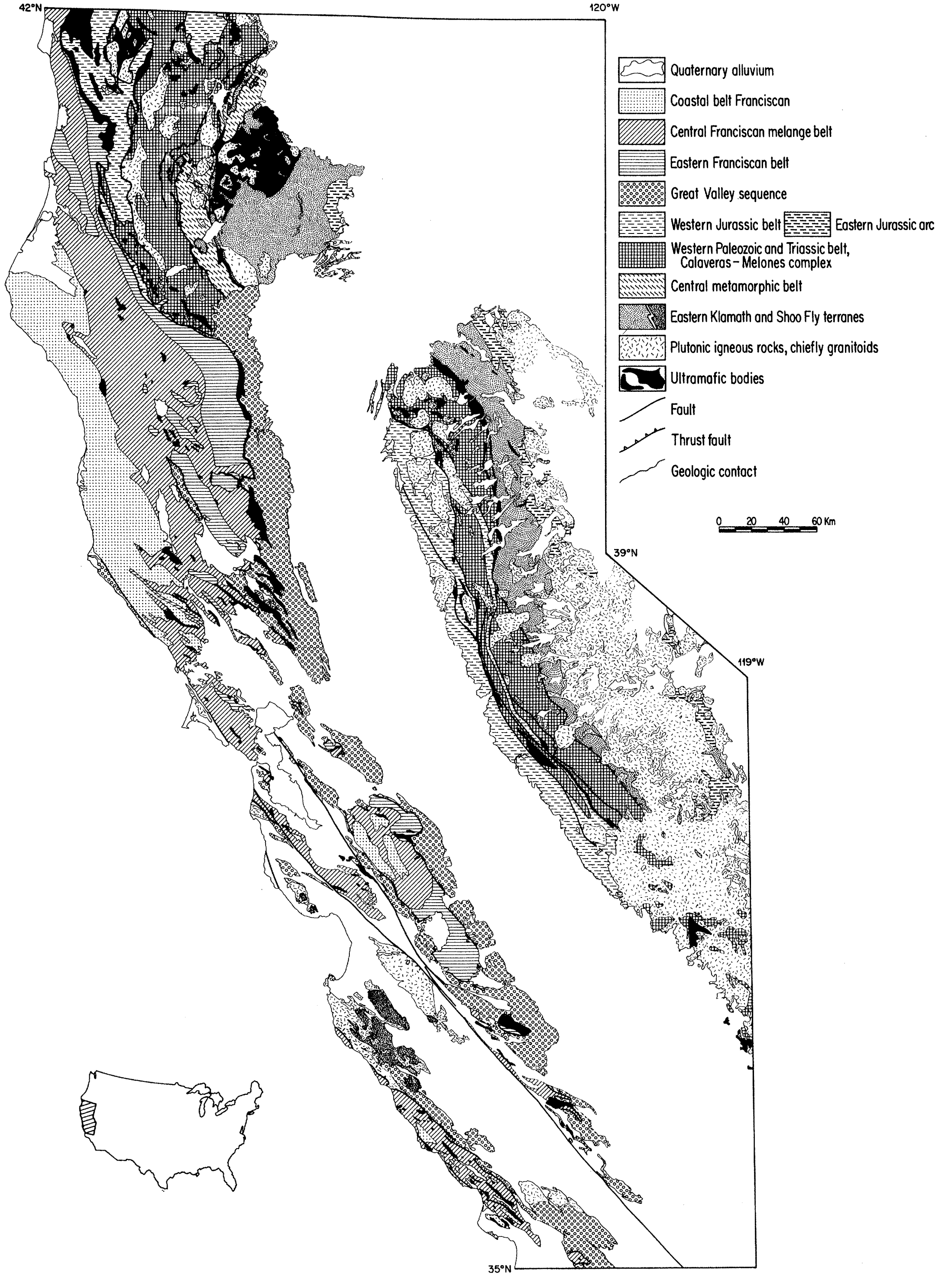

FIGURE 5. Lithotectonic belts of northern and central California based on the geologic map of California (Jennings 1977), and generalized by Ernst (1983) from numerous literature sources. The eastern, mid-Mesozoic sedimentary and volcanic stratified rocks of the eastern Klamath and northern Sierra are depicted with a map pattern similar to that of the western Jurassic belt because, although not necessarily related, these sections were deposited nearly contemporaneously.

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serpentinized peridotites, but the amount of ultramafic material decreases to the southeast. Different lithotectonic units (Irwin 1981; Sharp 1988) from east to west include: the early-to-mid-Paleozoic Shoo Fly and eastern Klamath terranes; the Feather River and Trinity peridotites; the central metamorphic belt (principally in the Klamaths); blueschists of the Melones fault zone and the Stuart Fork Formation; the late-Paleozoic–early-Mesozoic Sierran Calaveras–Melones complex and so-called western Triassic and Paleozoic belt of the Klamath Mountains; and the western Jurassic belt. These lithotectonic units display east-dipping imbrication; isoclinally folded, west-vergent sections have been recognized, but where primary flow tops and sedimentary laminations are preserved, sections typically face east (Clark 1964, 1976). Many of the individual belts may represent terrane assemblies (Irwin 1972; Silberling *et al.* 1987). In general, age of formation, metamorphic grade and structural complexity all

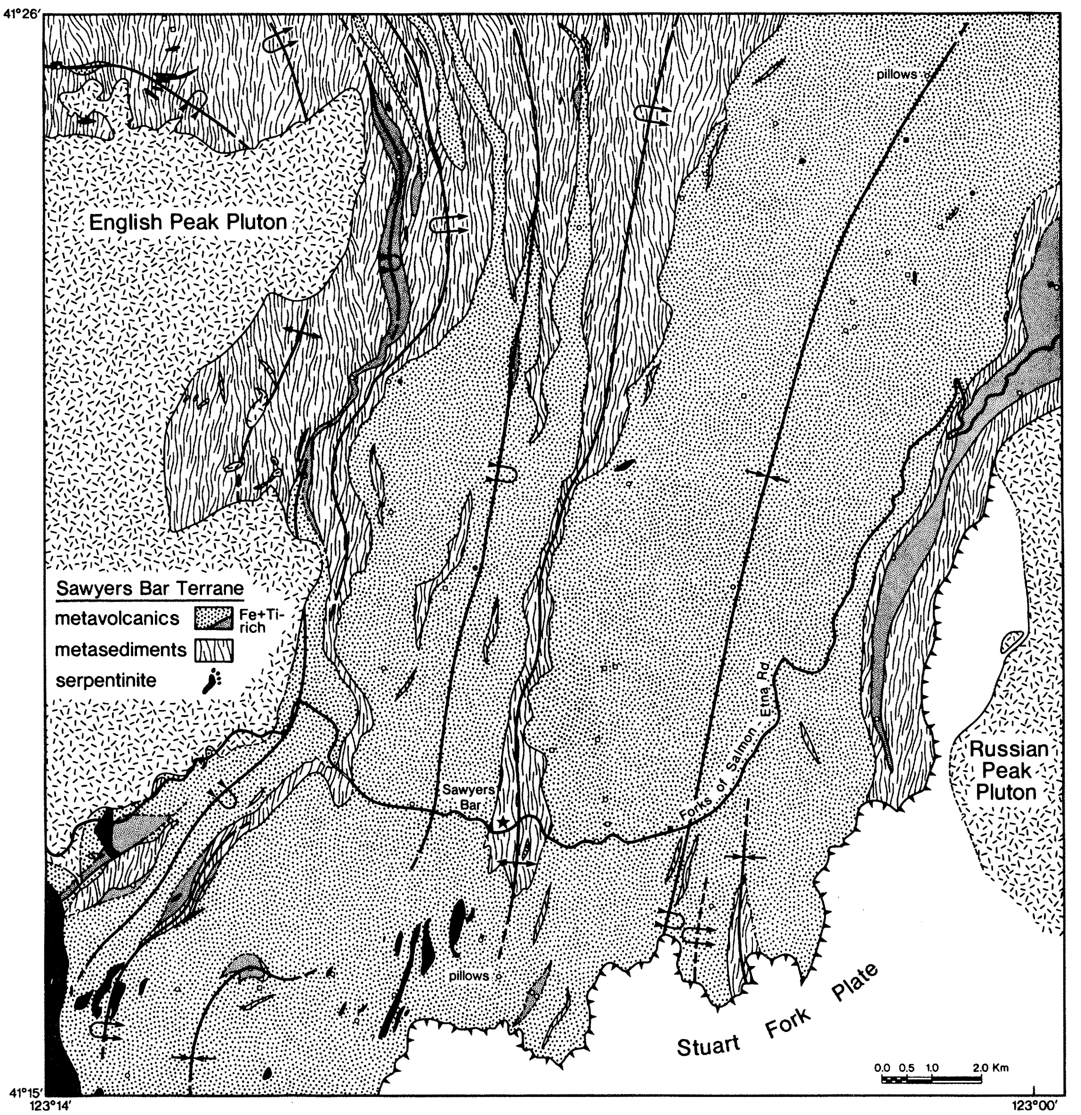

FIGURE 6. Geology of the Sawyers Bar area, central Klamath Mountains (after Ernst (1987) with additional mapping). See figure 4 for location. The intricately interfingered metasedimentary units of the more westerly (equivalent to Hayfork) and easterly (equivalent to North Fork and Salmon River) terranes are part of a single complex. The town of Sawyers Bar is indicated by a black star.

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increase eastward (Schweickert 1981; Schweickert *et al.* 1988). Outboard units contain terrigenous debris and tectonic blocks derived from the more landward terranes (Behrman & Parkison 1978; Wright 1982; Ando *et al.* 1983; Gray 1986; Hannah & Moores 1986), suggesting that most terranes are native to the North American margin.

As an example, detailed mapping of greenschist-facies rocks in the central part of the western Triassic and Palaeozoic belt of the central Klamath Mountains near Sawyers Bar, California, demonstrates stratal continuity and the interlayered nature of intricately folded, distinctive metabasaltic and metaturbiditic units. Geologic relationships are presented in figure 6. Although metavolcanic and metasedimentary units of this area were previously regarded as portions of several disparate terranes (Donato 1987; Silberling *et al.* 1987), these supracrustal rocks all belong to a single lithostratigraphic entity. Contacts in the mapped area are depositional rather than faulted, except for the east-dipping thrust fault bringing the Stuart Fork plate over Sawyers Bar rocks. Petrologic, structural, geologic, and geochemical studies demonstrate the absence of metamorphic, tectonic, stratigraphic, and bulk-rock compositional discontinuities. Evidently the Sawyers Bar segment of the western Triassic and Paleozoic belt formed and evolved as a single, possibly nearly in-place arc, rather than as a collage of unrelated, exotic crustal entities.

Within any one Sierran–Klamath complex, recrystallization intensity in general decreases oceanward, as does the age of formation, and this progression tends to hold on a grander scale for the various juxtaposed belts (Ernst 1983). For example, in the Klamaths, metamorphic grade decreases westward from upper amphibolite facies in the central metamorphic belt through greenschist facies to prehnite-pumpellyite facies in the western Jurassic belt (Irwin 1981; Burchfiel & Davis 1981; Coleman *et al.* 1988). The age of origin for the protoliths decreases commensurately from mid-Palaeozoic to late Jurassic. A comparable metamorphic–temporal regional arrangement exists in the northwestern Sierran foothills (Saleeby 1981; Day *et al.* 1988).

Northern and central Franciscan–Great Valley depositional complex

Franciscan and Great Valley units are areally associated from southern Oregon to west-central Baja California. Both consist dominantly of clastic sedimentary rocks, recrystallized to contrasting extents, and each has a latest Jurassic–Palaeogene depositional range. The ensimatic, tectonically imbricated prism of partly chaotic (Hsü 1968), chiefly east-dipping and east-facing Franciscan strata, lies closest to the Pacific Ocean and is confined to the Coast Range province; it is separated from the broadly contemporaneous Klamath–Sierran igneous arc by the well-bedded Great Valley Group. The two terrigenous sedimentary belts have been regarded as genetically related trench and forearc-basic deposits, respectively (Ernst 1970; Dickinson 1972, 1976).

However, palaeomagnetic and fossil data document the far-travelled nature of Franciscan deep-sea cherts and pillow basalts (see, for example, Blake 1984; Jayko & Blake 1984; Beck 1986). These facts have evoked the hypothesis of juxtaposition of unrelated Franciscan and Great Valley terranes (Blake & Jones 1978; Blake *et al.* 1988), compatible with the accretion of exotic terranes throughout the western Cordillera (Coney *et al.* 1980; Jones *et al.* 1983). The present spatial association of the two metasedimentary assemblages in the California Coast Ranges reflects relative westward thrusting of Great Valley strata and underlying Coast Range ophiolite over the high-*P* coeval Franciscan Complex (Bailey *et al.* 1964, 1970), followed by, or concurrent with, return flow for the subducted Franciscan (Suppe 1972; Cloos 1982; Platt 1986). Seismic reflection and refraction profiles indicate that the Franciscan may have wedged eastward between overlying Great Valley strata and the Sierran basement (Wentworth *et al.* 1984); however, inasmuch as Quaternary units are involved, this may represent chiefly Neogene deformation.

Although most rock types of oceanic character are exotic, geologic relations suggest that the volumetrically dominant clastic rocks of western California are native to the North American margin. Studies of paleocurrent vectors and sandstone plus conglomerate petrofacies demonstrate a common Klamath–Sierran provenance for Franciscan and Great Valley detritus (Telleen 1977; Jacobson 1978; Dickinson *et al.* 1982; Ingersoll 1979; Seiders & Blome 1984; Seiders 1988). Similarities of quartz, feldspar, and lithic-fragment proportions within the forearc basic and trench complex, inferred palaeogeography, and sediment-distribution trajectories are illustrated in figure 7. Spatial contiguity seems to be required during deposition of these units. Moreover, Upper Cretaceous Great Valley trench-slope units locally rest with angular unconformity on the underlying Franciscan (Maxwell 1974; Smith *et al.* 1979). Forearc deposition evidently took place in intimate proximity to a rising mass of decoupled trench melange.

Four major lithotectonic belts, divided by some workers into more numerous tectono-stratigraphic terranes, crop out in the northern Coast Ranges, and on a smaller scale, in

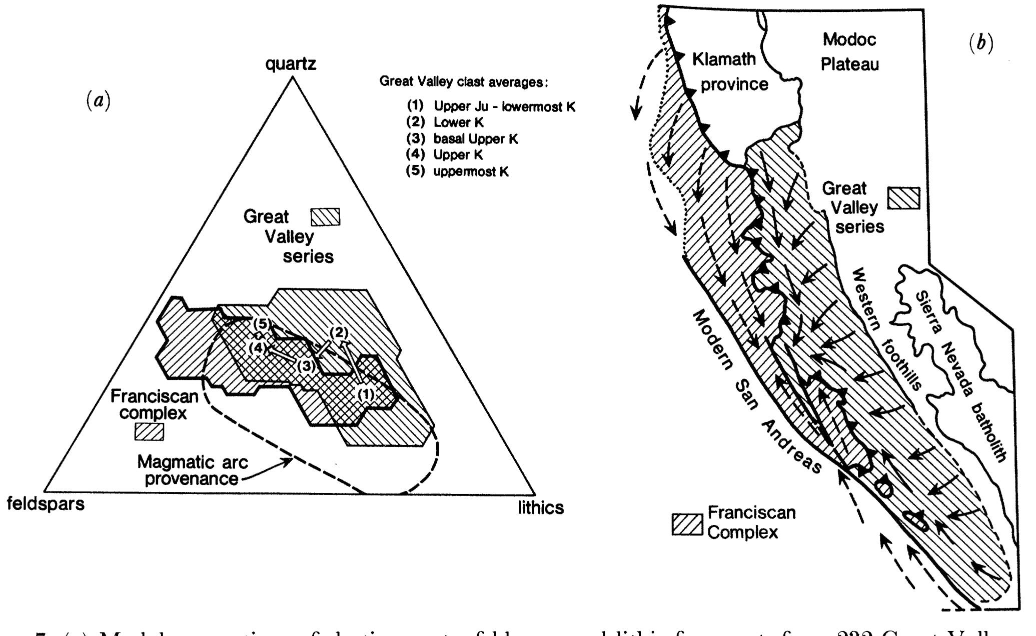

FIGURE 7. (*a*) Modal proportions of clastic quartz, feldspars and lithic fragments from 232 Great Valley and 203 Franciscan sandstones from northern and central California, compared with typical magmatic-arc derived sandstones, after Dickinson *et al.* (1982). Evolution in average Great Valley modes during unroofing of volcanic and metamorphic cover, and exposure of K-feldspar-bearing granitoids is illustrated by the petrostratigraphic intervals (1)–(5). Similarities in Great Valley and Franciscan conglomerate clasts have been documented by Seiders (1988). (*b*) Cretaceous palaeogeography and sediment distribution paths in northern and central California, after Dickinson *et al.* (1982). The major suture zone shown as a thrust contact with barbs on the upper plate is the Coast Range fault, which experienced compound movement, including earlier subduction (underflow and compression), and later uplift (return flow and extension) as documented by Bailey *et al.* (1970), Ernst (1970), Cloos (1982), Platt (1986), and Jayko *et al.* (1987).

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the southern Coast Ranges (Blake *et al.* 1985, 1988). From east to west, these are: (*a*) the Great Valley Group; (*b*) the eastern Franciscan belt; (*c*) the central Franciscan melange; and (*d*) the coastal belt of Franciscan. Great Valley strata rest unconformably on inboard Sierran–Klamath continental basement, and farther to the west, on the Coast Range ophiolite. Franciscan sediments were laid down on an unknown substrate, but mafic tectonic blocks present in the disrupted complex may represent outboard palaeo-Pacific oceanic crust.

(*a*) The well-bedded Great Valley accretionary prism constitutes an asymmetric synclinorium with a near-vertical western limb and gently west-dipping eastern limb (Hackel 1966). Clastic strata are feebly recrystallized to zeolite facies assemblages near the base of the thickest, westerly sections (Dickinson *et al.* 1969; Bailey & Jones 1973). Of similar metamorphic grade, the Coast Range ophiolite crops out discontinuously along the west side of the Great Valley (Bailey *et al.* 1970). It includes several geochemically different mafic–ultramafic units (Shervais & Kimbrough 1985). Some were generated *ca.* 165 Ma ago at an oceanic-spreading centre (Hopson *et al.* 1981), but others are locally associated with slightly younger (*ca.* 153 Ma) calc-alkaline arc rocks (Evarts 1977); most segments of the ophiolite are capped by Upper Jurassic deep-sea radiolarian cherts which pass upwards to rhythmically layered, thin-bedded Great Valley distal mudstones. Ophiolite overlain by magmatic-arc rocks may have been generated near the continental margin, whereas other occurrences, having remnant palaeomagnetic inclinations compatible with near-equatorial formation (Luyendyk 1982), probably are exotic.

(*b*) The eastern Franciscan belt and its southern extension in the Diablo Range consist of a relatively well-ordered series of tectonically imbricated phyllitic schists, quartzofeldspathic metagraywackes, dark metashales, pods of greenstone plus serpentinite, and widespread, thin chert layers. The complex is bounded to the east by the Coast Range fault and the structurally overlying ophiolite and Great Valley Group, to the west by a fault juxtaposing the tectonically lower central Franciscan melange. Sections within the eastern belt, as well as bounding faults, dip eastward (Suppe 1973). Depositional ages of turbiditic strata range from latest Jurassic to mid Cretaceous.

Rocks of the eastern belt are characterized by minor but ubiquitous neoblastic lawsonite. Two distinct lithostratigraphic assemblages make up this terrane: (i) Interlayered schistose metapelitic and metabasaltic blueschists occur in the northeastern part of the Franciscan Complex directly beneath the Coast Range fault (Blake *et al.* 1967; Irwin *et al.* 1974; Brown & Ghent 1983). This entity is the highest structural unit in a stack of east-dipping sheets (Worrall 1981). The minimum metamorphic K/Ar age of these schists is about 120 Ma (Lanphere *et al.* 1978). (ii) Relatively undeformed metagraywacke and metashale sequences, especially extensive along the east side of the Diablo Range, contain widespread metamorphic aragonite and associated jadeitic clinopyroxene + quartz (McKee 1962*a*, *b*; Ernst *et al.* 1970). The time of high-P, low-T recrystallization seems to have been about 90–120 Ma (Suppe & Armstrong 1972; Mattinson & Echeverria 1980).

A geologic map of the Pacheco Pass area of the east-central Diablo Range is shown in figure 8 as a representative area. Units dip predominantly to the east. The largely (meta-)detrital section, which consists of neoblastic jadeitic-pyroxene bearing graywackes and dark shale laminae possesses stratal coherence, judging by the lateral continuity of interbedded cherty layers. Pods of blueschist, greenstone, and minor serpentinite occur particularly in unit I, the stratigraphically lowest part of the metaclastic sequence. This unit in part may represent an olistostrome or tectonic melange. Mafic, chiefly intrusive meta-igneous rocks are rare in the stratigraphically higher members. Thickening and thinning, especially in unit II, is evident. The entire section, regarded by some as a tectonic aggregation of unrelated terranes (see, for example, Blake 1984) appears to be a coherent stratigraphic–metamorphic entity.

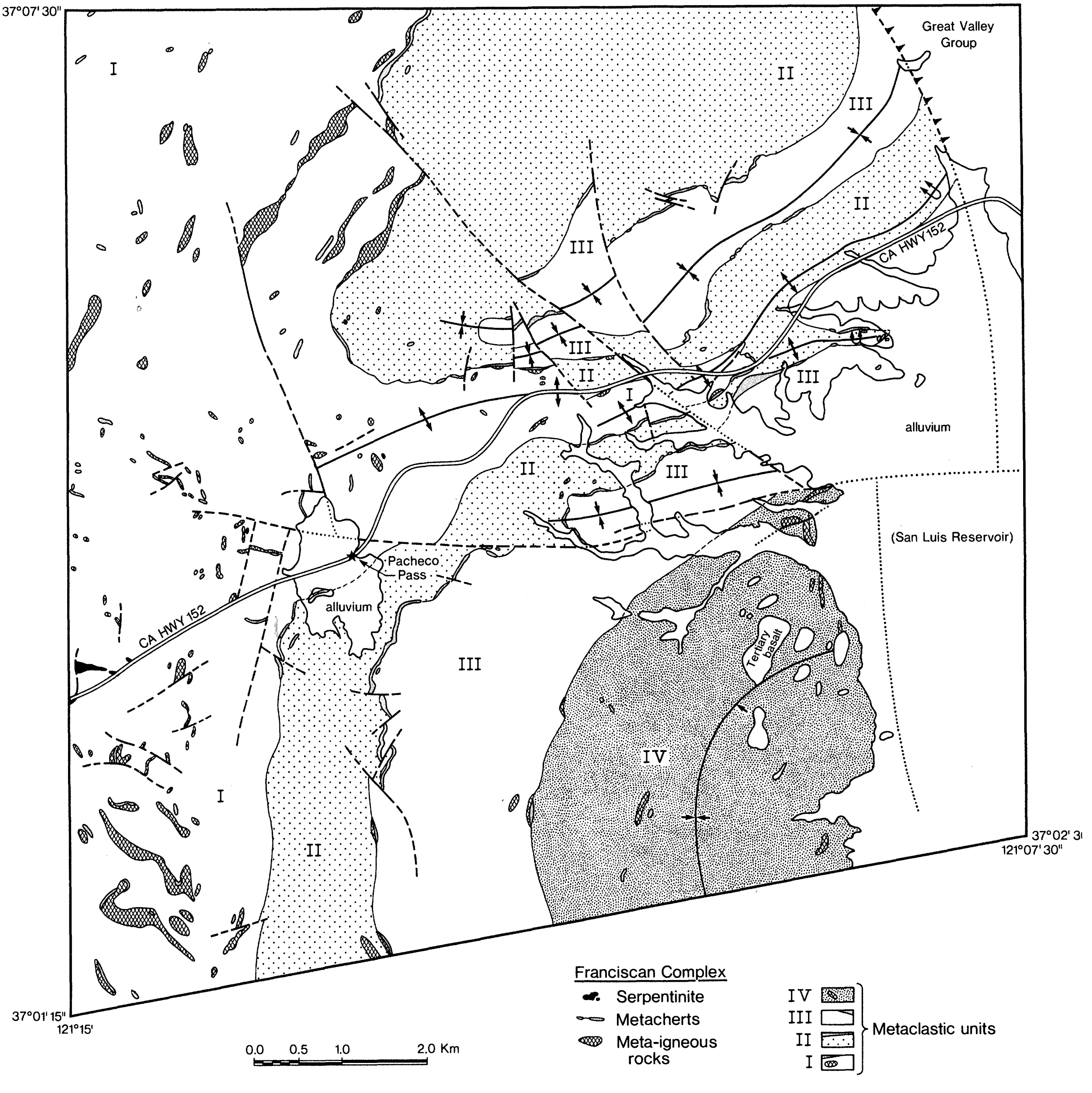

FIGURE 8. Geology of the Pacheco Pass area, eastern California Coast Ranges (after Ernst *et al.* (1970) with additional mapping). See figure 4 for location. Neoblastic jadeitic pyroxene is widespread in quartzose metagraywackes of this region (McKee 1962*a*; Ernst *et al.* 1970; Maruyama *et al.* 1985). The San Luis Reservoir, which covers the alluvium in the eastern part of the map, is not shown. Four local, stratigraphically coherent metaclastic units of this portion of the Franciscan Complex, referred to as units I–IV, are distinguished in this area. The lowermost, unit I, is rich in metavolcanic pods, and may be olistostromal. Stratal continuity is preserved in this part of the belt. Pacheco Pass is indicated by a black star.

(*c*) The central Franciscan belt consists mainly of chaotic melange, with variable proportions of more coherent strata. The sedimentary age of the shaly matrix appears to be mid and late Cretaceous, although included blocks and broken-formation slabs range in age from late Jurassic to late Cretaceous, and are of both foreign and cognate lithologies (Blake & Jones 1978). Fractured and attenuated blocks may be regarded as boudins, whereas with lesser degrees of disruption, tectonic melange passes gradually into semistratified broken formation (Hsü 1968, 1974). The lower the sandstone:shale ratio, the more thoroughly disrupted the sections appear to be. Laminar bodily flow within the subducted melange was modelled by Cowan & Silling (1978) and Cloos (1982). Foreign, previously metamorphosed eclogitic and amphibolitic blocks evidently were spalled off from different loci along boundaries of the subduction-induced circulation system; this phenomenon, coupled with density-induced differential settling velocities of high-grade blocks during flow, accounts for both the lithologic variation and size distribution of the tectonic fragments within the melange (Cloos 1982, 1986).

Metamorphism of the central Franciscan belt at modest P and T produced pumpellyite and lawsonite, but not jadeitic pyroxene (Blake *et al.* 1967; Suppe 1973; Cloos 1983). The recrystallization age of the matrix is probably late Cretaceous, judging by the contained mid-Cretaceous fossils. Mafic tectonic blocks of garnet-bearing blueschist, amphibolite and eclogite represent fragments of previously subducted oceanic crust, now engulfed in the melange. Although present in the eastern belt, they are most abundant in the central belt. Peripheral actinolite + chlorite or talc rinds indicate that the blocks were not in chemical equilibrium with the enclosing lower metamorphic grade matrix of the olistostrome, tectonic melange or serpentinite host. Recrystallization ages of these high-grade blocks typically are on the order of 160–163 Ma (Coleman & Lanphere 1971; Mattinson 1988), considerably older than the sparsely fossilferous, chaotic matrix in which they are found.

(*d*) The coastal Franciscan belt is bounded on the east by the steeply east-dipping coastal belt thrust, which separates it from the structurally higher central Franciscan melange. Lesser degrees of stratal disruption are characteristic of this rather arkosic Upper Cretaceous–Miocene lithotectonic unit (McLaughlin *et al.* 1982). Premetamorphic rock types include deep-water clastic strata on the west, apparently associated with an altered basaltic substrate and chert, passing eastward by degrees to mid-fan turbiditic, andesitic graywacke and abundant quartzofeldspathic graywacke (Blake & Jones 1978). Greenstone and serpentinite lenses are scarce, and high-grade tectonic blocks are extremely rare in this belt (Blake *et al.* 1988).

Metamorphism in the coastal belt is weak, and has not been investigated extensively. Laumontite seems to be widely distributed. A few metasedimentary parageneses include prehnite and/or pumpellyite, but *in situ* blueschists have not been reported (Bailey *et al.* 1964; McLaughlin *et al.* 1982). Phase assemblages are similar to those described from most deeply buried portions of the Great Valley Group. This seaward belt of Franciscan apparently was not subjected to profound underflow before decoupling from the subducting plate and underplating along the continental margin.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Subduction, transform motion and metamorphic belts of the western U.S. Cordillera

Post-Middle Jurassic sea-floor spreading is recorded in oceanic crust and overlying hemipelagic sediments of the Pacific Basin (Pitman *et al.* 1974; Engebretson *et al.* 1985; Debiche *et al.* 1987). Whereas parts of western limbs of several oceanic plates are still extant, eastern limbs of these spreading systems have been overridden by the North American plate during the past 165 Ma (Hamilton 1969). More than 10000 km of eastward subduction must have occurred (Ernst 1984), averaging about 6 cm a^{-1}. Thus, in spite of several thousand kilometres of northward drift of oceanic crust-capped lithosphere relative to North America, underflow was the dominant mechanism responsible for production of paired metamorphic belts and voluminous calc-alkaline igneous activity, reflecting Cordilleran continental growth and recrystallization during mid-Mesozoic to mid-Cenozoic time.

Based on measured high heat flow in the California Coast Ranges, fission track analyses, and reasonable mineralogic transformation rates, Dumitru (1989) calculated that rapid thermal obliteration of high-P metamorphic mineral assemblages is currently in progress at crustal depths greater than 5–10 km. The strike–slip régime of western California, therefore, evidently has been recently imposed on a chiefly convergent Mesozoic–Cenozoic continental margin (Atwater 1970); until recently, the process of subduction has sustained the nearly continuous refrigeration and preservation of blueschist lithologies in the Coast Ranges since their late Mesozoic formation. Peacock (1988) drew the same general conclusion to account for inverted metamorphic gradients in the westernmost Cordillera. Later terrane shuffling along the dextral shear system of the California Coast Ranges, therefore, has partly obscured the effects of the main constructional stage of sialic growth and metamorphism accompanying lithospheric plate descent.

Summary

Both the eastward underflow of great tracts of Palaeo-pacific oceanic lithosphere, and the apparent recent change in thermal structure of the westernmost continental crust argue for long-continued subduction as the chief plate tectonic process operating in the western U.S. Cordillera during mid-Mesozoic to mid-Cenozoic time. This mechanism explains the contemporaniety, spatial association, and contrasting P–T histories of landward calc-alkaline arcs, forearc-basin deposits, and oceanward trench complexes. The total absence of old blueschist belts within the interior of the U.S. Cordillera probably is due to thermal overprinting. The scarcity of negatively buoyant ophiolitic peridotites may reflect systematic downward sagging of dense mantle and mafic crustal material accompanying thermal softening and crustal remobilization.

True continental growth resulting from the separation of alkali- and Si-rich material from the mantle, in contrast to rearrangement of fragments of already extant sialic crust, requires an important component of convergent plate motion (Ernst 1984). Orderly Proterozoic and Phanerozoic metamorphism, the Precambrian isotopic provinces and rock record, the gradual oceanward decrease in initial ^{87}Sr:^{86}Sr ratios and increase in ϵ_{Nd} values in continental igneous rocks (see, for example, DePaolo 1981), and both large- and small-scale geologic relationships in Californian terranes all are compatible with nearly *in situ* crustal growth and metamorphism. Near the Pacific margin of the U.S., allochthonous ophiolitic debris is abundant, and exotic

Phanerozoic microcontinental fragments of uncertain source are present but rare. However, accretion primarily involved the sweeping back into the North American margin of native terrigenous debris and previously metamorphosed sialic fragments of local or regional provenance. Development of the late Mesozoic triad, Franciscan trench/Great Valley forearc/Sierran-Klamath calc-alkaline arc provides a relatively well-preserved example of the growth and reworking process; the nearly *in situ* setting is demonstrated by sedimentary provenance and transport vectors as well as by systematic metamorphic, isotopic, and petrochemical trends. Lateral rearrangement of genetically related slices of the margin, as well as occasional removal of continental-margin–island-arc sections and docking at distant sites are important complications. Nevertheless, subduction-related arc processes, and recycling in forearc, backarc, and trench environments, evidently have been responsible for most of the enlargement and attendant metamorphism of continental crust in the western U.S. Cordillera.

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Discussion

I. G. Gass, F.R.S. (*Open University, U.K.*). Professor Ernst claims the 'Yellow Dog' terrane came in (docked) 'steaming' and he describes dykes which invaded the terrane after it had accreted to western N. America. This implies that the terrane brought with it its own magma supply and perhaps heat source. In which case, what was the depth of cut off when the terrane became detached and does he regard such terranes as common or rare phenomenon? Is it possible that the magmatism was genetically associated with the N. American host? On what evidence did he decide that it was the allochthonous terrane that was steaming?

W. G. Ernst. The Sawyers Bar terrane consists of metamorphosed distal turbidites and interlayered – but predominantly overlying – Yellow Dog greenstones. Hypabyssal dikes and sills in the Yellow Dog metavolcanics are chemically and mineralogically identical, hence comagmatic with the extrusive rocks; the diabases are porphyritic and carry abundant relict phenocrysts of oscillatorily zoned hornblende. These same distinctive hypabyssals, on a lesser scale, transect chemically, mineralogically different rocks of the more easterly, structurally higher Stuart Fork late Triassic blueschist complex. Accordingly, the outboard (westerly) Sawyers Bar immature island-arc terrane must have been still active (steaming) as it collided with the previously deformed and metamorphosed, landward Stuart Fork complex, presumably along the western margin of North America. Because early–middle Jurassic regional greenschist facies metamorphism of both terranes accompanied this suturing event, and because thermobarometric data suggest physical conditions on the order of 400 °C at about 3 kilobar (3×10^8 Pa), the depth of decoupling of the Sawyers Bar section from the subducting Palaeopacific plate must have been approximately 10 km. I suspect that such events are common in the Circumpacific area in cases where marginal basin collapse has allowed the docking of offshore arcs along adjacent continental margins.

A. H. F. Robertson (*Grant Institute of Geology, University of Edinburgh, U.K.*). From my own field studies, I would strongly support Professor Ernst's view that the Great Valley Sequence and the Franciscan were essentially coupled as in classical plate tectonic interpretations; in particular, there is no field structural evidence of significant strike–slip faulting near the contacts. However, how would he envisage the origin to the ophiolitic slivers and eclogitic rocks within the Franciscan; were they slivered off the edge of the Coast Range ophiolite and transported northwards by strike–slip faulting, as has been suggested, or are there other explanations?

W. G. Ernst. According to many authors (e.g. Shervais & Kimbrough 1985), the bulk-rock geochemistry of basaltic/gabbroic/serpentinitic blocks contained within the Franciscan contrasts with that of the Coast Range ophiolite lying beneath the Great Valley Sequence. Thus, although the latter may represent the westward, more oceanic part of the North American lithospheric plate, Franciscan meta-ophiolite tectonic blocks probably were derived from a Palaeopacific substrate on which the voluminous terrigenous debris was deposited, then disaggregated in the subduction zone. Alternatively, such tectonic lenses may represent hanging-wall lithologies metamorphosed under high-P (and moderately high-T) conditions at the initiation of subduction in late(?) Jurassic time.

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