REVISION 1

Franciscan geologic history constrained by tectonic/olistostromal high-grade metamafic blocks in the iconic California Mesozoic-Tertiary accretionary complex

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ABSTRACT

Subduction generated an Andean arc along the Californian margin beginning at ~175 Ma. Coeval high-pressure (HP) transformation of oceanic crust in an east-dipping, inboard subduction zone probably accompanied plate convergence, but recovered eclogite and garnet blueschist blocks chiefly possess recrystallization ages of ~165-150 Ma. These Jurassic HP metamafic rocks were then sequestered in a low-temperature environment well into Cretaceous time. Actinolitic rinds partially surround many high-grade blocks. Slightly younger than the HP metamorphism, the rinds reflect metasomatic exchange between metabasalt and serpentinized harzburgite along the dynamic oceanic crust-mantle hanging wall during storage of the mafic rocks at moderate depth. High-grade tectonic blocks later were brought toward the surface in circulating, low-density mud-matrix mélange and/or in buoyant serpentinite bodies. Most exotic HP metamafic blocks occur in mélanges of the Franciscan Central Belt, reflecting tectonic insertion within the subduction zone—not near-surface additions to the clastic section. However, rare, high-grade clasts in feebly recrystallized Franciscan conglomerates suggest erosion and sedimentary deposition for some HP blocks. The addition of dense metabasaltic olistoliths to the mid- and Upper Cretaceous section requires that the HP material ~~was~~ be carried surfaceward first as tectonic fragments perhaps in part immersed in low-density serpentinite or mud-matrix mélange, then eroded and transported into the trench. HP rocks are conspicuously lacking in coeval Great Valley strata. Whatever the origin of particular high-grade rocks, widespread post-depositional shearing has largely obliterated their original natures, but all dense metamafic blocks of Jurassic recrystallization age must have been supplied to the Cretaceous

Franciscan accretionary complex by entrainment in a low-density, circulating muddy matrix or serpentinite diapir. The vast majority of exotic HP blocks resides in Central Belt mélanges, and appears to be tectonic rather than olistostromal in origin.

SIGNIFICANCE OF FRANCISCAN HIGH-GRADE BLOCKS

Pods and lenses of eclogite and garnet blueschist are minor, mineralogically spectacular petrologic components of the Franciscan Complex. These high-grade blocks with Middle to Late Jurassic ages of formation are relatively well known (Coleman and Lanphere, 1971; Wakabayashi, 1992; Anczkiewicz et al., 2004; Wakabayashi and Dumitru, 2007; Ukar et al., 2012). Initially solidified as Farallon or pre-Farallon oceanic crust distant from the North American margin, the HP rocks recrystallized in a relatively young (warm) oceanic-continental convergence zone along an unrefrigerated hanging wall, as deduced from mineral parageneses indicating counterclockwise P-T-time trajectories (Cloos, 1982, 1986; Wakabayashi, 1990, 1999; Saha et al., 2005; Page et al., 2007). Most HP tectonic blocks were transformed at ~10-12 kbar, and ~400-600°C, but some evidently formed at even higher P-T ranges (*e.g.*, Krogh et al., 1994; Tsujimori et al., 2006). These HP rocks then cooled (Carlson and Rosenfeld, 1981) attending continuing oceanic plate underflow.

In marked contrast to their relatively well-understood petrogenesis, field occurrences of the high-grade metamafic blocks are problematic, reflecting an obscure geologic context and uncertain origin. As evident from the example illustrated in **Figure 1**, most of these coarse-grained, penetratively deformed rocks rest on the Earth's surface with little or no apparent relationship to the surrounding, distinctly lower metamorphic grade Franciscan rocks. In many cases, the surrounding rocks consist of serpentinite or more commonly, mud-matrix mélange, or a mixture of pelitic and serpentinitic matrix materials. How the metamafic blocks and the spatially associated Franciscan, chiefly metasedimentary section were exhumed is a matter yet debated (*e.g.*, Ernst, 1971; Platt, 1986, 1993; Ring and Brandon, 2008). Regional geologic relations are illustrated in **Figure 2**. Some HP metabasalts exhibit partial or 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 rare cases where the Jurassic metamafic blocks are unambiguously enveloped in surrounding fine-grained mud-matrix or serpentinite bodies, the latter are substantially younger (*i.e.,* Late Cretaceous). Detailed histories of the HP blocks provide constraints for the Jurassic-Cretaceous convergent margin evolution of California and development of the accretionary Franciscan Complex. To frame the high-grade rocks in their geologic context, this work briefly summarizes recent studies of clastic strata of northern California that formed during a period mainly typified by oblique-to-orthogonal plate convergence (Ernst, 2011).

FRANCISCAN METAMORPHISM

Traditionally, the Franciscan Complex has been depicted as comprising three major, fault-bounded lithotectonic units of mainly clastic strata, namely the Eastern, Central, and Coastal belts (Bailey et al., 1964; Blake et al., 1988; McLaughlin et al., 2000). Although polylithic mélanges and broken formations occur in each belt, they are most abundant in the mud-dominant Central Belt. Strata of all three accretionary belts were deposited on oceanic crust as it approached the continent (Ernst, 2011). The Eastern and Coastal belts have long been recognized as imbricate collages consisting dominantly of sedimentary packages juxtaposed along gently east-rooting thrust faults (*e.g*., Blake et al., 1988; Ernst, 1993; McLaughlin et al., 2000). Generally, bedding is right-side-up with tops facing east; successive packets were successively accreted and young seaward. Although the Central Belt consists chiefly of muddy mélanges, it too represents an imbricate stack of largely sedimentary lithologies and is not simply a chaotically mixed but homogeneous unit (*e.g*., Gucwa, 1975; Prohoroff et al., 2012; Wakabayashi, 2012; Raymond, 2013; Bero, 2013).

Franciscan Eastern and Central belt sandstone units display pervasive effects of HP transformation, widely documented in metagraywacke sequences of northern California (Cloos, 1982, 1986; Blake et al., 1988; Jayko and Blake, 1989; Wakabayashi and Dumitru, 2007). In contrast, clastic units of the Coastal Belt exhibit weak, low-T, low-P recrystallization (Bachman, 1978; Underwood et al., 1987; Blake et al., 1988; Dumitru, 1989; Tagami and Dumitru, 1996). **Figure 3** presents generalized pressure-temperature conditions of recrystallization for rocks of the Franciscan Complex, including the exotic metabasalts (Coleman and Lanphere, 1971; Tsujimori et al., 2006).

The high-grade metamafic blocks are medium- to coarse-grained and contain mineral assemblages formed under more intense P-T conditions than the surrounding (*in situ*) blueschist facies and lower metamorphic grade Franciscan metasedimentary rocks. The low-grade glaucophane schists and related rocks in the surrounding units are typically fine-grained and exhibit relict igneous and sedimentary textures. The high-grade metamafic blocks (~400-600°C, ~10-12 kbar or more), and metasedimentary + meta-igneous rocks of the Franciscan Eastern and Central belts (~250°C, 5-8 kbar) lie along high-P, low-T prograde trajectories typical of Phanerozoic subduction-zones worldwide, whereas Coastal Belt rocks appear to show only the effects of diagenesis common in strata subjected to low-T, low-P burial (Ernst and McLaughlin, 2012).

JURASSIC CRUSTAL GROWTH

The late Paleozoic-early Mesozoic plate-tectonic evolution of northern California involved chiefly margin-parallel slip, and the episodic stranding of far-traveled ophiolite complexes + superjacent chert-argillite units (Saleeby, 1982, 1983; Dickinson, 2008). Scattered igneous rocks typified the Late Triassic sialic margin, but a massive Andean arc began forming ~~in~~ at the site of the Sierra Nevada Range and Klamath Mountains by ~175 Ma attending transpressive eastward underflow of the oceanic lithosphere (Dunne et al., 1998; Irwin, 2003; Dickinson, 2008). This arc shed clastic detritus into the ophiolitic realm of the Klamath Mountains and Sierra Nevada Foothills (Miller and Saleeby, 1995). The Klamath chert-argillite-rich North Fork and Eastern Hayfork ophiolitic terranes were sutured at ~175-165 Ma (Scherer and Ernst, 2008), whereas ~~the~~ proximal Mariposa and Galice volcanogenic strata in the Sierran Foothills and Klamaths respectively began accumulating by ~165-160 Ma (Snow and Ernst, 2008; Ernst et al., 2009a).

During initial construction of the volcanic-plutonic arc, recrystallization of the descending Farallon (or earlier) oceanic crust likely produced high-pressure metamafic lithologies, but except for scraps of the

~174 Ma Red Ant blueschists (Hacker, 1994) exposed in the northern Sierran Foothills, such HP metamorphic rocks have remained hidden. The oldest recovered eclogites and garnet blueschists in the Franciscan formed at ~165-150 Ma attending continuing transpressive underflow that generated the Jurassic Klamath-Sierran arc as well as the derivative Mariposa-Galice sedimentary aprons. HP metabasaltic blocks are absent from these Upper Jurassic proximal clastic units. The Jurassic high-grade metamafic blocks in the Franciscan Complex have been only feebly overprinted by lower grade assemblages, so apparently were subsequently stored at depth under relatively low-T conditions. They returned surfaceward mainly during Late Cretaceous time.

Some Franciscan high-grade metamafic rocks possess bulk-rock chemical affinities with mid-ocean-ridge basalts whereas others appear to be of alkalic or island-arc geochemistry (MacPherson et al., 1990; Saha et al., 2005; Wakabayashi et al., 2010; Ghatak et al., 2012). However, such exotic blocks are variably metasomatized, so petrotectonic conclusions based chiefly on bulk-rock compositions seem problematic. What is clear is that the Late Jurassic-Tertiary accretionary sections in northern California exhibit westward vergence, and an outboard progression in terrane younging. Such structural relationships are compatible with eastward subduction as sketched in Figures 4, 5 and 6.

CRETACEOUS-TERTIARY CRUSTAL GROWTH

At the end of Jurassic time, the Klamath Mountains terrane amalgam apparently was deformed and displaced ~100-200 km westward along the Oak Flat-Sulphur Spring sinistral fault zone (see Fig. 2) relative to the curvilinear Sierran arc (Ernst, 2012). This process gradually separated the stack of Klamath allochthons from the still active magmagenic zone beneath the Sierra Nevada volcanic-plutonic belt. Over two intervals, prior to 140 Ma (pre-slip) and after 136 Ma (post-slip), **Figure 4** shows the effect of the postulated underflow of an oceanic plate regionally ~~divided~~ split into slab segments on the Klamath crustal salient. A thin, warm slab of oceanic lithosphere is thought to have passed beneath the Klamaths largely decoupled from the overlying stack of gently east-dipping crustal allochthons. In contrast, thicker, older oceanic plate segments on both north and south apparently were strongly coupled to the continental margin, resulting in contraction and rotation of the accreted collages into relatively steeply inclined post-136 Ma sections (**Fig. 4a**). The original Sierra Nevada-Klamath-Blue Mountains arc is palinspastically restored to its pre-140 Ma configuration prior to the conjectured slip (**Fig. 4b**), with 20° clockwise rotation of the arc reversed; no attempt has been made to undo the accumulated strain caused by frictional drag during the slip that produced the westward arcuate bulge of the Klamath salient has not been removed.

In this scenario, the convergent plate junction in northern California apparently stepped seaward at ~140-136 Ma, trapping oceanic crust south of the Klamath Mountains as the Coast Range Ophiolite (CRO). Detritus from the dismembered igneous arc then began to accumulate on the basaltic crust flooring the Great Valley depositional basin. Clastic sediments carried past the forearc came to rest on the descending, outboard Farallon oceanic plate as the coeval Franciscan trench fill. Relatively intact forearc strata of the Great Valley Group (GVG) deposited on the nonsubducted North American plate to the east were largely protected from surface and subcrustal erosion. Although clastic deposition of Franciscan and GVG strata was initiated at ~140 Ma, massive arc erosion, sedimentation and accretion occurred during the ~125-80 Ma flare-up of the Sierran arc (Surpless et al., 2006: Snow et al., 2010; Dumitru et al., 2010). The youngest Sierran granites are ~80 Ma, reflecting Late Cretaceous extinction of the magmagenic zone beneath northern California, due to subhorizontal lithospheric plate underflow (Coney and Reynolds, 1977; Bird, 1988; Jacobson et al., 2011), but the high-standing, extinct igneous arc continued to supply quartzofeldspathic erosional debris to the forearc and trench well into Tertiary time (Dumitru et al., 2013).

Petrofacies analyses of graywacke-shale units and rare conglomerates of the Central and Eastern belts indicate derivation chiefly from the Andean arc in northern California (Dickinson et al., 1982; Seiders, 1983), similar to clastic strata of the inboard GVG (DeGraaff-Surpless et al., 2002). Terranes of the Coastal Belt contain clasts from the Klamath-Sierran arc as well as debris sourced from the Pacific Northwest (Dumitru et al., 2013). Minor occurrences of Franciscan clastic rocks include Eastern Belt metagraywackes as old as ~140 Ma (Wakabayashi and Dumitru, 2007; Snow et al., 2010). However, most Eastern Belt metagraywackes were deposited during the mid- and Late Cretaceous (Ernst et al., 2009b;

Dumitru et al., 2010). Sited in progressively more seaward positions, the Central and Coastal belts, for which detrital zircon U-Pb age data are now available, have Late Cretaceous (90-60 Ma) and Tertiary (65-25 Ma) maximum ages of deposition respectively (Dumitru et al., 2013). Zircons providing these age constraints were all separated from coherent Coastal Belt and broken formation Central Belt metasandstones. Detrital zircon spectra only yield maximum ages of sandstone sedimentation; furthermore, I assume that the analyzed rocks were deposited contemporaneously with the enclosing muddy matrix.

CONSTRAINTS FOR FRANCISCAN HIGH-GRADE METAMAFIC BLOCKS

Subduction of the oceanic lithospheric generated high-grade metabasaltic eclogites and garnet blueschists at depths of ~40-45 km or more attending construction of the Jurassic Andean arc. Actinolitic rinds and intimate association with serpentinized harzburgites rather than with xenoliths of deep-seated continental crust indicate that the HP metamafic section remained along the contact between the Farallon plate and the North American, partially hydrated mantle wedge (Shervais et al., 2011). Incompletely altered to lower-grade assemblages, the exotic metamafic rocks evidently rose—possibly transported in buoyant serpentinite—and were stationed at moderate depth (~20 km) during Early Cretaceous time, where retrogression would have been impeded by relatively low-temperature, subduction-induced refrigeration (Carlson and Rosenfeld, 1981).

Franciscan HP metamafic blocks returned surfaceward chiefly in the Late Cretaceous, judging by detrital zircon U-Pb ages of coherent Eastern and Central mélange belt metasandstones (Ernst et al., 2009b, Snow et al., 2010; Dumitru et al., 2010, 2013). At depth along the plate junction, major zones of fine-grained clastic units **circulated** within what became a dynamic progressive sequence of subduction channels typified by pervasive shearing and chaotic mixing. Over time, traction against the more coherent hanging-wall channel evidently spalled off high-grade metamafic fragments and entrained them as tectonic inclusions in the muddy matrix (*e.g.*, Cloos, 1982, 1986; Cloos and Shreve, 1988; Blake et al., 1988). This process involved traction of low-density flow mélange **zones** against the overlying hanging-wall plate, inducing shearing and tectonic insertion of high-grade blocks previously stored at modest mantle depth. Before the onset of rapid subduction and return flow of large volumes of Central Belt mud-matrix mélange, plate-margin shearing and frictional forces apparently were insufficient to cause the widespread calving off and injection of dense HP metamafic blocks into the subduction zone.

Several coherent thrust sheets composed of high-grade metamafic rocks also were emplaced in the Franciscan section (Ernst et al., 1970; Wakabayashi and Dumitru, 2007; Wakabayashi et al., 2010). Such HP slabs are petrologically and geochemically similar to isolated blocks of eclogite and garnet blueschist, but these thrust sheets were tectonically transported into the weakly recrystallized clastic section well after HP metamorphism, and are not olistolithic.

Serpentinite diapirs carrying HP tectonic blocks also likely rose into the forearc, where later erosion could have conveyed both metamafic and associated ultramafic debris as conglomerates and olistostromal slide blocks into the Franciscan trench section (Cowan, 1978; Moore and Liou, 1980; Erickson, 2011; Wakabayashi et al., 2010; Wakabayashi, 2011; Prohoroff, 2012). Sedimentary serpentinites are present in both the GVG and the Franciscan Complex, supporting the operation of this process (Lockwood, 1972; Phipps, 1984; Wakabayashi, 2012).

Eclogites and garnet blueschists are dense, so it seems likely that their ascent took place mainly as tectonic fragments immersed in low-density, buoyant lithologies. Schematic relationships are depicted both before (**Fig. 5a**, **b**) and well after (**Fig. 6a, b**) outboard displacement of the Klamath salient relative to the Sierran volcanic-plutonic arc. Apparently some Jurassic high-grade metamafic blocks were introduced into the Cretaceous subduction-zone metasedimentary section by prior ascent of HP block-bearing serpentinite diapirs into the forearc *at the surface*, followed by erosion and transportation into the trench depositional basin. In marked contrast, other HP blocks evidently were emplaced by tectonic injection of oceanic crustal material stored along the mantle wedge into circulating muddy mélange *at depth* within the subduction zone. In both cases, these eclogites and garnet blueschists attest to a stage of profound underflow, now recovered. Moreover, even olistostromal introduction of high-grade metabasaltic rocks into the Franciscan clastic section requires an earlier stage of exhumation, probably as tectonic blocks carried upward in low-density diapirs.

Reflecting pervasive convergent margin shearing of the Franciscan Complex, post-high-grade, but relatively high-pressure deformation of original olistostromal and/or tectonic units has obscured contact relationships between the weak transporting medium and the HP metamafic blocks. Clearly, the Jurassic, dense, high-grade metabasaltic rocks present in the Cretaceous accretionary prism were carried toward the surface by frictional forces accompanying buoyancy-driven entrainment in a low-density, incompetent material. Only two such carrier lithologies typify the Franciscan Complex—serpentinite and mud-matrix mélange.

DISCUSSION

Mafic eclogites and garnet blueschists formed during initial eastward subduction/construction stages of the Klamath-Sierran arc, and are now exclusively associated with serpentinite diapirs and/or younger Franciscan metasedimentary units. Upper Jurassic volcanogenic detritus shed from the volcanic-plutonic arc accumulated as the Mariposa-Galice strata; these overlap units totally lack exotic high-pressure metamafic blocks. Actinolitic rinds formed around some Franciscan HP metamafic blocks shortly after the high-grade subduction-zone metamorphism as a reaction between metabasalt and harzburgitic serpentinite. These HP rocks were then stored during the end of Jurassic through Early Cretaceous time along the Farallon- (or pre-Farallon)-North American plate junction at moderate depths in a low-temperature serpentinized mantle environment.

Although uncommon, eclogites and garnet blueschists are widespread in Franciscan clastic units, especially in the Upper Cretaceous Central Belt mélanges. Olistostromal supply to the trench involved gravity feed of high-grade metamafic blocks that once resided on or near the Earth’s surface. This in turn required upward transport from mantle storage sites—likely by serpentinite diapirs (Moore, 1984). Some such blocks occur in sedimentary serpentinite mélanges (Wakabayashi et al., 2010; Wakabayashi, 2011; Erickson, 2011). Rare eclogite and garnet blueschist pebbles in Franciscan metaclastic strata require the near-surface presence and erosion of at least these high-grade rocks (Wakabayashi, 2012). Yet, landward GVG strata are virtually devoid of HP clasts. Recognizing the widespread occurrences and near confinement of exotic HP metamafic blocks to mud-rich units of the Central Belt (Bailey et al., 1964; Coleman and Lanphere, 1972; Cloos, 1982, 1986; Blake et al., 1988), it seems likely that almost all represent tectonic calving off within the subduction zone (somewhat similar to the thrust origin of coherent high-grade metamafic slabs), rather than representing near-surface additions to the Franciscan section.

SUMMARY

Along the mid-Mesozoic Californian margin, onset of igneous arc construction by ~175 Ma required an important component of subduction attending transpressive eastward consumption of the Farallon plate beneath the North American lithosphere. Such Jurassic underflow also would have generated coeval high-grade metamorphism in the downgoing oceanic crust, but except for a few scraps of Red Ant blueschist exposed in the northern Sierran Foothills, no HP materials of this recrystallization age were brought back to the surface during the Jurassic. By ~165-150 Ma, eclogites and garnet blueschists were produced and preserved, but they occur mainly as exotic blocks in the Franciscan Complex of largely mid- and Late Cretaceous sedimentation and accretion age. This was also the time of deposition of much of the coeval Great Valley Group (DeGraaff-Surpless et al., 2002). Both GVG and Franciscan strata consist of clastic debris derived from the growing volcanic-plutonic arc.

These relationships support a geological history for northern California in which the HP metamafic blocks attest to Jurassic subduction followed by a poorly understood post-165-150 Ma ascent, perhaps transported as inclusions in serpentinite (?). These high-grade metabasaltic blocks were stored at modest depths at the end of Jurassic through Early Cretaceous time. The postulated seaward step-out of the oblique-to-orthogonal convergent plate junction at ~140 Ma may have signaled the arrival of a segmented part of the Farallon plate passing beneath the Klamath volcanic-plutonic arc. Relatively thin, warm plate underflow could have been responsible for the apparent westward extrusion of the gently east-rooting

Klamath Mountains allochthons, whereas the impingence of thicker, colder plate segments on both north and south would have caused a relative landward displacement of the Blue Mountains and Sierra Nevada Range respectively. In California, the step-out provided a commodious ensimatic basin of deposition for the Great Valley Group, and for the Franciscan trench assemblage seaward of the plate junction. Both GVG and Franciscan clastic strata have depositional ages distinctly younger than the recrystallization ages of the high-grade metamafic rocks.

These latter are chiefly metabasaltic tectonic blocks plucked from the mantle hanging wall at depth within the subduction zone by circulating mud-matrix zones of the Central Belt. Widespread Cretaceous and Cenozoic plate-margin deformation occurred after delivery of HP blocks to Franciscan metaclastic units; thus only in favorable cases can a ready distinction be made between a tectonic and an olistostromal origin for individual blocks. In any case, these high-grade metamafic rocks were supplied later to the less intensely recrystallized sedimentary units of the Franciscan Complex. At some stage, all such exotic HP fragments were carried surfaceward by buoyancy-driven entrainment in a low-density lithology.

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FIGURE LEGENDS

Figure 1. Photograph of an unusually large high-grade metamafic block spatially associated with serpentinite at Ring Mountain, Tiburon Peninsula, California (courtesy of J. G. Liou).

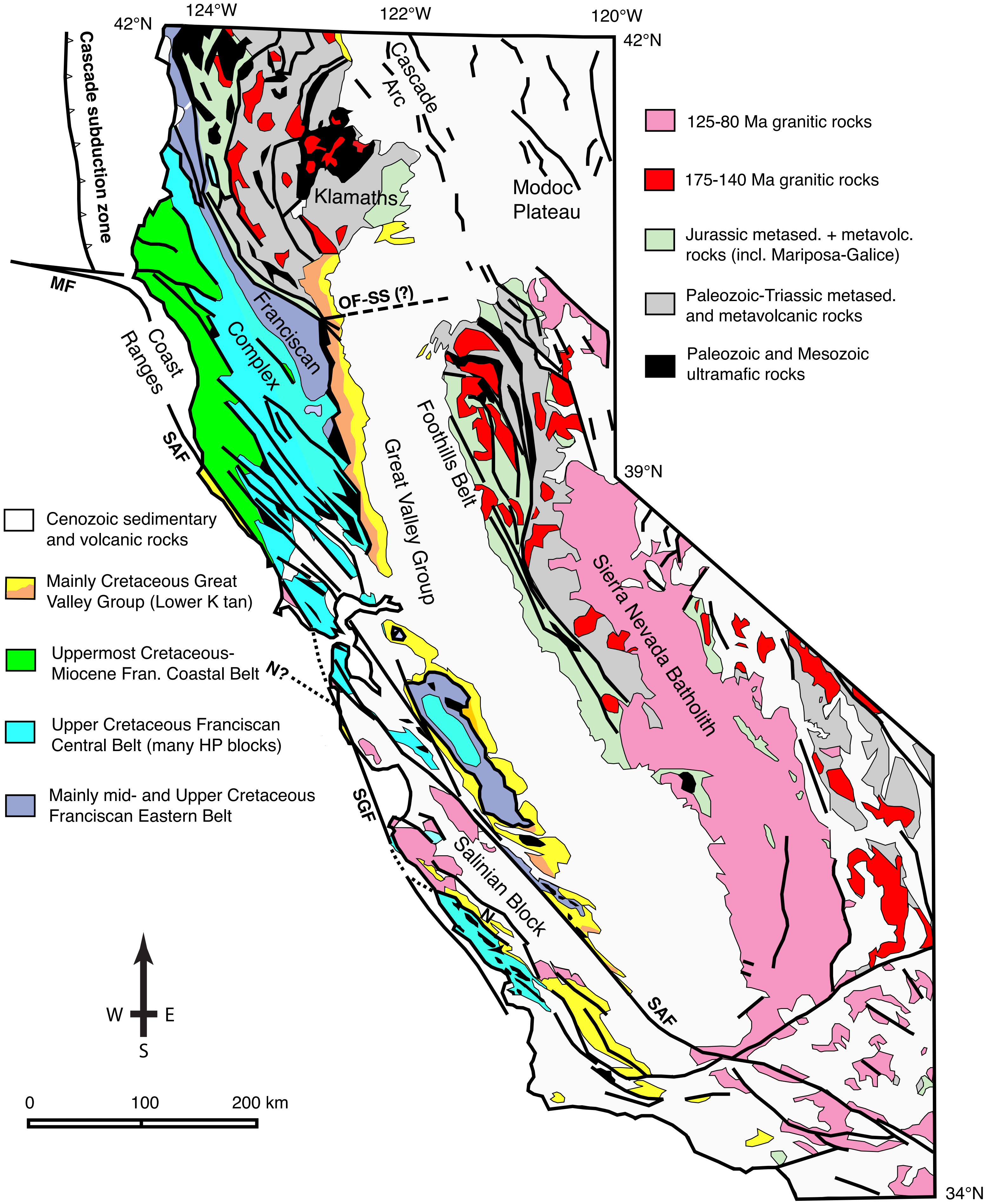
Figure 2. General geologic map of most of California, depicting the Jura-Cretaceous Klamath-Sierran volcanic-plutonic arc, GVG forearc, and Franciscan trench belts, after the U. S. Geological Survey and California Division of Mines and Geology (1966) map, the terrane map of Silberling et al. (1987), and coastal maps of Dickinson et al. (2005). All three belts are accretionary stacks of coherent + chaotically mixed units, whereas the Central Belt chiefly comprises mud matrix mélange. Fault zones: Oak Flat and Sulphur Spring = OF-SS; Nacimiento = N and N? San Gregorio-Hosgri = SGF; Mendocino = MF; San Andreas = SAF.

Figure 3. Phase diagram for northern California Franciscan metagraywacke bulk-rock compositions, modified from 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 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 rocks of metabasaltic composition (also, Liou et al., 1983). An = anorthite. Prograde metamorphic P-T paths for the Franciscan belts are after Ernst and McLaughlin (2012), extended schematically to include P-T conditions of the high-grade metabasaltic blocks (even higher pressures were calculated for a Tiburon Peninsula eclogite by Tsujimori et al. (2006, fig. 7). Retrograde paths are not shown. Deeply buried GVG strata and weakly recrystallized volcanogenic Mariposa-Galice units exhibit neoblastic mineral assemblages comparable to those of the Franciscan Coastal Belt.

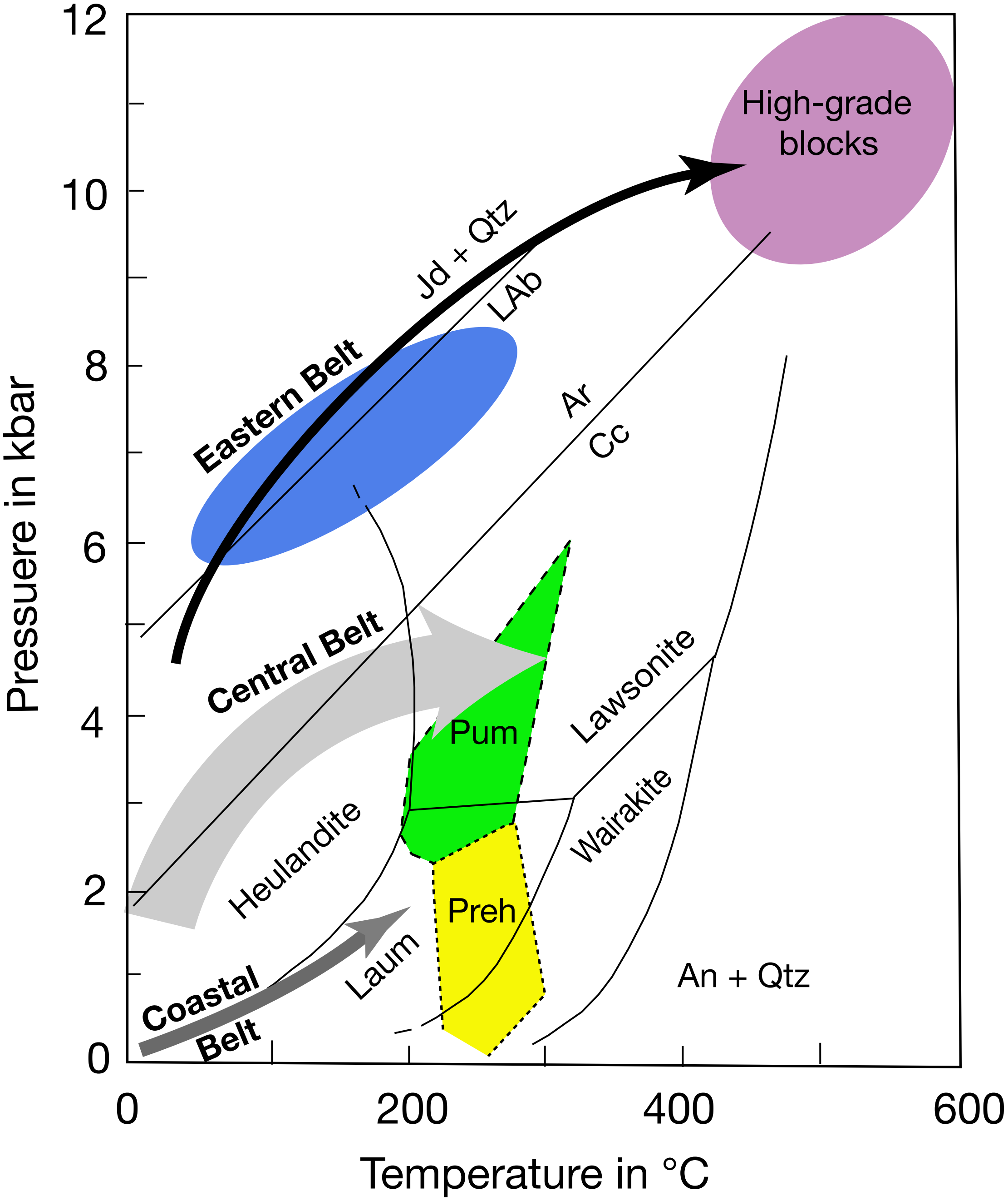
Figure 4. Underflow of a segmented Farallon plate beneath the North American margin at ~140-136 Ma proposed by Ernst (2012; map after Snoke and Barnes, 2006, fig.1). **(a)** After offset of the igneous arc, arrows show the proposed direction of relative crustal slip ± possible backarc extension as a segmented oceanic plate slid eastward beneath the continental margin. Bounding transforms of the Farallon lithosphere are assumed to have been subparallel, with ENE trends constrained by offsets in the pre-existing curvilinear arc. **(b)** Palinspastically restored Sierra Nevada-Klamath-Blue Mountains volcanic-plutonic arc prior to differential slip, including 20° clockwise rotation of the Klamath salient back to its Jurassic arc configuration.

Figure 5. Depths of recrystallization **(a)** and later, shallower storage **(b)** 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.

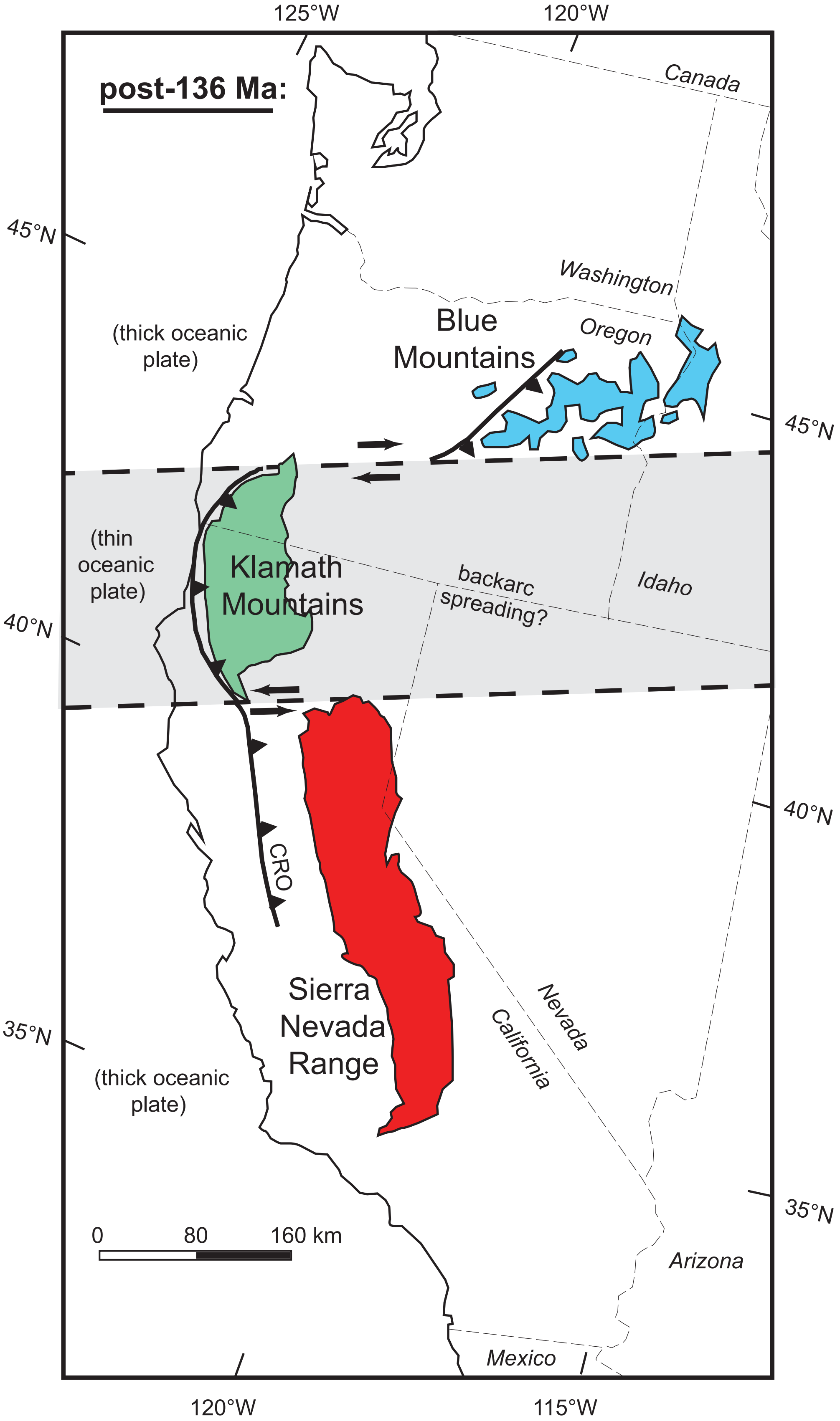
Figure 6. Schematic introduction of high-grade metamorphosed oceanic crustal blocks into the Franciscan Complex outboard from (**a**) the Klamath Mountains and (**b**) the Sierra Nevada Range. Sustained underflow of progressively younger, warmer Farallon lithosphere resulted in a gradually decreasing plate dip**.** Two-way flow within the subduction zone is indicated. Note *tectonic* insertion of HP 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 the tectonic imbrication. Also sketched are *olistostromal blocks* probably carried surfaceward by serpentinite diapirs (not shown), and introduced into the Franciscan sedimentary section through erosion, transportation, and deposition.


124°W
122°W
120°W
42°N
42°N
39°N
34°N
117°W
Cascade subduction zone
MF
Coast Ranges
SAF
Cascade Arc
Klamaths
Modoc Plateau
OF-SS (?)
Franciscan Complex
Foothills Belt
Great Valley Group
Sierra Nevada Batholith
N?
SGF
N
Salinian Block
SAF
W
E
S
0
100
200 km
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 ultramafic rocks
Cenozoic sedimentary and volcanic rocks
Mainly Cretaceous Great Valley Group (Lower K tan)
Uppermost Cretaceous-Miocene Fran. Coastal Belt
Upper Cretaceous Franciscan Central Belt (many HP blocks)
Mainly mid- and Upper Cretaceous Franciscan Eastern Belt

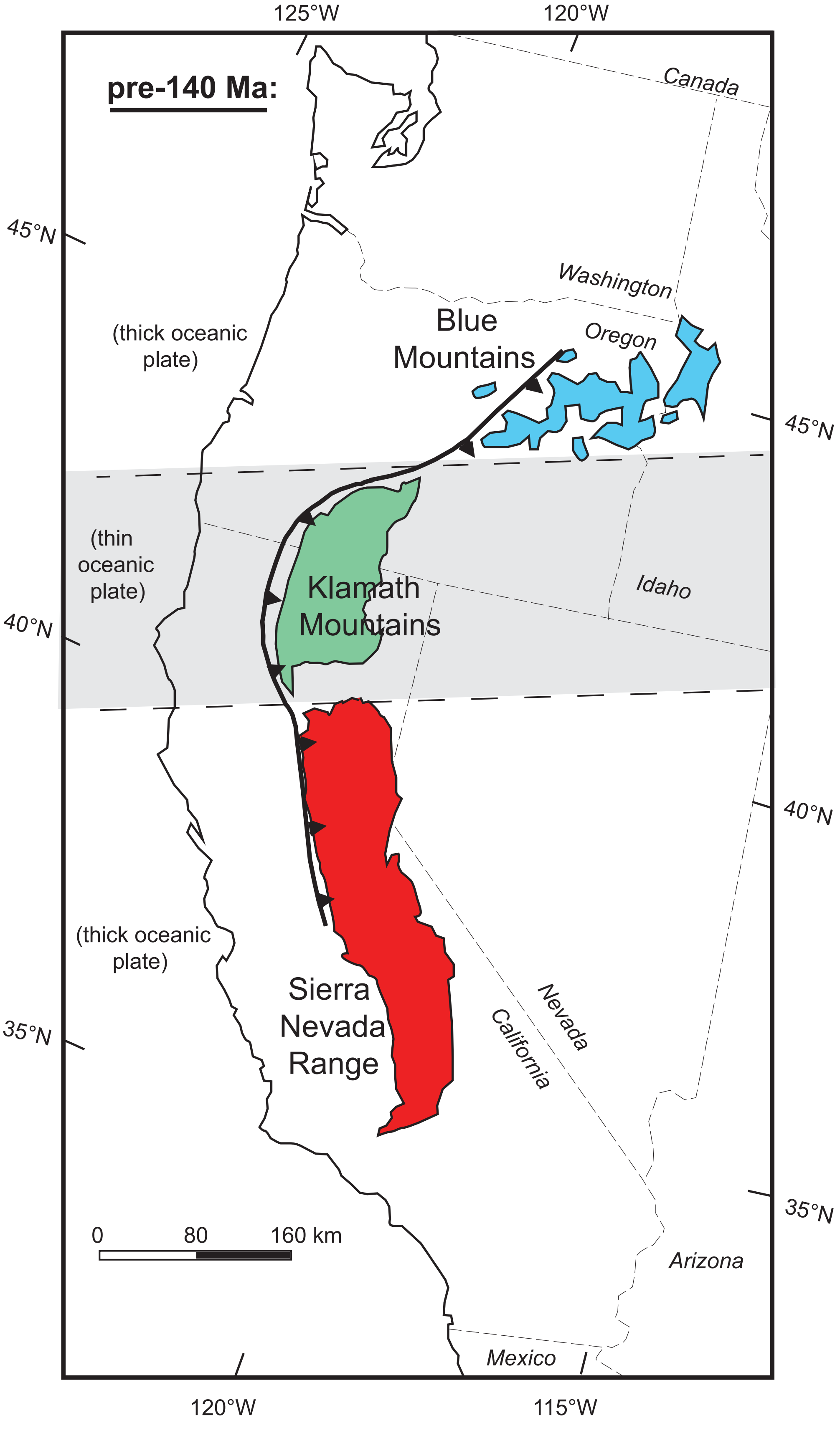
Ernst, Fig. 2.


12
10
8
6
4
2
0
Pressuere in kbar
0
200
400
600
Temperature in °C
High-grade blocks
Jd + Qtz
LAb
Eastern Belt
Ar
Cc
Central Belt
Pum
Lawsonite
Wairakite
Heulandite
Preh
Laum
Coastal Belt
An + Qtz

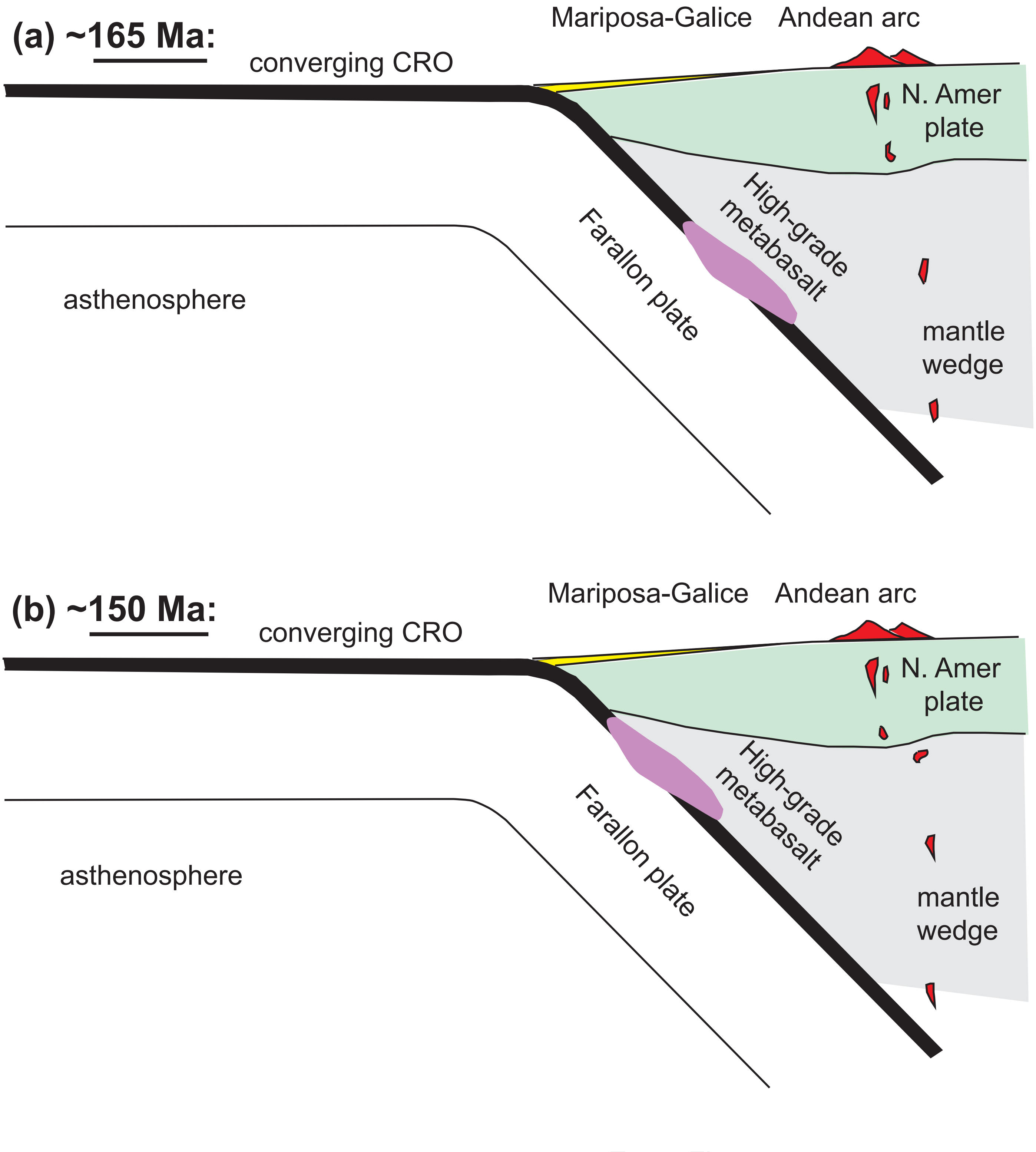
Ernst, Fig. 3


post-136 Ma:
125°W
120°W
Canada
45°N
Washington
Oregon
Blue Mountains
(thick oceanic plate)
45°N
(thin oceanic plate)
Klamath Mountains
backarc spreading?
Idaho
40°N
40°N
CRO
Sierra Nevada Range
Nevada
California
35°N
(thick oceanic plate)
35°N
0
80
160 km
Arizona
Mexico
120°W
115°W

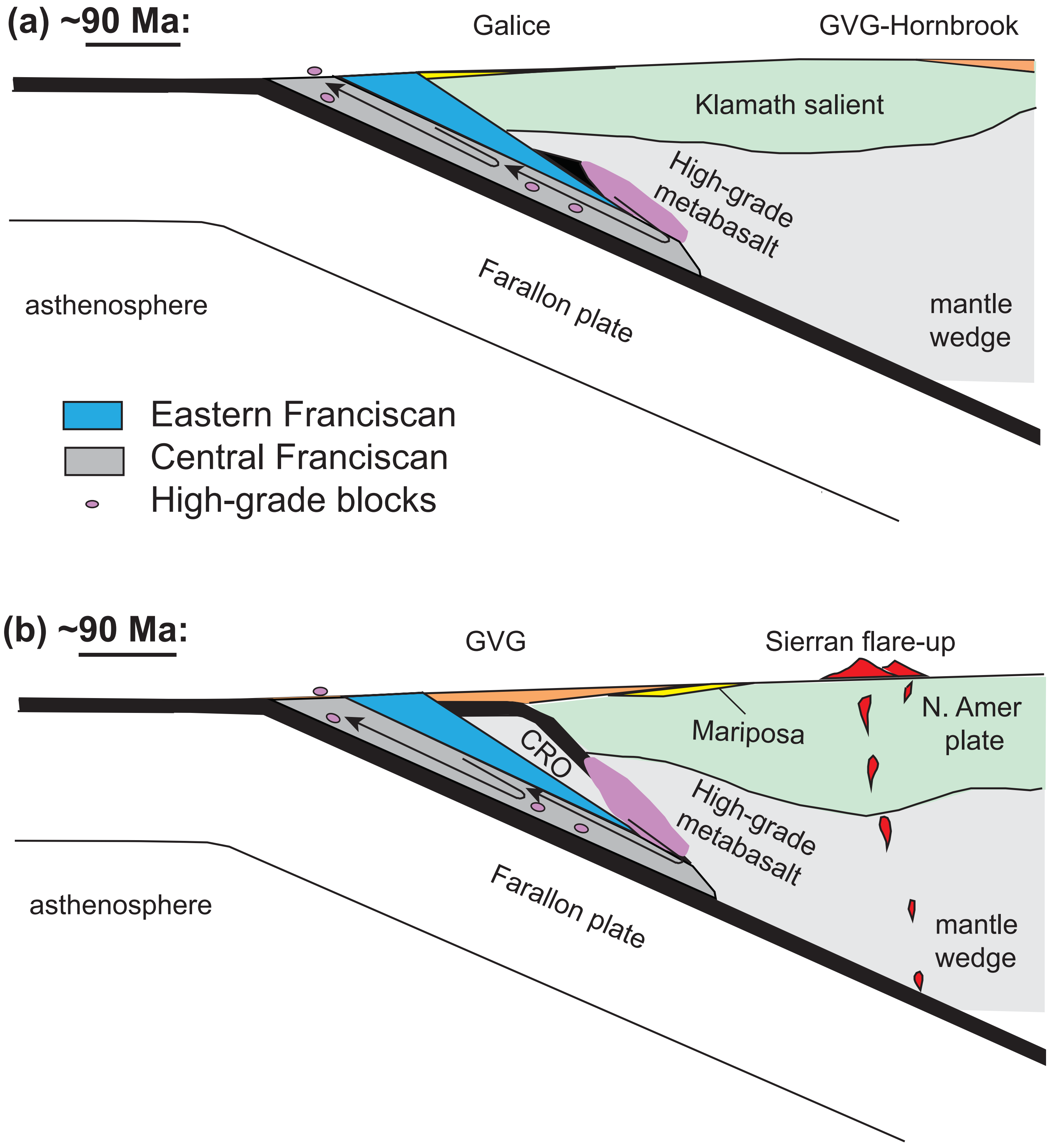
Ernst, Fig. 4a


pre-140 Ma:
125°W
120°W
Canada
45°N
Washington
(thick oceanic plate)
Blue Mountains
Oregon
45°N
(thin oceanic plate)
Klamath Mountains
Idaho
40°N
40°N
(thick oceanic plate)
Sierra Nevada Range
Nevada
California
35°N
35°N
0
80
160 km
Arizona
Mexico
120°W
115°W

Ernst, Fig. 4b


(a) ~165 Ma:
Mariposa-Galice
Andean arc
converging CRO
N. Amer plate
High-grade metabasalt
Faralllon plate
asthenosphere
mantle wedge
(b) ~150 Ma:
Mariposa-Galice
Andean arc
converging CRO
N. Amer plate
High-grade metabasalt
Farallon plate
asthenosphere
mantle wedge

Ernst, Fig. 5


(a) ~90 Ma:
Galice
GVG-Hornbrook
Klamath salient
High-grade metabasalt
asthenosphere
Faralon plate
mantle wedge
🟦 Eastern Franciscan
▨ Central Franciscan
● High-grade blocks
(b) ~90 Ma:
GVG
Sierran flare-up
N. Amer plate
Mariposa
CRO
High-grade metabasalt
asthenosphere
Farallon plate
mantle wedge

Ernst, Fig. 6