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ORIGINAL ARTICLE

Review of Late Jurassic-early Miocene sedimentation and plate-tectonic evolution of northern California: illuminating example of an accretionary margin

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Abstract Production of voluminous igneous arc rocks, high-pressure/low-temperature (HP/LT) metamafic rocks, westward relative migration of the Klamath Mountains province, and U–Pb ages of deposition, sediment sources, and spatial locations of Jurassic and younger, detrital zircon-bearing clastic rocks constrain geologic development of the northern California continental edge as follows: (1) At ~175 Ma, transpressive plate underflow began to generate an Andean-type Klamath-Sierran arc along the margin. (2) Oceanic crustal rocks were metamorphosed under HP/LT conditions in an inboard, east-inclined subduction zone from ~170-155 Ma. Except for the Red Ant blueschists, such lithologies remained stored at depth; most HP/LT mafic tectonic blocks returned surfaceward only during mid- and Late Cretaceous time, chiefly entrained in circulating, buoyant Franciscan mud-matrix mélange. (3) By ~165 Ma and continuing to ~150-140 Ma, erosion supplied volcanogenic debris to proximal Mariposa-Galice ± Myrtle overlap strata. (4) At ~140, immediately prior to the onset of paired Franciscan and Great Valley Group (GVG) + Hornbrook deposition, the Klamath salient was deformed and displaced ~100–150 km westward relative to the Sierran arc, stranding pre-existing oceanic crust on the south as the Coast Range Ophiolite (CRO). (5) After the end-of-Jurassic seaward step-out of the Farallon-North American convergent plate junction, terrigineous debris began to be deposited in the outboard Franciscan trench and intervening Great Valley forearc. (6) Voluminous sedimentation and accretion of Franciscan Eastern + Central belts and GVG detritus took place during paroxysmal igneous activity and rapid, nearly orthogonal plate convergence at ~125-80 Ma. (7) Sierran arc volcanism-plutonism ceased by ~80 Ma in northern California, signaling a transition to shallow, nearly subhorizontal eastward plate underflow attending Laramide orogeny far to the east. (8) Presently exposed Paleogene-lower Miocene Franciscan Coastal Belt sedimentary strata were deposited in a tectonic realm unaffected by HP/LT subduction. (9) Grenville-age detrital zircons are absent from the post-120 Ma Franciscan section. (10) Judging from petrofacies and zircon U–Pb data, the Franciscan Eastern Belt contains debris derived principally from the Sierra Nevada and Klamath ranges; detritus from the Idaho Batholith as well as Sierra Nevada Batholith may be present in some Central Belt sandstones, whereas clasts from the Idaho Batholith, Challis volcanics, and Cascade Range appear in progressively younger Paleogene-lower Miocene Coastal Belt sediments. (11) Gradual NW dextral offset of the Franciscan trench deposits of as much as ~1,600 km may have occurred relative to the native GVG forearc and basement terranes of the American Southwest.

Keyword Post-Paleozoic subduction · Franciscan-Great Valley strata · California crustal evolution · Jurassic-Miocene accretion

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1 Geologic introduction

This review summarizes some recent studies of clastic strata exposed in the Sierran Foothills, the eastern and western edges of the Klamath Mountains, and main units comprising the Sacramen to Valley + outboard California Coast Ranges—rocks deposited during a period typified by mainly transpressive to convergent plate motions. The times of sedimentation, provenance of these strata, and their post-depositional recrystallization P–T histories provide insights regarding the Late Jurassic through early Miocene petrotectonic evolution of northern California. This review is aimed particularly at Asian Earth scientists unfamiliar with northern California, because the area constitutes a relatively clear example of a 175-20 Ma convergent to transpressive plate margin that hosted a substantial infusion of new sialic crust, chiefly through subduction-induced partial melting at magmagenic depths followed by subsequent ascent and emplacement of primary calcalkaline igneous rocks (i.e., continental growth). Crustal construction also involved the generation of secondary products of clastic sedimentation and HP/LT metamorphism, both of which provide additional information regarding the regional plate-tectonic history. Figure 1 presents the broad geologic framework of the region, including most of California. Figure 2 is a more

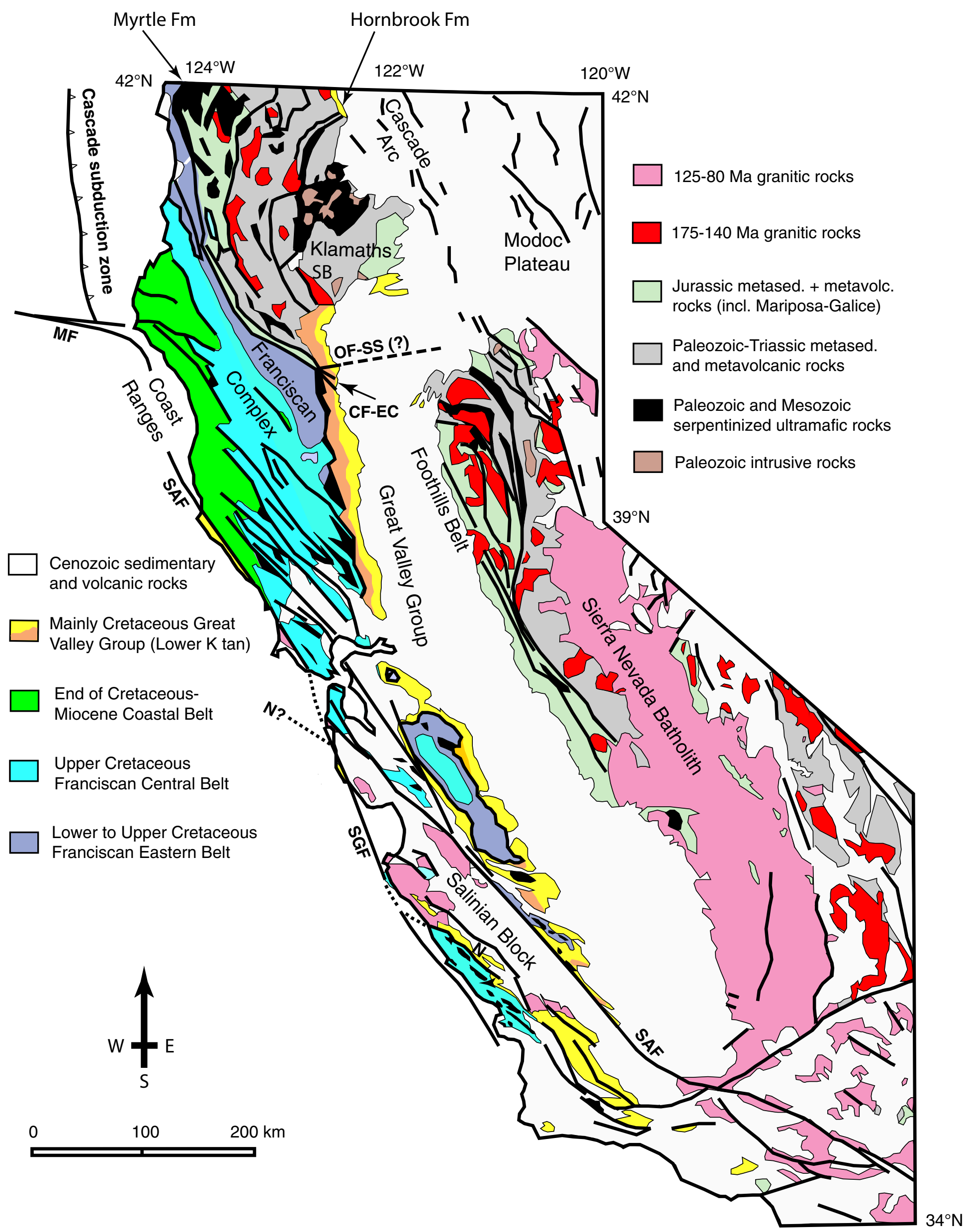


Fig. 1 General geologic map of most of California, depicting the 175-140 Ma Klamath-Sierranand 125-80 Ma Sierran volcanic-plutonic arcs, Great Valley Group forearc strata, and Franciscan trench belts, simplified from the U. S. Geological Survey and California Division of Mines and Geology (1966) geologic map, terrane map of Silberling et al. (1987), the Klamath Sierran map of Irwin (2003), land coastal maps of Dickinson et al. (2005). Shasta Bally pluton = SB. The South Fork and Coast Range faults juxtapose rocks of the Franciscan Complex against those of the Klamath province and the GVG respectively (e.g., Blake et al. 1999). Labeled fault zones: Oak Flat-Sulphur Spring = OF-SS; Cold Fork-Elder Creek = CF-EC; on-land and offshore segments of the Nacimiento, = N and N? San Gregorio-Hosgri = SGF; Mendocino = MF; San Andreas = SAF

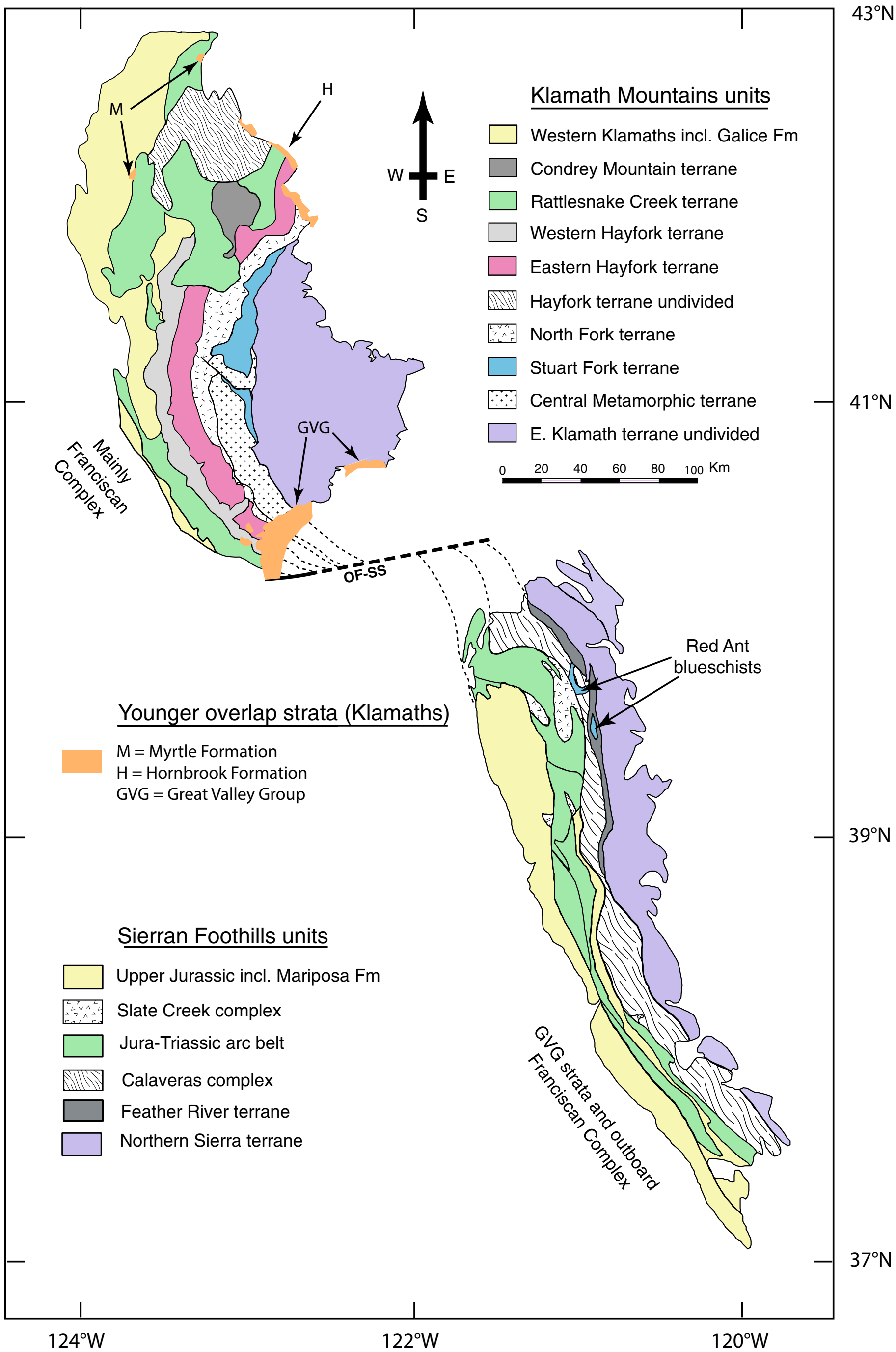


Fig. 2 Simplified lithostratigraphic terranemap of the Klamath Mountains and the western Sierran Foothills ignoring plutons, after Irwin (1981, 2003), Sharp (1988), Edelman and Sharp (1989), Ernst (1998), and Snow and Scherer (2006). The Galice and Mariposa formations are of Late Jurassic age. Klamath-margin locations of the northernmost Great Valley Group, Myrtle (M), and Hornbrook (H) formations are indicated. The Myrtle is of latest Jurassic-earliest Cretaceous age, whereas the GVG and Hornbrook are chiefly of mid- and Late Cretaceous age. Also shown is the Oak Flat-Sulphur Spring sinistral fault zone (OF-SS), but not the slightly younger Cold Fork-Elder Creek fault zone of Fig. 1. The Klamaths were displaced oceanward ~100–150 km relative to the northern extension of the Jurassic Sierran arc but separation across the OF-SS is only ~80–100 km because of viscous drag induced curvature ofthe imbricate salient

detailed view of the study area, and the disposition of Klamath, Sierran Foothills, Sacramento Valley, and northern Coast Range clastic sedimentary units treated in this paper.

1.1 Jurassic crustal growth

The late Paleozoic-early Mesozoic development of northern California was typified by chiefly margin parallel slip, episodic suturing of far-traveled ophiolitic complexes, and deposition of superjacent chert-argillite deep-marine sedimentary units (Saleeby 1981, 1982, 1983; Ernst et al. 2008). Scattered sialic igneous activity characterized the Late Triassic margin of California, but most lithologic sections of late Paleozoic-early Mesozoic age are oceanic in their genesis. However, a major Andean-type arc began to form in the Sierra Nevada and Klamath Mountains by ~175 Ma attending the transpressive eastward underflow of oceanic lithosphere (Dunne et al. 1998; Irwin 2003; Dickinson 2008). This volcanic-plutonic arc shed clastic detritus into the ophiolitic realm of the Jura-Triassic arc belt + Early and Middle Jurassic Eastern Hayfork + North Fork terranes, and the earliest Late Jurassic continental margin Mariposa + Galice formations of the Klamath and Sierran ranges, respectively (Miller and Saleeby 1995; Scherer et al. 2006). The Sierran Jura-Triassic arc belt and Klamath chert-argillite-rich North Fork and Eastern Hayfork units were laid down at ~175-165 Ma (Snow and Ernst 2008; Scherer and Ernst 2008), whereas the near-shore Mariposa-Galice formations began accumulating by ~165-160 Ma (Ernst et al. 2009a).

Transpressive plate convergence also generated HP/LT basaltic eclogites and garnet-glaucophane schists along the Middle and Late Jurassic convergent plate junction at ~170-155 Ma (Cloos 1986; Wakabayashi 1990; Tsujimori et al. 2006; Ukar et al. 2012).However, except for the ~174 Ma Red Ant blueschists (Hacker and Goodge 1990; Hacker 1994), such HP/LT metamafic rocks remained at depth, and fragments apparently returned surfaceward only during mid- and Late Cretaceous time as tectonic ± olistostromal blocks were sheared and gravity-fed into low-density Franciscan mud-matrix mélange. These relatively high-grade metamafic blocks formed much earlier during construction of the emergent arc. They were not intensely overprinted by low-grade metamorphic phases, so evidently were stored at rather shallow upper mantle depths as indicated by the common spatial association of HP/LT blocks with serpentinized peridotites—never with deep-seated xenoliths of continental crust. The arc-derived Mariposa-Galice volcanogenic strata predate formation of the Great Valley Group forearc and subparallel Franciscan trench depositional realms (Ernst 2011).Similar to the disaggregated fragments of transported oceanic lithosphere and capping deep-sea chert, the relatively old HP/LT tectonic blocks (e.g., Anczkiewicz et al. 2004) represent exotic additions to the Franciscan trench.

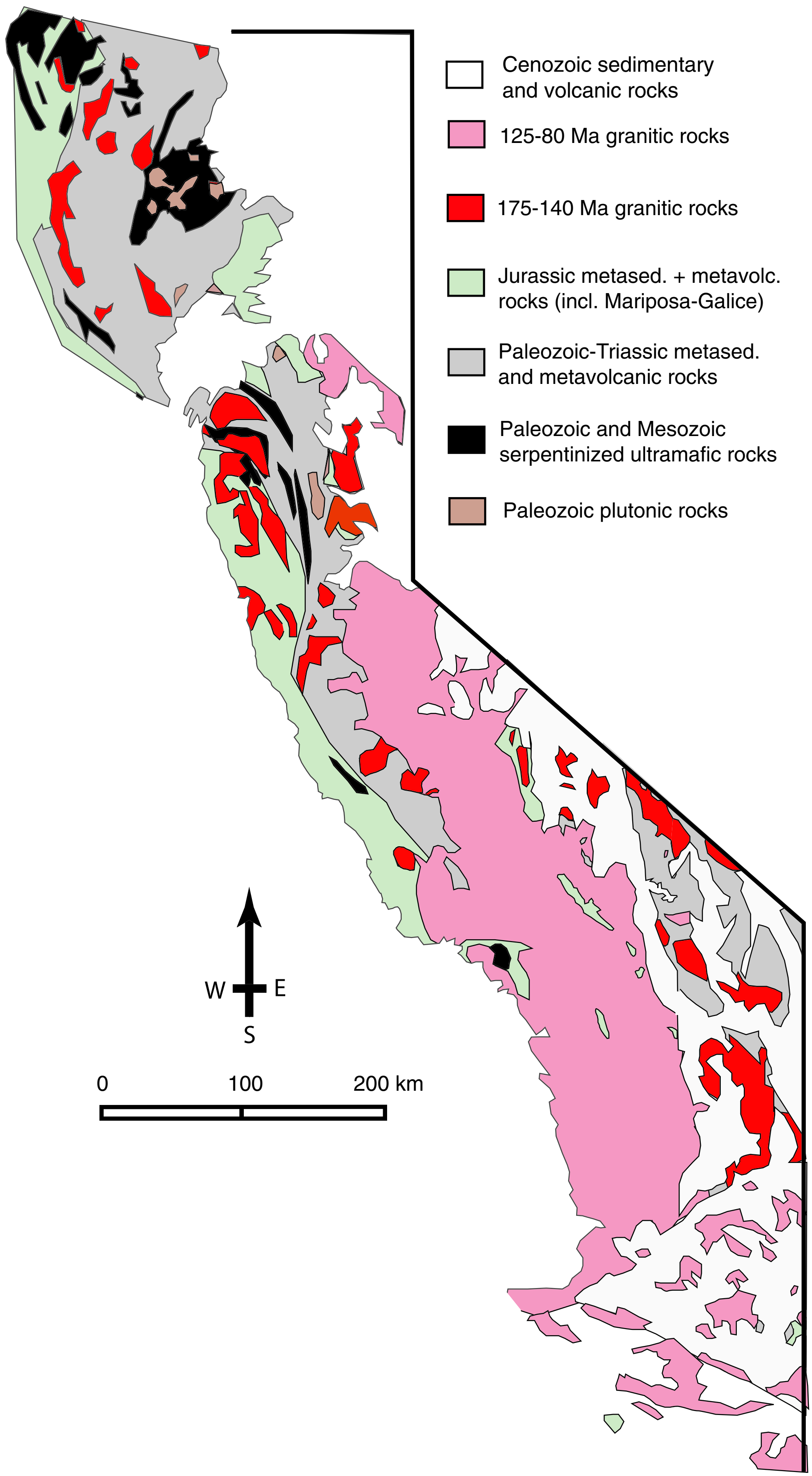
1.2 Formation of the Klamath Mountains salient

Paleozoic, fault-bounded Klamath Mountain units on the east are structurally high in the accretionary stack, whereas the formational ages of successively added lower allochthons decrease progressively toward the west (Irwin 1972, 1994). The tectonized, imbricate collage of west-vergent lithostratigraphic terranes consists of basal ophiolitic units, chiefly overlain by cherts and fine-grained terrigenous strata (e.g., Frost et al. 2006), all invaded by Jurassic calc-alkaline arc plutons. The accreted terrane assembly of the Klamath Mountains has long been correlated with the northern Sierran Foothills based on similar rock types, structures, ages of the rock packages, the progressive oceanward assembly of successively younger geologic units, and their times of deformation (Davis 1969; Davis et al. 1980; Wright and Fahan 1988; Wright and Wyld 1994; Irwin 2003). However, the accreted Sierran Foothill terranes stand nearly vertically, whereas the Klamath thrust sheets root gently to the east.

Fig. 3 Palinspastically restored Sierra Nevada-Klamath volcanic-plutonic arc prior to hypothesized differentialslip, including 20° clockwise rotation of the Klamath salient back to a contiguous Jurassic arc configuration. Underflow of a segmented Farallon plate beneath the North American margin at ~140-136 Ma was proposed (Ernst 2012) to account for the present outboard location of the Klamath Mountains relative to both the Sierra Nevada on the SE and the Blue Mountains on the NE (Snoke and Barnes 2006, Fig. 1). The Cretaceous batholith belt trends NNW compared to the NW-trending Jurassic Andean arc ▶

Figure 1 shows that the Klamath Mountains concave-to-the-east contractional assembly now lies well outboard of the trend of the Sierra Nevada Range. This salient appears to be situated ~100–150 km west of the formerly contiguous Sierran segment of the curvilinear arc. North of the Klamath promontory, a major eastward jog toward apparently correlative lithologic units in the Blue Mountains (LaMaskin 2011; LaMaskin et al. 2011; Schwartz et al. 2011) suggests the possibility of a greater oceanward offset of the Klamath Mountains relative to the late Mesozoic accretionary continental margin of eastern Oregon (Snoke and Barnes 2006). The manner in which this tectonic offset of the Klamath Mountains collage was accomplished remains obscure. However that may be, Fig. 3 provides a geologic restoration of what probably was an original, pre-Cretaceous, continuous arc in northern California.

At the end-of-Jurassic time, the Klamath accretionary terrane assembly was deformed and displaced ~100–150 km westward relative to the Andean arc, gradually removing the accretionary stack of Klamath allochthons from a site over the deep-seated magmagenic zone stoking the Sierra Nevada igneous belt (Ernst 2012). Abundant granitic plutons intruded the Klamath Mountains during 170-140 Ma (Hacker et al. 1995; Irwin and Wooden 1999; Irwin 2003; Snoke and Barnes 2006), with emplacement ages generally younging eastward. This igneous activity in the Klamaths ceased at the beginning of Cretaceous time. The youngest such body is the apparently ~136 Ma Shasta Bally pluton (Lanphere et al. 1968; Lanphere and Jones 1978; Irwin and Wooden 1999). However, this date may represent the time of cooling and


Cenozoic sedimentary and volcanic rocks
125-80 Ma granitic rocks
175-140 Ma granitic rocks
Jurassic metased. + metavolc. rocks (incl. Mariposa-Galice)
Paleozoic-Triassic metased. and metavolcanic rocks
Paleozoic and Mesozoic serpentinized ultramafic rocks
Paleozoic plutonic rocks
W
E
S
0
100
200 km

annealing of the pluton rather than the time of its emplacement. Geologic mapping by Blake et al. (1999) documented Hauterivian GVG strata resting with angular unconformity on exhumed, eroded Shasta Bally rocks, supporting a Valanginian or older age for the intrusive (SB locates the plutonon Fig. 1). Thus, prior to offset of the Klamath Mountains, a continuous Klamath-Sierra Nevada volcanic-plutonic arc was sited above the mantle hearth supplying melt to the crustal superstructure (Fig. 3).

The hypothesized westward step-out of the convergent plate junction at ~140 Mare positioned the trench directly offshore from the Klamath orogen. To the south, the new suture trapped pre-existing, far-traveled oceanic crust-capped lithosphere on the landward side as the ~175-165 Ma Coast Range Ophiolite ± overlying tuffaceous and distal oceanic strata (Shervais et al. 2005; Hopson et al. 2008). Slab rollback involving coeval suprasubduction-zone generation of the CRO would have produced an ophiolitic basement younger than the rifted apron of terrigenous sediments. Because this mafic crust is actually ~25 Myr older than the basal GVG sediments (e.g., Stern 2004; Stern et al. 2012; Shervais and Choi 2012), the postulated plate-junction step-out stranding pre-existing oceanic lithosphere appears to more fully accounts for the geologic relationships than would a gradual slab rollback.

1.3 Cretaceous crustal growth

At ~140 Ma, volcanic-plutonic detritus from the Klamath-Sierran arc started to accumulate on mafic basement within the Great Valley depositional basin, whereas clastic debris carried past the forearc came to rest on the descending Farallon oceanic plate as the outboard Franciscan deep-sea trench fill. Because the lowermost Cretaceous, relatively continuous GVG strata were laid down on the stable North American plate, protected from both surface erosion and subcrustal tectonic removal, inauguration of this forearc proximal-to-distal terrigineous sedimentation also signaled the onset of coeval deposition in the yet more distal, coeval Franciscan Complex, ~25–30 Myr after Middle Jurassic initiation of the Andean arc (Dumitru et al. 2010; Ernst 2011). Voluminous sedimentation and accretion of Franciscan and GVG rocks took place during the 125-80 Ma flare-up of the Sierran arc (Surpless et al. 2006; Snow et al. 2010; Dumitru et al. 2010; Sharman et al. in press). The youngest Sierran granites are ~80 Ma, reflecting Late Cretaceous quenching of the magmagenic zone beneath northern California. The end of continental margin arc activity generally has been ascribed to a lessening of the subduction dip and relatively shallow, subhorizontal oceanic plate underflow attending Laramide orogeny well to the east (Coney and Reynolds 1977; Dickinson and Snyder 1978; Bird 1988).

1.4 Paleogene-early Miocene crustal growth

Strongly deformed, weakly metamorphosed Paleogene-lower Miocene Franciscan Coastal Belt rocks (McLaughlin et al. 2000; Dumitru et al. 2013), still sourced in part from the now-inactive Sierranarc, contain significant amounts of quartzofeldspathic debris derived from yet more northerly arc terranes (Dumitru et al. 2013, in press). These Coastal Belt strata exhibit the effects exclusively low-pressure recrystallization (Bachman 1978; Underwood et al. 1987; Terabayashi and Maruyama 1998; Ernst and McLaughlin 2012). Reflecting near-surface accretionary offloading, such units apparently were never deeply subducted. Although important members of the Franciscan lithotectonic assemblage, the low-P transformation of Coastal Belt strata stand in marked contrast to much of the rest of the Franciscan Complex. Underplating of younger sections beneath older slabs of the Franciscan undoubtedly aided the buoyant ascent and erosional decapitation of the latter, so the farthest inboard sections have been exhumed to the greatest extent. It is thus possible that HP/LT tracts of the Coastal Belt currently are stored deep within the imbricate accretionary prism.

2 Late Jurassic time

2.1 Mariposa Formation clastic sedimentation

Snow and Ernst (2008) analyzed zircons from five volcanogenic metaturbidite layers from the upper part of the Mariposa Formation of the western Sierran Foothills using SIMS methods. Mesozoic U–Pb age populations are dominated by zircons exhibiting a broad unimodal distribution from ~175-155 Ma. The aggregate zircon U–Pb ages for these metasandstones suggest that the zircons were derived mainly from the Jurassic Klamath-Sierran orogenic belt, especially the mid-Paleozoic to mid-Mesozoic terrane collage, and the spatially associated younger Andean-type arc volcanic rocks + granitoids. This interpretation is compatible with Mariposa paleocurrent data indicating an overall southerly transport direction (Bogen 1985). Accumulation began at ~165-160 Ma and continued until at least 150 Ma (Ernst et al. 2009a). Indistinct age culminations at 1,000–1,200, 1,600–1,800, and ≥2,500 Ma (Snow and Ernst 2008) suggest minor derivation of the studied Oxfordian and younger Mariposa sandstones from Grenville, Mazatzal-Yavapai and older SW North American cratonal rocks, and/or younger, multicycle clastic strata sourced from these basement terranes.

2.2 Galice Formation clastic sedimentation

The turbiditic Galice Formation is the NW continuation of Mariposa-type volcanogenic lithologies in the western Klamath Mountains (Gray 2006; MacDonald et al. 2006). Miller and Saleeby (1995) reported a 153 Ma depositional age for the upper Galice, but sedimentation may have begun during or before earliest Oxfordian time based on biostratigraphic data summarized by Saleeby and Harper (1993). This is supported by the local interdigitation of Galice metaturbidites with pillow lavas of the subjacent 164-162 Ma Josephine ophiolite (Harper 2006; MacDonald et al. 2006). Like the Mariposa Formation, the provenance of Galice sandstones evidently was a combination of both ancient SW North American basement rocks and mid-Paleozoic to mid-Mesozoic oceanic ophiolite + chert-argillite complexes, and the younger, nearly coeval Andean arc (Snoke 1977; Frost et al. 2006).

2.3 Myrtle Formation clastic sedimentation

Scattered erosional remnants of uppermost Jurassic to early Lower Cretaceous Myrtle detrital strata rest on the Galice Formation in SW Oregon (Imlay et al. 1959; Dickinson 2008, Fig. 3a). By analogy with the underlying Galice, Myrtle detritus plausibly was derived from both the landward Klamath-Sierran arc ± minor old SW North American continental basement sources.

3 Earliest Cretaceous time

3.1 Pacificward relative displacement of the Klamath Mountains salient

Figure 4a shows that the Klamath Mountains stack of allochthons currently is located well outboard of the trend of the Sierra Nevada Range of northern California, as well as the Blue Mountains of SE Oregon. Palinspastic reconstruction combined with clockwise rotation of 20° of the Klamath salient as shown in Fig. 4b, would restore the complex to the end-of-Jurassic, presumably curvilinear Andean margin. Such a back-rotation also would help minimize the seemingly larger offset separating the Klamaths from the Blue Mountains. However, this simplified restoration does not address the arcuate bulge (i.e., eastward concavity) which likely reflects ~50–100 km of additional strain induced by differential slip of the Klamath Mountains salient relative to the adjacent segments of the once-continuous volcanic-plutonic arc.

Just how relative displacement of the Klamath tectonostratigraphic belts took place remains obscure, but constraints provided by the sedimentary section suggest a mainly earliest Cretaceous (~140-136 Ma) westward offset and minor counterclockwise rotation of the salient relative to the Sierran Foothills (Ernst 2012). Upper Jurassic Galice-Mariposa, and uppermost Jurassic-lowermost Cretaceous Myrtle strata rest unconformably on the western flanks of the Klamath Mountains and Sierran Foothills segments of the emergent Andean arc whereas, as pointed out below, post-140 Ma Great Valley + Hornbrook clastic units lie outboard of the Sierran arc but inboard of the Klamath salient. Whether the Klamath Mountains moved westward, or the Sierra Nevada + Blue Mountains moved eastward, or both tracts were displaced, is unclear. Here, only the differential slip and its timing are considered.

Geologic relationships among units of the Klamath Mountains province, the Franciscan Complex, and the GVG in the vicinity of the Yolla Bolly triple junction (Jones and Irwin 1971; Sliter et al. 1984; Blake et al. 1999) include several important fault systems. In addition to the major terrane bounding, NW-trending South Fork and Coast Range faults, Blake et al. (1999) mapped numerous transverse breaks transecting GVG stratigraphic units in this area. Significant faults include, from north to south, the Oak Flat, Sulphur Spring, Cold Fork, and Elder Creek structures. The Oak Flat-Sulphur Spring fault zone strikes ENE and is properly oriented to accommodate the conjectured earliest Cretaceous sinistral slip in northern California, although the offset is only ~80–100 km. To the south, Wright and Wyld (2007) interpreted the NW-trending Cold Fork-Elder Creek fault zone as an important discontinuity defining several hundred kms of dextral slip. Judging by geologic field relations documented by Blake et al. (1999), the Cold Fork-Elder Creek fault zone and subparallel structures truncate the Oak Flat-Sulphur Spring faults. Thus, oceanward relative displacement of the Klamath Mountains salient along the Oak Flat-Sulphur Spring fault zone apparently was mainly completed in Valanginian-Hauterivian time, prior to the right-lateral motion described by Wright and Wyld—which therefore represents Barremian and younger offset. Thicknesses of the Lower Cretaceous GVG units in the Yolla Bolly triple junction area monotonically increase northward, so these breaks underwent at least some slip to as late as ~125 Ma (Constenius et al. 2000; Wright and Wyld 2007).

Perhaps due to the complex sequence of strike-slip and subduction-exhumation compound motions that occurred in the vicinity of the Yolla Bolly triple junction, the published aeromagnetic anomaly map of this area (Roberts and Jachens 1999, Fig. 2) fails to show clear paleomagnetic evidence supporting a major discontinuity that could be linked to a postulated deep-seated sinistral offset along the Oak Flat-Sulphur Spring zone.

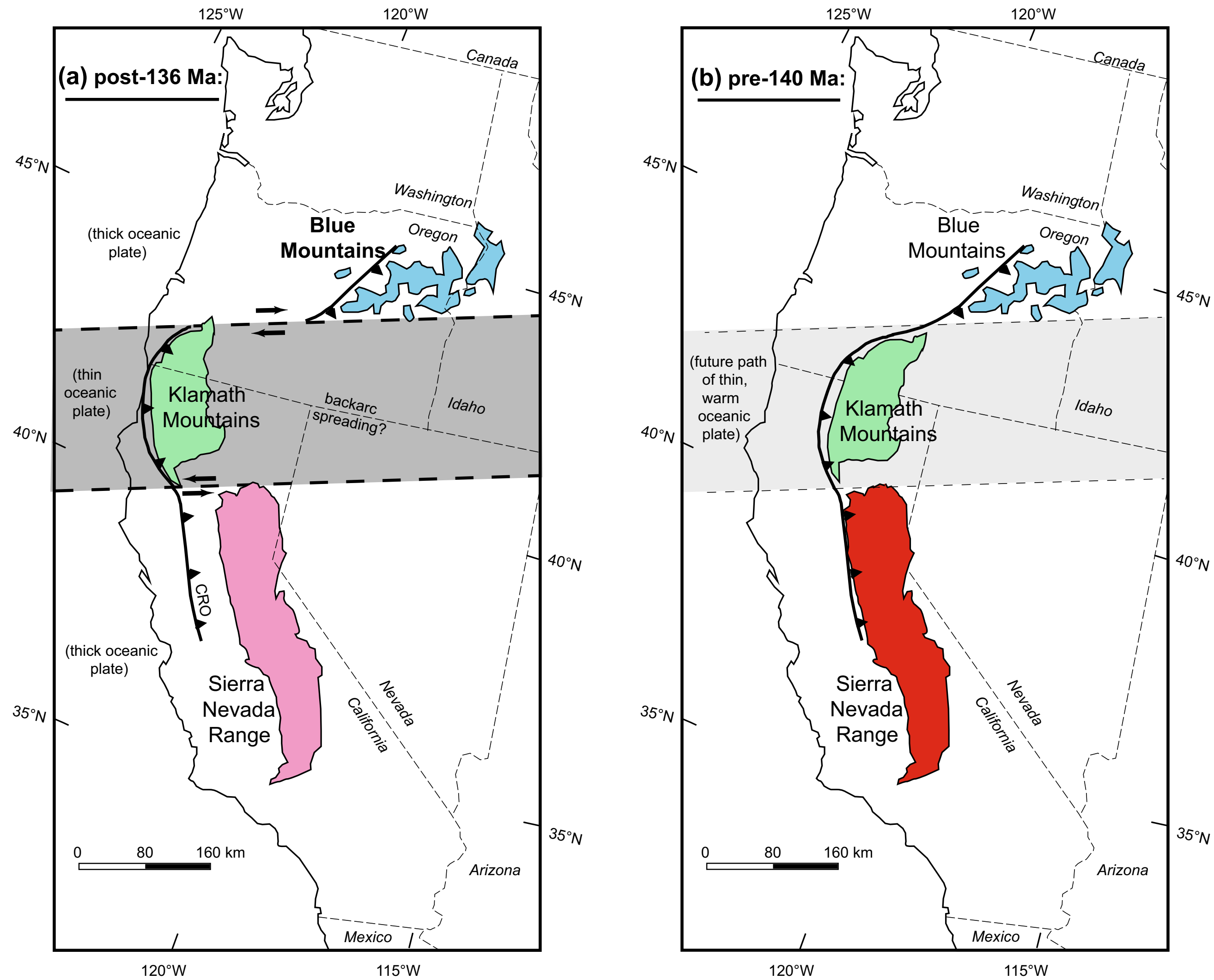


Fig. 4 Diagrammatic sketch of the hypothesized underflow at ~140-136 Ma of a segmented Farallon plate beneath the North American margin (Ernst 2012). **a** At the beginning of Cretaceous time, a thin, warm slab of oceanic lithosphere slidbeneath the Klamath Mountains, largely decoupled from the overlying section of gently east-dipping CCW-rotating crustal allochthons. Thicker, older Farallon plate segments on both north and south were strongly coupled to the continental margin, resulting in contraction and deformation of the accreted collages into relatively steeply dipping sections. *Arrows* show direction of relative crustal slip ± possible backarc extension. Bounding transforms of the Farallon oceanic lithosphere have subparallel, ENE trends constrained by fault offsets in the pre-existing curvilinear arc. **b** Inferred palinspastically restored original Sierran-Klamath-Blue Mountains arc prior to the end-of-Jurassic offset, including 20° clockwise rotation of the Klamath salient (such CW rotation reduces the apparent offset between the Klamaths and the Blue Mountains). No attempt has been made to undo the accumulated strain caused by frictional drag during the postulated slip that produced the westward arcuate bulge of the salient

3.2 Hypothesized Klamath salient displacement mechanism

The Early Cretaceous Farallon lithospheric plate evidently approached the western edge of California in a largely convergent but dextral transpressive fashion (Engebretson et al. 1984; May and Butler 1986; Schettino and Scotese 2005; Sager 2007; Doubrovine and Tarduno 2008). It appears to have fragmented into several smaller east-dipping plate segments (Wang et al. 2013). Plate-tectonic models accounting for the structure and offset of the Klamath Mountains relative to the Andean arc require impingence of far-traveled oceanic plate transporting, for example: (a) a mantle plume; (b) a spreading ridge; (c) a thermal high generating backarc extension; (d) a microcontinent or island arc; or (e) an oceanic plateau. After consideration and rejection of this diverse set of geologic models, Ernst (2012) instead proposed a different scenario: (f) two subparallel transform faults bounding a thin, relatively warm oceanic slab.

Shown schematically in Fig. 4, this model postulates the underflow of a relatively young slab of the Farallon plate beneath the Klamath Mountains beginning at ~140 Ma. The warm, plastically deformable platelet, bordered on both north and south across hypothesized ENE-trending transform faults by old, cold, much thicker, stiffer oceanic lithosphere, would have been largely decoupled from the Klamath stack of gently east-rooting crustal allochthons. Collision of thick oceanic lithosphere on both north and south could have been responsible for contraction and eastward displacement of the North American continental marginal relative to the Klamath Mountains, which would thus assume its salient configuration. Moreover, shortening in the Sierran arc might have caused rotation of the Foothills terrane collage to the present stack of near-vertical imbricate sheets. Whatever the origin of outboard relative displacement of the Klamath Mountains at ~140-136 Ma relative to the Sierra Nevada Range and the Blue Mountains, it seems likely that segmented eastward underflow responsible for the architecture that developed in the crust of northern California was sited in the end-of-Jurassic to earliest Cretaceous upper mantle lithosphere and subjacent, flowing asthenosphere.

4 Early Cretaceous-Miocene

4.1 Great Valley Group clastic sedimentation

West of the Cretaceous Sierran arc, the slightly to somewhat younger Great Valley Group clastic strata exhibit a largely Sierran-Klamath provenance based on sedimentary petrofacies analysis (Ingersoll 1978, 1979, 1983; Linn et al. 1992). The well-developed GVG forearc, laid down on the Coast Range Ophiolite and the inboard edge of the Klamath province, began receiving detritus by Valanginian time. Except for far-traveled basal sandstones that contain distinctive CRO debris ± a cap of very-fine-grained deep-sea turbidites of Tithonian age, the younger quartzofeldspathic section was derived chiefly from the Middle Jurassic to Late Cretaceous igneous arc. Abundant volcanic clasts typify many of the lower GVG beds, whereas in general, Upper Cretaceous strata are richer in plutonic quartz and alkali feldspars (Dickinson and Rich 1972; Dickinson et al. 1982; Surpless in press). The largest volume of Great Valley sedimentary strata formed during Late Cretaceous time, especially in the San Joaquin section (Mansfield 1979; Moxon 1990). GVG sandstones include widespread but small numbers of zircon grains, typified by igneous U–Pb ages mostly in the ~175-140 and 120-60 Ma ranges (DeGraaff-Surpless et al. 2002; Surpless et al. 2006; Wright and Wyld 2007; Sharman et al. in press). Minor concentrations of Early Cretaceous magmatic zircons in the basal clastic sediments suggest that shallow intrusives and the more voluminous Jurassic extrusive arc units in the Sierra Nevada-Klamath belt supplied debris to the initial forearc. Great Valley Group deposition evidently began at ~140 Ma, with detritus largely derived from the inboard igneous arc. Because the Sierran magmatism died by ~80 Ma, some of the youngest GVG igneous zircons probably had a more northerly source.

A few pre-Mesozoic, multicycle grains were reported from basal GVG sandstones by DeGraaff-Surpless et al. (2002) and Wright and Wyld (2007). These zircon ages provide Precambrian peaks at 1,000–1,200, 1,400, 1,800–2,000, and 2,600 Ma, suggesting that minor ultimate sources including the Grenville, Mazatzal-Yavapai, and Wyoming or Superior provinces.

4.2 Hornbrook Formation clastic sedimentation

The mid- and Upper Cretaceous Hornbrook Formation, correlative with the far more voluminous Great Valley Group, rests with angular unconformity on the landward margin of the Klamath Mountains near the California-Oregon border (Sliter et al. 1984; Nilsen 1993; Surpless and Beverly 2013). Like the GVG strata of northern California, the Albian and younger Hornbrook Formation rests on the eastern edge of the province, so clearly accumulated after seaward relative displacement of the Klamath promontory. Detrital zircon U–Pb spectra indicate that clastic materials were supplied chiefly by the nearby Sierran and Klamath volcanic-plutonic arcs ± possible igneous sources in the Pacific Northwest, with only minor contributions from recycled debris originally sourced in Grenville, Proterozoic and latest Archean basement (Surpless and Beverley 2013).

4.3 Franciscan Complex clastic sedimentation

Three major, fault-bounded tectonic belts of the Franciscan Complex, consisting dominantly of clastic sedimentary strata, crop out in northern California—the Eastern, Central mélange, and Coastal belts (Bailey et al. 1964; Blake et al. 1988; Jayko et al. 1989; McLaughlin et al. 1994, 2000). The Eastern Belt comprises two principal lithotectonic units, the Pickett Peak and structurally lower Yolla Bolly terranes, whereas the Coastal Belt contains three major entities, the inboard, structurally higher Yager, medial Coastal, and outboard, structurally lower King Range terranes (Blake et al. 1988). Although tectonic and olistostromal mélanges characterize the Central Belt, mélanges also are present in all three Franciscan belts (Cowan 1978; Raymond 1984, in press; Aalto 2014). Rocks of these three accretionary belt assemblies apparently were deposited on far-traveled oceanic crust as it neared the continental margin (Ernst 1965, 2011). Petrofacies analyses of graywacke-shale and rare conglomeratic units of the Central and Eastern belts indicate derivation chiefly from the northern Californian Andean arc (Dickinson et al. 1982; Seiders 1983), similar to clastic strata of the directly inboard GVG. Terranes of the Coastal Belt contain similarly sourced debris but also include clasts derived in part from the Pacific Northwest (see below).

Most detrital zircons separated from Eastern Belt sandstones possess Jurassic igneous SIMS U–Pb ages of ~180-160 Ma (Dumitru et al. 2010), but a fewigneous zircon grains occupy the ~120-80 Ma age range (Joesten et al. 2004; Tripathy et al. 2005; Unruh et al. 2007). The oldest Franciscan clastic unit is the Skaggs Spring Schist (Wakabayashi and Dumitru 2007; Snow et al. 2010), so deposition of the Franciscan apparently began at ~140 Ma. Prior to recent work, Late Jurassic-Early Cretaceous age assignments for the Eastern and Central belt strat a relied on the presence of the bivalve, *Buchia*, but these occurrences probably reflect redeposited macrofossils, as documented by Dumitru (2012). The source of such transported specimensmight have included Upper Jurassic proximal facies rocks of the Mariposa-Galice overlap sequence. In any case, most of the Eastern Belt Yolla Bolly quartzofeldspathic units accumulated during the mid- and Late Cretaceous (120-80 Ma; Ernst et al. 2009b; Dumitru et al. 2010), and were exhumed and exposed shortly thereafter (Mitchell et al. 2010). Sited in progressively more seaward positions, the Central and Coastal belts, for which zircon U–Pb age data have now become available (Dumitru et al. 2013, in press), have Late Cretaceous (~90-60 Ma) and Tertiary (65-20 Ma) maximum depositional ages, respectively. The presence of young igneous zircons in clastic rocks of the Coastal Belt indicate progressive sedimentary supply to the Yager, Coastal, and King Range terranes of detrital zircons derived from the Idaho Batholith, Challis volcanic pile, and Cascade arc.

In addition to post-Paleozoic arc sources, analyzed zircons from Franciscan rocks exhibit small Precambrian age peaks as follows. Pickett Peak terrane: 1,000, 1,400-1,600, 1,800, and 2,200 Ma (Dumitru et al. 2010). Yolla Bolly terrane: Pacheco Pass (Ernst et al. 2009b) 1,350, 1,800, 2,600–2,900 Ma; San Francisco Bay area (Snow et al. 2010) 1,500–1,700, 2,000, 2,500 Ma; NW Coast Ranges (Dumitru et al. in press) 1,300–1,400, 1,800, > 2,500 Ma. Except for a few Grenvillian zircons in analyzed Eastern Belt Skaggs Spring-Pickett Peak metasandstones, these age data suggest ultimate derivation of the more voluminous Yolla Bolly strata in part from the Mazatzal-Yavapai and Wyoming or Superior basement provinces. Central Belt strata include zircon ages of 1,300–1,400, 1,600–1,750 Ma, indicating minor Mazatzal-Yavapai Middle Proterozoic sources, but lacking Late Archean provenance; Coastal Belt zircons yield Precambrian ages peaking at 1300-1400 Ma, suggesting an orogenic granite sources from the Mazatzal-Yavapai realm. Thus, except for the ~140 Ma Skaggs Spring and slightly younger Pickett Peak metagraywackes, Franciscan clastic rocks lackzircon grains of Grenvillian affinity.

5 HP/LT recrystallization of the Franciscan Complex

Franciscan Eastern and Central belt sandstones display pervasive effects of HP/LT subduction-zone metamorphism, as widely documented in the Cretaceous Franciscan sections of northern California (Cloos 1982, 1986; Blake et al. 1988; Jayko and Blake 1989; Jayko et al. 1989; Wakabayashi and Dumitru 2007). In contrast, presently exposed clastic units of the chiefly Tertiary Coastal Belt only show the effects of feeble, low-T, low-P recrystallization (Bachman 1978; Underwood et al. 1987; Blake et al. 1988; Dumitru 1989; Tagami and Dumitru 1996; Ernst and McLaughlin 2012). Deeply buried Lower Cretaceous strata of the Great Valley Group and the moderately recrystallized volcanogenic Mariposa-Galice units exhibit neoblastic mineral parageneses similar to those typifying Franciscan Coastal Belt rocks (Dickinson and Rich 1972; Gray 2006; Snow and Scherer 2006). However, the Mariposa-Galice units show strong grain flattening and platy metamorphic cleavage, unlike weakly metamorphosed strata of the Coastal Belt.

Prograde phase relations and schematic physical conditions for Franciscan Eastern, Central, and Coastal belt rocks, and essentially also for the GVG, Mariposa and Galice formations, are illustrated in Fig. 5. The metasedimentary rocks of the Franciscan Eastern coherent and Central mélange belts display prograde HP/LT geothermal gradient paths of 100–300 °C 5–8 kbar as typically followed by units subjected to subduction-zone P–T conditions, whereas in contrast, other sandstone sections summarized in this review simply appear to show the effects of diagenesis common in rocks involved in low-P burial. Because subduction-zone refrigeration continued during the episodic return toward the surface of Eastern and Central belt Franciscan sections, their retrograde (i.e., decompression) P–T trajectories more-or-less followed their prograde paths in reverse, but at slightly lower pressures for a given T.

In addition to the in situ post-Jurassic, dominantly metasedimentary Franciscan section, lenses of much higher grade eclogite and garnet glaucophane schist are present as rare, but mineralogically spectacular phase assemblages. These high-grade blocks of mid- to Late Jurassic metamorphic age are relatively well studied (Coleman and Lanphere 1971; Wakabayashi 1992; Anczkiewicz et al. 2004; Wakabayashi and Dumitru 2007; Ukar et al. 2012).

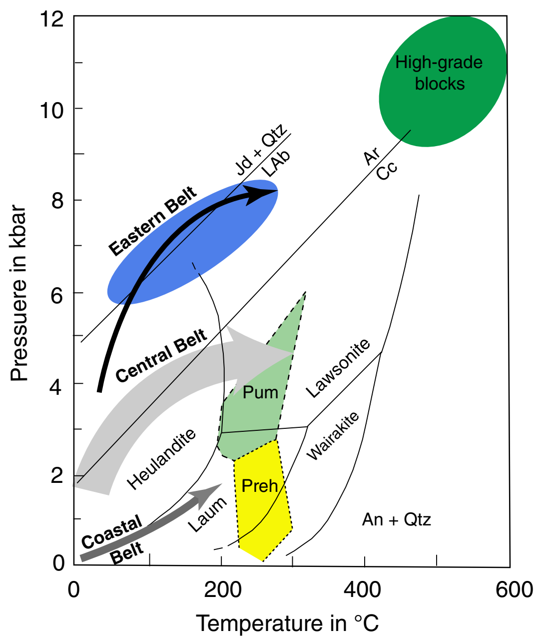


Fig. 5 Phase diagram for northern California Franciscan metagraywacke compositions, partly after Terabayashi and Maruyama (1998, Fig. 7). P_{fluid} is assumed equal to lithostatic pressure. Stability fields for heulandite, laumontite (Laum), lawsonite and wairakite are from Liou (1971), the calcite-aragonite (Cc-Ar) transition is from Carlson (1983) and the low albite-jadeite + quartz phase boundary (LAb-Jd + Qtz) is from Newton and Smith (1967). Also shown are the Frey et al. (1991) computed P–T stability fields for prehnite (Preh) and pumpellyite (Pum) in metabasaltic rocks (Liou et al. 1983). An = anorthite. Prograde metamorphic P–T paths for the Franciscan belts are from Ernst (1993) and Ernst and McLaughlin (2012), extended to include P–T conditions attending recrystallization of the high-grade metabasaltic blocks. Retrograde P–T paths are not shown. Deeply buried GVG strata and weakly transformed Mariposa-Galice units have new phase assemblages comparable to those of the Franciscan Coastal Belt

Initially solidified as Farallon oceanic crust far from the North American margin, these rocks recrystallized in a relatively young, warm oceanic-continental convergence zone along an unrefrigerated, relatively warm mantle hanging wall, as reflected by HP/LT mineral parageneses indicating counterclockwise decompression P–T-time trajectories (Cloos 1982, 1986; Wakabayashi 1990, 1999; Saha et al. 2005; Page et al. 2007; Ukar and Cloos 2014). Most high-grade tectonic blocks were transformed at ~10–12 kbar, and ~400–600 °C (Fig. 5), but some evidently formed at even higher P–T ranges (e.g., Krogh et al. 1994; Tsujimori et al. 2006).

In contrast to their relatively well-understood petrogenesis, field occurrences of these high-grade metamafic blocks are problematic, reflecting an obscure geologic context. Most such coarse-grained, penetratively deformed rocks rest on the Earth's surface with no apparent genetic relationship to the regionally extensive, distinctly lower metamorphic grade Franciscan lithologies. In some cases, the bedrock consist of serpentinite, more commonly of mud-matrix mélange, or a mixture of pelitic and serpentinitic matrix materials. How the high-grade metamafic blocks and spatially associated Franciscan, chiefly metasedimentary section were exhumed is a matter yet debated (e.g., Ernst 1971; Platt 1986, 1993; Ring and Brandon 2008). Some HP metabasalts exhibit nearly complete rinds of actinolite ± chlorite ± talc that are slightly younger than the high-grade blocks (Moore 1984; Catlos and Sorensen 2003; Ukar 2012; Ukar et al. 2012). In the rare cases where Jurassic metamafic blocks are clearly enveloped in surrounding fine-grained mud-matrix or serpentinite bodies, the latter are substantially younger (e.g., mid- to Late Cretaceous). Detailed histories of the exotic HP/LT blocks provide additional constraints on the Jurassic-Cretaceous convergent margin evolution of northern California and development of the accretionary Franciscan Complex during a period typified by oblique-to-orthogonal plate convergence (Ernst 2011).

6 Clastic strata of northern California: ages and provenance

A relatively continuous record of mid-Jurassic through early Miocene sedimentation is preserved in the sandstones cropping out in northern California. Approximate maximum depositional age spans of these units, largely constrained by detrital zircon U–Pb data, are: North Fork + Eastern Hayfork, 175-165 Ma; Mariposa + Galice, 165-150 Ma; Myrtle, 150-140 Ma; Great Valley Group ± Hornbrook, 140-60 Ma; Franciscan Eastern Belt, ~140-80 Ma; Central Belt mélange, ~90-60 Ma; Coastal Belt, 65-20 Ma. Except for GVG and Hornbrook strata situated directly inboard from the Klamath Mountains salient, maximum depositional ages of these tectonostratigraphic units systematically decrease seaward.

Detrital zircons separated from the studied rocks were sourced dominantly from pre-existing igneous rocks, chiefly Mesozoic granitoids and their comagmatic volcanic equivalents. Generalized temporal relationships between these primary igneous sources and derived sedimentary products considered here are shown on Fig. 6. Precambrian zircon grains are rare, but of those present, most are well rounded, and undoubtedly underwent multiple cycles of erosion, transportation, and deposition. Prior to deposition in their present host rock, most probably last resided in Paleozoic clastic strata derived from the Precambrian basement. Interpreted ultimate source terranes for the described detrital units, illustrated in the map of Fig. 7, are as follows: Mariposa-Galice ± Myrtle = Sierran-Klamath arc, Grenville, Mazatzal-Yavapai, and older SW North American cratons; basal Great Valley Group and Franciscan Skaggs Spring Schist-Pickett Peak terrane = Sierran-Klamath arc,

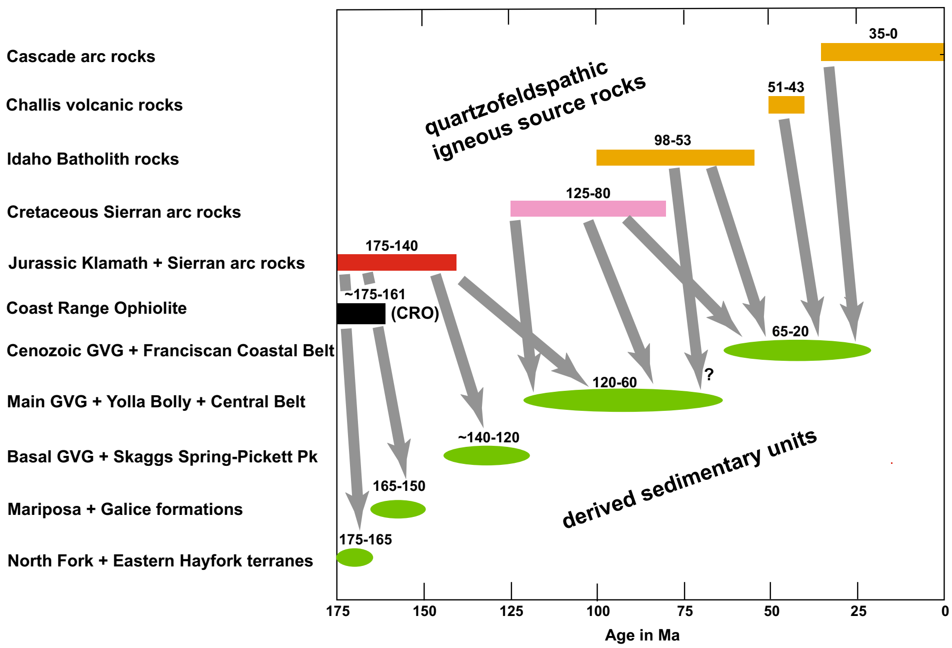


Fig. 6 Schematic diagram of mid-Mesozoic and younger California-Pacific Northwest igneous arcs inferred to have provided much of the quartzofeldspathic debris to the sandstones treated here. Ages of volcanic-plutonic generation, the CRO, and largely arc-derived clastic sedimentary strata are summarized from Irwin (2003), Shervais et al. (2005), Wakabayashi and Dumitru (2007), Hopson et al. (2008), Scherer and Ernst (2008), Snow and Ernst (2008), Snow et al. (2010), Ernst et al. (2009a, b, 2010), and Dumitru et al. (2010, 2013, in press). Zircon U–Pb age data are not available for the uppermost Jurassic to lowermost Cretaceous Myrtle clastic strata, but on this diagram it would lie stratigraphically above the Mariposa-Galice formations, and below-to-coincident with the basal GVG

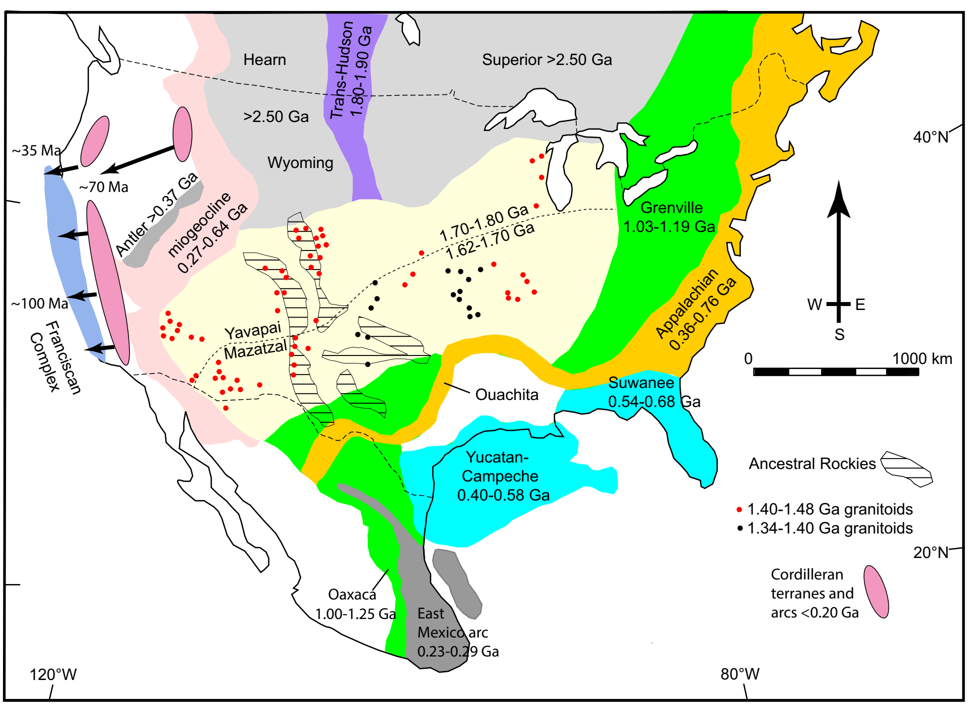


Fig. 7 Basement map of some North American geologic provinces and their ages of formation, after Dickinson and Gehrels (2009, Fig. 1) and Gehrels et al. (2011, Fig. 7). Heavy black arrows show inferred westward transport directions of erosional debris shed from Cordilleran volcanic-plutonic arcs during the ~140-25 Ma accumulation of the Franciscan Complex. Detrital zircon ages suggest possible NW drift of the trench fill as sedimentation-accretion continued and new volcanic-plutonic arcs lit up on the north. A progressive increase over time in the arrival of detritus from younger NW igneous arcs could equally well explain the changing source patterns recorded in native (i.e., non-drifting) Franciscan terranes

Grenville, Mazatzal-Yavapai, and late Archean basement; main GVG ± Hornbrook = Sierran-Klamath arc, Idaho Batholith, minor Grenvillian, Mazatzal-Yavapai, and Wyoming or Superior cratonal sources; Franciscan Yolla Bolly terrane = Sierran-Klamath arc, Mazatzal-Yavapai and Wyoming or Superior basement; Franciscan Central Belt mélange = Sierran arc ± Idaho Batholith, Mazatzal-Yavapai basement; Franciscan Coastal Belt = Sierran arc, Idaho Batholith, Challis-Cascade volcanic units.

7 Mid-Jurassic-early Tertiary evolution of northern California

The new detrital zircon U–Pb data summarized here support previous radiometric, geologic, structural, and paleontologic studies on a broad range of post-Paleozoic sandstones, further documenting the crustal growth of northern California. Middle and Upper Jurassic clastic strata draped over the western flanks of the Klamath + -Sierra Nevada orogenic belts, the Cretaceous GVG lying along the westernmost margin of the Sierra Nevada but along the eastern edge of the Klamath Mountains, and the yet farther outboard Tertiary sedimentary sections all attest to a gradual seaward growth of the continent. The Mariposa-Galice ± Myrtle formations define the Pacific margin of sialic crust at 165-150 Ma to possibly as young as ~140 Ma. In northernmost California, Hauterivian Great Valley Group and Albian Hornbrook strata lying inboard from the Klamath Mountains document the time of essential completion of oceanward relative displacement of the salient. To the south, the suture between the basal GVG forearc and the Franciscan trench complex defines the position of the convergent plate junction after ~140 Ma. Varying degrees of convergence regionally lasted into the Miocene. As known from prior work (e.g., Bailey et al. 1964), sedimentary ages of the Franciscan imbricate tectonostratigraphic terranes decrease toward the Pacific Ocean. Maximum times of deposition and nearly coeval tectonic accretion range from Early to Late Cretaceous for the east-rooting Pickett Peak and tectonically underlying, younger Yolla Bolly terrane metagraywackes of the Eastern Belt, through overlapping latest Cretaceous deposition and recrystallization for Central Belt metasandstones interstratified with mud-matrix mélanges, to Paleogene-early Miocene for structurally lower Coastal Belt sandstones.

Jurassic volcanic-plutonic + Cretaceous Sierran Batholith, Late Cretaceous-Paleocene Idaho Batholith, early Eocene Challis volcanics, and Oligo-Miocene Cascade arcs supplied most of the igneous zircons to the clastic strata described here. Although the Middle and Upper Jurassic proximal sequences contain substantial contributions derived from Grenvillian source terranes, 1,000–1,200 Ma zircons appear to be rare in most GVG strata (Surpless in press), and are absent from all but the oldest Franciscan metasedimentary units—i.e., the Skaggs Spring-Pickett Peak terrane. Cretaceous emergence of the growing Sierranvolcanic-plutonic arc may have blocked the outboard regional supply of recycled Grenvillian materials from the continental interior. Overthe course of time, the Franciscan Complex clearly began receiving greater proportions of young igneous arc detritus from more northerly sources. GVG sandstone petrofacies analyses show an analogous south-to-north trend from basement uplift—> dissected arc—> transitional arc—> undissected arc (Ingersoll 2012). Older Franciscan bedrock sources on the SE included the Mazatzal-Yavapai 1,400 Ma anorogenic granites and 1,700–1,800 Ma basement terranes. Grenville and Appalachian igneous zircons are missing from the Franciscan section deposited after ~120 Ma, suggesting the possibility of as much as 1,600 km for progressive, post-depositional NW offset of the trench deposits relative to the Great Valley Group forearc and craton of the SW conterminous U. S. and NE Mexico. Figure 7 shows the hypothetical extent of dextral offset of the Franciscan Complex attending its post-120 Ma accumulation (see also Jayko and Blake 1993).

Other explanations instead may account for the absence of Grenville zircons in Franciscan mid-Cretaceous to lower Miocene clastic sediments. These include: (1) non-erosion of Grenvillian rocks due to cover and/or low elevation; (2) intervening topographic divides diverting the transport of detritus away from the Pacific margin; (3) channeling of arc debris by a few river systems that fluctuated in flow direction over time; (4) sample bias and/or SIMS analytical error. Provenance studies described here for northern California indicate coeval deposition and possible later NW translation of the Franciscan section; ~1,600 km is merely a reasonable value for the conjectured offset. Alternatively, a systematic NW increase in the supply of detritus from progressively younger volcanic-plutonic arcs might have been solely responsible for the changing source patterns recorded in these tectonostratigraphic terranes as igneous belts to the south died whereas others to the north became active.

8 Mid-Jurassic to Miocene northern California geohistory

Before Middle Jurassic time, chiefly ophiolite + chert-argillite terranes arrived at, and were stranded along the continental margin, reflecting dominantly transform ± transpressive plate motions during the mid-Paleozoic to Early Jurassic assembly of northern California (Saleeby 1981, 1982, 1983; Silberling et al. 1987; Ernst et al. 2008). This older oceanic terrane collage was capped by mid-Jurassic and younger sedimentary and volcanic rocks derived from an emergent igneous arc constructed along the continental edge. Middle and Late Jurassic Andean volcanism-plutonism in the Klamath + Sierra Nevada ranges (Dunne et al. 1998; Irwin 2003; Dickinson 2008) reflects an important component of eastward subduction of the Farallon oceanic plate commencing no later than ~175 Ma, and continuing until ~140 Ma. Underflow also resulted in the generation and storage at depth of HP/LT metamafic rocks, now present as tectonic ± olistostromal blocks in mélanges chiefly of the Franciscan Central Belt (Cloos 1982, 1986; Wakabayashi et al. 2010). Middle and Late Jurassic oceanic plate motion probably involved oblique convergence rather than nearly orthogonal subduction (Ernst et al. 2008), because if a major forearc basin and trench had formed during this stage, evidence of this subparallel couplet has since disappeared completely. Alternatively, a substantial component of transform slip or subcrustal erosion (Wright and Wyld 2007; Scholl and von Huene 2007; Stern and Scholl 2010; Dumitru et al. 2010) might removed all but the farthest inboard Mariposa-Galice ± Myrtle overlap strata.

In the Franciscan Complex, the famous 170-155 Ma high-grade metabasaltic eclogites and garnet-blueschists formed during early stages of the underflow that generated the emergent mid- and Late Jurassic Klamath-Sierran arc as well as the derivative Mariposa-Galice proximal sedimentary aprons. The HP/LT mafic tectonic blocksevidently were sequestered at moderate depths, predating onset of the lengthy period of subduction that produced the paired GVG and Franciscan sedimentary belts. In general, intrusion of ~170 Ma granitoid bodies in the western Klamath Mountains and progressive geographic restriction of younger plutons to the more easterly Klamath lithotectonic belts (Hacker et al. 1995; Irwin and Wooden 1999; Irwin 2003) suggest that seaward migration of the salient might have started earlier, perhaps at ~155-140 Ma, as the crustal assembly of ophiolitic terranes and superjacent clastic + volcanogenic rocks gradually began to migrate off the deep-seated magmagenic zone along or directly above the descending paleo-Pacific plate. This west-directed oblique offset of the imbricated Klamath belts apparently occurred during a relatively brief period characterized by widespread left-lateral slip along the western margin North America (Saleeby 1992; Saleeby et al. 1992).

Attending Late Jurassic termination of Mariposa-Galice ± Myrtle sedimentation, the Klamath promontory rotated ~20° counterclockwise and moved outboard ~100–150 km (+ arcuate deformation of 50–100 km) relative to the formerly contiguous Sierran arc (e.g., Coleman et al. 1988; Constenius et al. 2000; Ernst 2012). The manner in which the tectonic offset was accomplished remains unclear, but may have been a crustal response in the Klamaths to the arrival and underflow of a segmented Farallon plate. Most of the differential slip occurred prior to Early Cretaceous deposition of the GVG-Hornbrook strata along the landward SE + NE edges of the Klamath Mountains, respectively (Figs. 1, 2). Modest additional sinistral displacement evidently continued across the Oak Flat-Sulphur Spring fault zone during Early Cretaceous time (Ernst 2012). Schematic relationships among the Jurassic volcanic-plutonic Andean arc rocks, and depositional histories of the Mariposa-Galice ± Myrtle sediments are diagrammed in the cross-sections of Fig. 8, reflecting the tectonic configuration of northern California prior to the postulated end-of-Jurassic oceanward step-out of the Farallon lithospheric plate. After this ~140 Ma step-out, spatial relationships involving the Cretaceous Sierran Batholith, Great Valley-Hornbrook, and Franciscan clastic strata are depicted in the cross-sections of Fig. 9.

Late Jurassic sequestration of HP/LT metamafic schists at moderate depths along the mantle wedge and later tectonic transference of exotic blocks and lenses into buoyant mélanges ascending along the subduction channel (Cloos 1982, 1986; Cloos and Shreve 1988) of the progressively less steeply east-dipping oceanic plate well after the ~140 Ma step out are also illustrated schematically.

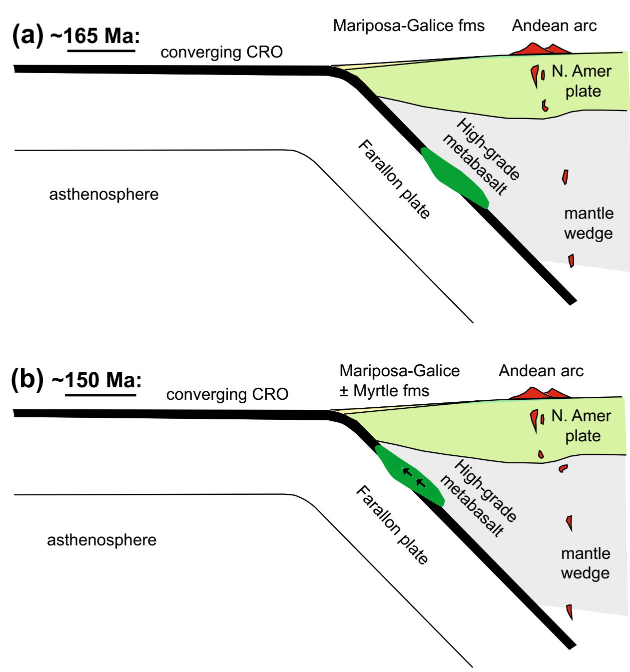


Fig. 8 **a** Diagrammatic depths of recrystallization, and **b** later, ascent and modest-depth storage of high-grade metabasaltic rocks of the descending Farallon plate. Relationships exaggerated for clarity are shown before stranding of pre-existing oceanic lithosphere as the Coast Range Ophiolite inboard from the ~140 Ma plate junction. The mechanism allowing the sequestered HP metabasaltic material to ascend along the plate junction (*arrows*) may have involved transportation as blocks in buoyant serpentinite

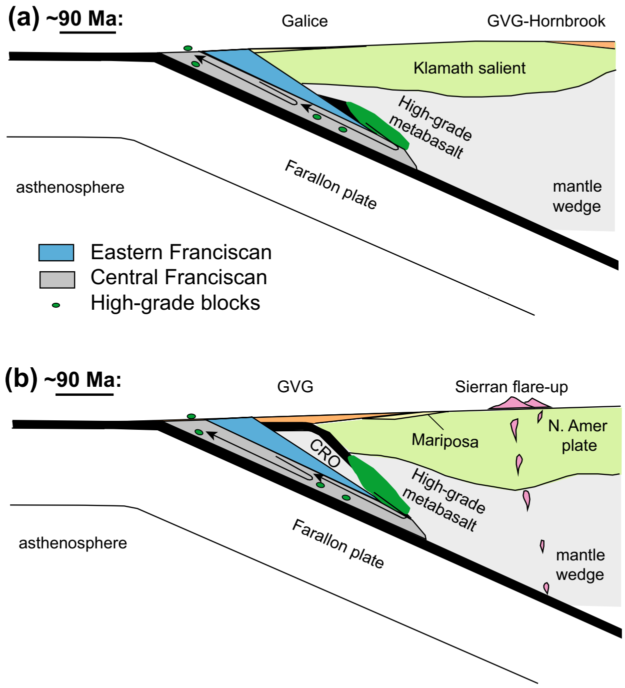


Fig. 9 Schematic introduction of high-grade metamorphosed oceanic crustal blocks into the Franciscan Complex outboard from **a** the Klamath Mountains and **b** the central Sierra Nevada Range. Sustained underflow of progressively younger, warmer Farallon lithosphere resulted in a gradually decreasing lithospheric plate dip. Two-way flow within the subduction zone is indicated. Note insertion of HP *tectonic blocks* into the voluminous, low-density, Upper Cretaceous Franciscan circulating mud matrix and net upward transport. Although the thickness of the circulating mélange zone in the Central Belt is exaggerated for clarity, it probably consisted of a progressively seaward-younging series of much thinner subduction channels, judging from mapped tectonic imbrications. Also sketched are *olistostromal blocks* probably carried surfaceward by serpentinite diapirs (not shown), and introduced into the Franciscan section through erosion, transportation, and sedimentary deposition

Insertion of the high-grade tectonic blocks involved a process whereby traction of circulating subduction-zone, low-density mélange against an overlying stable lithospheric plate induced shearing and plucking of HP/LT tectonic blocks and lenses previously stored along the mantle hanging wall into a Cloos-type subduction channel. How these Jurassic HP/LT units previously had ascended to shallower storage depths remains unclear, but metasomatic actinolitic rinds on many tectonic blocks suggest their early-stage inclusion in buoyant serpentinites. Prior to the ~125 Ma onset of nearly orthogonal, rapid subduction and return flow of large volumes of Central Belt mud-matrix mélange, plate-margin shearing apparently was insufficient to cause the tractive insertion of dense metamafic blocks into the subduction channel.

During mid-Paleozoic to mid-Jurassic time, predominantly margin-parallel differential slip involved the episodic docking of ophiolitic complexes along the continental edge. In contrast, Andean-type arc magmatism (Barth et al. 2013) was vigorous over the period ~175-140 Ma, and became paroxysmal during mid- and Late Cretaceous time (~125-80 Ma) during the change from a southward to a northward tangential component of drift of the Pacific-Farallon plate junction (Engebretson et al. 1984; May and Butler 1986; Schettino and Scotese 2005; Sager 2007; Doubrovine and Tarduno 2008). U–Pb ages of detrital zircons document the presence of relatively small volumes of Lower Cretaceous clastic strata, and in general, much larger masses of Upper Cretaceous sediments in the Franciscan Complex. Based on these relationships, Dumitru et al. (2010) proposed that, reflecting the change in relative plate motions, coastal California transitioned from a non-accretionary to an accretionary margin at ~123 Ma. Although plausible, nearly head-on convergence also would result in larger tracts of lithosphere descending through the magmagenic zone—and increasing generation of arc magmas—hence rapid, nearly orthogonal mid- and Late Cretaceous plate convergence might equally well have been responsible for the ~125-80 Ma flair-up in igneous arc activity and consequent production of voluminous Upper Cretaceous GVG and Franciscan clastic units (Blake et al. 1988; Ernst et al. 2008; Cloos and Ukar 2010).

The Middle to Late Jurassic Andean + Cretaceous Sierran arc, and Paleocene-Miocene Idaho Batholith, Challis complex, and Cascade volcanic rocks supplied most of the igneous zircons to the Franciscan clastic strata discussed in this paper. Although Middle and Upper Jurassic continental margin proximal sequences contain substantial contributions derived from Grenvillian source terranes, 1,000–1,200 Ma zircons appear to be sparse in Cretaceous GVG strata, and are absent from all but the oldest Franciscan trench units. With the passage of time, the Franciscan Complex began receiving greater proportions of younger arc detritus from more northerly source areas. This change in provenance raises the possibility, but does not require up to ~1,600 km of post-120 Ma northwesterly transport of the Franciscan trench complex during deposition, relative to the Great Valley Group forearc and tracts of the SW North American basement terranes.

9 A final word

Like many other parts of the world, northern California has received the detailed investigative attention of geologists, geochemists and geophysicists for more than a century. Accordingly, much of the geologic-geophysical framework and geochemical-petrotectonic development of the crust briefly sketched in this summary has been well understood for decades. However, the advent of TIMS and SIMS microanalyses of individual detrital zircon grains and their aggregate populations has made possible a relatively independent way to study the diverse igneous, metamorphic and sedimentary lithologic assemblages. Integrated with spatial knowledge of the region, these data provide new constraints on the geohistory (i.e., plate tectonic development). This review of independent age and provenance constraints reflected in the zircon U–Pb data represents just one example of how the study of new geochemical systems can increase our understanding of a critical portion of the Earth—in this example, the post-Triassic convergent plate margin of northern California. The attempt has been to elucidate a few principles involving accretionary crustal growth for Asian Earth scientists unfamiliar with California, because every area is different. However, although the geologic histories of east Asia and NW California contrast markedly, the governing principles are likely the same.

Acknowledgments Stanford University supports my field and analytical studies of Californian lithotectonic belts. The National Science Foundation provided additional aid through grant NSF EAR 0948676 to Marty Grove. Various workers carried out the detrital zircons U–Pb age determinations on which this summary in based, chiefly employing the SHRIMP-RG at the Stanford-USGS Micro-Analysis Center and the LA-ICPMS at the University of Arizona LaserChron Center. Many of of these works are already published, but as noted in the text, some of the zircon U–Pb data are still in press.

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