Plate Motions Recorded in Tectonostratigraphic Terranes of the Franciscan Complex and Evolution of the Mendocino Triple Junction, Northwestern California

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By R.J. McLAUGHLIN, W.V. SLITER, N.O. FREDERIKSEN,
W.P. HARBERT, and D.S. McCULLOCH

U.S. GEOLOGICAL SURVEY BULLETIN 1997

U.S. DEPARTMENT OF THE INTERIOR
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U.S. GEOLOGICAL SURVEY
Robert M. Hirsch, Acting Director

Text edited by George A. Havach
Illustrations edited by Taryn A. Lindquist

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1994

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Library of Congress Cataloging-in-Publication Data

Plate motions recorded in tectonostratigraphic terranes of the Franciscan complex
and evolution of the Mendocino triple junction, northwestern California/ by
R.J. McLaughlin ... [et al.].
p. cm. — (U.S. Geological Survey bulletin ; 1997)
Includes bibliographical references.
1. Plate tectonics—California. Northern. 2. Geology, Structural—
California, Northern. I. McLaughlin, Robert E. II. Series.
QE75.B9 no. 1997
[QE511.4]
557.3 s—dc20
[551.1'36'09794] 92-23140
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Plate Motions Recorded in Tectonostratigraphic Terranes of the Franciscan Complex and Evolution of the Mendocino Triple Junction, Northwestern California

By R.J. McLaughlin, W.V. Sliter, N.O. Frederiksen, W.P. Harbert, *and* D.S. McCulloch

Abstract

The Mendocino triple junction area of northern California is underlain by the Coastal belt of the Franciscan Complex, flanked on the east by the Central and Eastern belts of the Franciscan Complex. The Coastal belt is further divided into three tectonostratigraphic terranes, from northeast to southwest, the Yager, Coastal, and King Range terranes. Upper Cretaceous through middle Miocene rocks included in these terranes were accreted to the North American plate margin partly during normal convergence with the Farallon plate between 49 and 25 Ma at poleward rates of 2 to 5 cm/yr (Coastal and Yager terranes), and partly during translation with the Pacific plate between 14 and 2 Ma at poleward rates of 3 to 6 cm/yr (King Range terrane). Except for sparse blocks of Upper Cretaceous limestone and basalt scraped off the Farallon plate, as well as rare blocks of blueschist of uncertain origin, the Coastal belt terranes are composed principally of Paleocene to Eocene arc- and continental-margin-derived turbiditic detritus. Midlatitudinal affinities of foraminifers and palynomorphs in the Coastal and Yager terranes, and the presence of an Eocene conglomerate containing clasts of jadeitic and lawsonitic metasandstone, radiolarian chert, and serpentinite, suggest no more than about 600 km of right-lateral postdepositional displacement of the clastic rocks. Furthermore, the presence of arc-derived turbidites with interbedded Late Cretaceous ocean-ridge or seamount basalt near Usal, Calif., suggests access of sediment derived from the American plate to the Pacific-Farallon Ridge area sometime between 82 and 69 Ma. Uplift of the California convergent margin during the middle Miocene (ca. 15 Ma) resulted in overlap of the Franciscan rocks already accreted to the margin by shelf and slope deposits. These overlap deposits, in turn, were downfaulted later in the Neogene to form the Humboldt forearc and related smaller basins. Until middle to late Miocene time, strata of the King Range terrane were deposited in a trench-slope or slope setting along the Farallon-North American plate boundary, possibly as far as 435 km south of Cape Mendocino. A 13.8-Ma metalliferous hydrothermal system, as well as evidence indicating that the accompanying thermal anomaly affected the entire King Range terrane, suggests that these rocks were rifted from the California margin about 14 Ma, over a slabless window (slab gap) at the north end of the San Andreas transform, and accreted to the northeast side of the Vizcaino structural block of the Pacific plate. The King Range terrane then was translated northward with the Mendocino triple junction and obductively reaccreted to North America during the early Pleistocene. Compressional tectonics at the northwestern California margin since about 3 Ma accounts for active uplift and thrusting near Cape Mendocino, compression of earlier-formed, Neogene pullapart basins, and the absence of Coast Range volcanism north of Clear Lake. Offshore and onshore structural relations suggest that the present-day Mendocino triple junction is situated near the hamlet of Petrolia, Calif., north of the King Range terrane, rather than off shore, where it has traditionally been located. The San Andreas fault zone thus may include the east and north boundaries of the King Range terrane.

INTRODUCTION

This report describes the Late Cretaceous to late Cenozoic evolution of the tectonostratigraphic terranes surrounding the Mendocino triple junction. We focus on determining the structure and boundary relations of the various tectonostratigraphic terranes of the Franciscan Complex, their ages, formational settings, amounts of displacement, and the timing and mechanisms of their accretion to the California margin. We attempt here to relate the evolution of terrane accretion to recent models of relative motions between plates in the adjacent Pacific Basin during the Mesozoic and Cenozoic (Engebretson and others, 1985; Tarduno and others, 1986; Stock and Molnar, 1988). Our reconstructions indicate that although a convergent subduction setting dominated the northern California accretionary margin during early Cenozoic time, major dextral motion occurred during the Late Cretaceous and earliest Tertiary and, to a lesser extent, also contributed to

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Manuscript approved for publication, May 17, 1991.

the motion between rocks of the Franciscan Complex and North America during Paleogene time.

Furthermore, our investigations suggest that the King Range terrane of the Franciscan Complex was accreted to the California margin during late Cenozoic time after undergoing dextral displacement of about 435 km within the San Andreas fault system. Structures associated with the presently active Mendocino triple junction reflect northeast-southwest-oriented compression between the North American and Pacific plates.

Acknowledgments.— Our investigations in the Mendocino triple junction region have involved cooperation, exchanges of data and ideas, and discussions with many professional colleagues, over a timespan of at least 8 years. The senior author has greatly benefited from the work and insights of the following geologists: E.C. Beutner (Franklin and Marshall College, Lancaster, Pa.); K.R. Lajoie, S.D. Ellen, and S.H. Clarke (U.S. Geological Survey); G.A. Carver, K.R. Aalto, and S.D. Morrison (Humboldt State University, Arcata, Calif.); and M.B. Underwood (University of Missouri, Columbia, Md.). D.E. Champion and R.E. Wells (U.S. Geological Survey), D.C. Engebretson and S.G. Miller (University of Washington, Bellingham) and R. Sharps (Stanford University, Stanford, Calif.) generously provided their time and expertise to paleomagnetic pilot studies in the region, and A. Griscom (U.S. Geological Survey) has been helpful in providing insights into the deep-crustal structure beneath the triple-junction area from aeromagnetic data. In addition to the paleontologic contributions of the coauthors of this report, we acknowledge additional support from the following paleontologists: J.A. Barron, C.D. Blome, B.L. Murchey, K. McDougall, and R.Z. Poore (U.S. Geological Survey); W.R. Evitt (Stanford University, Stanford, Calif.); K.D. Berry (Chevron Oil Co.); B. Roth (California Academy of Sciences, San Francisco, Calif.); R. Feldman (Kent State University, Kent, Ohio); S.A. Kling (Micropaleo Co., Encinitas, Calif.); and G. Keller (Princeton University, Princeton, N.J.). Numerous property owners have allowed us access to their land in the course of this project; without their support, this study would have been impossible. In particular, we thank the following individuals for their continued cooperation and interest in our work: Mary and Mike Etter, Jan Smith, and the Chambers family of the Mattole Valley and coastal area; and Thornton Smith of Harris, Calif. We also thank the Georgia Pacific Lumber Co. for permitting access to their land near Usal.

TECTONOSTRATIGRAPHIC FRAMEWORK OF THE CAPE MENDOCINO REGION AND ADJACENT NORTHERN COAST RANGES

The basement rocks of the Cape Mendocino region are assigned to the Franciscan Complex. In northern California, the Franciscan Complex is divided into three broad belts, the Eastern, Central, and Coastal (fig. 1), which generally become younger and less metamorphosed from east to west and have different structural relations to adjacent rocks (Irwin, 1960; Blake and others, 1985, 1988). Within each of these belts, numerous tectonostratigraphic terranes have been mapped (Blake and others, 1982, 1985; McLaughlin and Ohlin, 1984). In this report, we are concerned primarily with the terranes and tectonostratigraphic framework of the Coastal belt.

We here subdivide the Coastal belt into three fault-bounded terranes that overlap in age and composition, from northeast to southwest: the Yager terrane of Paleocene(?) and Eocene age; the Coastal terrane of Late Cretaceous, Paleocene, and Eocene age; and the King Range terrane of Late Cretaceous, possibly Paleogene, and middle Miocene age (fig. 2).

Franciscan Central Belt and its Contact Relations with the Coastal Belt

Rocks of the Franciscan Central belt in the Cape Mendocino region compose a tectonic melange that consists of numerous tectonostratigraphic terranes enclosed in a penetratively sheared argillite matrix metamorphosed to at least pumpellyite, possibly as high as low blueschist, grade. In addition to enclosing the tectonostratigraphic terranes, this melange matrix also encloses outcrop-size to larger exotic blocks of glaucophane schist, eclogite, garnet amphibolite, and other rocks of high-temperature and high-pressure metamorphic-mineral assemblages. The terranes enclosed by the melange matrix, though diverse, are generally separable into two types. The first type consists chiefly of sandstone and argillite, representing remnants of disrupted deep-sea-fan, slope, and trench-slope depositional settings. The second type consists of ultramafic and mafic intrusive rocks, basaltic flows, flow breccias and tuffs, radiolarian chert, and pelagic limestone, representing various oceanic settings. Some of the terranes are composites of oceanic rocks overlain by terrigenous rocks.

Some of these oceanic or composite oceanic and terrigenous assemblages are inferred to be fragments of the Coast Range ophiolite and Great Valley sequence displaced from the west side of the Great Valley into the Central belt of the Franciscan Complex during an episode of dextral translation in Late Cretaceous to Paleocene time (McLaughlin and others, 1988a). Paleomagnetic and paleontologic data strongly suggest that other oceanic assemblages associated with pelagic limestone and radiolarian chert, such as the Calera Limestone and Laytonville Limestone (informal usage of Alvarez and others, 1980), and rocks of the Nicasio Reservoir, Marin Headlands, and The Geysers basalt-chert localities, were deposited near the Equator and translated northward on one or more plates of the late Mesozoic to early Cenozoic Pacific Basin (Alvarez and others, 1980; Grommé, 1984; Tarduno and others, 1985, 1986; Hagstrum and Murchey, 1991).

The various sandstone-argillite terranes of the Central belt vary widely in age (from Late Jurassic to late Late Cretaceous) and composition (from lithic-volcanic and chert rich to arkosic). The sandstone terranes also vary considerably in their degree of metamorphism. Numerous large slabs of metasandstone entrained in the eastern part of the Central belt, which locally are interleaved with chert and mafic igneous rocks and contain blueschist metamorphic-mineral assemblages, are correlative with the Eastern belt of the Franciscan Complex (McLaughlin and others, 1988a). Other arkosic to lithic sandstone units, generally of mid-Cretaceous to Late Cretaceous age, containing incipient prehnite-pumpellyite or pumpellyite-lawsonite metamorphic-mineral assemblages, are of uncertain relation to rocks in the Eastern belt. Some large sandstone-argillite terranes of the southwestern part of the Central belt are metamorphosed to laumontite-prehnite-bearing zeolite assemblages and consist of lithic to arkosic sandstone containing abundant detrital K-feldspar. These K-feldspar-bearing, zeolite-grade sandstone terranes are generally mid-Cretaceous or Late Cretaceous in age and, except for their older ages, resemble the sandstone terranes in the Coastal belt to the west.

The west boundary of the Central belt is a shallowly to steeply east dipping thrust fault. Movement on this fault has resulted in emplacement of the Central belt over rocks of the Coastal belt (fig. 3). This thrust fault is generally known as the Coastal belt thrust (Jones and others, 1978), although the names "Eel River fault" or "Garberville thrust" have been proposed for this feature in the vicinity of Garberville (Underwood, 1982; Bachman and others, 1984). The Coastal belt thrust is a nearly flat contact that is warped into a broad southeast-plunging synform and antiform (figs. 2, 3). Overridden rocks of the Yager terrane of the Coastal belt contain fossils as young as late Eocene and are complexly folded, indicating that emplacement of the Central belt over the Coastal belt occurred after late Eocene time and either accompanied or postdated the folding. Mildly folded, middle Miocene to Pliocene marine strata overlap the Coastal belt thrust on the northeast side of the Eel River basin and in the vicinity of Garberville, and rocks of early Miocene age (Chetelat and Ingle, 1987) occur at the base of the postaccretionary Wildcat Group along the coast south of Centerville Beach. These constraints argue that displacement of the Central belt along the Coastal belt thrust must have occurred largely during the Oligocene, when a marine depositional hiatus occurred in the north coastal region.

Northeast of Arcata, zircon from small trachytic alkalic intrusions have been dated (Meyer and Naeser, 1970) at about 35.3±2.0 Ma (Fickle Hill) and 36.0±0.9 Ma (intrusion north of Fickle Hill) by fission-track techniques (fig. 2). Somewhat northeast of these localities, at Coyote Peak, the Central belt is intruded by another Oligocene, diatreme-like alkalic intrusion (Morgan and others, 1985). These Oligocene volcanic rocks apparently intruded the Central belt concurrently with or after emplacement of the Central belt over the Yager terrane along the Coastal belt thrust. Broad, northwest-trending folds that deform the upper and lower plates of the Coastal belt thrust probably were initiated during or after the late Miocene.

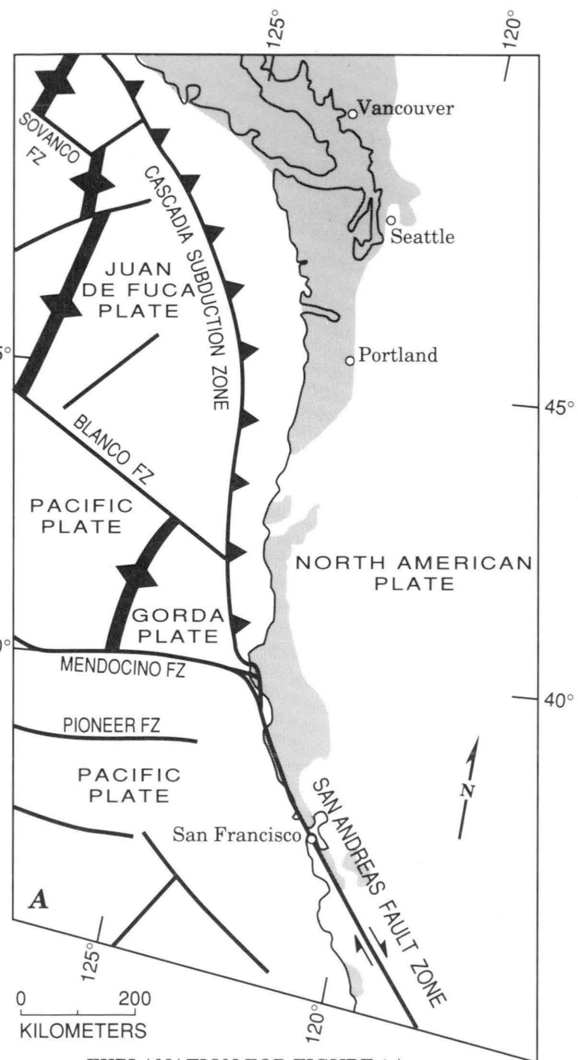
Yager Terrane of the Coastal Belt

Rocks of the Yager terrane were initially named the Yager Formation by Ogle (1953), who believed them to be Late Cretaceous in age. More recent investigations (Evitt and Pierce, 1975; Underwood, 1983; McLaughlin and others, 1985a), however, have shown these rocks to be of early Tertiary age. The strata are highly deformed by folding, and the terrane is fault bounded. Because of its complex structure, we assign the Yager terrane to the Franciscan Complex (Underwood, 1983; Blake and others, 1985; McLaughlin and others, 1985a) as a tectonostratigraphic terrane of the Coastal belt.

The Yager terrane is composed largely of silty mudstone, sandstone, and conglomerate. Mudstone and thin-bedded sandstone generally dominate the northeastern part of this terrane (fig. 4*A*). Thick-bedded channelized sandstone is most abundant along the southwest and northeast sides of the terrane, although it also locally dominates the section in other areas.

Conglomerates of the Yager terrane are polymict, containing generally subrounded and rounded clasts as large as boulders, composed chiefly of resistant rock types. These resistant clasts consist of silicic, tuffaceous, and porphyritic volcanic rocks and shallow-intrusive rocks; black, green, and red felsite and chert; and quartzite. The remaining clast component includes lesser amounts of mafic igneous rocks, metavolcanic rocks, reworked metasandstone, and autoclastic argillite. Locally, some of the chert and, possibly, some metasandstone clasts may be reworked from rocks of the Central belt of the Franciscan Complex. The conglomerates occur as lens-shaped channels, as much as several tens of meters thick and more than a kilometer long, along the west side of the Yager terrane between Bull Creek and Honeydew (fig. 4*B*).

Sandstone of the Yager terrane is predominantly arkosic to feldspathic; it is locally lithic, containing abundant clasts of chert or mudstone autoclasts. Chloritized detrital biotite commonly delineates ripple-drift laminations. After felsite and silicic volcanic-rock fragments, biotite and pink to white muscovite are the most common detrital accessories, followed by epidote and clinozoisite, zircon, and garnet. The sandstone beds range in thickness from thin-bedded flysch with abundant fine-scale sedimentary structures, to channeled units as much as 167 m thick near Cummings.



EXPLANATION FOR FIGURE 1A

Exposed Mesozoic and younger rocks that were accreted to continental margin before Eocene time

Fault or fracture zone—Arrows indicate direction of relative movement

Subduction zone—Sawteeth on upper plate

Spreading ridge and transform fault

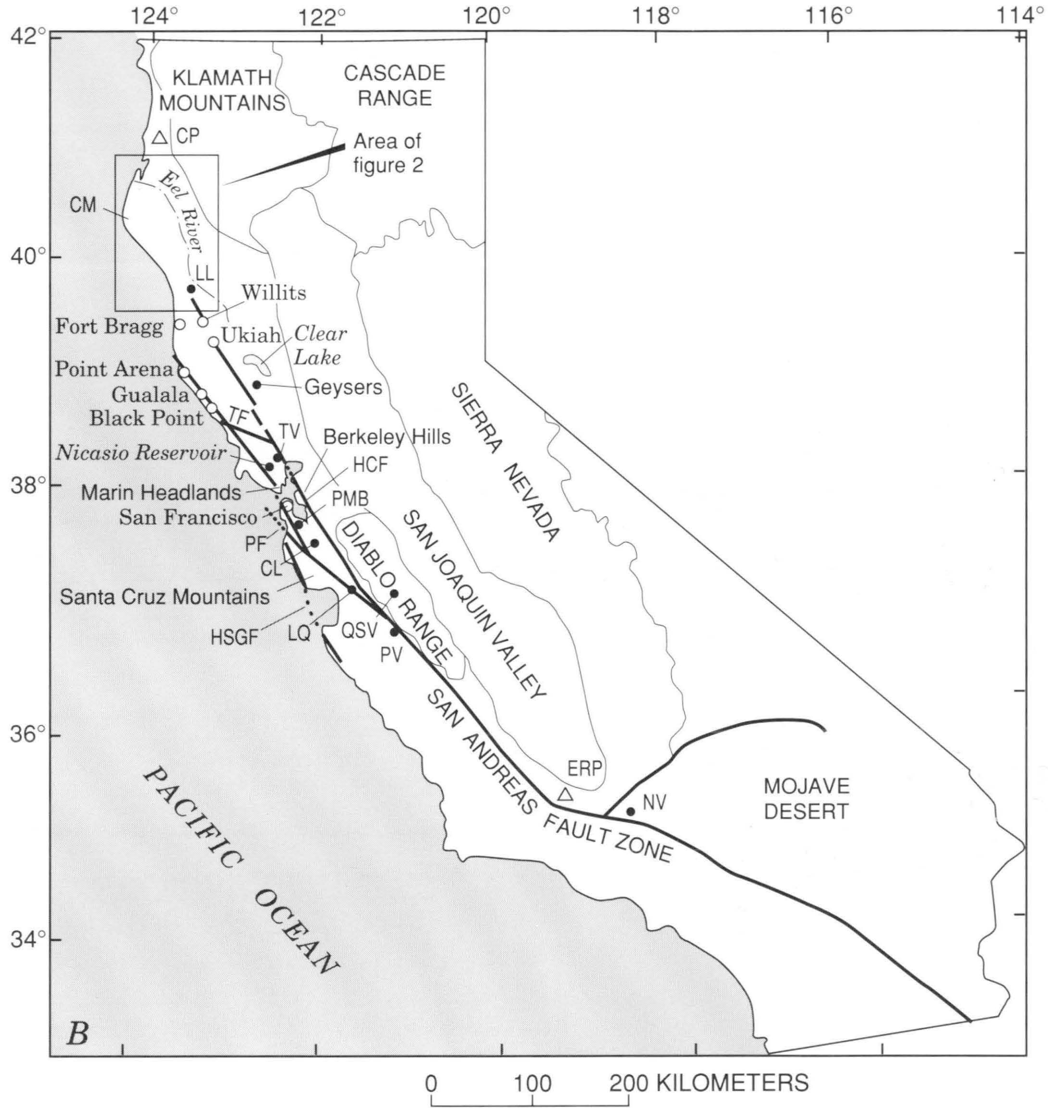


Figure 1. Index maps showing locations of geologic and geographic features mentioned in text. *A*, Tectonic features along coast of North America. FZ, fracture zone. *B*, Major geologic features in California. Faults dotted where concealed by water. CL, Calera Limestone; CM, Cape Mendocino; CP, Coyote Peak; ERP, Eagle Rest Peak; HCF, Hayward-Calaveras fault; HSGF, Hosgri-San Gregorio fault; LL, Laytonville Limestone; LQ, Logan Quarry; NV, Neenach Volcanics; PF, Pilarcitos fault; PMB, Page Mill Basalt; PV, Pinnacles Volcanics; QSV, Quien Sabe Volcanics; TF, Tolay fault, TV, Tolay Volcanics. *C*, Cape Mendocino area.

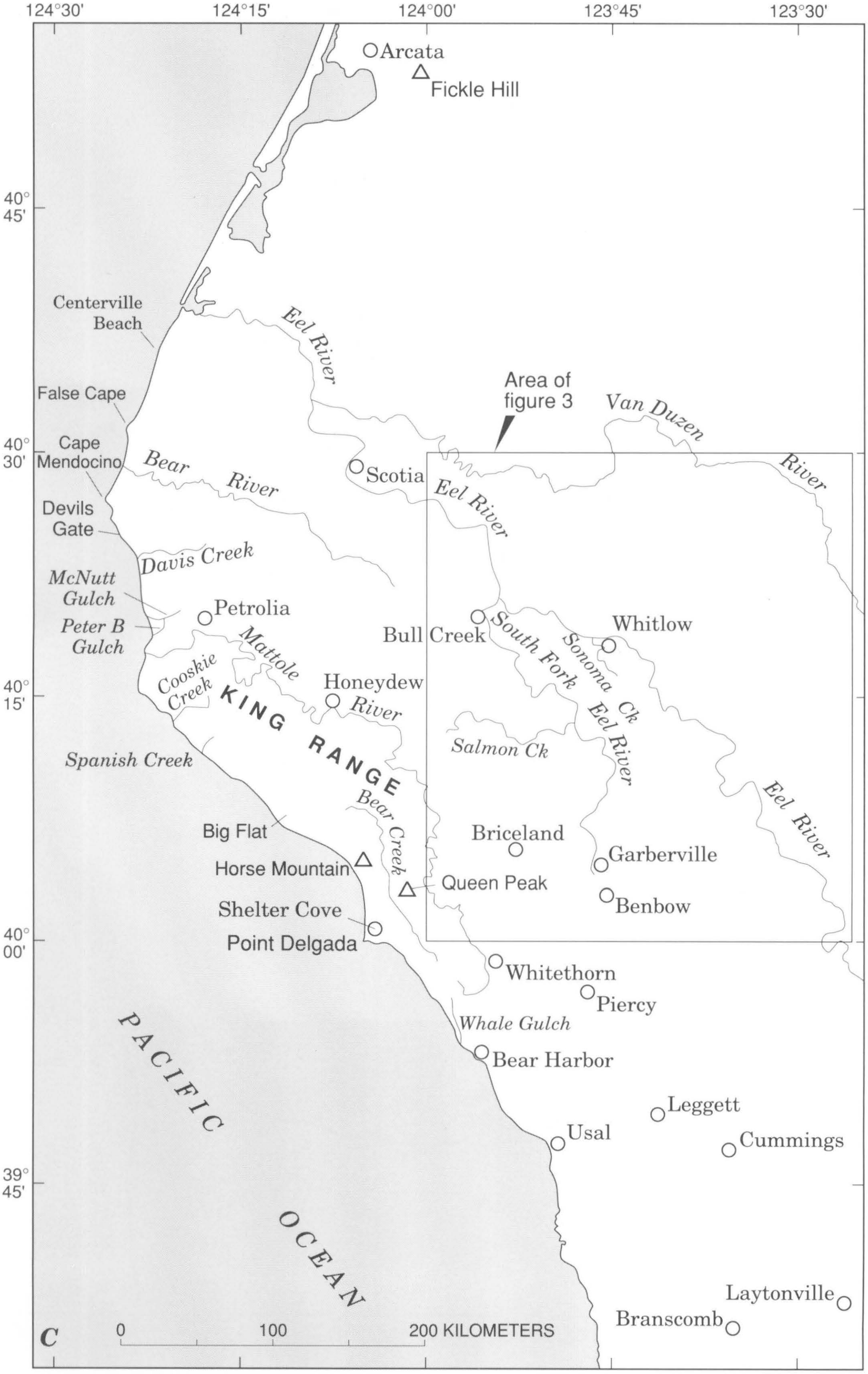
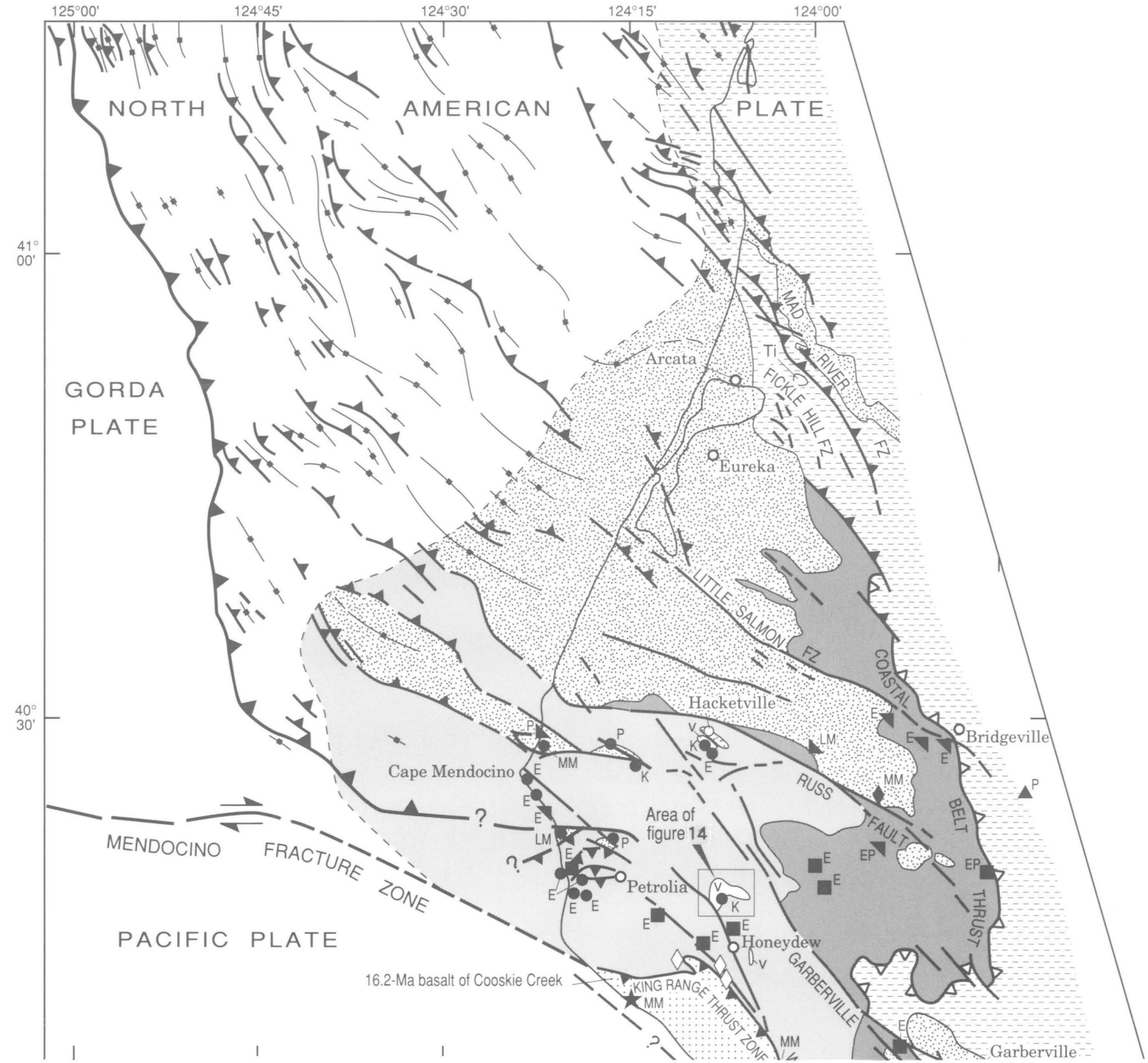


Figure 1.—Continued



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MAD RIVER FZ
FICKLE HILL FZ
Eureka
LITTLE SALMON FZ
COASTAL BELT THRUST
Hacketville
Bridgeville
RUSS FAULT
Cape Mendocino
Area of figure 14
Petrolia
Honeydew
GARBERVILLE
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16.2-Ma basalt of Cooskie Creek
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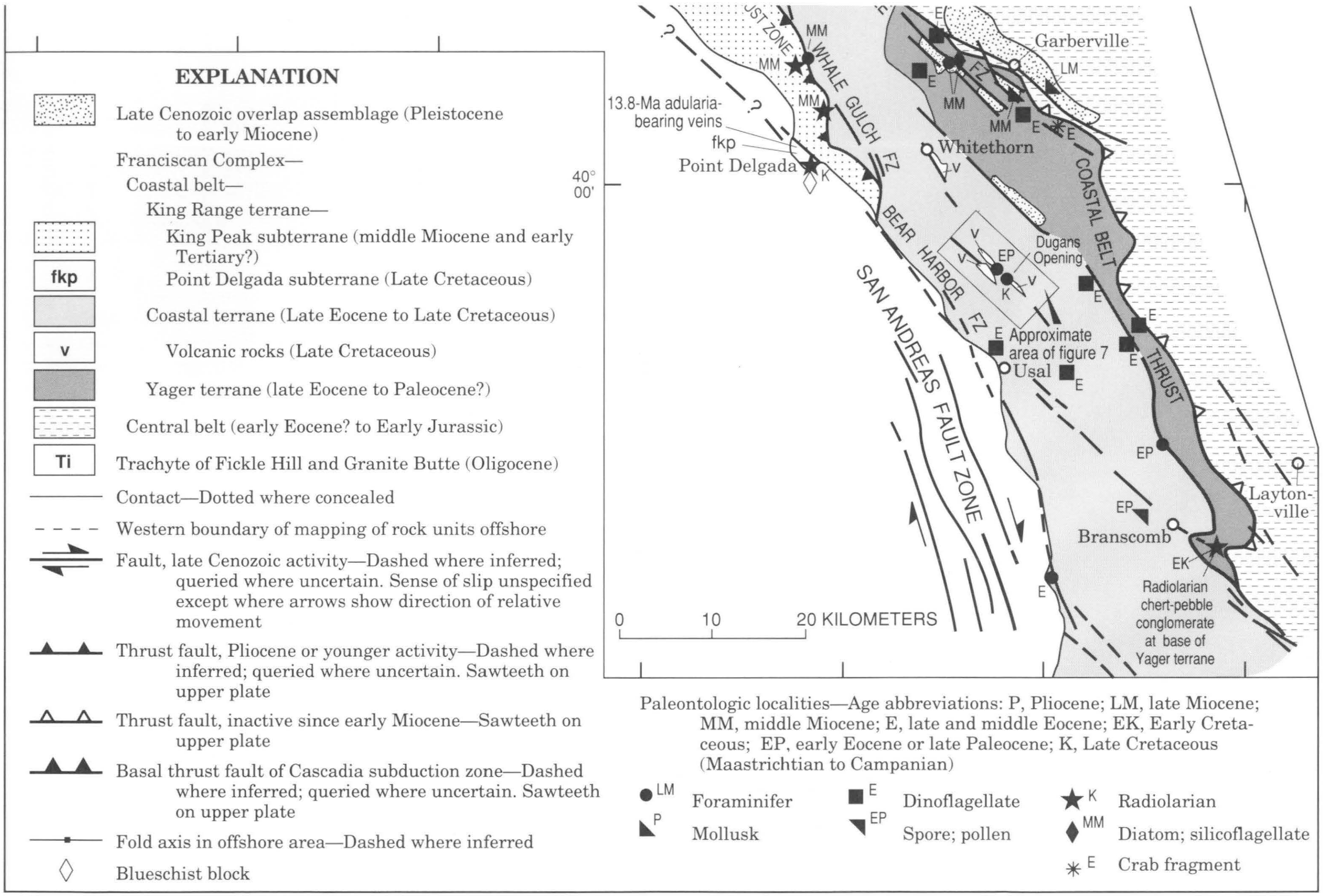
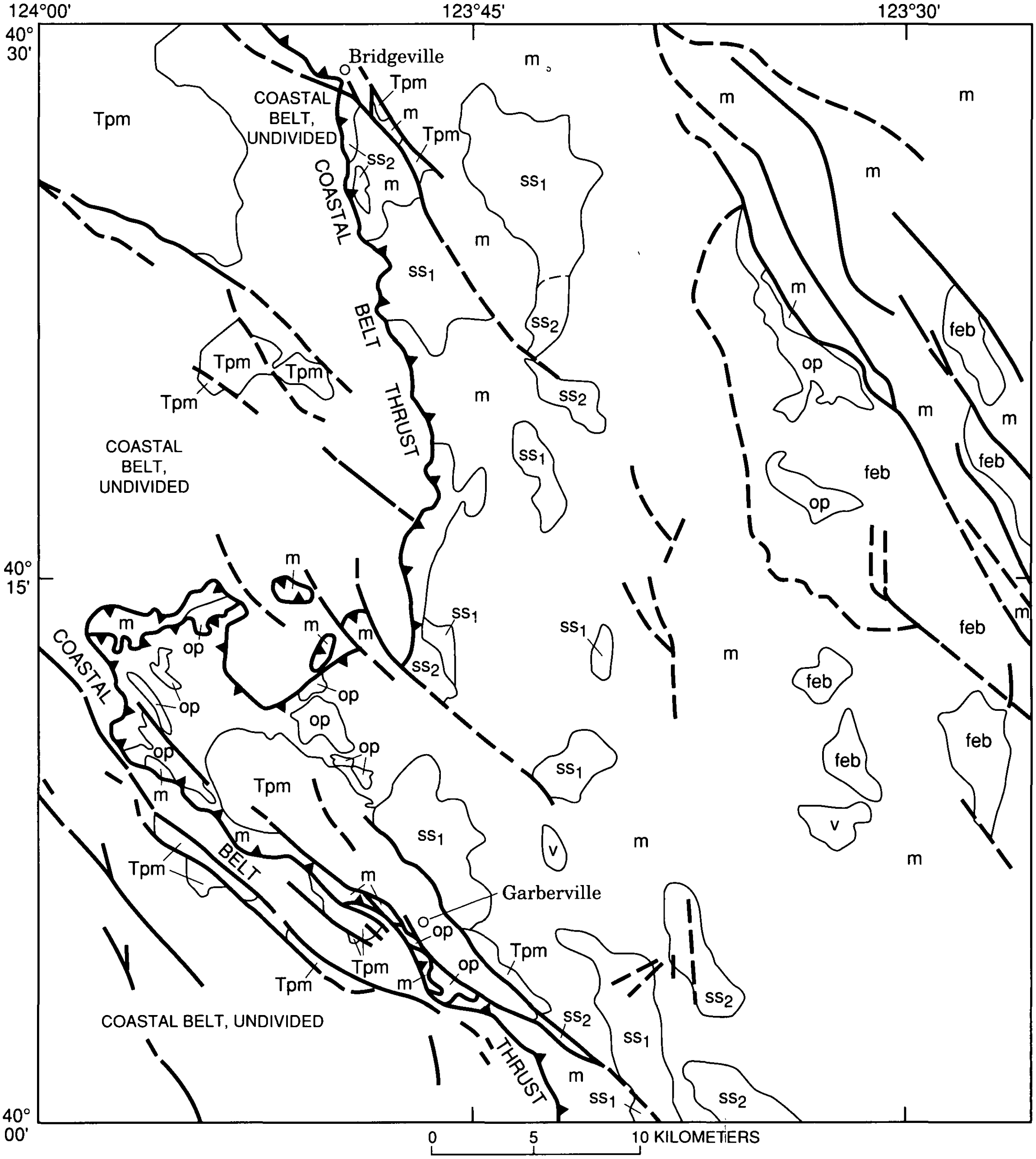


Figure 2. Geologic map of Cape Mendocino region, showing major tectonostratigraphic terranes, distribution of paleontologic sample localities, and locations of radiometrically dated rocks discussed in text. Offshore geology from McCulloch (1987a) and Clarke and Field (1989). FZ, fault zone. See figure 1*B* for location.



EXPLANATION

| Tpm | Marine overlap deposits (Pliocene and Miocene)

Central belt of Franciscan Complex (early Eocene? to early Jurassic)—Consists of:

| m | Melange—Includes blocks of limestone, sandstone, chert, basaltic rocks, and high-grade blueschist, all mixed in argillite matrix. Locally, matrix includes large blocks, here divided into:

| ss1 | Sandstone containing less than 2 percent K-feldspar

| ss2 | Sandstone containing more than 2 percent K-feldspar—Locally laumontitic

| v | Basaltic rocks—Locally includes lenses of chert

| feb | Metasandstone derived from Eastern belt of Franciscan Complex—Locally includes minor metabasalt and metachert

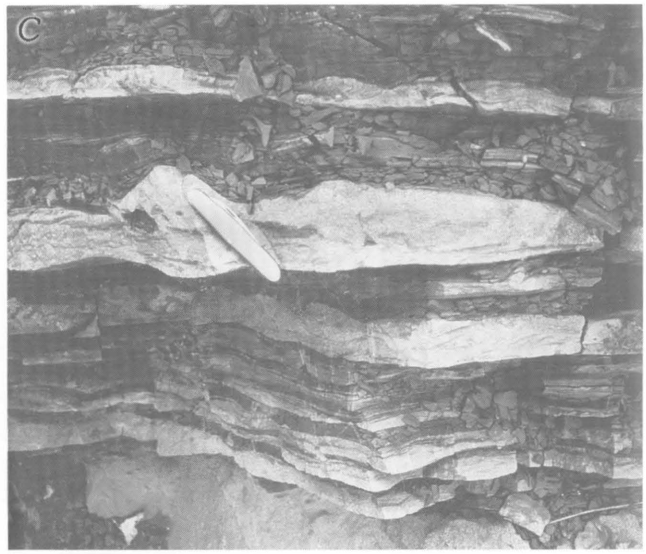
| op | Rocks of Coast Range ophiolite (Jurassic) and associated overlying strata of Great Valley sequence (Late Jurassic and Early Cretaceous)

Contact—Dashed where inferred

Fault—Dashed where inferred

Thrust fault—Sawteeth on upper plate

Figure 3. Geologic map of Central belt of the Franciscan Complex near Garberville, illustrating contact relations between Central and Coastal belts. Geology mapped by R.J. McLaughlin, S.D. Ellen, A.S. Jayko, and M.C. Blake, Jr., 1982–85. See figure 1*C* for location.



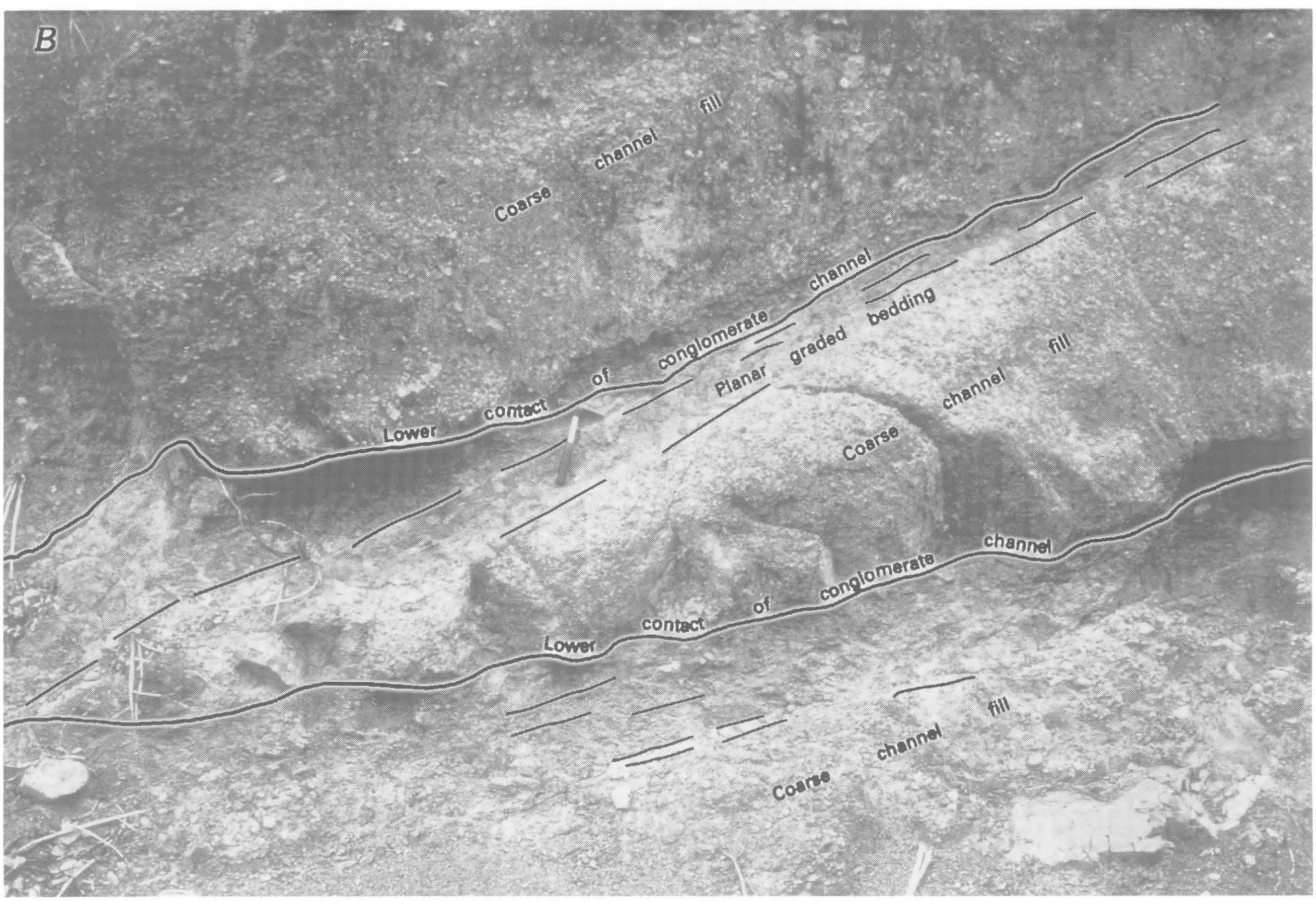


Figure 4. Sedimentary rocks of Yager terrane. *A*, Massive argillite intercalated with thinly laminated, fine-grained sandstones. Beds show fine-scale dislocation or slump features and ripple-drift structure. Beds are right side up. *B*, Rounded polymict conglomerate in stacked channels, located east of Honeydew. Note flat tops and irregular, tapered lower contacts of channels, which are marked by load features. *C*, Well-bedded, upside-down argillite and sandstone, showing conspicuous crossbedding and load features.

The channeled sequences commonly display upsection thickening (Piercy-Leggett area) and upsection thinning (Cummings area). The sandstone turbidites commonly exhibit fine-scale ripple-drift crosslaminations, as well as convolute or traction structures near the tops of beds indicative of downslope creep (fig. 4*C*).

The Yager terrane is thought to have been deposited in a channeled-slope setting or in a series of slope basins (Underwood, 1983; Bachman and others, 1984). The presence of conglomerate, stacked sandstone channels, and overbank-channel-levee deposits in many areas suggests the proximity of a major sediment-distributary system. Underwood and Bachman (1986) proposed a mixed provenance for the Yager sandstones, including granitic-metamorphic sources in the Idaho batholith, a quartz-rich Sierra Nevada plutonic source, recycled detritus from an orogenic backarc area, volcanic detritus from an active Paleogene magmatic arc, and recycled Franciscan detritus.

The Yager terrane is bounded by both low-angle and steep faults that separate it from the Coastal terrane on the west and the Central belt on the east. Differences in the age, lithology, metamorphism, and structural state of rocks across the Coastal belt thrust suggest that significant shortening has occurred between the Central belt and Yager terrane across this fault. Although sandstones of the Coastal terrane vary more widely in composition, compositional similarities to sandstones of the Yager terrane make it difficult to evaluate the magnitude of displacement along the Yager-Coastal terrane boundary; indeed, this displacement may be relatively minor. Underwood (1983) suggested that sandstones of the Coastal terrane that are similar in composition and appearance to those of the Yager terrane may have been deposited in distributary channels which carried Yager sediment across the continental slope, into the lower-slope and trench-slope areas, where sandstones of the Coastal terrane were being deposited and deformed.

Age and Paleolatitudinal Setting

The ages of rocks of the Yager terrane are based almost entirely on fossil dinoflagellates and pollen and spores. Many of the dinoflagellate localities within the Yager terrane were reported on by Evitt and Pierce (1975) and Damassa (1979). We have since collected from additional localities for this and related studies (for example, McLaughlin and others, 1982; Sliter and others, 1986). We have, in addition, separated and dated radiolarians from green chert pebbles in a conglomerate near the easternmost exposed part of the Yager terrane west of Laytonville, and collected fragments of a fossilized crab from a carbonate concretion in thin-bedded mudstone near Garberville. The distribution of fossil localities in the Yager terrane are shown in figure 2, and palynomorph ages are listed in table 1.

Dinoflagellate assemblages from the Yager terrane range in age from Paleocene to late Eocene (Evitt and Pierce, 1975; Damassa, 1979). The spore and pollen floras indicate an age range from late Paleocene to middle or late Eocene, although probable reworked Cretaceous and Paleocene to early Eocene forms occur in many samples (table 1; Evitt and Pierce, 1975). The presence of reworked palynomorphs introduces some uncertainty into the age of the Yager terrane, and so we assign a Paleocene(?) through early(?) to late Eocene age to the Yager terrane of the Coastal belt.

South of the study area, Damassa (1979) studied dinoflagellate flora from the eastern part of the Coastal belt near Ukiah (which may, in fact, be correlative with a part of the Yager terrane) and assigned an early Paleocene (Danian) age to those rocks. She observed that many dinoflagellate taxa in the Coastal belt of the Willits-Ukiah area are restricted in their distribution to the eastern part of the Coastal belt. We also note from our data (table 1) that numerous genera and species of dinoflagellates (including *Areoligera* sp., *Danea impages*, and *Spiniferites* spp.) are largely restricted to the Yager terrane. Damassa noted that terrestrially derived spores and pollen were sparse in her Danian sample from the Coastal belt, in contrast to the partly age equivalent, middle to outer neritic Moreno Formation of the San Joaquin Valley. She attributed this difference to closer proximity of the Moreno Formation depositional setting to a continental source of detritus. The depositional setting of the Yager terrane may thus have been closer to the California margin than that of the Coastal terrane, a conclusion consistent with sedimentologic and structural data.

Reworked spores and pollen of Cretaceous age from the Yager terrane include *Aquilapollenites*, *Eucommiidites*, *Vitreisporites*, and at least some *Corollina* and members of the Normapolles group (except the early Tertiary species *Nudopollis terminalis*), as well as *Proteacidites* and *Siberalpollis* (table 1). The presence of *Aquilapollenites*, a middle- to northern-latitude genus, suggests its derivation from a Cretaceous source terrane in central to northern California (Frederiksen, 1987). Reworked dinoflagellates observed in samples from the Yager terrane include *Isabelidinium* of Late Cretaceous age (W.R. Evitt, written commun., 1985) and *Gonyaulacysta jurassica* (Deflandre) (Evitt and Pierce, 1975), which occurs in both the Yager and Coastal terranes and requires reworking of unmetamorphosed source rocks of Kimmeridgian or Oxfordian age.

The crab fragments were identified by Rodney Feldmann (written commun., 1986) as belonging to *Callianassa* sp., a crab group of Cenozoic or younger age. Related *Callianassa* species are now found living in coarsely clastic, moderately nearshore habitats of the gulf coast. Thus, the crab fragments in the Yager terrane were probably displaced downslope from a shallower depositional environment into a slope or slope-basin setting.

The Yager terrane is essentially devoid of any foraminifers or radiolarians. A likely explanation for the absence of marine microfossils is that the depositional site of the Yager

Table 1. Pollen in rock samples from the Coastal and Yager terranes

[Samples arranged generally from southwest to northeast. All samples are from Humboldt County except R3425N, which is from Mendocino County. X, present; P, probably present; ?, possibly present; —, absent. C, definite Cretaceous taxa; Pa, taxa probably not ranging above the Paleocene; P–LE, taxa mainly confined to the Paleocene and lower Eocene; LE, taxa probably confined to the lower Eocene; ME, taxa probably not ranging below the middle Eocene]

	Coastal terrane		Yager terrane							
	1	2	3	4	5	6	7	8	9	10
Sample(s)	R3469	R3425N	R3473A-D	R3425B	R3712A	R3472A-D	R3470A-C	R3425D,	R3712B	R3712C,
Field No(s)	S-85-133	MT-213-83	NF85C 16-19	MT-4-83	MT-165-85	NF85C 12-15	NF85C 1-3	MT-35-83	MT-174-85	MT-174-85, MT-175-85
Alangiopollis cribellata (Srivastava) Frederiksen (PA)	—	—	—	—	X	—	—	—	—	—
sp. 1 of Frederiksen, 1983 (ME?)	—	—	—	—	—	—	—	X	—	—
Alnipollenites verus Potonie	X	X	X	X	X	X	X	X	X	X
Annutriporites subconvexus Frederiksen (ME)	X	—	X	—	—	X	P	—	X	P
Aquilapollenites sp. (C)	—	—	—	—	—	X	—	—	—	—
Betulaepollenites spp. (P–LE)	X	—	—	—	X	X	X	X	X	—
Bombacacidites fereparilis Frederiksen	X	—	—	—	—	—	—	—	X	—
cf. *B. fereparilis* (rounded triangular)	—	—	—	—	—	—	—	—	—	X
nanobrochatus Frederiksen + *Bombacacidites* aff. *B. nanobrochatus*	—	X	—	X	X	—	X	X	X	X
cf. *B. nanobrochatus* (rounded triangular)	X	—	—	—	—	X	—	—	—	—
reticulatus Krutzsch	—	X	—	—	—	—	—	—	—	—
"*Bombacacidites nacimientoensis*" (Anderson) Elsik of Drugg (1967)	X	X	—	—	—	—	—	—	—	—
Carya spp.(<29 mμ)	—	X	?	X	?	P	?	X	X	X
Caryapollenites prodromus Nichols and Ott + *C. imparalis* Nichols and Ott (PA)	X	—	—	—	X	X	—	—	X	—
Cercidiphyllites sp	—	—	—	—	—	—	—	—	X	—
Corollina spp. (PA)	—	—	—	—	—	—	—	X	X	—
Corsinipollenites sp. 1 of Frederiksen 1983 (ME)	X	—	—	X	—	X	—	—	—	?
Cupanieidites sp.	—	—	—	X	—	—	—	—	—	—
Cupuliferoidaepollenites spp	—	—	—	X	—	—	—	—	—	—
Eucommiidites sp. (C)	—	—	—	—	—	X	—	—	—	—
Insulapollenites spp.	X	X	—	—	X	X	?	—	—	—
Intratriporopollenites pseudinstructus Mai	—	—	—	X	X	—	—	—	X	X
Momipites coryloides Wodehouse+*M. strictus* Frederiksen and Christopher	—	—	—	—	X	—	X	—	X	—
Normapolles group (Cretaceous forms) (C)	—	—	—	—	—	—	X	X	X	—
Nudopollis terminalis (Pflug and Thomson) Pflug	—	—	—	—	X	—	—	—	—	—
Paraalnipollenites confusus (Zaklinskaya) Hills & Wallace (P–LE)	—	P	—	—	X	X	—	—	X	—
Pistillipollenites macgregorii Rouse	X	X	X	—	—	X	X	X	X	X
Platycaryapollenites triplicatus (Elsik) Frederiksen and Christopher (LE)	—	—	—	—	—	—	—	X	—	—
Proteacidites spp. + *Siberiapollis* spp	X	X	X	X	X	X	X	X	X	X
Subtriporopollenites aff. *S. anulatus* Pflug and Thomson	—	—	—	—	—	—	—	—	X	—
Triatriopollenites intermedius (Gladkova) Kedves (ME)	—	—	—	—	—	—	—	—	X	—
lubomirovae (Gladkova) Kedves	—	—	—	—	—	—	—	—	P	—
triangulus Frederiksen	—	—	—	—	X	—	—	—	X	—
Triporopollenites spp. (simple morphology)	X	X	—	—	X	X	X	X	X	—
Ulmipollenites krempii (Anderson) Frederiksen	—	X	—	—	—	—	—	—	—	—
tricostatus (Anderson) Frederiksen	X	—	—	—	—	—	X	X	—	—
undulosus Wolff	—	—	—	—	—	—	—	—	X	—
Vitreisporites spp. (C)	—	—	—	X	X	X	X	X	X	—

Sample locations:
1. Cape Mendocino 7.5' quadrangle, SE1/4 sec. 3, T. 1 S., R. 3 W.
2. Lincoln Range 7.5' quadrangle, NW1/4 sec. 19, T. 21 N., R. 16 W.
3. Red Crest 7.5' quadrangle, NE1/4 sec. 11, T. 1 N., R. 2 E.
4. Weott 7.5' quadrangle, SE1/4 sec. 27, T. 1 S., R. 2 E.
5. Garberville 7.5' quadrangle, E1/2 sec. 22, T. 5 S., R. 4 E.
6. Bridgeville 7.5' quadrangle, NW1/4 sec. 17, T. 1 N., R. 3 E.
7. Bridgeville 7.5' quadrangle, NE1/4 sec. 16, T. 1 N., R. 3 E.
8. Myers Flat 7.5' quadrangle, NW1/4 sec. 32, T. 1 S., R. 3 E.
9. Harris 7.5' quadrangle, W1/2 sec. 21, T. 5 S., R. 4 E.
10. Harris 7.5' quadrangle, E1/2 sec. 22, T. 5 S., R. 4 E.

terrane received a thick and rapid influx of land-derived, organic-rich, fine-grained siliciclastic materials which greatly diluted the micro-organisms, or, alternatively, that the sparse foraminifers and radiolarians were removed through postdepositional diagenesis. A deep-marginal basin high on the continental slope or a marine deltaic setting might provide an appropriate depositional model for the Yager terrane.

Local source areas in the Central belt probably provided detritus to the Yager terrane during Paleocene(?) to late Eocene time. West of Laytonville, along the east side of the Yager terrane, thick lenses of conglomerate occur. Although most of the conglomerate clasts are rounded, one lens at the faulted base of the Yager terrane is composed of angular green radiolarian chert similar in appearance to bedded chert occurrences in the adjacent Central belt of the Franciscan Complex. Radiolarians from these chert clasts are Early Cretaceous (Berriasian to Valanginian) in age (C.D. Blome, written commun., 1983) and are identical to assemblage MH–5 of the Marin Headlands and Geysers chert terranes of the Central belt (McLaughlin and Pessagno, 1978; Murchey, 1984; Murchey and Jones, 1984). Furthermore, this radiolarian fauna is restricted to the Franciscan Complex and does not occur in the Great Valley sequence. *Acanthocircus dicranocanthos*, which occurs in the radiolarian assemblage from chert clasts of the Yager terrane, was noted by Murchey (1984), Pessagno and others (1984), and Pessagno and Blome (1986) as indicative of a low-paleolatitude oceanic setting.

Deformation

The Yager terrane underwent complex deformation characterized by multiple folding (fig. 5) within the broad time interval between the last deposition of Yager strata (ca. 41 Ma) and the earliest deposition of little-deformed, nonaccretionary rocks above the Yager and Coastal terranes (ca. 22 Ma). The folding was accompanied or followed by penetrative shearing, especially near faulted contacts with the Central belt to the east and the Coastal terrane to the west.

We do not know whether this folding and shearing occurred during the entire 19-m.y.-long Oligocene to Miocene interval or, instead, was relatively brief. For example, the deformation may have lasted only 6 m.y. if, as local field relations suggest, it preceded the 36- to 35-Ma intrusion of trachytic rocks near Arcata into the upper plate of

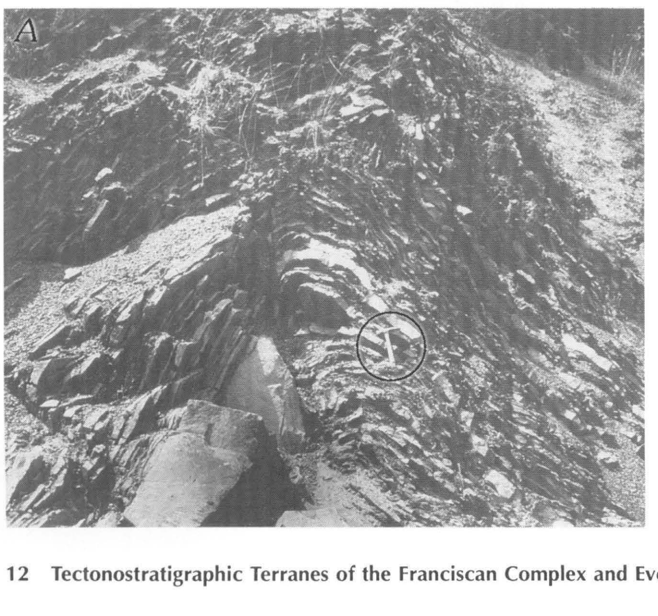


Figure 5. Folds in sedimentary rocks of Yager terrane. *A*, Upright fold, located along Van Duzen River. Note faulting of fold crest and truncation of thick sandstone bed by fault in apex of fold. Fold plunges north. Hammer (circled) shows scale. *B*, Refolded rocks, located along Eel River near Garberville. Beds in fold are overturned, indicating an earlier fold event that predates fold exposed here. *C*, Recumbent fold, located east of Briceland. Fold axis dips southwest, and vergence is eastward. Note hammer (circled) for scale.

the Coastal belt thrust. However, if these intrusions are not rooted below the thrust or are sheared off by it, then they have no bearing on the timing of Yager deformation.

At least three major fold sets are evident in the Yager terrane. The earliest folds (f_1) consist of map- and outcrop-scale recumbent folds with subhorizontal axes. In the few areas where overturned f_1 fold limbs can be observed, tectonic transport to the north-northeast is indicated. This direction may have been associated with early, landward-vergent tectonic transport of the Yager terrane during Oligocene time, which preceded displacement across the Coastal belt thrust. The f_1 folds are refolded by upright to asymmetric isoclinal folds (f_2) that are overturned steeply to the southwest or northeast, indicating continued northeast-southwest-oriented compression. We speculate that those f_2 folds may have been associated with later Oligocene to early Miocene emplacement of the Central belt over the Yager terrane along the Coastal belt thrust. A much later, f_3 generation of open, map-scale folds has warped lower-plate Yager terrane, upper-plate Central belt, and overlying middle Miocene to Pliocene strata into anticlinal and synclinal warps that plunge southeast. This latest folding probably occurred in association with transpression during northward propagation of the San Andreas fault system in very late Cenozoic time.

Penetrative deformation has also occurred within rocks of the Yager terrane, especially along its faulted east and west sides. This deformation is characterized by the development of anastomosing, undulatory shear surfaces, boudinage, and brittle fracturing. Southeast of Benbow, at least two shallowly dipping zones of penetratively sheared rocks, several hundreds of meters thick (melange zones), cut the Yager terrane. These melange zones apparently crosscut both f_1- and f_2-fold trends and are, in turn, folded by latest f_3 folds. Their low-angle trend, subparallel to the Coastal belt thrust south of Garberville, suggests that they may be cogenetic with emplacement of the Coastal belt thrust. However, detachment faulting may be as defensible as thrusting for the origin of the melange zones within the Yager terrane. Melange zones along the western margin of the Yager terrane locally exhibit extensional deformation and may be related to normal faulting along the margin of the Yager Basin. Extensional deformation of the Yager terrane possibly occurred in conjunction with uplift of the adjacent Coastal terrane to the west.

Rocks of the Yager terrane, together with those of other terranes of the Coastal belt, are metamorphosed to zeolite grade, though less so than those of the Coastal terrane. Where sandstone beds of the Yager terrane are broken, fractured, or shattered, the fractures are filled with laumontite+calcite+quartz. This zeolite assemblage is especially prevalent along the faulted west and east sides of the Yager terrane, where the rocks are most extensively fractured. This fracturing apparently increased rock permeability locally and enhanced the circulation of hydrothermal fluids from which the zeolites precipitated.

Paleomagnetic Studies

Sampling of the Yager terrane for paleomagnetic study has been limited to unweathered river-bottom exposures of thin-bedded, carbonate-cemented, fine-grained siltstones showing common ripple-drift laminations. The areas that have been sampled include a section along Salmon Creek (D.E. Champion, oral commun., 1985), the Eel River at Scotia (R.E. Wells and others, unpub. data, 1985); and Sonoma Creek, a tributary to the Eel River near Whitlow (S.G. Miller, oral commun., 1985). Sample suites from these localities failed inclination-only fold tests and (or) showed evidence of major postdepositional remagnetization. The timing and mechanism of this remagnetization are unknown, and so, to date, all paleomagnetic data from the Yager terrane are inconclusive.

Coastal Terrane of the Coastal Belt

The Coastal terrane of the Coastal belt, like the Yager terrane, is composed of sandstone and argillite. Unlike the Yager, however, the Coastal terrane includes (1) minor but significant exotic blocks of basaltic intrusive rocks, flows, and breccias that in places are associated with pink to gray pelagic limestone; and (2) rare blocks of garnet-bearing glaucophane schist. In addition, sandstones of the Coastal terrane are compositionally more heterogeneous than those of the Yager terrane, a significantly larger area of the Coastal terrane is composed of tectonic melange and rocks deformed by penetrative shear, and parts of the Coastal terrane are significantly older than the Yager terrane.

Sandstone, Shale, and Conglomerate

Sandstones of both the Coastal and Yager terranes range petrographically from feldspathic to arkosic, typically containing more than 50 volume percent plagioclase in outcrops in the northern parts of the Yager and Coastal terranes, more than 50 volume percent monocrystalline quartz in the south, and as much as 20 volume percent K-feldspar along the entire length of both terranes (Underwood and Bachman, 1986). Many sandstones of the Coastal terrane are more lithic than those of the Yager (Underwood and Bachman, 1986), although there is essentially 100-percent overlap of the compositional field of the Yager terrane by that of the Coastal terrane. The most distinctive lithic components in sandstones of the Coastal terrane are igneous-rock fragments of shallow-intrusive and extrusive origin. These igneous-rock fragments are dominantly silicic in composition and microfelsitic to coarsely porphyritic in texture, suggesting an island-arc derivation. The other fragments consist of lesser amounts of silicic tuff, chert, mafic igneous rocks, quartz- and white mica-bearing schist, phyllite, slate, and shale. Nonopaque detrital heavy-mineral accessory assemblages are dominated by chloritized biotite, muscovite, epidote-clinozoisite, sphene, garnet, zircon, and schorlitic tourmaline. As is true of the Yager terrane, these data suggest a mixed provenance, including major deeply eroded plutonic sources that were plagioclase rich to the north and more quartzose to the south; a magmatic arc; and regionally metamorphosed orogenic terranes from which recycled detritus was derived (Underwood and Bachman, 1986).

Conglomerates of the Coastal terrane consist of clastic suites identical to those of the Yager terrane. For example, conglomerates of the Coastal terrane, like those of the Yager terrane, contain recycled rounded clasts of hypabyssal intrusive and extrusive igneous rocks of intermediate to silicic composition, black and green chert and metachert, quartzite, hornfelsic meta-argillite, and metaigneous rocks.

At one locality in the Coastal terrane, approximately 5 km south of Cape Mendocino near Devils Gate, conglomerate is interbedded in an unusually intact sequence of arkosic sandstone and argillite of Eocene age (see subsection below entitled "Age of the Coastal Terrane"). The sandstone and argillite at this locality display very well preserved graded bedding, ripple-drift laminae, and traction features indicative of channelized turbidite deposition on a submarine slope and overbank deposition in interchannel areas. Abundant soft-sediment deformational features, including liquefaction and load structures and soft-sediment extensional structures, suggest deposition in an area of submarine slope failure (figs. 6*A*, 6*B*). The conglomerate at Devils Gate contains, in addition to the clastic suite mentioned above, another clastic suite indicative of derivation from the Eastern and Central belts of the Franciscan Complex. This second clastic suite includes subangular to subrounded, pebble- to boulder-size clasts of red radiolarian chert and metachert, metabasalt, serpentinized peridotite, and rare clasts of lawsonite- and jadeite-bearing metasandstone reconstituted to textural zone 2 (of Blake and others, 1967) (figs. 6*C*–6*E*). Blueschist-grade metasandstone of the Franciscan Complex that contains jadeite in the same abundance as found in the conglomerate clasts at Devils Gate (approx 5–7 volume percent) is known in California mainly from the central Diablo Range, particularly in the Mount Hamilton area (Maddock, 1955; Kerrick and Cotton, 1971). These data suggest that the Coastal terrane may have received detritus from uplifted rocks in the vicinity of the central Diablo Range during Eocene time.

Basaltic Rocks

Blocks of basaltic rocks have been mapped in several areas of the Coastal terrane. The most extensive exposures occur along Parkhurst Ridge, near Honeydew, and near Usal, southwest of Piercy. Minor but significant outcrops of basalt flows occur near Hacketville, Whitethorn, and south of Fort Bragg along the coast. Elsewhere in the Coast Ranges, Kramer (1976) mapped a large area of basaltic volcanic rocks in the Coastal terrane west of Willits. The basalts chiefly are pillow flows, flow breccias, and glassy aquagene tuff (hyaloclastite). However, diabase

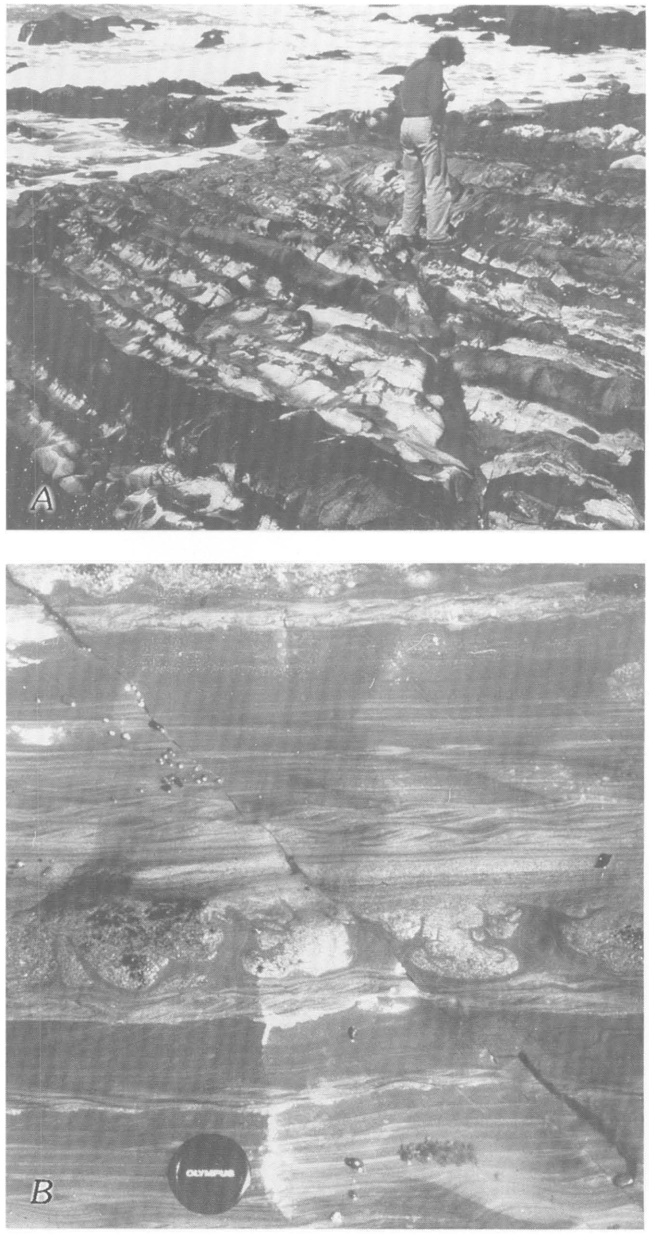


Figure 6. Sedimentary rocks of Coastal terrane from Devils Gate area. *A*, Well-bedded sandstone and argillite slope deposits. Section faces north (to right). *B*, Right-side-up ripple-drift crosslaminae and soft-sediment deformation. *C*, Metasandstone clast (to right of hammer) in conglomerate lens, displaying pronounced metamorphic fabric. Contains both lawsonite and jadeite, indicating derivation from Eastern belt of Franciscan Complex, probably from Diablo Range. *D*, Photomicrograph of metasandstone clast shown in *C*; magnification, ×100. J, jadeitic pyroxene; L, lawsonite. Crossed nicols. *E*, Same as figure 6*D*, but with uncrossed nicols.

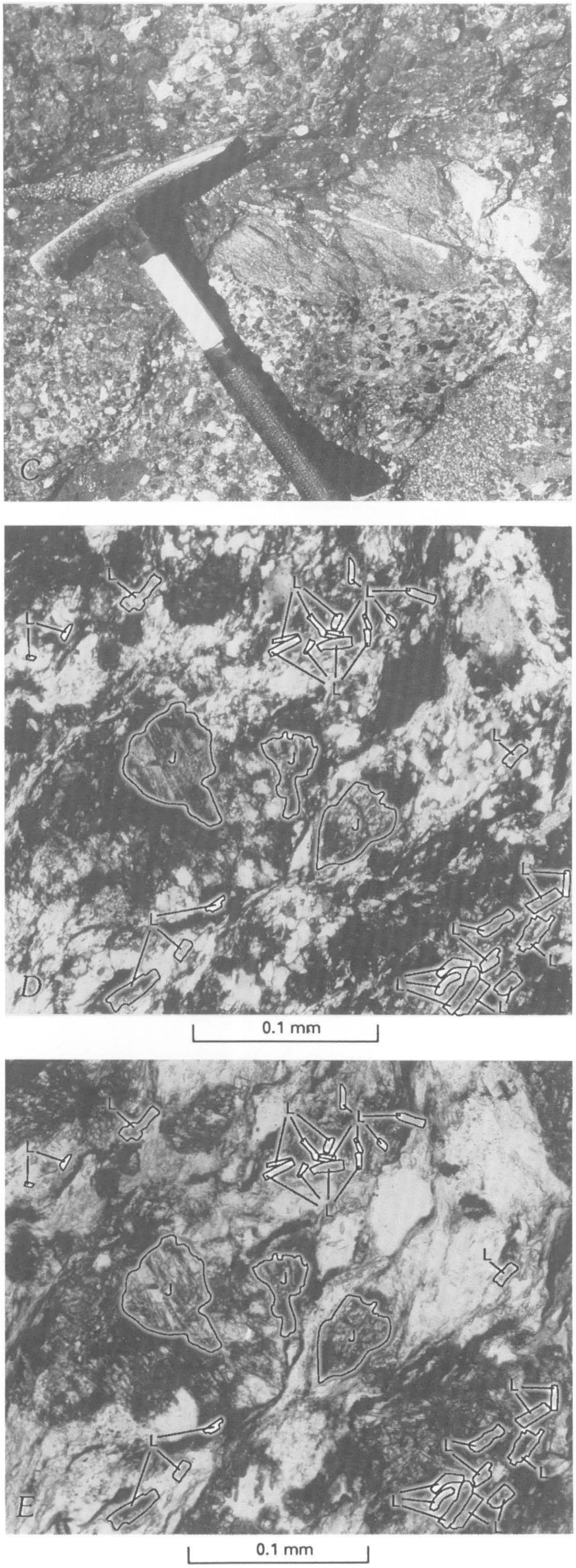


Figure 6.—Continued

dikes and sills occur with the extrusive rocks at Parkhurst Ridge and Usal, and isolated diabase intrusive bodies occur at Whitethorn. At all of these localities except Usal, the basaltic rocks are in fault contact with enclosing sheared sandstone and interbedded argillite of the Coastal terrane and thus are considered to be tectonic blocks. In the Usal area near Dugans Opening, basalt flows are interbedded with thick beds of arkosic sandstone, argillite, and altered glassy basaltic tuff (figs. 7, 8). The interbedded sandstone, argillite, tuff, and basalt form a composite block in this area, a point of some importance to our plate-tectonic reconstruction of the Coastal terrane. Basaltic rocks of the Coastal terrane are associated with pink to gray, manganiferous, pelagic, foraminiferal limestone at many localities.

The basaltic rocks have glassy to intersertal ophitic textures but locally are vesicular, suggesting local extrusion in a shallow submarine setting (Usal). The intrusive rocks are subophitic to ophitic. Primary clinopyroxenes are predominantly augite (locally, titanaugite) and pigeonite; the plagioclase is largely albitized; accessory opaque minerals include magnetite, ilmenite, and pyrite; and nonopaque accessories include sphene and apatite. Glass in the flow rocks and tuffs commonly is altered to pumpellyite, celadonite, and smectite, and vesicles and vugs are filled with calcite+quartz+chlorite or pumpellyite. An early, moderate-temperature (290–400°C) alteration assemblage, suggestive of subsea hydrothermal activity, includes chlorite+pumpellyite or chlorite+prehnite+pumpellyite. A later, lower-temperature, vein-filling zeolite assemblage indicative of temperatures from 225 to 230°C at about 3 kbars (Liou and others, 1985) includes chlorite+laumontite+calcite+pumpellyite+natrolite+datolite (see Blake and others, 1988).

The formational setting of basaltic rocks of the Coastal terrane is suggested by various plots of their chemistry (figs. 9, 10; table 2). On a ternary discrimination plot of MnO versus P_2O_5 versus TiO_2 contents (fig. 9*A*; Mullen, 1983), the basalts lie dominantly within the compositional field of midoceanic ridge basalts. Three samples from the vicinity of Usal plot in the field of island-arc tholeiites, one very close to the calc-alkaline boundary; however, these rocks are from an area of widespread secondary Mn mineralization, probably due to submarine hydrothermal processes. One sample, from Parkhurst Ridge near Honeydew, plots in the field of seamount tholeiites. On a plot of Na_2O+K_2O versus SiO_2 contents (fig. 9*B*), the basalts are transitional from tholeiitic to alkalic in composition. On a discrimination plot of P_2O_5 versus TiO_2 contents (fig. 9*C*; Ridley and others, 1974), the basalts clearly lie within the compositional fields of oceanic-ridge and seamount basalts. On a plot of TiO_2 content versus FeO/MgO ratio (fig. 9*D*; Hekinian and Fouquet, 1985; Shervais and Kimbrough, 1985), the basalts follow fractionation trends typical of East Pacific Rise basalts and midoceanic-ridge basalts in general, unlike arc-related basaltic rocks.

On figure 10, we present several scatter plots of minor and trace elements in an attempt to further discriminate the formational settings of basaltic rocks of the Coastal terrane. It is relatively clear from these plots that the basalts formed in an ocean-floor or ridge setting and not in an island arc, as shown in figures 10*A* and 10*B* by high Ti content (7,500–17,000 ppm) relative to Cr (80–230 ppm) and V (60–500 ppm), in figure 10*C* by high Ni content (60–200 ppm) and high Ti/Cr ratios, and in figure 10*D* by high Ti and low to moderate Zr contents (60–160 ppm). Although the plots of Ti versus Cr contents (fig. 10*A*), V versus Ti contents (fig. 10*B*), and Ti/Cr ratio versus Ni

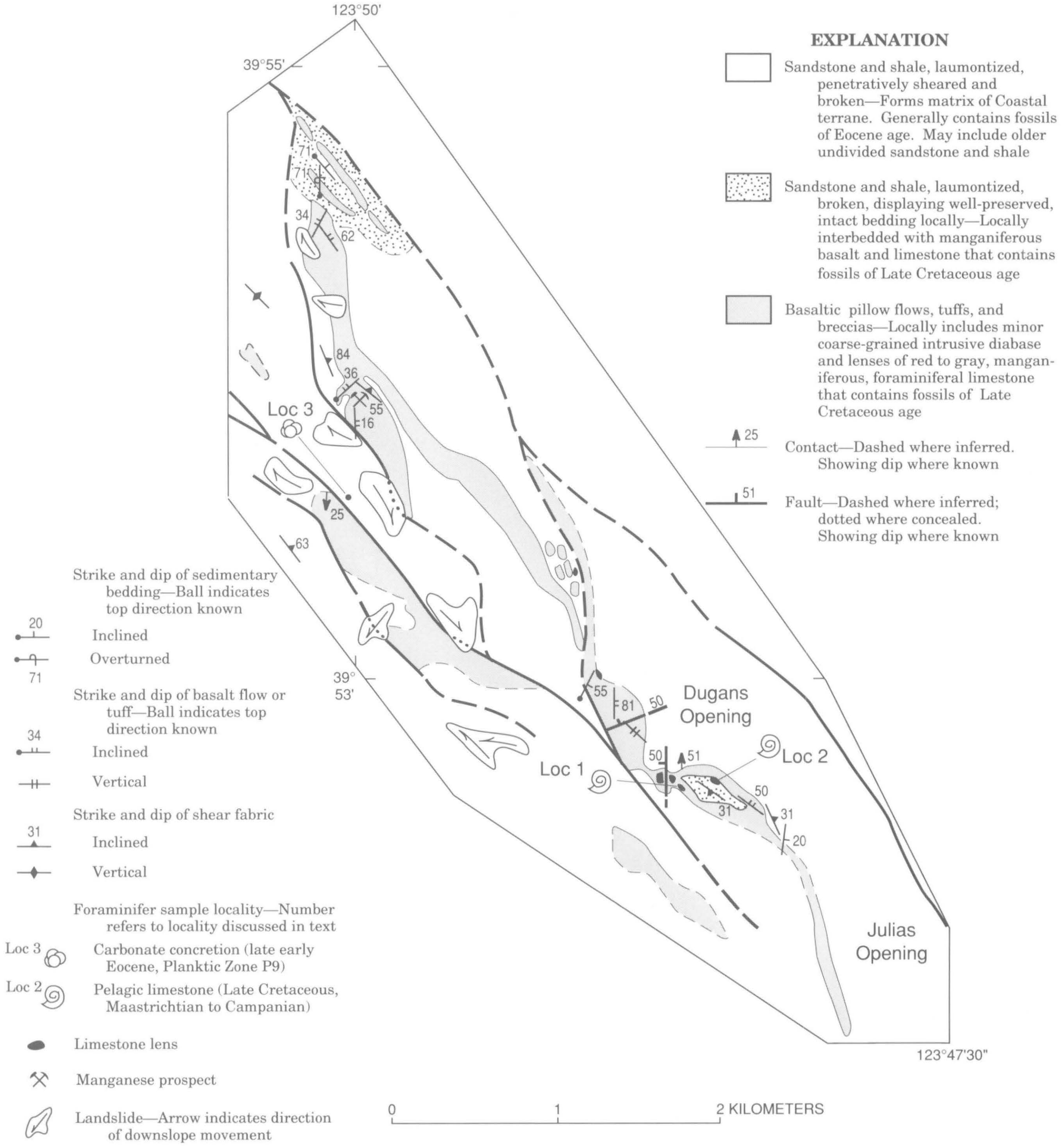


Figure 7. Detailed geologic map of part of Coastal terrane near Usal, showing location of foraminifer samples discussed in text. Geology mapped by R.J. McLaughlin, 1983–85. See figure 2 for location.

Figure 8. Volcanic rocks and interbedded arkosic sandstone of Coastal terrane, located in Dugans Opening area near Usal. *A*, Basalt flow interbedded with arkosic sandstone. Basalt (dark rocks, left, with hammer (circled) for scale) overlies tuffaceous shale and thinly interbedded laumontized sandstone (white streaked beds, right center), which, in turn, overlie thinning- and fining-upward sequence of channeled laumontized sandstone (light colored rocks, far right). Section faces east (to left). Basaltic rocks are associated with ferromanganese mineralization. *B*, Thinning- and fining-upward sequence of arkosic sandstone depositionally below and west (to right) of basalt flow shown in *A*. Note undulatory loading along base of sandstone beds and local channeling into underlying shaly sequences. Section faces east (to left). Note hammer (circled) for scale. *C*, Attenuated and laumontized basalt flows intercalated with altered glassy tuff (hyaloclastite). *D*, Photomicrograph of basaltic tuff, extensively altered to smectite mineral assemblages (filling conspicuous parting in upper center); magnification, ×40. Plagioclase laths are locally altered to laumontite, and clinopyroxene is locally replaced by epidote-group minerals (epidote, pumpellyite, clinozoisite).

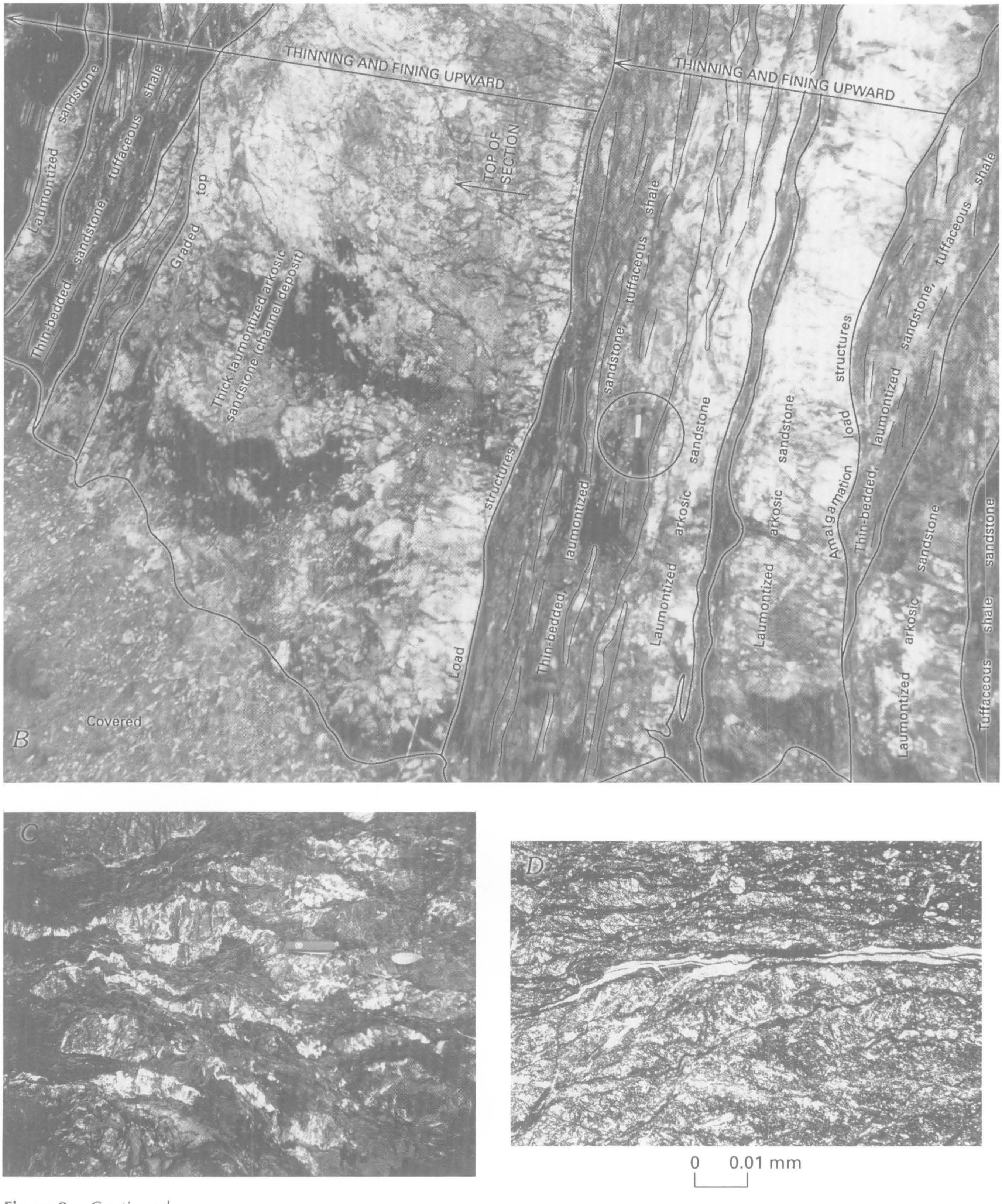


Figure 8.—Continued

content (fig. 10*C*) suggest affinities to midoceanic-ridge basalts, the plot of Ti versus Zr contents (fig. 10*D*) suggests that an elevated offridge oceanic setting, probably a seamount or plateau, may best fit the data.

Thus, the field relations, petrography, and geochemistry all indicate oceanic near-ridge and (or) somewhat-offridge formational settings for basaltic rocks of the Coastal terrane. Some of the vesicular flow rocks were likely extruded at or near sea level. This oceanic setting contrasts with the apparent arc-continental provenance of the sedimentary rocks within which the basaltic rocks are tectonically incorporated. In spite of this overall contrast, at Usal, sandstones are clearly interbedded with and overlie basaltic flow rocks (figs. 8*A*, 8*B*). These sandstones are also arkosic, containing angular quartz and feldspar, as well as 14 to 21 volume percent K-feldspar. Furthermore, the interbedded sandstones contain minor detrital quartz-mica schist, biotite, muscovite, garnet, and epidote-group minerals, consistent with their derivation from deeply eroded granitic-plutonic and regionally metamorphosed orogenic sources along the American plate margin. Together, these data argue that basaltic rocks of the Coastal terrane formed in a near-ridge oceanic setting which was at least within reach of sediment derived from the American plate margin.

Basaltic rocks of the Coastal terrane are Late Cretaceous in age (Campanian to Maastrichtian), on the basis of the ages of planktic foraminifers in pink to gray pelagic limestone locally interleaved with the flow rocks (Sliter and others, 1986) at several localities (fig. 2). This relation requires that the arkosic sedimentary rocks interbedded with the basalts at Usal are coeval, although the sheared arkosic sandstone and argillite which tectonically enclose the basalts (and interbedded sandstone) at Usal and elsewhere in the Coastal terrane are early to late Eocene in age (see subsection below entitled "Age of the Coastal Terrane").

Limestone

Limestone of the Coastal terrane occurs in two distinctly different lithologic settings of varying depositional origin. The first occurrence is as carbonate concretions within thin-bedded sequences of black argillite and minor interbedded sandstone, which commonly are penetratively deformed into zones of scaly argillite mapped as melange. The second occurrence is as reddish-pink, greenish-gray, or white pelagic limestone lenses, from less than 7 to more than 10 m thick and as much as 500 m long, intercalated with or overlying basaltic rocks.

Carbonate Concretions and Thin Carbonate Beds

The carbonate concretions in the Coastal terrane are similar in their associations to the carbonate concretions in the Yager terrane. However, the associated argillitic rocks of the Coastal terrane commonly are significantly more deformed than the argillite of the Yager terrane, as reflected by a penetrative shear fabric (fig. 11*A*). These argillitic rocks of the Coastal terrane probably represent hemipelagic and interchannel-overbank deposition in a lower-slope or trench-slope setting.

Locally, thin carbonate-bearing beds occur within areas of mildly deformed, thin-bedded flysch, interbedded with channelized sandstone and conglomerate. These intact carbonate-bearing sequences have sedimentary structures (ripple-drift laminations, load structures, current features, and synsedimentary deformation structures) and sandstone compositions similar to those in the Yager terrane. Carbonate-bearing beds in these intact blocks commonly are laterally more extensive than in more deformed, argillitic parts of the Coastal terrane.

The carbonate concretions associated with argillitic rocks of the Coastal terrane, particularly in the area surrounding Petrolia, have a high organic content, as indicated by an abundance of carbonized plant matter, palynomorphs, and rare occurrences of liquid hydrocarbons. Unlike those in the Yager terrane, however, the carbonate concretions in the Coastal terrane locally contain planktic foraminifers (fig. 11*B*) and commonly show abundant bioturbation features.

Pelagic Limestone

The pelagic limestone associated with basaltic rocks of the Coastal terrane, unlike the carbonate concretions associated with argillitic rocks, is relatively pure. It locally contains minor admixed mafic, glassy volcanic detritus (fig. 12*A*), laminar horizons of chemically precipitated red to green clay, manganese oxide, or cherty tuff (Parkhurst Ridge) that possibly represents devitrified ash. Bioturbation and dissolution partings are common to abundant. At Usal, where arkosic terrigenous sandstone is interbedded with basalt, pink pelagic limestone from within the basalt sequence is invaded along microfractures by microscopic clastic dikes of arkosic silty sandstone (figs. 12*B*, 12*C*).

Blueschist

Blocks of garnet-free and garnet-bearing glaucophane schist (types III and IV blueschist of Coleman and Lee, 1962) occur locally within melange of the Coastal terrane along its contact with the King Range terrane. These blueschist blocks, which probably were originally amphibolite and garnet amphibolite (Moore and Blake, 1986), are identical to those in the Central belt of the Franciscan Complex (McLaughlin and others, 1982). The melange zones in which these blueschist blocks occur have been viewed as sutures between the King Range terrane on the west and other terranes of the Coastal belt to the east (McLaughlin and others, 1982). The restricted occurrence

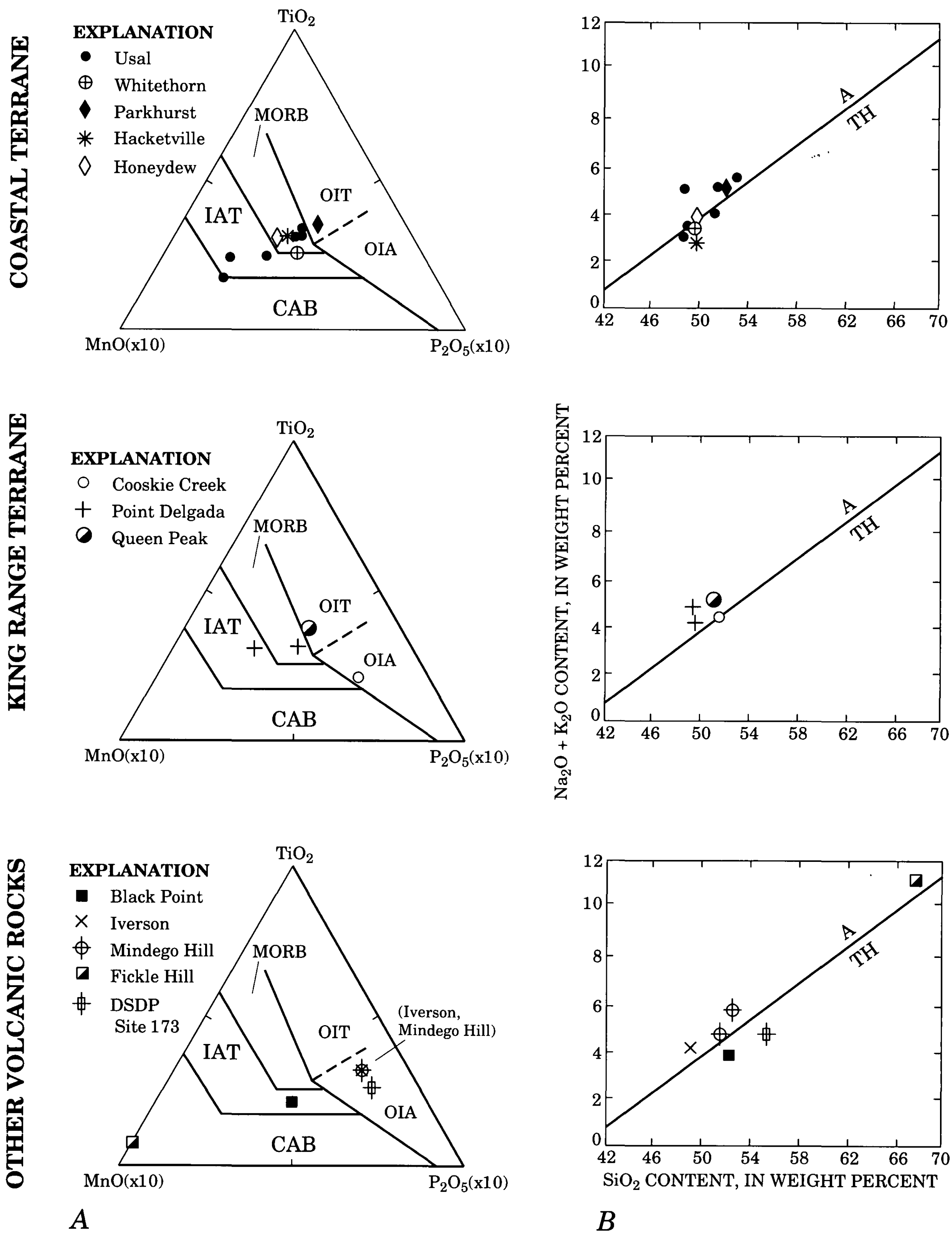
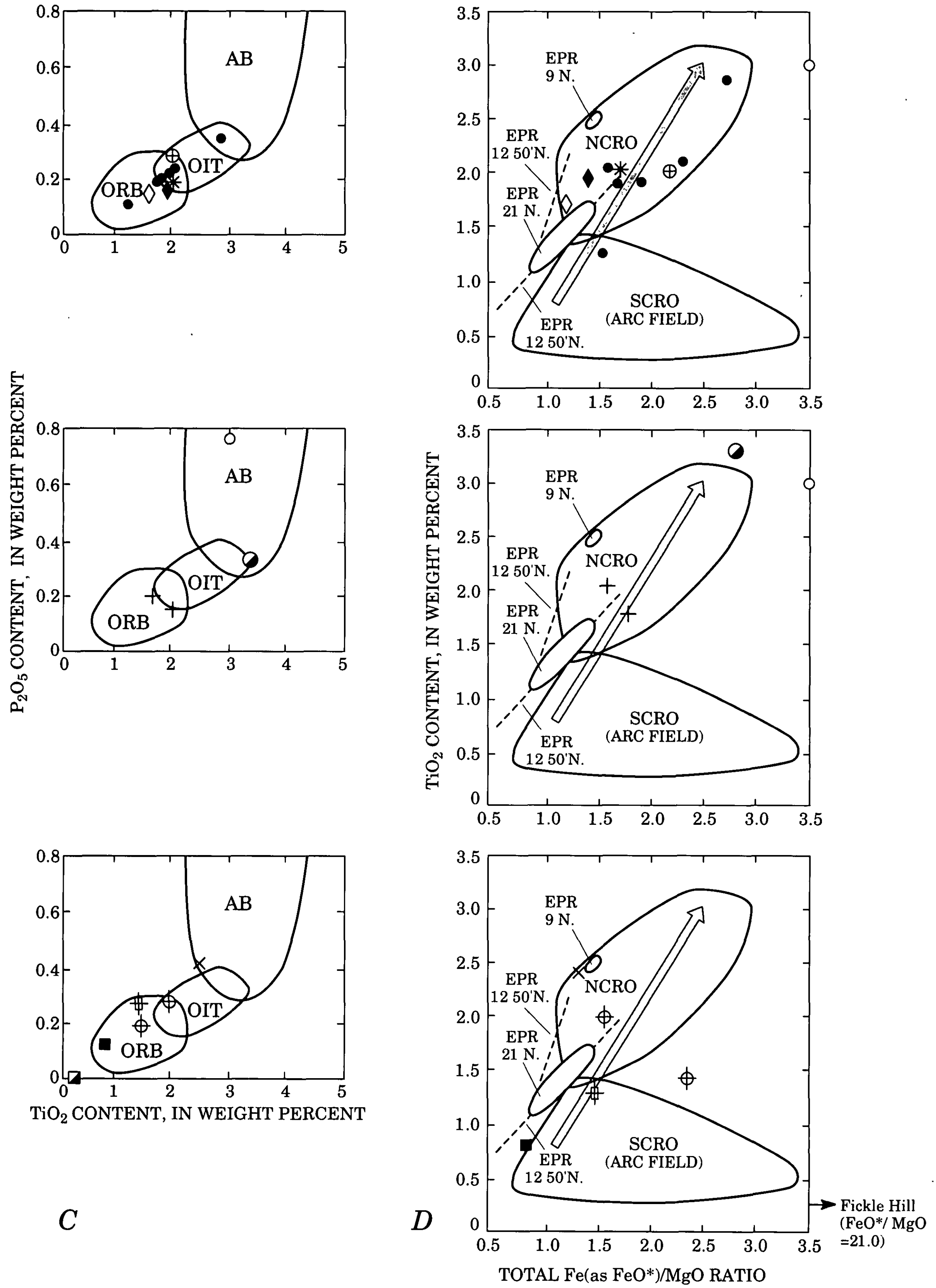


Figure 9. Major-element chemistry of volcanic rocks from terranes of Coastal belt, in comparison with selected other volcanic rocks. Analytical data given in table 2. *A*, Ternary plot of TiO_2, MnO, and P_2O_5 contents, showing fields for island-arc tholeiites (IAT), oceanic-island tholeiites (OIT), midoceanic-ridge basalts (MORB), calc-alkaline basalts (CAB), and oceanic-island alkali basalts (OIA) from Mullen (1983). Dashed line, approximate field boundary. *B*, Na_2O+K_2O versus SiO_2 contents, showing boundary between fields of alkalic (A) and tholeiitic (TH) compositions from Macdonald and Katsura (1964). *C*, P_2O_5 versus TiO_2 contents, showing fields of alkali basalts (AB), oceanic-island tholeiites (OIT), and oceanic-ridge basalts (ORB) from Ridley and



others (1974). *D*, TiO_2 content versus total Fe (recalculated as FeO*)/MgO ratio, showing trends and fields for rocks from East Pacific Rise (EPR) from Hekinian and Fouquet (1985), as well as fields for rocks from northern Coast Range ophiolite (NCRO), southern Coast Range ophiolite (SCRO), and trend for open-system fractionation of midoceanic-ridge basalts (open arrow) from Shervais and Kimbrough (1985). Two different fractionation trends for rocks from EPR at lat 12°50′ N. are shown (dashed lines).

Table 2. Major-, minor-, and trace-element chemistry of basaltic rocks of the Coastal belt and of other selected igneous rocks

[Major-element analyses in weight percent; minor- and trace-element analyses in parts per million. Analysts: 1–4, 7, D. Vivit and J. Kent (X-ray-Hamlin ("single solution" method of Shapiro, 1975); 15, 16, P. Elmore, S. Botts, G. Chloe, L. Artis, and H. Smith (methods of Shapiro and Brannock, Data sources: 15, 16, Wentworth (1966); 17, 18, Haehl and Arnold (1904); 19, MacLeod and Pratt (1973); all others, this report]

Analysis	1	2	3	4	5	6	7	8	9	10	11
Terrane	Coastal	Coastal	Coastal	Coastal	Coastal	Coastal	Coastal	Coastal	Coastal	Coastal	King Range
Location	Usal	Usal	Usal	Usal	Usal	Usal	Whitethorn	Honeydew	Parkhurst Ridge	Hacketville	Point Delgada
Sample	MT-38-85	MT-47-85	MT-58-85D	MT-50-85	MT-43-82	MT-43.1-82	MT-181B-85	MTB-15C-82	MT-74-82	MT-30-82	MK-14
Major elements											
SiO_2	45.9	50.1	47.5	44.5	49.8	46.6	46.1	47.2	50.2	46.6	47.4
Al_2O_3	12.6	15.5	14.7	14.0	14.8	13.9	12.6	14.3	16.0	12.6	16.2
Fe_2O_3	14.4	10.3	11.8	17.0	10.8	15.2	15.2	10.5	8.69	13.5	9.6
FeO	---	---	---	---	---	---	---	---	---	---	1.8
MgO	7.44	5.97	5.56	5.52	6.00	5.83	6.12	7.62	5.49	7.11	7.2
CaO	9.80	6.74	8.22	4.10	8.75	8.06	9.29	10.5	9.31	10.1	8.2
Na_2O	2.32	2.48	2.98	2.42	3.22	2.69	2.87	3.64	3.49	2.49	2.9
K_2O	.56	2.73	.76	.83	1.74	2.10	.32	.04	1.51	.21	1.6
H_2O^+	---	---	---	---	---	---	---	---	---	---	2.9
H_2O^-	---	---	---	---	---	---	---	---	---	---	.26
TiO_2	1.71	1.18	1.75	2.56	2.03	2.00	1.87	1.55	1.83	1.86	1.6
P_2O_5	.18	.10	.19	.33	.22	.22	.26	.15	.19	.18	.18
MnO	.20	.28	.29	.88	.19	.19	.24	.18	.12	.20	.16
CO_2	---	---	---	---	---	---	---	---	---	---	.03
Minor elements											
Nb	13	<10	<10	<10	---	---	13	---	---	---	---
Rb	<10	53	10	27	---	---	<10	---	---	---	---
Sr	260	140	270	190	---	---	270	---	---	---	---
Zr	110	60	110	160	---	---	160	---	---	---	---
Y	28	22	30	56	---	---	40	---	---	---	---
Trace elements											
Ba	200	270	130	380	---	---	140	---	---	---	---
Ce	<30	<30	30	30	---	---	40	---	---	---	---
La	30	<30	<30	<30	---	---	<30	---	---	---	---
Cu	200	290	120	120	---	---	160	---	---	---	---
Ni	90	72	87	110	---	---	60	---	---	---	---
Zn	90	180	97	180	---	---	90	---	---	---	---
Cr	150	150	230	80	---	---	100	---	---	---	---
V	362	241	312	451	---	---	74	---	---	---	---

[1] Reported as CaO

of blueschist blocks along this fault boundary suggests that these rocks were tectonically incorporated into the Coastal terrane during emplacement of the King Range terrane. It is unclear, however, whether the blueschist blocks (whose protoliths were basaltic rocks) were somehow tectonically recycled from the Central belt (which may underlie the Coastal belt) or whether they are derived directly from sources deep in the crust or upper mantle.

Age of the Coastal Terrane

The ages of rocks of the Coastal terrane are based on palynomorphic and foraminiferal assemblages in limestone. These fossils indicate that the carbonate concretions associated with argillitic rocks contain faunas and floras distinctly different in age and depositional setting from those in the pelagic limestone associated with basaltic rocks.

Age of the Carbonate Concretions Associated with Argillitic Rocks

The carbonate concretions associated with argillitic rocks of the Coastal terrane have yielded planktic foraminifers, dinoflagellates, and spores and pollen. Planktic foraminifers identified in samples from numerous localities between Hacketville to the north and the Mattole River to the south (fig. 2) are of middle Eocene, possibly late middle Eocene age, on the basis of their assignment by Sliter and others (1986) to the *Globigerapsis subconglobatus* and *Morozovella lehneri* Zones (P 11 to 12, 49–43 Ma) and the *Truncorotaloides rohri* Zone (P 14, ca. 42.5–41 Ma). On the basis of the absence of keeled subtropical to tropical forms and the abundance of *Globigerina officinalis*, a temperate form, these early Tertiary faunas are believed to indicate deposition at temperate, middle latitudes between lat 30° and 40° N. (fig. 11*B*). Berry (1982) reported the presence of an early Eocene planktic fauna from the Coastal fluorescence and inductively coupled plasma spectroscopy); 11–13, J. Reid and P. Hearn (X-ray spectroscopy and methods of Shapiro, 1975); 14, Z. 1962); 17, 18, E.T. Allen; 19, unknown (methods of Shapiro and Brannock, 1962, supplemented by atomic-absorption spectroscopy and spectrography).

Analysis	12	13	14	15	16	17	18	19	20
Terrane	King Range	King Range	King Range	Black Point	Iverson Basalt	Santa Cruz Mountains	Santa Cruz Mountains	Vizcaino Block	Fickle Hill
Location	Point Delgada	Queen Peak	Cooskie Creek	Gualala	Gualala	Mindego Hill Basalt	Mindego Hill Basalt	DSDP Site 173	Trachyte
Sample	MK668	G-20	SK-178	6240	6243	Diabase I	Diabase II	Core 36	FHT4A
					Major elements				
SiO_2	48.2	48.5	49.9	50.6	48.0	50.12	49.60	51.3	47.2
Al_2O_3	14.8	15.0	12.0	13.9	16.2	18.52	16.56	16.6	14.3
Fe_2O_3	3.1	12.8	3.7	1.5	3.2	2.47	4.28	5.0	10.5
FeO	7.7	1.7	11.4	6.6	6.7	4.11	4.44	2.7	...
MgO	6.5	4.6	4.2	9.8	7.4	2.68	5.38	5.0	7.62
CaO	11.1	5.0	8.0	9.6	8.5	8.99	9.22	6.6	10.5
Na_2O	3.1	4.7	2.8	3.7	3.2	5.22	3.31	3.3	3.64
K_2O	.84	.11	1.3	.14	.85	1.46	1.25	1.1	.04
H_2O^+	2.6	2.1	1.3	3.1	2.4	1.64	1.44	2.1	...
H_2O^-	.28	.67	.48	.25	1.2	3.09	2.58	4.2	...
TiO_2	1.9	3.2	2.9	.71	2.3	1.33	1.86	1.2	1.55
P_2O_5	.14	.30	.75	.11	.4	.18	.30	.26	.15
MnO	.27	.23	.27	.17	.12	trace	.08	.06	.18
CO_2	.04	.04	.71	.3	.05	...	...	[1].05	...
					Minor elements				
Nb	...	...	...	...	...	...	...	<15	...
Pb	...	...	...	...	...	...	...	...	...
Sr	...	...	...	...	...	...	...	420	...
Zr	...	...	...	...	...	...	...	200	...
Y	...	...	...	...	...	...	...	36	...
					Trace elements				
Ba	...	...	...	...	...	...	...	560	...
Ce	...	...	...	...	...	...	...	...	...
La	...	...	...	...	...	...	...	<30	...
Cu	...	...	...	...	...	...	...	20	...
Ni	...	...	...	...	...	...	...	15	...
Zn	...	...	...	...	...	...	...	...	...
Cr	...	...	...	...	...	...	...	190	...
V	...	...	...	...	...	...	...	160	...

terrane northwest of Branscomb, characterized by *Morozovella* (*M. aragonensis*, *M. Caucasica*, *M. subbotinae*) and *Acarinina pseudotopilensis*. We also found late early Eocene faunas assignable to the *Acarinina pentacamerata* Zone (P 9, 53.4–52 Ma) in the Usal area. The Usal faunas are meager, but they also include rare fish debris and large nodosariid and agglutinated benthic foraminifers that appear to have been transported from a shallow-neritic to upper-bathyal setting and redeposited. Farther south, near Ukiah, the matrix of a melange unit assigned to the Coastal belt was found by Orchard (1979) to contain foraminifers of late early Eocene age. This fauna is characterized by agglutinated taxa in addition to *Epistomina helicella* and *Quinqueloculina triangularis,* which Orchard interpreted to indicate an outer-shelf setting. Thus, the highly deformed rocks of the Coastal belt may be older to the south and may contain strata that were originally deposited closer to the California margin, although the fauna referred to by Orchard also occurs in slope settings at bathyal depths. In contrast, the rare benthic foraminifers that occur within some matrix concretions in the Coastal terrane to the north include *Cyclammina*, *Frondicularia*, *Gyroidina*, and *Haplophragmoides*, consistent with a slope setting at bathyal depths.

Dinoflagellate assemblages indicate a probable late Eocene age for matrix concretions in the western part of the Coastal terrane between Cape Mendocino on the north and the Mattole River and Honeydew to the south (W.R. Evitt, written commun., 1983). Several of the species listed in table 1 are absent in the one sample of this age from the Yager terrane that was examined, and so some of these forms may be restricted to the Coastal terrane. As in rocks of the Yager terrane, reworked dinoflagellates of Mesozoic age have been noted in rocks of the Coastal terrane. These reworked taxa include *Gonyaulacysta jurassica* (Deflandre) of Kimmeridgian or Oxfordian age (Evitt and Pierce,

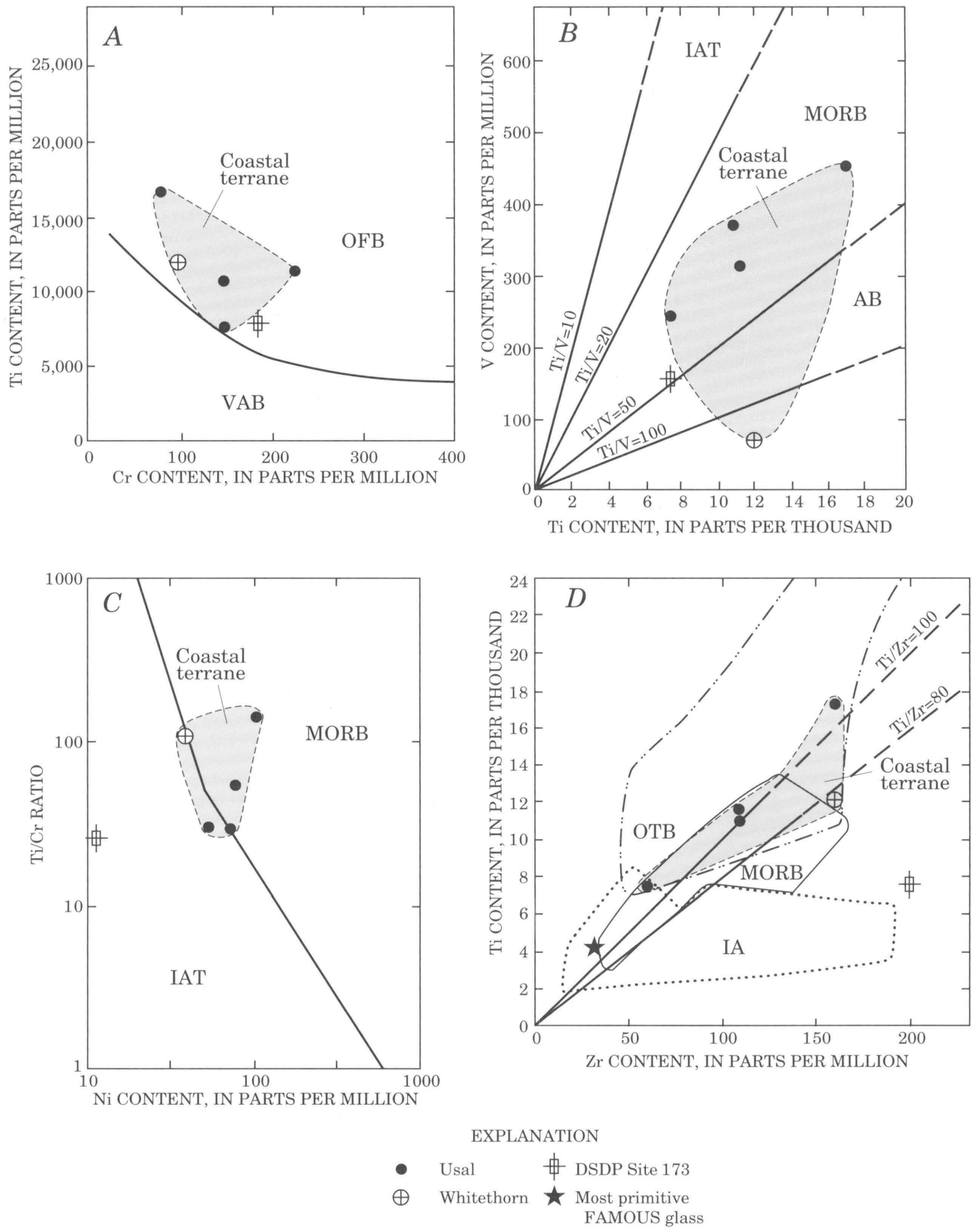


Figure 10. Minor- and trace-element chemistry of volcanic rocks of Coastal terrane and from Deep Sea Drilling Project (DSDP) Site 173. Analytical data given in table 2. Ti content converted from TiO_2. *A*, Ti versus Cr contents, showing boundary between fields of ocean-floor basalts (OFB) and volcanic-arc basalts (VAB) from Garcia (1976). *B*, V versus Ti contents showing boundary between fields of island-arc tholeiites (IAT), midoceanic-ridge basalts (MORB), and alkali basalts (AB) from Shervais (1982). *C*, Ti/Cr ratio versus Ni content, showing boundary between fields of island-arc tholeiites (IAT) and midoceanic-ridge basalts (MORB) from Beccaluva and others (1979). *D*, Ti versus Zr contents, showing field of oceanic tholeiites (OTB) from Floyd and Winchester (1975), fields of midoceanic-ridge basalts (MORB) and island-arc basalts (IA) from Pearce and Cann (1973), and plot of most primitive glass from French-American Mid-Ocean Undersea Survey (FAMOUS) from Shervais and Kimbrough (1985).

1975) and *Paleocystodinium* of Coniacian or younger age (J.L. Clark, written commun., 1986).

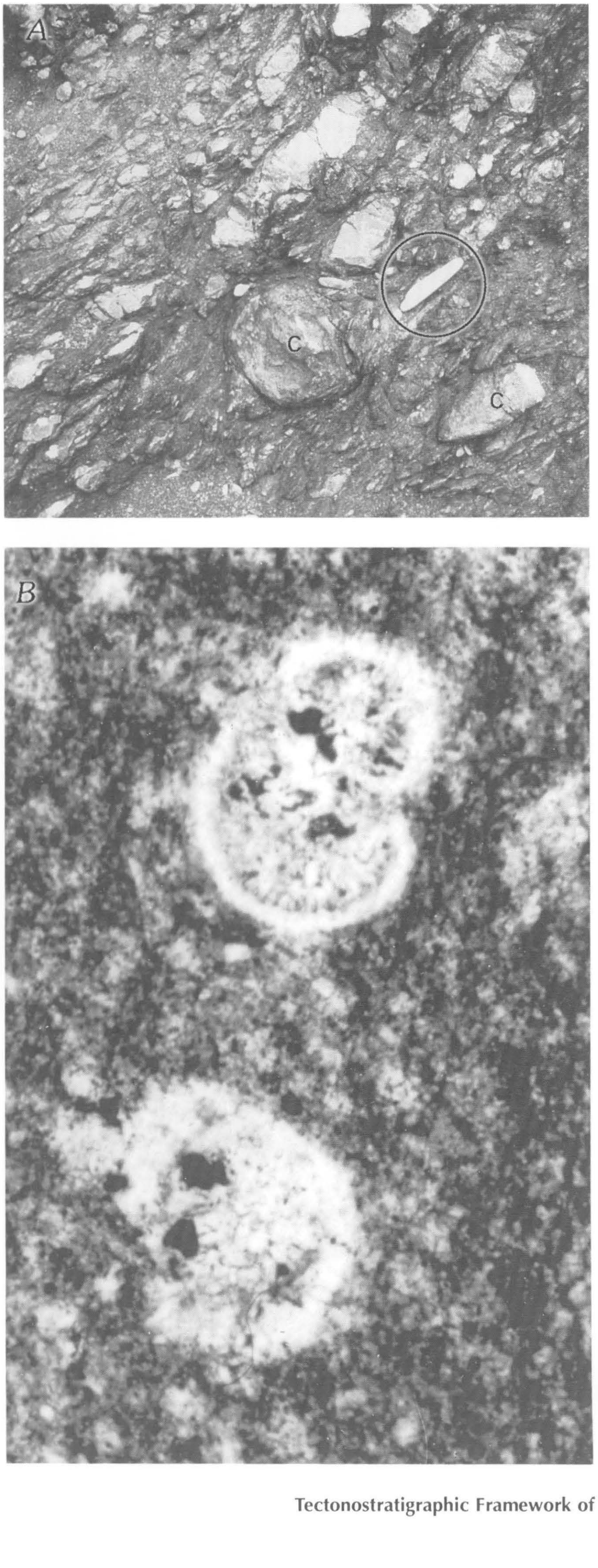
Spores and pollen examined from two widely separated localities in the Coastal terrane (table 1) contain middle Eocene and late Paleocene or Eocene floras, respectively. The middle Eocene flora comes from the Devils Gate locality near Cape Mendocino; in addition, these rocks contain probable reworked Cretaceous forms (*Proteacidites* and *Siberiapollis*) and probable reworked Paleocene to early Eocene taxa (*Betulaepollenites*, *Caryapollenites prodromus*, and *C. imparalis*). About 90 km southeast, west of Branscomb, terrigenous rocks of the Coastal terrane contain a late Paleocene or Eocene flora and little, if any, reworked pollen.

The collective fossil evidence indicates that the terrigenous strata which compose the matrix of the Coastal terrane in the Cape Mendocino region are predominantly middle to late Eocene in age. The presence of strata of Paleocene and early Eocene age from about Usal southward suggests that the Coastal terrane becomes older to the south. Dinoflagellates, spores and pollen, and foraminifers in the Cape Mendocino region indicate that the terrigenous rocks of the Coastal terrane are predominantly younger (middle to late Eocene) than those of the Yager terrane (Paleocene? to middle Eocene), which is dated chiefly on the basis of spores and pollen and some dinoflagellates. The palynomorphic and foraminiferal data also suggest that most terrigenous matrix rocks of the Coastal terrane (excluding sandstones interbedded with basalts at Usal) were deposited at middle latitudes north of about lat 30° N., probably in an outer-slope or inner-trench-slope setting, at bathyal depths. In the southeastern part of the Coastal terrane, the depositional setting may have been shallower and somewhat closer to the continental margin.

Age and Depositional Setting of the Pelagic Limestone Associated with Basaltic Rocks

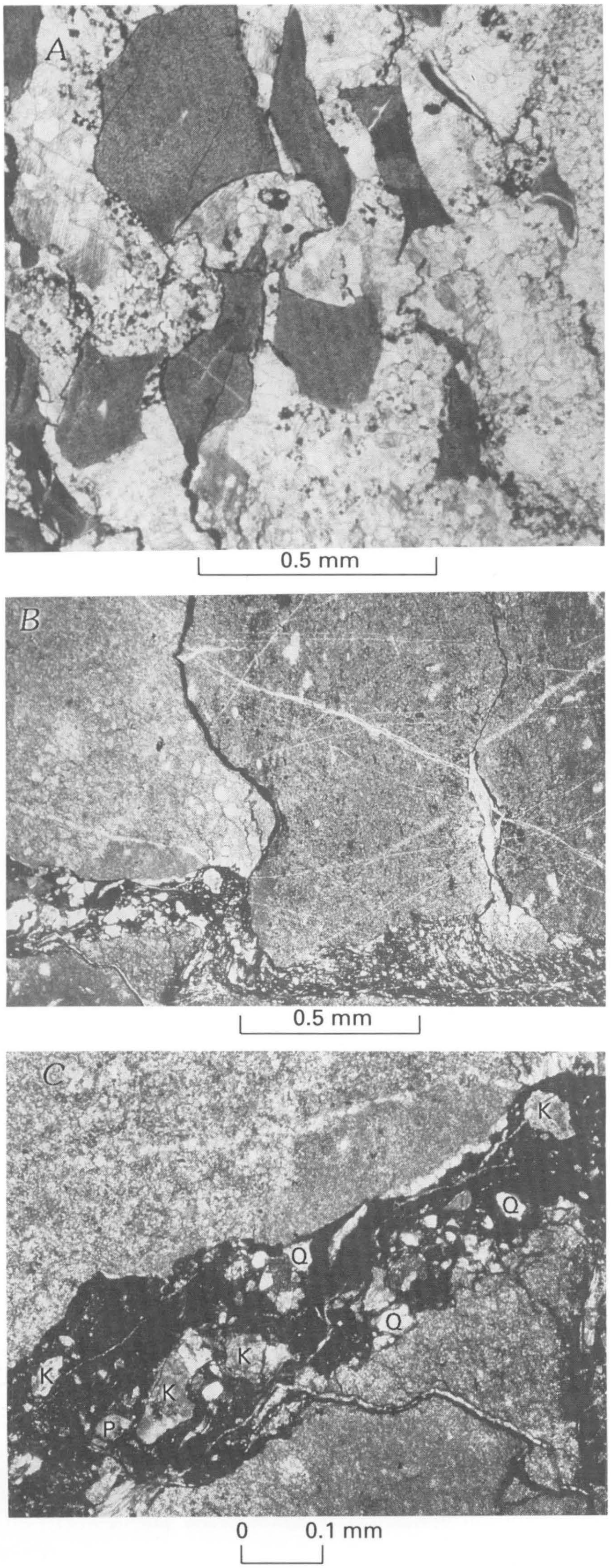
The pelagic limestone, which is interbedded with exotic blocks of oceanic basalt, contains planktic foraminifers (fig. 12*B*) ranging in age from early Campanian (ca. 82 Ma) to middle Maastrichtian (ca. 71–69 Ma) (Sliter, 1984; Sliter and others, 1986). The pelagic fauna in these rocks is characterized by the presence of keeled forms (fig. 13) typical of low-latitude (lat 20° N. to 20° S.) Tethyan environments of the Pacific Ocean (for example, *Gansserina gansseri* s.l. and *Rosita walfischensis* s.l.; Harbert and others, 1984; Sliter, 1984; Sliter and others, 1986).

Several biofacies recognizable in the pelagic limestone suggest its deposition near active volcanic edifices at bathyal



◄ **Figure 11.** Melange of Coastal terrane, located south of Cape Mendocino. *A*, Melange matrix of scaly, sheared argillite. Armored, rounded to lenticular fragments below and to right and left of knife (circled) are carbonate concretions (C); other fragments are attenuated sandstone beds. *B*, Photomicrograph of carbonate concretion, showing foraminifers of midlatitudinal affinity; magnification, ×100. Located at mouth of Peter B. Gulch near Petrolia.

depths, in a slope or basinal setting. At Parkhurst Ridge, at least two manganiferous biofacies occur: a mildly bioturbated facies and a highly bioturbated dissolution facies. The mildly bioturbated biofacies contains rare, small planktic foraminifers and benthic foraminifers that include *Aragonia*, large, coiled, calcareous *Gyroidinoides* spp. and *Ellipsoglandulina*? sp., agglutinated *Bathysiphon*, and rare fish debris. This fauna indicates deposition in a deep, lower-bathyal setting at or just below the carbonate-compensation depth (approx 3,000 m) that probably received rare debris displaced downslope. The highly bioturbated facies consists of stylolitic micrite containing distinct layers of fragmented and distorted planktic and benthic foraminifers that include small agglutinated genera, broken nodosariids, and small gyroidinids. These fossils have undergone partial dissolution as a result of either their downslope transport to well below the carbonate-compensation depth or, alternatively, their proximity to areas of hydrothermal venting. Manganiferous pelagic limestone near Usal contains a meager foraminiferal fauna assignable to the Campanian and to the early Maastrichtian *Globotruncanella havanensis* Zone (ca. 74 Ma).



◀ **Figure 12.** Photomicrographs of pelagic limestone of Coastal terrane, from Dugans Opening near Usal. *A*, Volcanic-glass fragments cemented by foraminiferal limestone; magnification, ×20. *B*, Clastic dikelet of K-feldspar-bearing arkosic sandstone cutting foraminiferal limestone; magnification, ×20. Note discordance of dikelet to stylolitic partings in limestone. *C*, Same clastic dikelet as in *B*, but at ×40 magnification and with crossed nicols. K, detrital K-feldspar; P, plagioclase; Q, quartz.

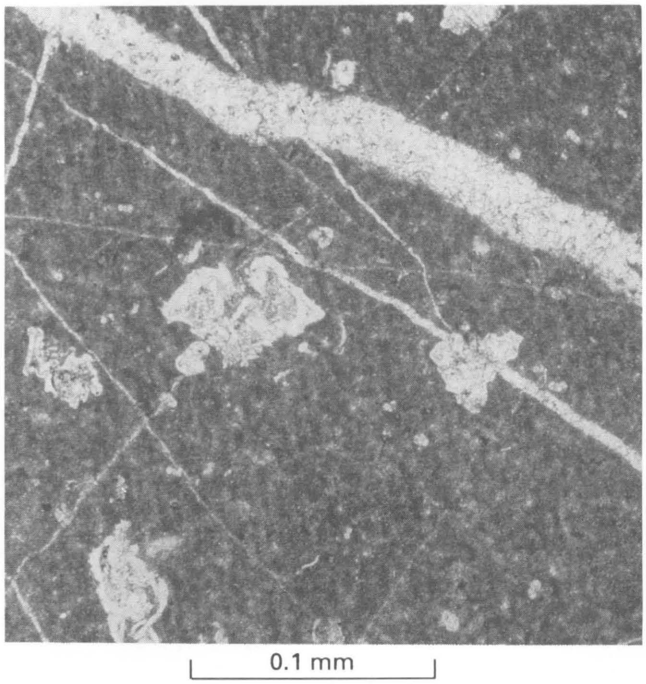


Figure 13. Photomicrograph of pelagic foraminiferal limestone of Coastal terrane, located near Parkhurst Ridge, showing keeled, low-latitude Campanian foraminifers; magnification, ×100.

Rare, reworked, calcareous benthic foraminifers, bivalve fragments, and fish debris present in this fauna probably were transported downslope, from outer-neritic and upper-bathyal (200–500 m) depths, to a predominantly bathyal setting. Other transported debris associated with these limestones include abundant volcaniclastic rocks (some vesicular) and angular clasts of radiolarian ooze, further suggesting proximity to a volcanic edifice. Both the detrital and foraminiferal components of the pelagic limestone at Usal display graded bedding, suggesting that turbidity currents may have been involved in their transport to bathyal depths.

The local interbedded relation of arkosic sandstone with the pelagic limestone associated with basaltic rocks at Usal (figs. 8*A*, 8*B*) indicates that at least some terrigenous rocks of the Coastal terrane also are of Late Cretaceous age and were deposited at a low-latitude site. The complex relation between the composite terrane of Upper Cretaceous basalt, limestone, and interbedded sandstone and the enclosing Eocene argillite and sandstone matrix of the Coastal terrane near Usal is illustrated in figure 7. The following Late Cretaceous planktic foraminifers have been identified from the Coastal terrane near Usal (locs. 1, 2, fig. 7):

Aragonia sp.
Archaeoglobigerina cretacea
Globotruncana arca (Cushman)
  bulloides
  linneiana (d'Orbigny)
  rosetta
  ventriocosa White
Globotruncanita stuarti
  stuartiformis (Dalbiez)
Planoglobulina sp.
Pseudotextularia sp.
Rosita fornicata (Plummer)
  plummerae (Gandolfi)

The following Early Tertiary planktic foraminifers have been identified from the same area (loc. 3, fig. 7):

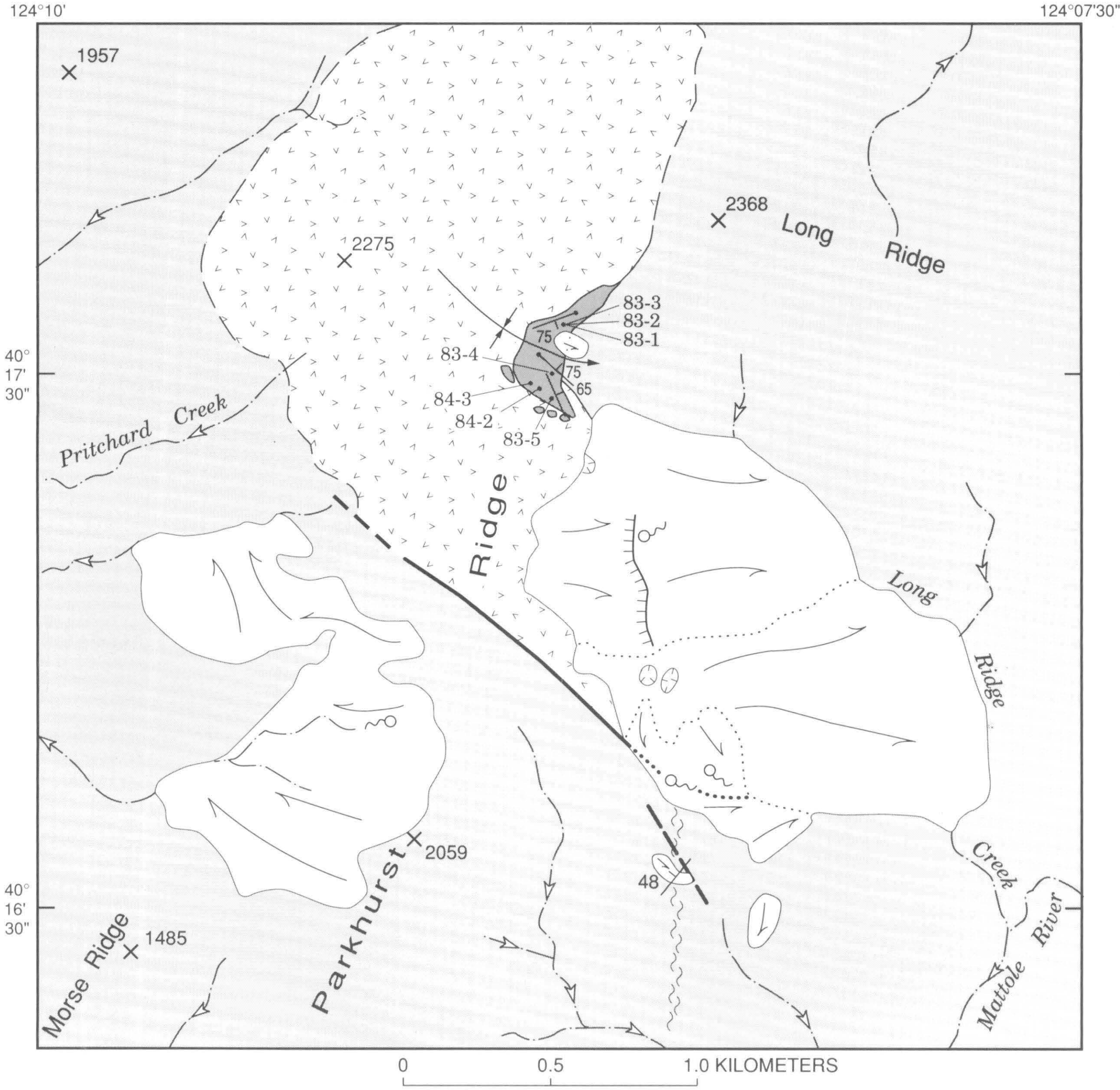
Acarinina Broedermanni (Cushman and Bermudex)
  spinuloinflata (Bandy)
Planorotalites pseudoscitula
Pseudohastigerina micra (Cole)
Subbotina linaperta (Finlay) group
  senni (Beckmann)
Truncorotaloides topilensis (Cushman)

Pink to red pelagic limestones intercalated with basaltic flows and aquagene tuffs at Dugans Opening near Usal (loc. 1, fig. 7) have yielded a low-latitude Campanian to Maastrichtian fauna. Nearby, a carbonate concretion within a lenticular body of sandstone enclosed by basalt (loc. 1, fig. 7) contains a similar low-latitude Campanian to Maastrichtian fauna. However, approximately 2 km northwest of Dugans Opening (loc. 3, fig. 7), several limestone concretions collected from sheared argillitic matrix of the Coastal terrane contain late early Eocene (planktic zone P 9) foraminifers, indicative of deposition at temperate, middle latitudes. Approximately 2 km north of this locality, basaltic flow rocks are interbedded with thick beds of laumontized arkosic sandstone, presumably of Late Cretaceous age, similar to the sandstone lens within basalt at Dugans Opening to the southeast (figs. 7, 8).

Paleomagnetic Data

Paleomagnetic studies have been conducted on the terrigenous and low-latitude oceanic components of the Coastal terrane. Paleomagnetic data from the Devils Gate area yield no evidence for the latitude of deposition of these rocks. Cores collected from well-bedded unweathered terrigenous rocks at Devils Gate were found to have a characteristic remanent magnetization that was acquired after folding, indicating that the rocks are remagnetized. The timing of remagnetization is constrained only by the middle Eocene age of the Devils Gate section, and so it could be any time between the middle Eocene (possibly during early interaction of the California margin with the oceanic component of the Coastal terrane) and the Pleistocene.

Another locality in the Coastal terrane that was studied in some detail is on Parkhurst Ridge north of Honeydew (fig. 14). At this locality, a large lens of low-latitude, pink to red limestone of Campanian to Maastrichtian age is folded into a steeply east plunging syncline (Harbert and others, 1984; Sliter and others, 1986). The limestone depositionally overlies a large composite body of diabase dikes and pillow basalt (fig. 15). Harbert and others (1984) found that the observed mean inclination of this limestone (I=–47°) is about 23° shallower than the expected mean cratonal inclination for North America (I=–62.8°) during Campanian to Maastrichtian time. This result was interpreted to approximate the primary remanent inclination of the limestone, although application of a fold test to the data was inconclusive at the 95-percent-confidence level, owing to the steep plunge of the folded limestone. Harbert and others concluded from their paleomagnetic and paleontologic data that the limestone on Parkhurst Ridge was deposited between 80 and 70 Ma at latitudes near or at the Pacific-Farallon Ridge between about lat 20° and 28° N.; the paleomagnetically determined mean is lat 28° N. Recently, Hagstrum (1990) has suggested that the remanent magnetization in the limestone of Parkhurst Ridge could reflect a remagnetization acquired before folding, but at the time that the limestone reached the subduction margin. By his interpretation, the limestone would have formed south of lat 28° N. Also, he has made tenuous assumptions (1) that the limestone was flat and undeformed until reaching the subduction margin



EXPLANATION

Sandstone

Limestone

Basalt

Quaternary landslide complex—Dotted line shows smaller landslide unit within composite slide. Arrow indicates direction of downslope movement. Hachured line shows landslide scarp; solid line indicates base of scarp, and hachures point uphill. Locally, includes:

Closed depression within landslide complex

Spring within landslide complex

Contact—Dashed where inferred; dotted where concealed

Fault—Dashed where inferred; dotted where concealed

Syncline—Dashed where inferred. Arrow indicates direction of plunge

Gouge zone

75 Strike and dip of bedding—Ball indicates top direction known

84-3 Paleomagnetic coring site—Locality number refers to table 2 in Harbert and others (1984)

1485 Spot elevation

Drainage pattern—Arrow indicates downstream direction

Figure 14. Detailed geologic map of Coastal terrane at Parkhurst Ridge near Honeydew, showing location of samples cored for paleomagnetic studies. Interpretation of data from selected coring sites given in Harbert and others (1984). Geology mapped by R.J. McLaughlin, 1982. See figure 2 for location.

and (2) that the limestone did not reach the margin until the Oligocene.

Structure

The overall structure of the Coastal terrane has been characterized by earlier writers as "broken formation" (usage of Hsu, 1968). The western part of the Coastal terrane, however, including most of the Cape Mendocino region, is deformed by highly penetrative shearing (fig. 16) and contains exotic blocks of blueschist and far-traveled oceanic rocks, and so it is more appropriately termed a melange (Hsu, 1968). The eastern part of the Coastal terrane is less penetratively deformed, and large areas of intact folded strata are interrupted by closely to widely spaced fractures and faults commonly lined with calcite+laumontite. In some areas, sandstone-rich parts of the section have the appearance of being shattered as a result of pervasive fracturing. We regard the pervasively sheared argillitic zones that are interspersed with broken rocks as a melange matrix (fig. 11*A*). The broken rocks are largely Paleocene to late Eocene in age but are, at least in part, Late Cretaceous (Campanian to Maastrichtian) locally (for example, in the Usal area). The argillitic matrix rocks (excluding the exotic and far-traveled blocks) are early to late Eocene in age.

Deformational structures composing the tectonic fabric of melange in the Coastal terrane of the Cape Mendocino region record a Cenozoic transition from obliquely convergent subduction to transpressional right slip. Investigations of these deformational structures (Beutner and Hansen, 1975) indicate that the earliest structure in these rocks is a widespread penetrative shear fabric (S_1) characterized by north- to northeast-directed thrusting. Beutner and Hansen considered the date of this early deformation to be 55–45 Ma, but the youngest affected rocks of the Coastal terrane are late Eocene in age. Thus, the S_1 fabric and all later deformation in these rocks formed after about 41 Ma. We suggest that these early, north-northeast-directed thrusts are related to emplacement of the Coastal terrane along the California accretionary margin, possibly over or against a "backstop" composed of the Central belt. The direction of tectonic transport and the timing of this S_1 deformation appear to correspond to f_1 recumbent folding in the Yager terrane, suggesting that eastward obductive emplacement of both terranes occurred during the Oligocene (possibly with the Yager terrane already overlying the Coastal terrane). The S_1 fabric of the Coastal terrane is folded into upright compressional folds (f_2) with orientations suggesting that east-northeast- to west-southwest-oriented compression followed S_1 deformation. The clockwise- rotated compression exhibited by f_2 structures (Beutner and Hansen, 1975) may

Figure 15. Pelagic foraminiferal limestone overlying basalt of Coastal terrane, located at Parkhurst Ridge. Note drill holes in limestone where cores used in paleomagnetic study were taken. Limestone contains foraminifers of Late Cretaceous (Campanian) age. Section faces east (to left).

Figure 16. Boudined sandstone in penetratively sheared argillite in melange of Coastal terrane, located on beach below lighthouse at Cape Mendocino.

reflect somewhat more head-on convergence along the California subduction margin after initial emplacement of the Coastal terrane. These f_2 folds, which may also correspond to f_2 folds in the Yager terrane, are overlapped by the less severely deformed Miocene and younger Bear River beds of Haller (1980) and the Wildcat Group of Ogle (1953).

Beutner and Hansen (1975) also found that several steeply dipping shear zones, trending east-west to northwest, developed sequentially from south to north, that they exhibit left-lateral slip, and that all of these shear zones postdated S_1 and f_2 structures. Our mapping suggests that this shearing is not confined to discrete zones except where incompetent argillitic rocks are present (for example, near Petrolia) and that it is discontinuous over relatively short distances.

Rocks of the Neogene Wildcat Group were reported by Ogle (1953) to be offset along east-west shears of the False Cape shear zone (fig. 17*A*). Related strata of middle Miocene and Pliocene age, exposed along the Bear River to the south of False Cape, are also juxtaposed with the Coastal terrane along faults of the same orientation as the shearing within the Coastal terrane and Ogle's False Cape shear zone. Harbert and Cox (1986) proposed that a major clockwise rotation by about 20° of the Pacific-Farallon Ridge (now the Pacific-Gorda and Pacific-Juan de Fuca Ridges) occurred between 3.86 and 3.4 Ma, revising the earlier work of Cox and Engebretson (1985). This rotation is thought to have initiated transpression along the San Andreas transform margin of California, as well as deformation of the Gorda plate due to a slowing of spreading at the south end of the Gorda Ridge (Wilson, 1986). Structural relations seemingly resulting from this deformation of the Gorda plate include (1) steepening and reorientation of subduction-related thrusts in the offshore accretionary wedge, as indicated by their present alignment with east-west- to northwest-southeast-oriented structures in the onshore Coastal terrane south of Cape Mendocino; and (2) overprinting of these subduction-related faults by east-west- to northwest-southeast-oriented, left-lateral shearing where the faults bend onshore. We tentatively attribute the northward-younging, left-lateral shearing described by Beutner and Hansen (1975) to sequential coupling of the Gorda plate to North America since 3.86–3.4 Ma (fig. 17*B*).

South of Cape Mendocino, between Petrolia and the north boundary of the King Range, the foliation of east-west- to northwest-trending shearing in the Coastal terrane dips at moderate to low angles south-southwest into and beneath the King Range terrane. Near Petrolia, a south-dipping wedge of silty Pliocene mudstone containing a lower-bathyal (2,000–4,000 m) foraminiferal fauna is imbricated with the Coastal terrane along thrust faults associated with this shearing (fig. 2). Nearby, Upper Miocene rocks assigned to the Wildcat Group that contain a middle- to lower-bathyal foraminiferal fauna also are faulted against the Coastal terrane (Miller and others 1983). Adjacent to the King Range, rare blocks of high-grade blueschist occur in melange formed by this youthful Neogene shearing. We consider the late Cenozoic shearing to be associated with obductive north-northeast-directed emplacement of the King Range terrane over the Coastal terrane during Pliocene to Pleistocene time.

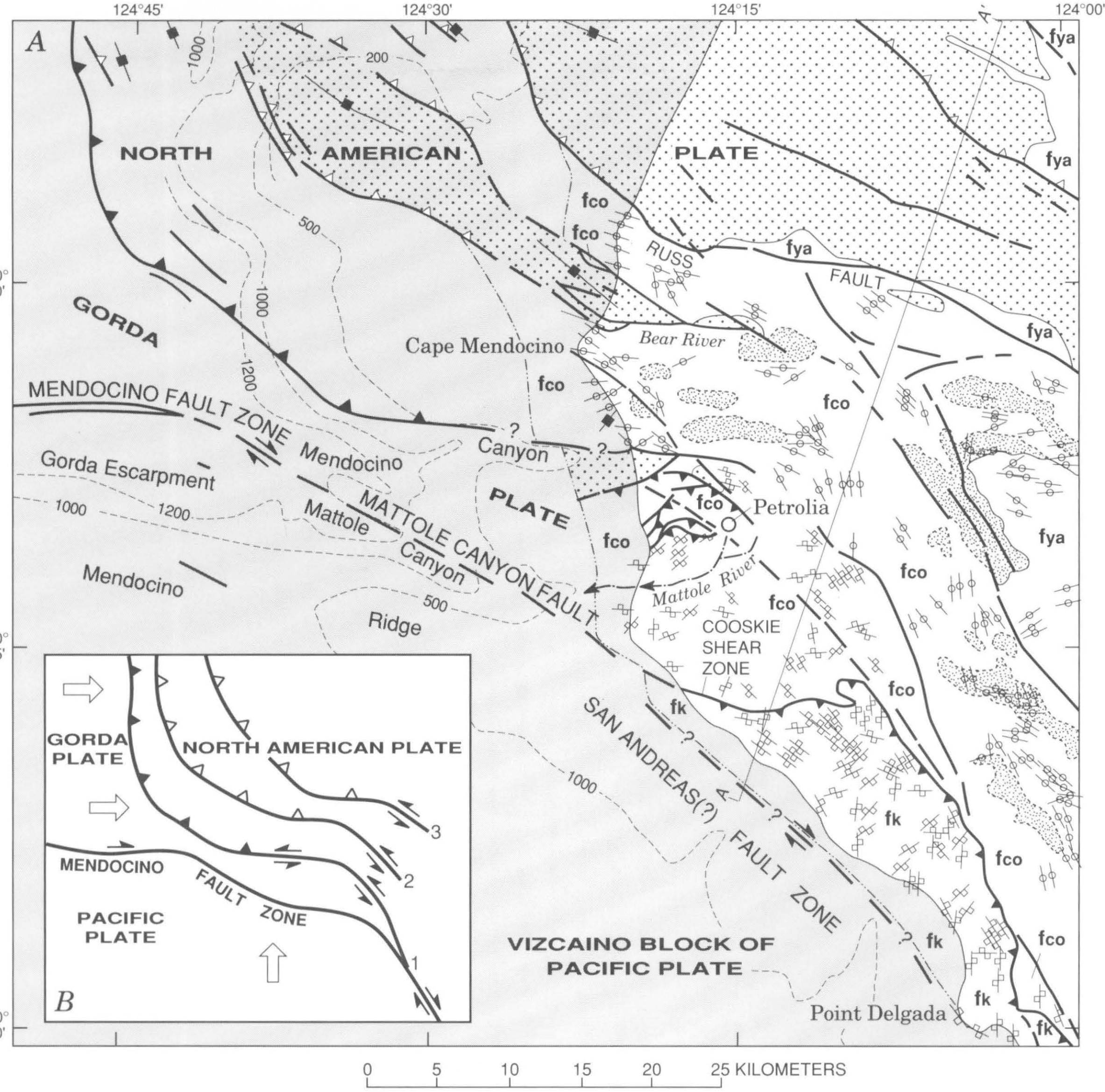
Implications of Structure for Hydrocarbon Exploration

South-dipping, late Cenozoic thrust faults associated with emplacement of the King Range terrane in the Petrolia area have important implications for hydrocarbon exploration in the onshore and offshore area. Historical oil production near Petrolia (MacGinitie, 1943) and numerous oil seeps that issue from argillitic rocks of the Coastal terrane along the coast between Cape Mendocino and the mouth of the Mattole River are evidence that the Coastal terrane is a source of hydrocarbons. Although high-paraffin-base hydrocarbon occurrences in this area probably are derived from organic-rich argillic rocks of the Coastal terrane, economically exploitable hydrocarbons probably are present only in the more permeable rocks. Permeability potentially provided by the highly fractured sandstone lithofacies of the Coastal terrane is compromised by the extensive laumontization of these rocks. Potential reservoir rocks with good permeability may, instead, be provided by the sandy lithofacies of tectonically buried remnants of Neogene strata thrust beneath rocks of the Coastal terrane. Such buried thrust remnants may be present in the offshore area west of Petrolia, north of the Mendocino Fracture Zone, and in the area immediately north and east of the King Range terrane boundary on shore. However, the youthful deformation and structural setting at the junction of the seismically active Mendocino Fracture Zone and the San Andreas fault may pose a considerable hazard, especially, to offshore exploration.

Accretion of the Coastal Terrane

Using the techniques of M.G. Debiche of Stanford University, Stanford, Calif., and Engebretson and others (1985), Harbert and others (1984) formulated a terrane-trajectory model constraining the depositional latitude of the limestone on Parkhurst Ridge, the timing of its incorporation into the Coastal terrane along the North American plate margin, and its final accretion to northern California. In their reconstruction, the date of initial interaction of the pelagic limestone with North America is considered to be approximately 40 Ma because the limestone is enveloped by middle to upper Eocene terrigenous rocks. The field relations near Usal described in this report require a refinement of this model (figs. 18, 19).

The age and paleolatitudinal setting of the pelagic limestone and the composition of associated basaltic rocks of the Coastal terrane suggest that the limestone and basalt



EXPLANATION FOR FIGURE 17*A*

- Late Cenozoic overlap assemblage (Pleistocene to early Miocene)
- **fk** King Range terrane (middle Miocene and Late Cretaceous)
- **fco** Coastal terrane (late Eocene to Late Cretaceous)
- Resistant map-scale block, largely of broken sandstone and argillite—Enclosed in melange matrix of Coastal terrane
- **fya** Yager terrane (late Eocene to Paleocene?)
- Contact
- Boundary of mapping of offshore units
- Fault—Dashed where inferred; queried where uncertain. Arrows indicate direction of relative movement
- Thrust fault—Dashed where inferred; queried where uncertain. Sawteeth on upper plate
- Thrust fault within offshore accretionary wedge—Dashed where inferred. Sawteeth on upper plate
- Basal thrust of Cascadia subduction zone—Dashed where inferred; queried where uncertain. Sawteeth on upper plate
- Fold axis within offshore accretionary wedge
- Onshore course of Mattole River and offshore submarine canyon
- 500 Bathymetric contour—Shown in meters
- Strike of planar element (bedding, shear fabric, axial plane of fold) associated with onshore projection of Cascadia subduction complex
- Strike of planar element (bedding, shear fabric, axial plane of fold) within area that is compressed between Pacific and North American plates and broken by southwest-dipping thrust faults
- A A' Location of cross section shown in figure 29*C*

Figure 17. Structure of Cape Mendocino area. *A*, Offshore and onshore structural elements. Offshore geology modified from Clarke and Field (1989). Franciscan rocks south of Russ fault zone were originally designated as False Cape shear zone by Ogle (1953). *B*, Hypothetical relation of sinistral shearing in Coastal terrane to coupling between North American plate and deforming Gorda plate. Numbers 1 through 3 indicate relative ages of northward-younging sinistral shearing of North American plate (from Beutner and Hansen, 1975). Solid sawteeth, basal thrust of Cascadia subduction zone; open sawteeth, thrust fault within offshore accretionary wedge; small arrows, sinistral shearing; open arrow, plate motion with respect to North American plate.

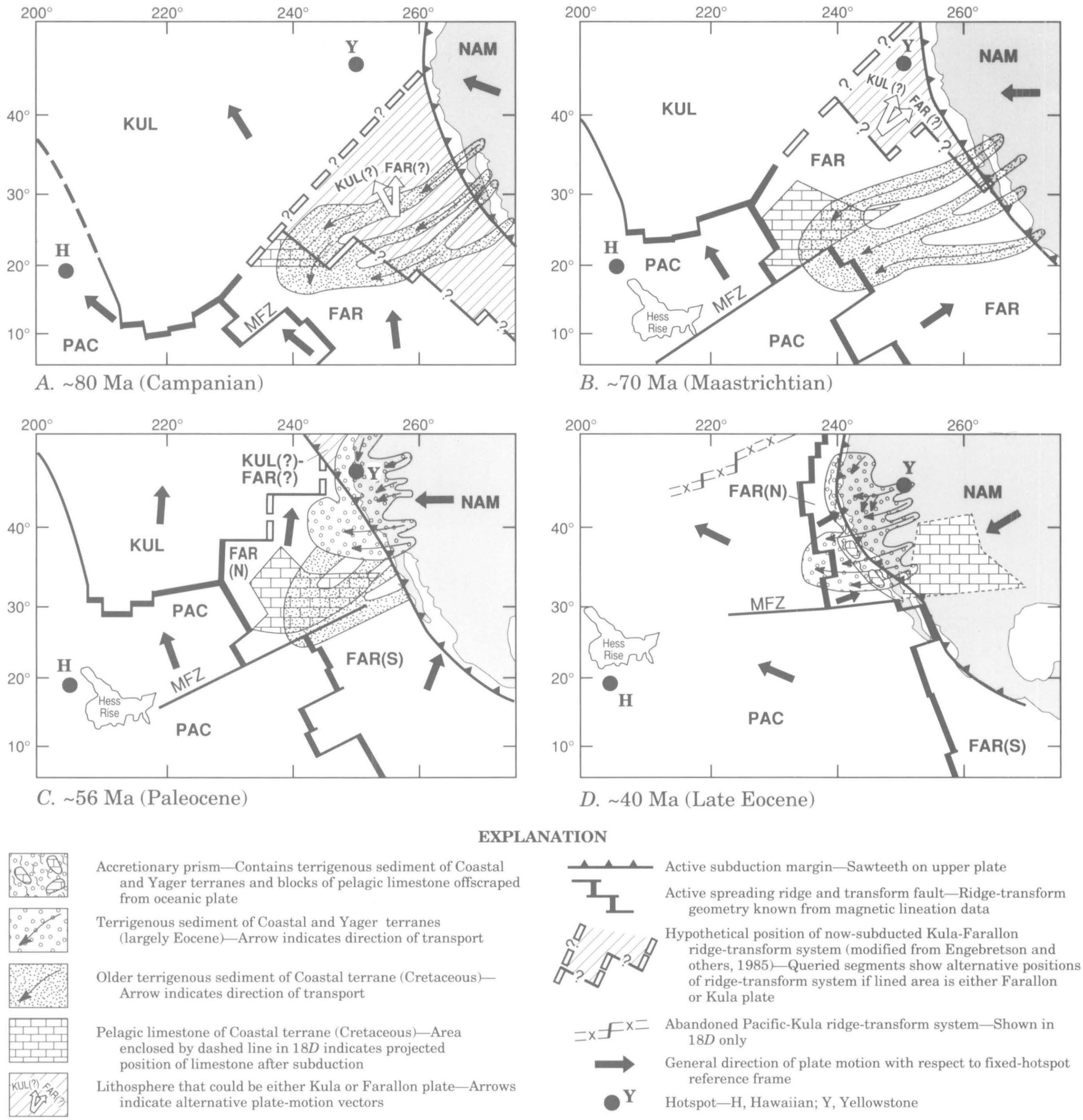


Figure 18. Plate-tectonic model for accretion history of Coastal terrane, modified from reconstructions in fixed-hotspot reference frame by Engebretson and others (1985). FAR, Farallon plate (N, north; S, south); KUL, Kula plate; MFZ, Mendocino Fracture Zone; NAM, North American plate; PAC, Pacific plate. Longitudes in degrees east of Greenwich; present-day North American coastline shown for reference. *A*, From 82 to 80 Ma, pelagic limestone is deposited on Farallon plate northeast of Kula-Farallon-Pacific Ridge triple junction, and sediment derived from continental margin at approximate latitude of present-day northern Mexico is sporadically transported by submarine fans or canyons and deposited in near-ridge area. *B*, From 70 to 69 Ma, pelagic limestone continues to be deposited on Farallon plate north of Mendocino Fracture Zone between lat 20° and 28° N., and terrigenous sediment continues to be sporadically deposited near ridge. *C*, By about 56 Ma, new supply of sediment, derived from interior of present-day California and Oregon, is deposited in trench and on trench slope above subduction zone of Farallon plate as now-composite terrane of pelagic limestone, basalt, and terrigenous clastic deposits nears continental margin. *D*, Between 56 and 40 Ma, central part of Farallon plate is nearly completely subducted, carrying most of pelagic limestone and terrigenous clastic deposits beneath North American plate, and accretionary prism is formed above trench of subduction margin by tectonic mixing of offscraped blocks, which include basalt, limestone, and interbedded low-latitude sandstone, with continually supplied, largely Eocene sedimentary deposits. Between 40 and 24 Ma, Coastal terrane is completely accreted to North American plate.

formed between lat 20° and 28° N., in a near-ridge setting, between early Campanian (ca. 82 Ma) and middle Maastrichtian (ca. 69 Ma) time (fig. 19). The present position and interstratification of terrigenous sedimentary rocks with basalt and limestone near Usal further require that the oceanic-ridge system at the time of deposition was both within reach of sediment derived from the American plate margin and north of the Mendocino Fracture Zone (figs. 18*A*, 18*B*). To satisfy these conditions, using the plate reconstructions of Engebretson and others (1985), the depositional setting of the pelagic limestone at 70 Ma is uniquely located at or just east of the Pacific-Farallon Ridge, near the Pacific-Kula-Farallon plate triple junction. Speculatively, sediment derived from the North American

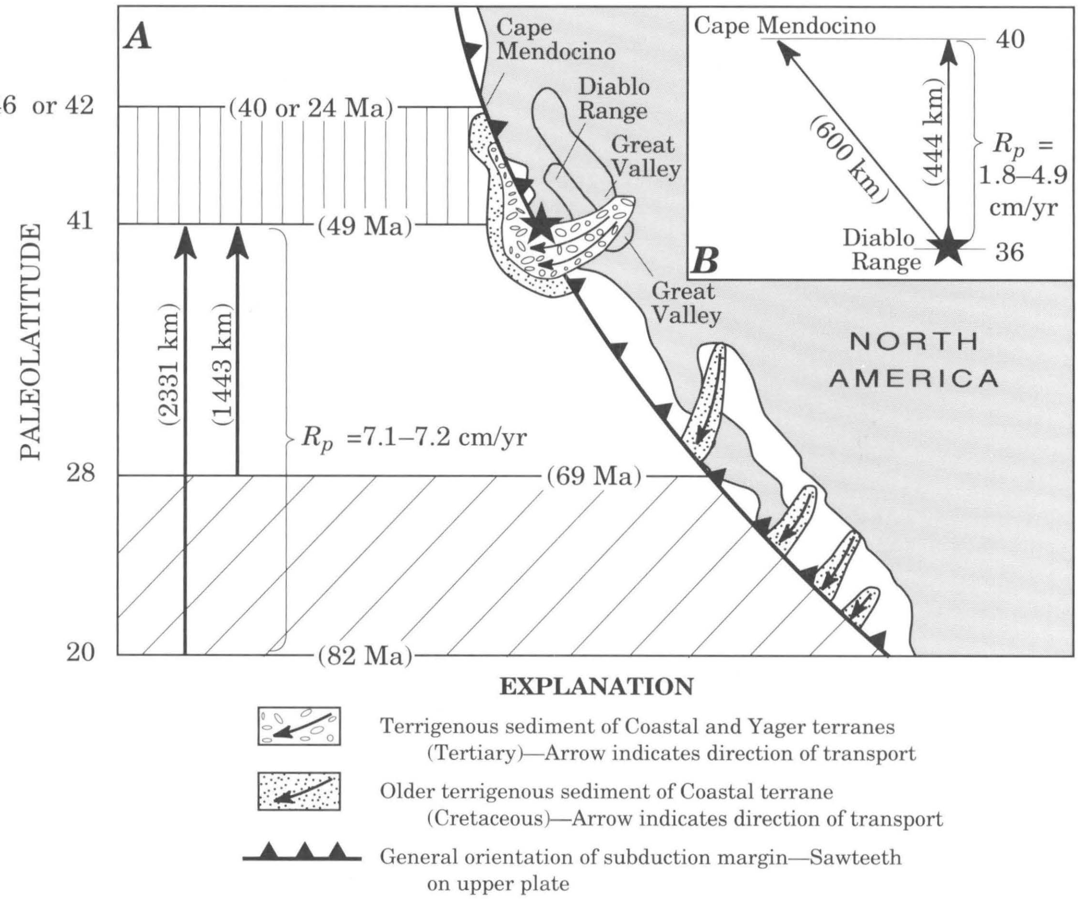


Figure 19. Summary of accretion history of pelagic limestone and associated sedimentary rocks of Coastal terrane near Cape Mendocino, showing change in rate of poleward component of motion (R_p) before and after encounter with continental margin at 49 Ma. Paleolatitudes derived from reconstructions of Harbert and others (1984) and Engebretson and others (1985); poleward distances calculated by assuming that 1° of latitude equals 111 km. Present-day coastline of North America shown for reference. *A*, Deposition of pelagic limestone of Coastal terrane (diagonal lines) occurred between 82 and 69 Ma at paleolatitudes between 20° and 28° N. During this time, detritus from continental margin near northern Mexico was deposited in vicinity of Kula-Farallon-Pacific plate triple junction and transported northward with limestone on Farallon plate. Time and position of encounter with North American plate margin (star) is based on presence of jadeitized metasandstone detritus of inferred Diablo Range (paleolatitude 41° N.) provenance in middle Eocene (ca. 49 Ma) conglomerate of Coastal terrane. Final accretion at Cape Mendocino (vertical lines) must have occurred sometime between about 40 and 24 Ma on the basis of late Eocene age (ca. 40 Ma) of youngest fossils in Coastal terrane and early Miocene age (ca. 22 Ma) of oldest strata that overlap rocks of Coastal terrane. Position of Cape Mendocino on North American plate moved southward relative to Farallon plate between 40 Ma (paleolatitude 46° N.) and 24 Ma (paleolatitude 42° N.). Range of R_p values before 49 Ma is based on poleward distances of either 13° (1,443 km) in 20 m.y. or 21° (2,331 km) in 33 m.y. *B*, Range of R_p values after 49 Ma is based on present-day poleward distance between Diablo Range (lat 36° N.) and Cape Mendocino (lat 40° N.) of 4° (444 km), which is distance traveled in either 9 m.y. (final accretion at 40 Ma) or 25 m.y. (final accretion at 24 Ma); distance traveled parallel to present-day continental margin may have been as far as 600 km.

margin at the 70-Ma latitude (present position of northern Mexico, fig. 18*B*) may have been transported to the vicinity of the Pacific-Farallon Ridge in a major submarine-canyon or fan system, possibly analogous to the Zodiac Fan system of southern Alaska (Scholl and others, 1977; Byrne, 1979; Harbert, 1987).

Cretaceous oceanic and terrigenous strata deposited on the Farallon plate moved obliquely northeastward toward the American plate margin at a poleward rate of about 7.1 to 7.2 cm/yr (fig. 19). These rocks next interacted with younger sediment derived from the American plate margin between late Paleocene and late Eocene time (ca. 55–41 Ma). A significant component of terrigenous detritus in the Coastal terrane near Cape Mendocino probably was derived during middle Eocene time (ca. 49 Ma) from the vicinity of the southern Diablo Range (figs. 18*C*, 18*D*) on the basis of the occurrence of conglomerate clasts of metasandstone containing abundant jadeitic pyroxene with a probable source in the present-day Diablo Range (figs. 6*C*–6*E*). From about 49 to 41 Ma, as the Farallon plate continued its oblique convergence with North America at poleward rates of 1.8 to 4.9 cm/yr (fig. 19), terrigenous sediment, supplied to the slope and trench-slope area from the interiors of California, Oregon, Washington, and Idaho, contributed to formation of the accretionary margin of California (Underwood and Bachman, 1986). Latest late Paleocene and early Eocene (ca. 60–52 Ma) channeled shelf and slope deposits (not part of the Franciscan) unconformably overlie the Central belt of the Franciscan Complex and Great Valley sequence in the Coast Ranges locally (Short and Cummings, 1987). These channeled sequences may have transported the sediment that fed distributary-channel systems of the Coastal and Yager terranes.

Accretion of the near-ridge basalt and pelagic limestone to the California margin and its incorporation into the Coastal terrane occurred after about 40 Ma, on the basis of the youngest terrigenous strata of the Coastal and Yager terranes (fig. 18*D*). Between latest Eocene (ca. 40 Ma) and latest Oligocene (ca. 24 Ma) time, poleward translation of the limestone-basalt slowed from about 5 to less than 2 cm/yr (fig. 19), as it was scraped off the subducting Farallon plate and imbricated with slope and trench-slope sediment above the California subduction margin. This imbrication was accompanied by landward-directed thrusting onto the Central belt of the Franciscan Complex and relative westward emplacement of the Central belt over the Coastal and Yager terranes along the Coastal belt thrust.

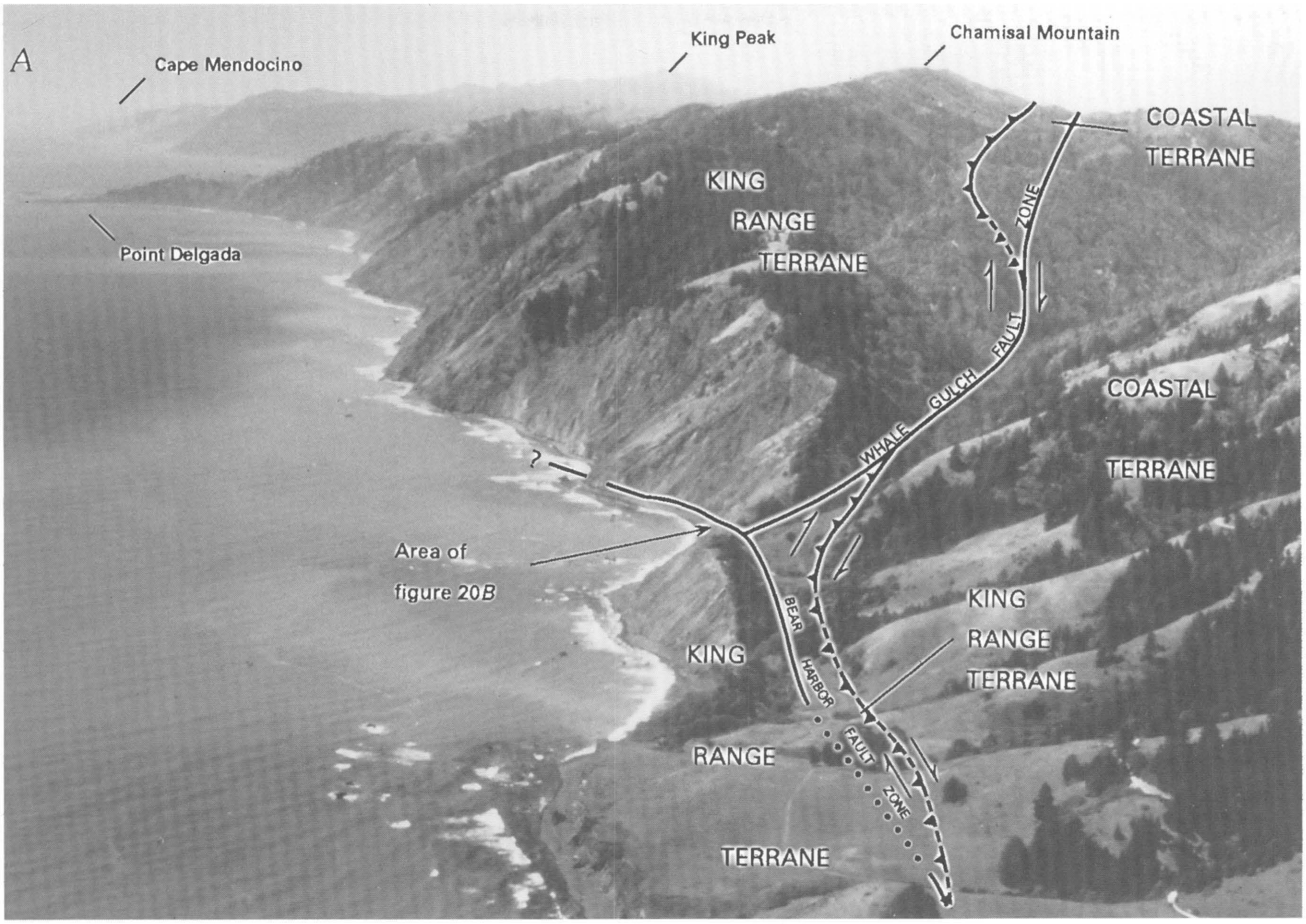
Accretion was apparently completed by the early Miocene (fig. 19) because lower-bathyal strata of this age (ca. 22 Ma) occur in lowermost Neogene strata of the Bear River area and in the Eel River basin (Chetelat and Ingle, 1987). These strata locally overlie rocks of the Coastal and Central belts unconformably.

King Range Terrane of the Coastal Belt

The King Range terrane, which is the westernmost terrane of the Coastal belt, contains the youngest accreted rocks of the Franciscan Complex. The King Range terrane is subdivided into two subterranes on the basis of the structural discontinuity, contrasting lithology, and age differences of the rocks. These subterranes are considered to form the composite King Range terrane because both subterranes were affected by a major thermal event during mid-Miocene time that did not affect adjacent rocks of the Coastal terrane. The north boundary (Cooskie shear zone, which intersects the coast north of Cooskie Creek) and east boundary (which approximately aligns with Bear Creek) of the King Range terrane are marked by highly sheared and crushed rocks considered to be discrete shear zones by some workers (Nason, 1968; Beutner and Hansen, 1975). We interpret this boundary to be a major terrane suture but consider most shear deformation to be within the lower plate of the suture. On the basis of structural and aeromagnetic data, this suture dips about 30° SW., indicating that the King Range terrane structurally overlies the Coastal terrane (Griscom, 1980b; McLaughlin and others, 1982).

The San Andreas fault zone may mark the southwest boundary of the King Range terrane, although this fault has never been located in the offshore area between the Mendocino Fracture Zone and Point Delgada (fig. 17*A*). South of Point Delgada and opposite the mouth of Whale Gulch, the northernmost mapped segment of the offshore San Andreas fault zone is a zone of faulting as much as 10 km wide (fig. 2; McCulloch, 1987a, b). The east side of this zone of faulting projects northward, parallel to the Bear Harbor fault along the coast (fig. 20*A*), and aligns with youthful faulting in Whale Gulch (Beutner and others, 1980). Another steep, conspicuous, north-south-trending fault at this latitude projects toward Point Delgada and is traceable southward to Point Arena (Curray and Nason, 1967; McCulloch, 1987a). This segment, which is generally regarded as the trace of the San Andreas fault that was active during the 1906 San Francisco earthquake, may step westward and continue northward from Shelter Cove in the offshore area. Therefore, we regard the King Range terrane as bounded on the east, west, and north by faults

► **Figure 20.** South end of King Range, showing rocks of King Range terrane thrust northeastward over Coastal terrane. *A*, Southeast boundary of King Range terrane along Bear Harbor and Whale Gulch fault zones. Faults are dashed where inferred, dotted where concealed, and queried where uncertain; sawteeth on upper plate. Arrows indicate direction of relative movement. View northward. Photograph by D.G. Herd, U.S. Geological Survey. *B*, Fault zone at mouth of Whale Gulch (see *A* for location). View northeastward.


A
Cape Mendocino
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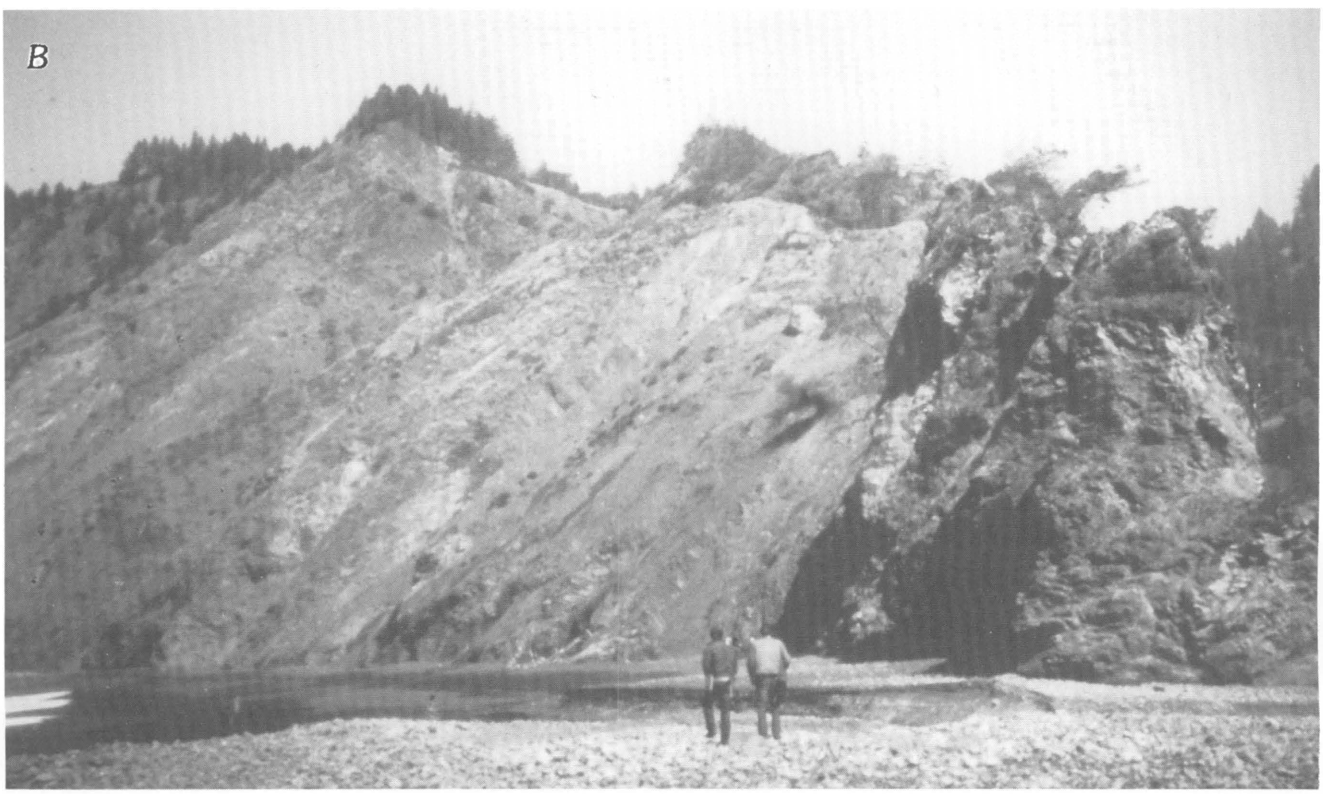

B

of the San Andreas system and Mendocino Fracture Zone (fig. 2). The rocks on the southwest side of the presumed offshore San Andreas fault zone adjacent to the King Range terrane are assigned to the Vizcaino structural block (McCulloch, 1987a). Because the King Range terrane is adjacent to, and may have been displaced along, the San Andreas fault zone, its accretionary history and its relation to the presently adjacent Coastal terrane are controversial (McLaughlin and others, 1982; Miller and others, 1983; Bachman and others, 1984; Underwood, 1987).

Composition and Structural Framework

The King Range terrane is a composite terrane, consisting of rocks of diverse lithology that range widely in age and are structurally complex. It is divided into the Point Delgada and King Peak subterranes (fig. 2).

Point Delgada Subterrane

The Point Delgada subterrane is exposed only at Point Delgada in the intertidal area beneath Quaternary marine and nonmarine deposits (McLaughlin and others, 1982). The subterrane consists chiefly of basaltic pillow flows, flow breccias, and tuffs that locally are cut by diabase dikes (fig. 21). Red and gray calcareous mudstone intercalated with the volcanic flows contains a Late Cretaceous (Coniacian to Campanian) radiolarian fauna.

Overlying and intercalated with the upper volcanic rocks is a melange consisting of sheared pebbly to bouldery mudstone. The clastic assemblage of this olistostromal melange is polymict, consisting of a mixture of rounded porphyritic hypabyssal rocks of intermediate composition, dark chert, mafic metaigneous (greenschist facies) rocks, metasandstone, and fine-grained grayish-brown limestone derived from calcareous concretions. Included within the melange unit is a large, subrounded, slickensided block of glaucophane schist (type IV of Coleman and Lee, 1962), approximately 3 m long. The melange unit is overlain by arkosic sandstone and shale turbidites derived from an arc-related terrigenous source.

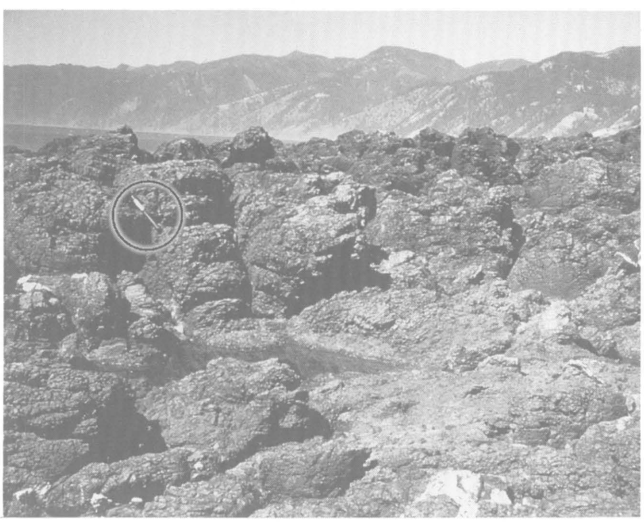


Figure 21. Pillow basalt of Point Delgada subterrane. View northward. Note hammer (circled) for scale.

Sandstone and volcanic rocks of the Point Delgada subterrane are mildly metamorphosed to prehnite-pumpellyite grade, and both the sandstone and volcanic rocks are hydrothermally altered and mineralized locally along north-south- to northeast-trending normal faults that are conjugate with northwest-trending faults of the San Andreas fault system. Unlike the Coastal terrane, sandstone of the Point Delgada subterrane generally lacks detrital K-feldspar, although this mineral may have been present before metamorphism and hydrothermal alteration. Potassic alteration, including hydrothermal K-feldspar, is locally conspicuous along mineralized faults. The Point Delgada sandstones are arkosic to feldspathic (24–42 volume percent plagioclase, 26–48 volume percent quartz) and moderately lithic (27–36 volume percent nonchert rock fragments), containing sparse volcanic detritus (less than 20 volume percent) and moderately abundant chert detritus (0.6–1.0 times as abundant as nonchert lithic materials). The volcanic rocks, melange, and sandstone are folded into tight southeast-plunging folds and separated from the King Peak subterrane to the northeast by a nearly vertical, northwest-trending fault thought to be a segment of the San Andreas fault system (McLaughlin and others, 1982, 1985b).

Late Cretaceous igneous rocks of the Point Delgada subterrane are somewhat enriched in alkalis (K, Na) and Mn, largely owing to hydrothermal alteration (figs. 9*A*, 9*B*). However, their P_2O_5/TiO_2 ratios (fig. 9*C*) and $TiO_2/(FeO/MgO)$ ratios (fig. 9*D*) are typical of oceanic-ridge basalt. The occurrences of calcareous red pelagic mudstone with pillowed volcanic flows and of subrounded basalt clasts in flow breccias suggest their deposition on the slopes of an oceanic volcanic edifice that reached wave-base elevations. We interpret the volcanic rocks of Point Delgada to have formed along the flanks of a ridge or near-ridge volcanic edifice. The setting of these rocks is, therefore, about the same as that of basaltic rocks of similar age in the Coastal terrane. Olistostromal melange and arc-derived terrigenous rocks intercalated in the upper part of the Point Delgada subterrane probably represent sediment deposited in a trench-slope setting, where the Late Cretaceous trench at the Farallon-American plate margin was close to the Pacific-Farallon Ridge. Alternatively, the terrigenous rocks may represent sediment that bypassed the filled trench and was, instead, deposited in an outer-trench or near-ridge setting.

King Peak Subterrane

The King Peak subterrane composes the main body of rocks referred to as the King Range terrane (McLaughlin and others, 1982). This subterrane is in contact on the west with the Point Delgada subterrane along a steeply northwest trending fault. It is also faulted to the north against the Coastal terrane along an east-west-trending shear zone (Cooskie shear zone of McLaughlin and others, 1982). To the east, the King Peak subterrane is in fault contact with the Coastal terrane along a northwest-trending shear zone aligned with Bear Creek and Whale Gulch. These shear zones, which separate the King Range and Coastal terranes, correspond to the low-angle, southwest-dipping suture that underlies the King Peak subterrane (fig. 2).

The King Peak subterrane is composed dominantly of argillite, sandstone, and minor pelagic chert, limestone, and basalt. As is true of other terranes of the Franciscan Complex, the pelagic chert and limestone and associated basaltic rocks are considered to be oceanic rocks scraped off at the American plate margin (McLaughlin and others, 1982).

Sandstone and minor interbedded argillite in the King Peak subterrane, much like those in the Coastal terrane, are characterized by graded bedding, load and current traction features, and ripple-drift laminations, suggestive of deposition in a channeled-slope or trench-slope setting. The sandstone of this subterrane is arkosic to feldspathic (20–62 volume percent feldspar, 23–57 volume percent quartz) and moderately to highly lithic (9–46 volume percent nonchert fragments). The most common lithic constituents include rounded to subangular mafic rocks, cherty felsite, and arc-derived, silicic to intermediate volcanic and plutonic rocks. We estimate that mafic detritus may be 0.3 to 1.3 times as abundant as silicic to intermediate volcanic-rock fragments; chert detritus may be as much as 3 times as abundant as nonchert fragments and as much as 5 times more abundant than volcanic detritus. Predominant detrital biotite and muscovite and minor epidote and clinozoisite compose the principal sandstone accessory minerals. K-feldspar makes up 7 to 42 volume percent of the rock.

Many coastal and eastern exposures of the King Peak subterrane consist of black, thin-bedded to massive, cherty and calcareous argillite and fine-grained sandstone. These sedimentary rocks probably represent hemipelagic and overbank-slope deposition. Soft-sediment slump folds and deformed burrows commonly are present. The argillitic rocks commonly are overprinted by a penetrative shear fabric, especially along the northern, eastern, and coastal margins of the King Peak subterrane. Locally, these rocks form a true melange.

Basaltic rocks occur as rare blocks in melange of the King Peak subterrane; they range in length from a few meters along the coast to many hundreds of meters in the Queen Peak area northeast of Point Delgada. The basalts occur as pillowed flows, tuffs, and flow breccias, associated with pink to red pelagic limestone or red to green tuffaceous radiolarian chert. Two major-oxide analyses of these basaltic rocks, one of basalt from Queen Peak, another of basalt from Cooskie Creek, indicate that the rocks are alkalic and oceanic in derivation (fig. 9). The high P_2O_5/TiO_2 ratios (fig. 9*C*), FeO:MnO:P_2O_5 proportions (fig. 9*A*), and $TiO_2/(FeO/MgO)$ (fig. 9*D*), ratios all suggest that the basalts may have formed in a seamount setting.

Rocks of the King Peak subterrane are of middle Miocene age, on the basis of radiolarians and planktic and benthic foraminifers. Early Tertiary foraminifers also are present locally, but at least some occur in rocks containing both radiolarians and foraminifers of middle Miocene age. The early Tertiary forms, therefore, are reworked (McLaughlin and others, 1982). At Queen Peak, a radiolarian fauna characterized by *Cyrtocapsella tetrapera* Haeckel and *Stichocorys* spp. occurs along with nondiagnostic diatoms in a tightly folded composite block of manganiferous and tuffaceous chert overlying pillow basalt. The same radiolarian fauna occurs in hemipelagic thin-bedded chert and interbedded calcareous argillite along the coast, and is associated with carbonate concretions in thin-bedded argillite and fine-grained terrigenous sandstone along the east side of the King Range. Planktic foraminifers of middle Miocene age occur in carbonate concretions with this radiolarian fauna on Horse Mountain along the east side of the King Range, and in argillitic sections along the coast north of Point Delgada (McLaughlin and others, 1982). The age of basalt in the Cooskie Creek area (fig. 2), based on whole-rock K-Ar analysis, is 16.2±0.5 Ma (McLaughlin and others, 1985b).

Rocks of the King Peak subterrane are complexly folded, penetratively deformed, and pervasively veined with laumontite. Penetrative shearing predated or accompanied early folds, which vary in orientation from the northern to the southern part of the King Peak subterrane. Asymmetric early folds in the north half of the King Peak subterrane exhibit a consistent northward to northeastward vergence (fig. 22*A*), whereas folds in the south half exhibit largely westward to northwestward vergence (fig. 22*B*). The relation of these early folds to each other is unclear from our data, although Beutner and Hansen (1975) suggested two discrete fold generations: a north- to northeast-vergent generation (f_1) overprinted by a later generation of chevron and complex folds (f_2) whose axial surfaces are generally upright and trend northwest. Later broad, open warps (f_3) with east-west-trending axes may be relatable to north-south compression and tectonic transport associated with the San Andreas fault system. Late deformation of rocks in the King Peak subterrane is exhibited in highly sheared and crushed rocks along the terrane margin north of Cooskie Creek and along its east boundary. Earlier penetrative shearing of rocks of the King Peak subterrane, as well as f_1 and f_2 folding, probably resulted from east-west convergence along the Farallon-North American plate boundary before about 14 Ma. We speculate that f_3 warping was initiated much later in the Cenozoic, possibly during an episode of northward translation between about 14 Ma and the present. Shearing associated with the King Range terrane suture, which includes coparallel shearing in the adjacent Coastal terrane to the north, occurred during final tectonic transport and accretion of the King Peak subterrane to northern California. This shearing is considered to have occurred between the Miocene and Pleistocene, on the basis of the earlier-described imbrication of Pliocene marine rocks into the Coastal terrane near Petrolia.

King Range Terrane Thermal Anomaly

The King Range terrane was affected by a high-temperature thermal event during middle Miocene time. At Point Delgada, this thermal event is indicated by hydrothermal alteration and mineralization that includes an unusual assemblage of epithermal Pb-, Zn-, and high-Ag-bearing sulfides (McLaughlin and others, 1985b). The hydrothermal mineralization at Point Delgada occurs along north-northeast-trending tension faults conjugate to the north-south- to northwest-oriented faults of the San Andreas system. The base-metal sulfide mineralization crosses a presumed trace of the San Andreas fault system that separates the Point Delgada and King Peak subterranes (McLaughlin and others, 1985b). Adularia associated with the potassic hydrothermal alteration and sulfide mineralization yielded a K-Ar age of 13.8±0.4 Ma (fig. 2). Thus, the Point Delgada and King Peak subterranes were amalgamated before 13.8 Ma.

Vitrinite-reflectance studies in the Coastal belt of the Franciscan Complex (Underwood, 1987; Blake and others, 1988) clearly show that the 13.8-Ma thermal event affected the entire King Range terrane (fig. 23). These data support the proposition that the Point Delgada and King Peak subterranes have been a composite terrane since the middle Miocene and, as such, have undergone negligible right-lateral slip relative to each other subsequently (McLaughlin and others, 1985b). Therefore, any presently or recently active segments of the San Andreas fault system along which major right-lateral offset has occurred (such as faults forming the present boundary between the North American and Pacific plates) must lie either inland, along the suture between the King Range and Coastal terranes, or offshore, west of or at the contact with the Vizcaino structural block.

Figure 22. Folded rocks of King Peak subterrane. *A*, Overturned, northward-vergent synclinal fold, located near north end of King Peak subterrane between Cooskie and Spanish Creeks. *B*, Complex westward-vergent folds in thin-bedded siliceous argillite and calcareous sandstone, located south of Big Flat. View northward.

Vizcaino Structural Block

The Vizcaino structural block (McCulloch, 1987a, b) is a large, structurally complex terrane on the Pacific plate in the offshore area south of the Mendocino Fracture Zone, immediately west of the King Range terrane (figs. 17*A*, 24).

Lithologic data for the Vizcaino block are scant (fig. 24), and so, although complex structures are mapped from numerous seismic profiles (McCulloch, 1987a, b), a detailed comparison of these rocks with those of the adjacent King Range terrane on shore is not presently possible. Quartz-mica schist and slate recovered from the bottom of an exploratory drill hole at the southwest corner of the Vizcaino block just north of Point Arena (loc. L–1, fig. 14) have been provisionally identified as Salinia terrane basement (Hoskins and Griffiths, 1971; Bachman and Crouch, 1987; McCulloch, 1987a, b). Because the location of this drill hole is at the faulted southwest boundary of the Vizcaino block, it is unclear whether the sampled basement was actually in the block or southwest of it, where Salinia rocks are known to occur.

A conspicuous undated, northwest-trending, offshore magnetic anomaly that is truncated at the San Andreas fault just north of Point Arena strongly suggests that the southeastern part of the Vizcaino block is underlain by shallow ophiolitic and (or) oceanic basement rocks at 0.5 to 2.5 km below sea level (Griscom, 1980a; Griscom and Jachens, 1989). Onshore, south of Point Arena, basaltic basement rocks underlie Upper Cretaceous (Campanian) turbidites at Black Point near Gualala (Wentworth, 1968, 1972). The undated basalt of Black Point is tholeiitic (fig. 9*B*) and oceanic in composition with respect to TiO_2 and P_2O_5 contents and FeO/MgO ratio (figs. 9*C*, 9*D*). Owing to its elevated MnO content, however, it shows affinities to island-arc tholeiites in a ternary plot of MnO, TiO_2, and P_2O_5 contents (fig. 9*A*). These Campanian or older basaltic rocks may correspond to the upper part of the "ophiolitic" basement associated with the magnetic anomaly offshore and thus may compose part of the composite basement of the Vizcaino block, along with the overlying Upper Cretaceous and Paleogene to lower Miocene sedimentary section at Point Arena. Paleomagnetic data (Kanter and Debiche, 1985) suggested 37° of northward translation of the basaltic rocks of Black Point since the Early Cretaceous: 16° of translation of the overlying lower Tertiary section (German Rancho Formation of Wentworth, 1968) since the Paleocene, and 10° of translation of the overlying Tertiary volcanic section (Iverson Basalt of Weaver, 1944) since the early Miocene (25 Ma). The chemistry of the lower Miocene Iverson Basalt (Wentworth, 1966) indicates that these rocks are alkalic, with ocean-floor (seamount) affinities (figs. 9*A*, 9*D*). The Iverson Basalt is compositionally similar to diabase and basalt of the approximately coeval Mindego Basalt in the Santa Cruz Mountains of the San Francisco Bay region. The Mindego Basalt presumably was erupted through Salinian basement. The Iverson Basalt also is compositionally similar to the Oligocene or early Miocene "andesitic" basement reported from the bottom of the drill hole at Deep Sea Drilling Project (DSDP) Site 173 (MacLeod and Pratt, 1973) at the northwest corner of the Vizcaino block.

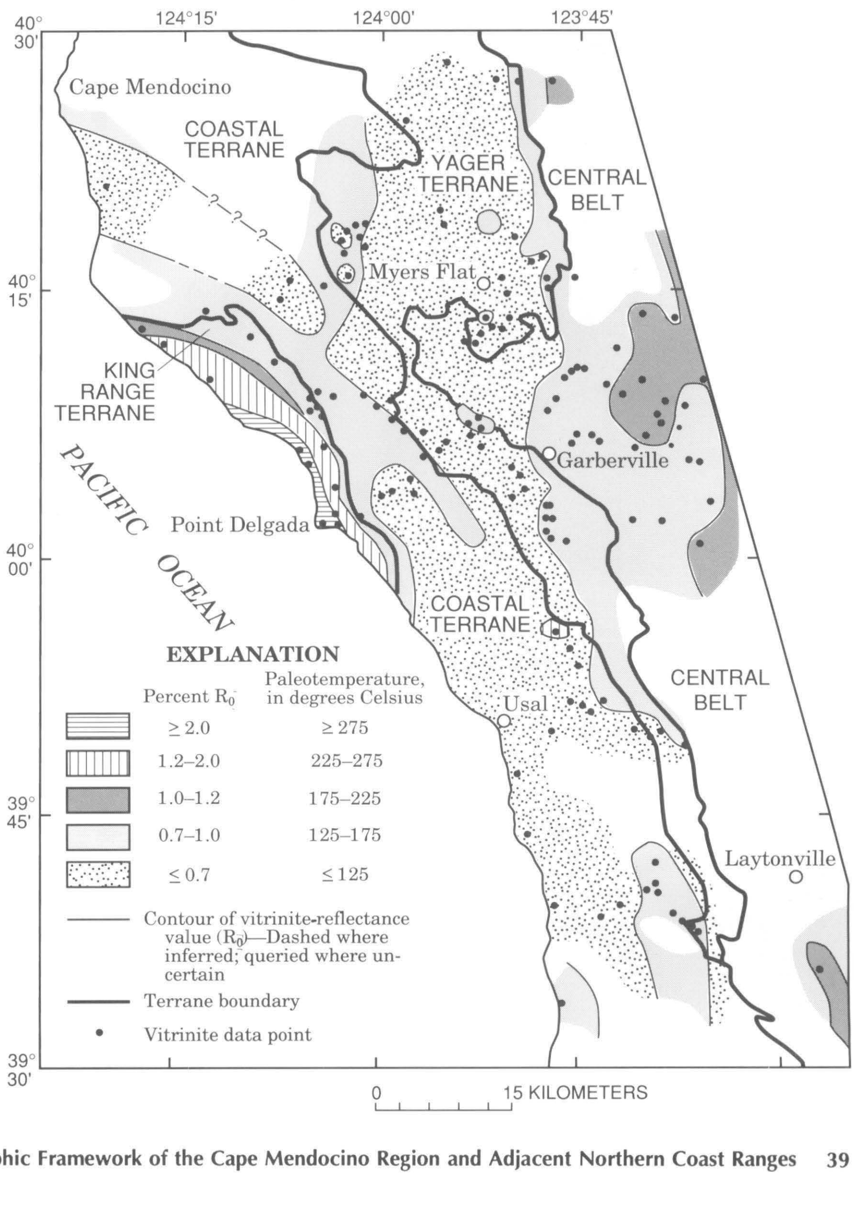
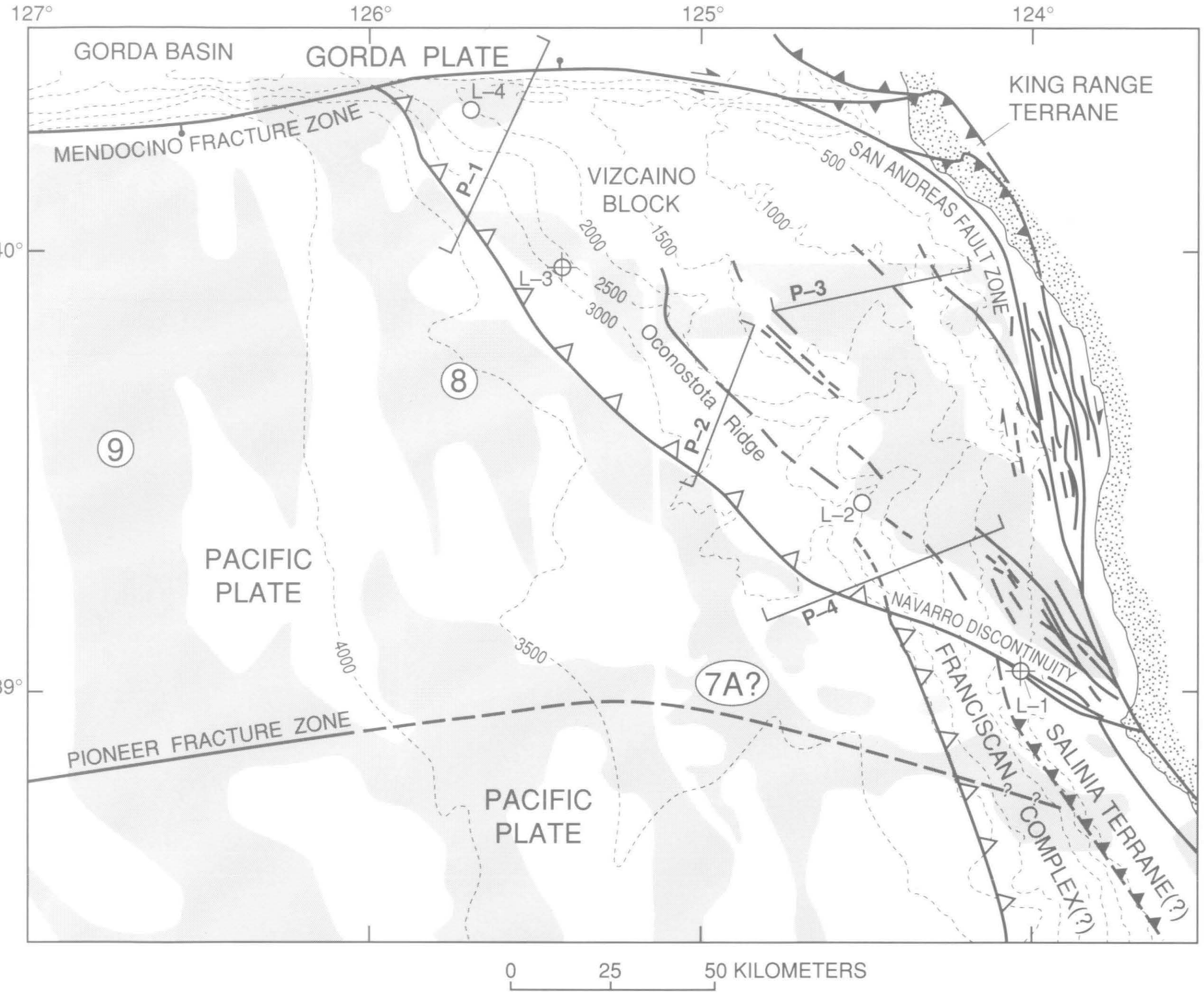


Figure 23. Contoured vitrinite-reflectance (R_0) values and inferred paleotemperatures of metasedimentary rocks of Franciscan Complex in Cape Mendocino region. Modified from Underwood (1987) and Blake and others (1988).



EXPLANATION

8 — Positive magnetic anomaly—Circled number is assigned anomaly number

P–2 — Location of seismic profile

Uninterpreted reflection—Probably largely sedimentary contacts (shown in seismic profiles only)

Unconformable contact on deformed basement (shown in seismic profiles only)

Fault or fracture zone—Dashed where inferred; queried where uncertain. Ball and bar on downthrown block. Arrows indicate direction of relative movement

Thrust fault—Sawteeth on upper plate. Dashed where inferred; queried where uncertain

Inactive(?) convergent margin—Sawteeth on upper plate

2500 — Bathymetric contour—In meters

L–4 ○ — Locality of lithologic data from dredge haul or drill hole on Vizcaino block. Lithologic descriptions:

- L–1 — Quartz-mica schist and slate, possibly Salinia terrane(?) basement—From bottom of exploratory drill hole (Hoskins and Griffiths, 1971)
- L–2 — Fine-grained sandstone containing Eocene to Oligocene nannofossils—Dredged from Noyo Submarine Canyon
- L–3 — Volcanic basement overlain by uppermost Oligocene and younger siliceous pelagic strata containing reworked Cretaceous radiolarians—From drill hole DSDP 173 at depth of 306.5 to 320 m
- L–4 — Basalt, basaltic conglomerate, and serpentinite—Dredged from Mendocino Ridge

L–1 ⊕ — Drill hole

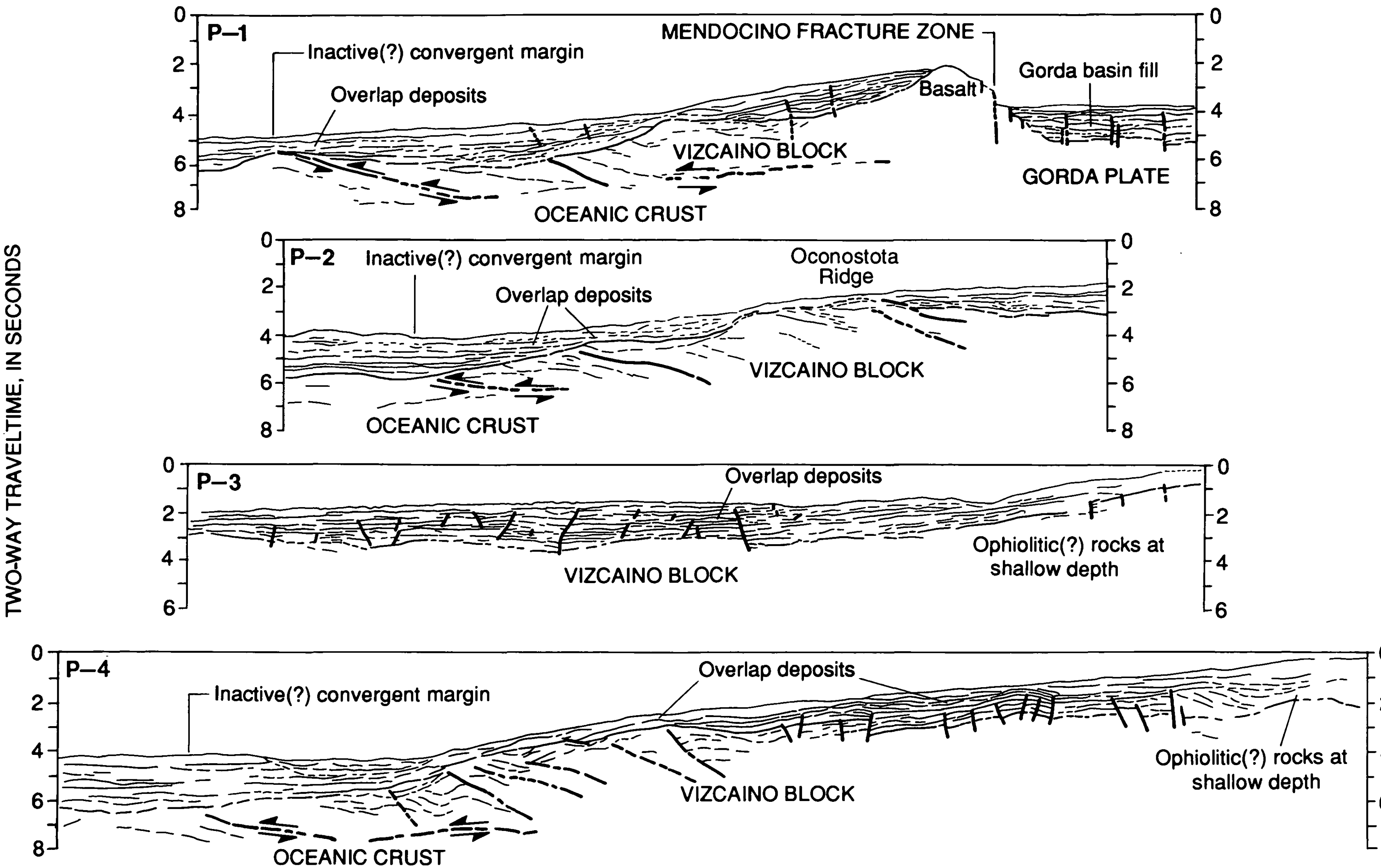


Figure 24. Offshore area south of Mendocino Fracture Zone, showing locations of positive magnetic anomalies of Pacific plate and Vizcaino structural block, lithologic data and structural features of Vizcaino block and adjacent offshore area, and interpreted seismic profiles across major structures bounding Vizcaino block and Pacific plate (modified from McCulloch, 1987a, b). Ages of units delineated on seismic profiles: overlap deposits, middle Miocene(?) and younger; Gorda basin fill, Miocene and younger; oceanic crust, Oligocene and older; Vizcaino block, Oligocene to Cretaceous or Jurassic(?).

Table 3. Radiolarians and planktonic foraminifers from the King Range terrane and the lower part of the drill hole at Deep Sea Drilling Project (DSDP) Site 173

[Ages: K, Cretaceous; M, Miocene; T; Tertiary. R, reworked. Data from Ingle (1973), Kling (1973), von Huene and others (1973), and McLaughlin and others (1982)]

	King Range terrane	DSDP 173
Radiolarians		
Amphipyndax? sp.	K	- -
Archaeodictyomitra sp.	K	- -
Cryptamphorella sphaerica (White) of Foreman (1973)	K	- -
Cyrtocapsella japonica Nakaseko	M	M
tetrapera Haeckel	M	M
Cyrtocapsella ? sp.	M	- -
Dictyocephalus sp. of Pessagno (1963)?	K	- -
Dictyomitra duodecimocostata Foreman	K	- -
formosa Squinabol of Pessagno (1976)	K	- -
koslovae Foreman	K	- -
multicostata Zittel of Pessagno (1976)?	K	K(R)
Lychnocanoma grande (Campbell and Clark)	M	- -
Ommatartus? sp.	M	M
Sphaeropyle robusta Kling	M	M
Stichocorys delmontensis (Campbell and Clark)	M	M
sp.	M	- -
Theocorys redondoensis (Campbell and Clark)	M	- -
Planktonic foraminifers		
Acarinina sp.	T	- -
Globigerina juvenilis Bolli	M	M
sp.	M	- -
Globigerinita glutinata (Egger)	M	M
Morozovella sp.	T	- -
Orbulina sp.	M	M
Planorotaloides sp.	T	- -
Subbotina sp.	T	- -

Northwest of the drill holes offshore from Point Arena, fine-grained sandstone containing a nannofossil assemblage ranging in age from middle Eocene to Oligocene (McCulloch, 1987a, b) was dredged from the southwest wall of Noyo Submarine Canyon from a depth of about 2,500 m (loc. L–2, fig. 24). These rocks are interpreted (McCulloch, 1987a, b) to be in the lower part of an accretionary prism, a depositional setting consistent with that for rocks of similar age in the Coastal terrane. Alternatively, these rocks could be part of a somewhat more distal or downslope lithofacies of the German Rancho Formation near Point Arena.

Presumed basement rocks were sampled from two other localities (locs. L–3, L–4, fig. 24) in the northwestern part of the Vizcaino block, both west of long 125° W. Submarine volcanic breccia was recovered from the bottom of the drill hole at DSDP Site 173 (loc. L–3, fig. 24) at 3,233.5 to 3,248 m below sea level. On the basis of texture and a silica content similar to those of arc-related volcanic rocks of the Cascades, MacLeod and Pratt (1973) considered these rocks to be andesitic. However, the major-oxide and minor- and trace-element compositions are more compatible with ocean-floor or alkalic seamount volcanism in all the discrimination plots of figures 9 and 10 except for (Ti/Cr)/Ni ratio (fig. 10*C*). Thus, these basement rocks may form part of a remnant of Oligocene or older ocean floor.

A thick, relatively undeformed section of siliceous, pelagic mud containing a lower bathyal radiolarian and foraminiferal fauna of latest Oligocene to late Miocene age overlies the volcanic unit at DSDP Site 173 (Ingle, 1973; Kling, 1973). Identical radiolarian and foraminiferal faunas are found in the middle Miocene part of the King Range terrane (table 3). Radiolarians of the *Dictyomitra multicostata* group, interpreted to be reworked from a Cretaceous Franciscan source, were also identified at the bottom of the sedimentary section at DSDP Site 173 (Kling, 1973). This same radiolarian group occurs in a Late Cretaceous (Campanian or Coniacian) fauna at Point Delgada in the King Range terrane. A dredge haul along the crest of the Mendocino Ridge immediately northwest of DSDP Site 173 and east of long 126° W. (loc. L–4, fig. 24) consisted of basaltic flows and conglomerate, and serpentinite (Krause and others, 1964). The Miocene section at DSDP Site 173 thus appears to be faunally equivalent to that of the King Range terrane (in part), and the reworked Cretaceous radiolarians reported from DSDP Site 173 could have been eroded and transported from Point Delgada.

Unlike the DSDP Site 173 rocks, however, the King Range terrane includes a major component of coarse terrigenous detritus, and rocks of the terrane are severely disrupted by folding and penetrative shearing. In addition, rocks of the King Range are veined with calcite and laumontite. The depositional setting of DSDP Site 173, therefore, differed significantly from that of the King Range terrane. The setting of DSDP Site 173 during the middle Miocene appears to have been distal and oceanic, and that of the King Range terrane more closely associated with a near-trench environment, within reach of terrigenous sedimentation.

Seismic profiles across the northwest corner and west central part of the Vizcaino block, coupled with magnetic-lineation data (fig. 24; McCulloch, 1987a, b) show that oceanic crust within the Pacific plate, dated as Oligocene in age, is overlain by rocks of the Vizcaino block along a northeast-dipping low-angle fault. This low-angle fault bounds the southwest side of the Vizcaino block and extends along the entire California margin west of the San Andreas transform system (profile P–1, fig. 24). This southwest boundary of the Vizcaino block and its extension southward of Point Arena have been interpreted as a late Oligocene or early Miocene "paleosubduction" boundary between the Pacific and North American plates (McCulloch, 1987a, b). According to this interpretation, the southwest boundary of the Vizcaino block represents part of the Oligocene to early Miocene subduction margin of the North American plate. This interpretation, however, conflicts with earlier work, because Oligocene to early Miocene motion of the Pacific plate relative to the North American plate is inferred to have been transtensional south of the Mendocino Fracture Zone, according to the plate reconstructions of Atwater (1970), Engebretson and others (1985), and Stock and Molnar (1988), and so subduction between the Pacific and North American plates would be difficult to achieve.

Accretion of the Vizcaino Structural Block to the Pacific Plate and Initiation of the San Andreas Transform System

A reconstruction of the accretion of the Vizcaino structural block to the Pacific plate constrains the tectonic mechanism(s) involved in initiation of the San Andreas transform and its subsequent propagation northward (fig. 25). Any such reconstruction must address the apparent enigma posed by offshore evidence for convergence between the Vizcaino block and the underthrusted oceanic (Pacific) plate, during a time when transtensional stress is inferred to have been dominant along the California margin.

Although most plate models for the late Oligocene to early Miocene California margin south of the Mendocino Fracture Zone suggest that a transform setting had developed between the Pacific and North American plates, unequivocal geologic evidence is absent for San Andreas-related transform motion (that is, transform motion tied to northward propagation of the Mendocino Fracture Zone) before about 16 Ma. Although restoration of pre-Tertiary basement rocks of the Coast Ranges to their original configurations apparently requires movements along faults that predate the modern San Andreas transform, restoration of middle Miocene or later right slip on the modern San Andreas fault system (here considered to include the San Andreas-Pilarcitos, Hosgri-San Gregorio, and Hayward-Calaveras faults) apparently establishes continuity between some older units offset across the San Andreas fault, such as the Late Jurassic gabbros of Logan and Eagle Rest Peak (fig. 26).

Northward-younging patterns of volcanism, together with strike-slip-fault-bounded structural basins that young northward, have been linked to northward propagation of the San Andreas transform system (Dickinson and Snyder, 1979; McLaughlin and Nilson, 1982; Fox and others, 1985). The ages of the volcanic rocks, as well as of basin fillings that exhibit this northward-younging pattern, appear to be younger than about 15 to 16 Ma (fig. 26). Widespread volcanism and basin formation also occurred earlier, especially about 24–22 Ma, east and west of the San Andreas fault. This earlier volcanism, which shows no obvious space-time relation to present or past positions of the Mendocino triple junction, is thought to be related to extensional tectonism rather than strike slip (Stanley, 1987). These data suggest that although a transtensional setting existed at least from 24 to 16 Ma, the modern San Andreas transform was not well developed, and so significant right slip did not occur until after about 16 Ma (fig. 25*B*).

Structural relations along the north and southwest boundaries of the Vizcaino block indicate that its accretion to the Pacific plate resulted from eastward extension of the Mendocino Fracture Zone across the convergent boundary between the Vizcaino block and oceanic rocks of the Pacific plate, connecting the Mendocino Fracture Zone to the newly initiated San Andreas transform. Offshore data show that this jump of the Mendocino Fracture Zone occurred sometime between formation of magnetic anomaly 8 on the Pacific plate about 28–27 Ma and overlap of the convergent margin of the Vizcaino block by undeformed pre-Mohnian (probably middle Miocene, 16–12 Ma) sediment (fig. 24; see also, McCulloch, 1987a, b). The absence of any known strike-slip fault west of the Vizcaino block along which Pacific-North American plate transform motion could have been taken up before this eastward jump of the fracture zone suggests that all transform movement of the San Andreas system has been taken up along faults that broke to the east of the convergent west boundary of the Vizcaino block and its southward extension. The present positions of the Mendocino Fracture Zone and Vizcaino block are north of the Salinia terrane, and the position of the northern San Andreas fault system is east of the Salinia terrane (fig. 24). In comparison with reconstructions of the change in position of the Mendocino Fracture Zone over time (Atwater, 1970; Engebretson and others, 1985; Stock and Molnar, 1988) and with

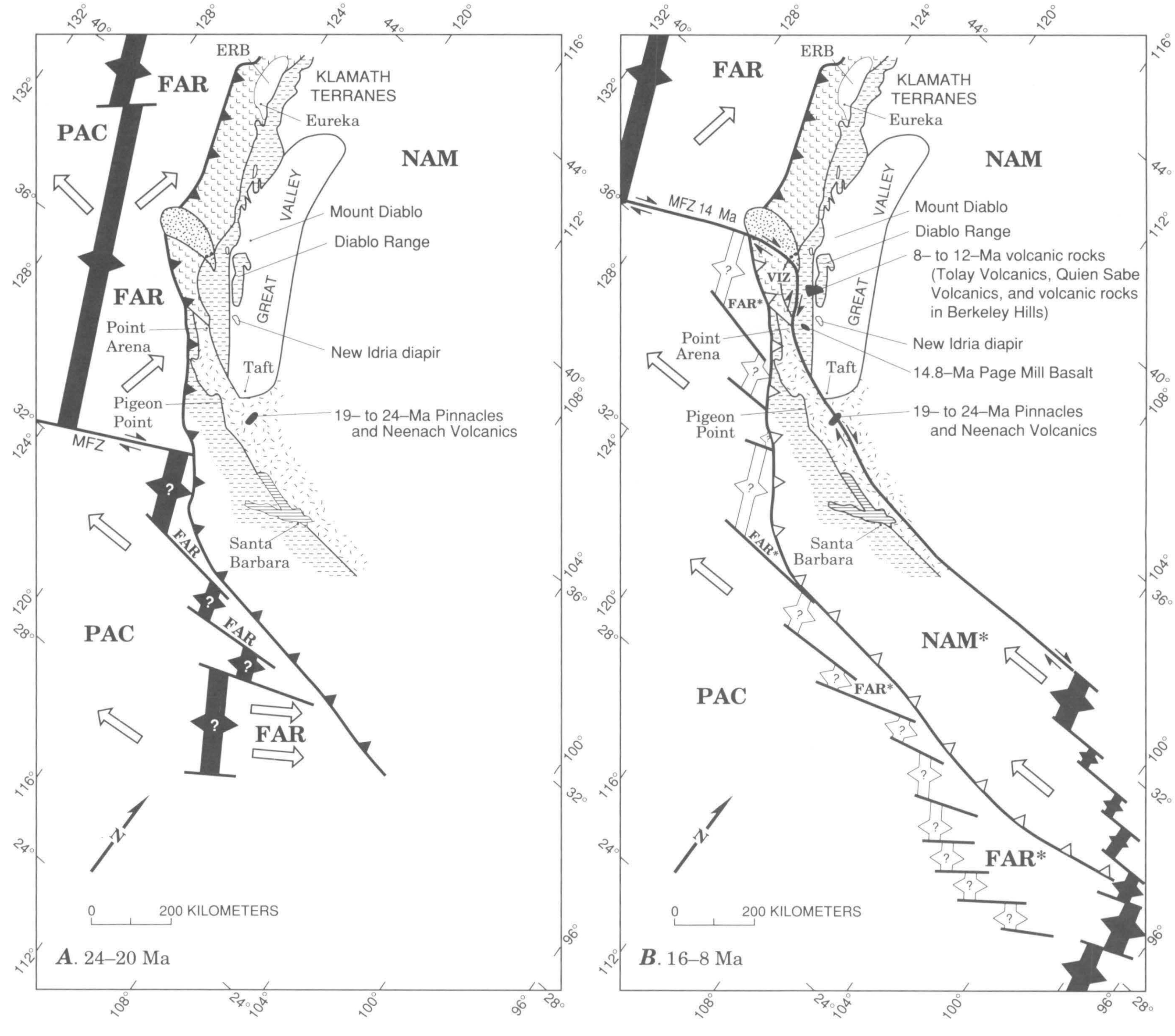
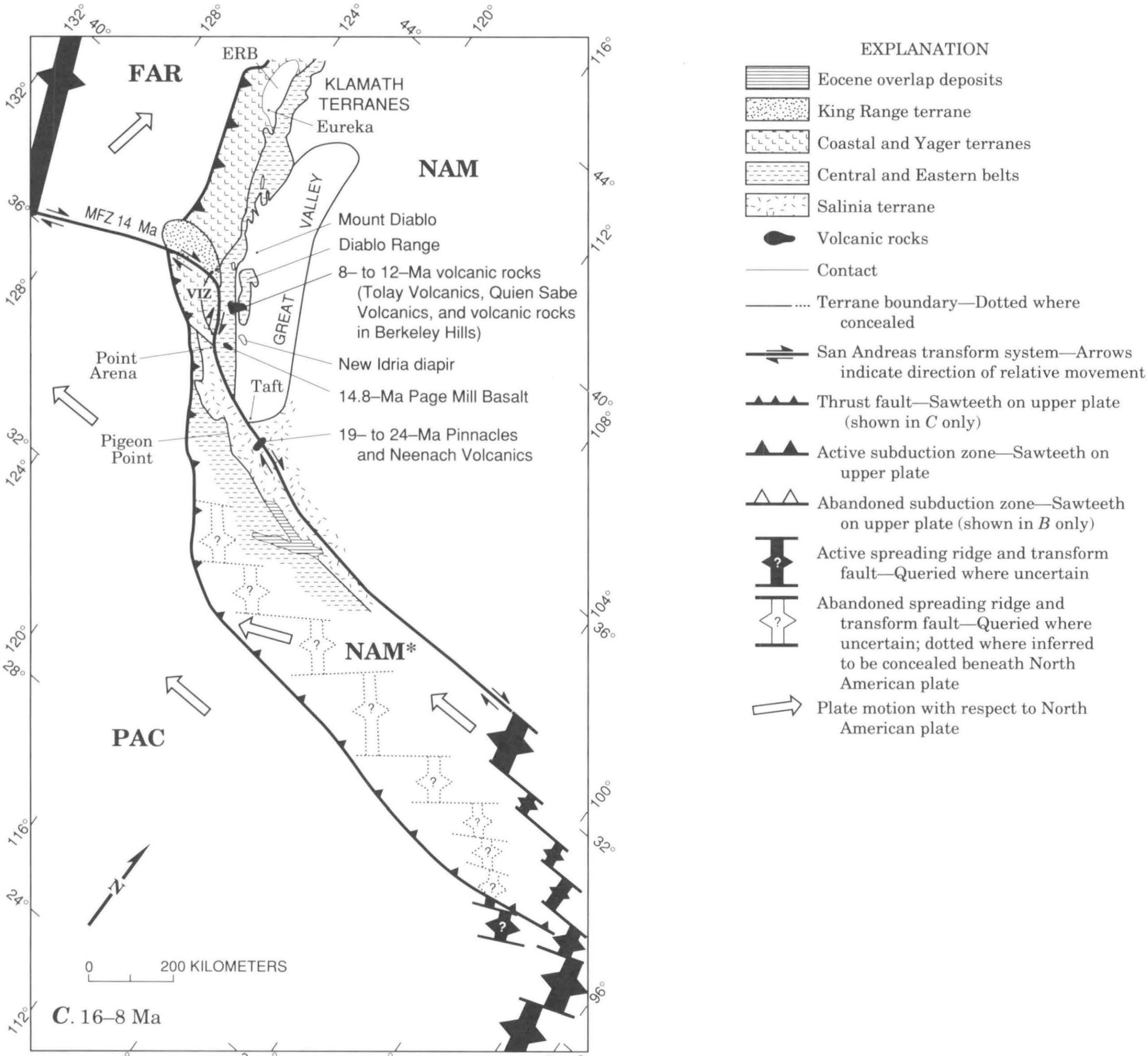


Figure 25. Plate-tectonic model for early Miocene initiation of modern San Andreas transform, offering two hypotheses for convergent deformation along Pacific-North American plate margin after 16 Ma. Plate reconstructions, relative motions, and projections modified from fixed-hotspot reference-frame model of Engebretson and others (1985). ERB, deposits of Eel River basin; FAR, Farallon plate; FAR*, old Farallon plate that is now part of Pacific plate; MFZ, Mendocino Fracture Zone; NAM, North American plate; NAM*, old North American plate that is now part of Pacific plate; PAC, Pacific plate; VIZ, Vizcaino structural block. *A*, Pacific-Farallon Ridge initially came in contact with North American plate about 30 Ma, but we assume here that Farallon-North American plate margin north of present-day Gulf of California remained convergent until sometime after 24 to 20 Ma. During that period, Pacific-Farallon Ridge and increasingly segmented Farallon plate were compressed between North American and Pacific plates. *B*, First model suggests that convergent deformation along Pacific-North American plate margin was driven by active subduction of Farallon plate beneath North American plate and that west-convergent boundary of Vizcaino block represents now-abandoned subduction zone; model assumes existence of pieces of old Farallon plate and segments of failed Pacific-Farallon Ridge west of old subduction margin. By this model, Pacific-Farallon Ridge collided with North American plate about 16 Ma, and subduction stalled, resulting in reorientation

restored offsets of the San Andreas fault system (fig. 26), this geometry indicates that eastward extension of the fracture zone, resulting in accretion of the Vizcaino block to the Pacific plate and formation of the modern San Andreas fault system, could not have occurred earlier than about 16 Ma.

Although the Miocene and older west convergent boundary of the Vizcaino block and its southward extension may be inconsistent with transtensional motion between the Pacific and North American plates for that time, a subduction margin is compatible with Oligocene to Miocene motion of



of active ridge, extinction of older ridge segments, and preservation of remnants of Farallon plate between abandoned subduction margin and extinct ridge. Reorientation of active ridge was accompanied by extension and rifting of North American plate near present-day Gulf of California between 16 and 12 Ma. About 14 Ma, Mendocino Fracture Zone broke eastward, connecting with newly oriented active ridge and initiating modern San Andreas transform. Reorientation of ridge and transform fluctuated until at least 8 Ma, resulting in transfer of various structural blocks, including Vizcaino block, to North American plate and back to Pacific plate near propagating north end of San Andreas transform. *C*, Alternatively, convergent deformation was driven by extension and rifting in hinterland of North American plate, which caused thrusting along Pacific-North American plate margin; this model assumes that Pacific-Farallon Ridge had been subducted beneath or, possibly, overridden by North American plate and was no longer present west of subduction zone. Crustal thinning, extension, and rifting of North American plate above subducted ridge caused west-northwest-directed thrusting along Pacific-North American plate boundary. About 14 Ma, as in *B*, Mendocino Fracture Zone connected with newly oriented Pacific-Farallon Ridge, and San Andreas transform was initiated, transferring large piece of North American plate, including Vizcaino block, to Pacific plate.

the Farallon plate relative to North America (fig. 25*A*). This compatibility leads us to suggest the presence of failed (or extinct) segments of the Pacific-Farallon Ridge west of the Vizcaino block (fig. 25*B*).

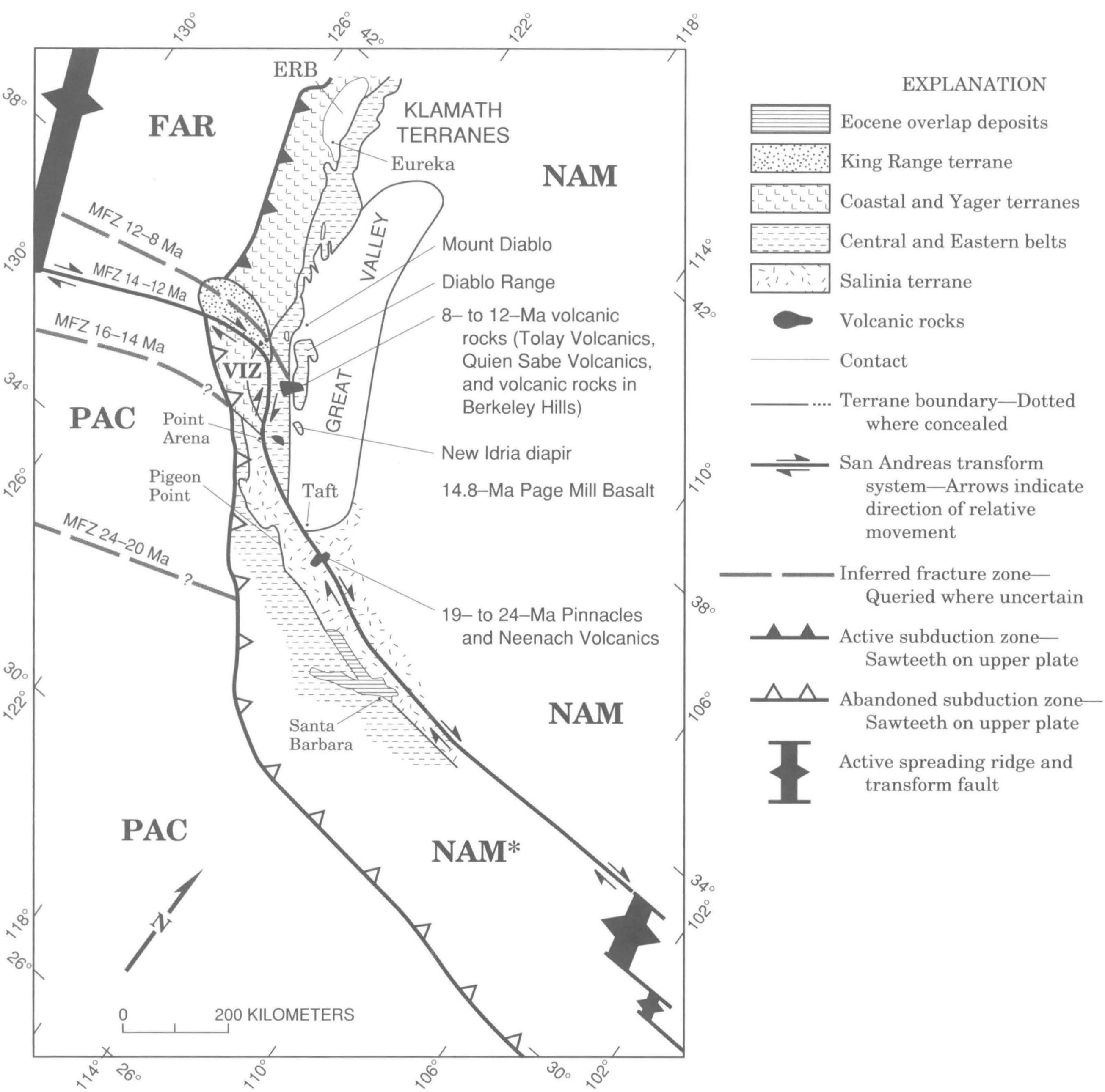


Figure 26. Model for northward migration of Mendocino Fracture Zone and propagation of San Andreas transform fault, showing reconstructed positions from approximately 16 to 8 Ma of major terranes, structural blocks, and Eocene or younger rocks that overlap accreted terranes along North American plate margin. Model suggests that, before about 16 Ma, San Andreas transform had not been initiated, or lay either entirely within offshore Pacific plate or along northeast-dipping Pacific-North American plate boundary. After 16 Ma, modern San Andreas transform was initiated when Mendocino Fracture Zone broke eastward into North American plate margin, connecting newly reoriented Pacific-Farallon Ridge to Mendocino Fracture Zone. Increasing convergence of northwardly propagating triple junction with North American plate resulted in numerous northeastward jumps of Mendocino Fracture Zone and San Andreas transform fault, accompanied by dextral displacement and temporary to permanent transfer to Pacific plate of several fault blocks that were caught west of newly broken transform segments; two of these blocks are Salinia terrane and Vizcaino structural block. ERB, deposits of Eel River basin; FAR, Farallon plate; MFZ, Mendocino Fracture Zone; NAM, North American plate; NAM*, part of North American plate that has been transferred to Pacific plate; PAC, Pacific plate; VIZ, Vizcaino structural block.

By this model, remnants of the Farallon plate would be caught between segments of the failed Pacific-Farallon Ridge and a preserved subduction margin between the Farallon and North American plates, represented by the southwest boundary of the Vizcaino block. We speculate that subduction of this trapped remnant of the Farallon plate south of the Mendocino Fracture Zone may have persisted until 16–12 Ma after initial contact of the Farallon-Pacific Ridge with the North American plate. Between 28 and 16 Ma, the subducting remnant of the Farallon plate would have become increasingly fragmented as the segmented Pacific-Farallon Ridge approached the subduction margin and transtension developed along an increasingly larger area of contact between the North American and Pacific plates (fig. 25*A*). Simultaneously, motion of the Pacific plate would have propagated the Mendocino Fracture Zone northward to a position along the North American plate margin north of the Salinia terrane. Between about 16 and 14 Ma, dying segments of the Pacific-Farallon Ridge would have been accreted to the Pacific plate with the Vizcaino block, as the Mendocino Fracture Zone simultaneously extended eastward and the modern San Andreas transform was initiated, connecting the fracture zone to the active Pacific-Farallon Ridge system to the south (fig. 25*B*).

If this model is valid, evidence for extinct ridge segments, in the form of west-to-east reversals in the age sequence of magnetic anomalies on the Pacific plate, should be present among undated anomalies between anomaly 8 (28–27 Ma) and anomaly 5 (10–9 Ma). However, confirmation of such age reversals would be difficult, owing to attenuation of the magnetic anomalies and complex faulting of the sea floor (D.C. Engebretson, oral commun., 1988). Progressive fragmentation and incorporation of parts of the Farallon plate into the Pacific and North American plates have been proposed previously (Menard, 1978). In addition, failed segments of spreading ridges and (or) rift-initiation sites have been recognized elsewhere in some microplate fragments that formerly were part of the Farallon plate (Mammerickx and others, 1988).

Alternatively, westward-directed thrusting could have occurred in response to extension and rifting above segments of the Pacific-Farallon Ridge that were subducted a considerable distance south of the Mendocino Fracture Zone (fig. 25*C*). This extension-related thrusting would have occurred after Oligocene ridge subduction and before establishment of a transform boundary between the Mendocino Fracture Zone and the ridge system at 16–14 Ma. This model is attractive because it eliminates the necessity for hypothetical extinct segments of the Pacific-Farallon Ridge west of the Vizcaino block.

Both of these models suggest that at least some of the so-called "transtensional volcanism" in the Coast Ranges before 16 Ma (Stanley, 1987) may actually have been generated above an active convergent margin.

Models for Accretion of the King Range Terrane and Their Relation to Propagation of the San Andreas Transform

Two different models have been proposed to explain the accretionary setting and heat source for the thermal anomaly of the King Range terrane. One model implies significant right-lateral displacement of the King Range terrane; the other does not.

Proximal-Ridge and Leaky-Fracture-Zone Models

Between 16 and 12 Ma, the Pacific-Farallon Ridge system was very close to the North American plate subduction margin (Engebretson and others, 1985; Underwood, 1987, 1989). The presence of youthful, hot, buoyant oceanic crust along the subduction margin would have promoted hydrothermal circulation of connate fluids in marine sediment deposited in the trench and on the inner trench-slope and slope. A variation of this model appeals to a shallow magma point source leaked from along "unstable" precursors of the Blanco, Sovanco, or Surveyor Fracture Zones that may have intersected the Cape Mendocino margin during middle Miocene time (Underwood, 1987, 1989). These models assume that little, if any, northward translation of the King Range had occurred, that hydrothermal circulation was initiated at about the present latitude, and that the King Range terrane was merely "troweled" aside as the Mendocino triple junction propagated to its present latitude (fig. 27; Underwood, 1987, 1989).

Although the above models offer a reasonable explanation for the present setting of the King Range terrane and for the formation of its thermal anomaly, several details remain unclear. If proximity of the Pacific-Farallon Ridge to North America promoted hydrothermal activity, we would expect a significant thermal anomaly to be expressed in near-trench middle Miocene deposits along the Washington to Oregon margin. The presence of such an anomaly needs confirmation to validate this model. Moreover, at present we know of no areas of hydrothermal sulfide mineralization of middle Miocene age (16–13 Ma) along the subduction margin north of the Mendocino Fracture Zone with a paragenesis comparable to that of Point Delgada (McLaughlin and others, 1985b). A subduction-related structural setting that includes Upper Cretaceous oceanic rocks (Point Delgada subterrane) juxtaposed against middle Miocene slope and trench-slope deposits (King Peak subterrane) has no known analogs along the Cascadia subduction margin. Thus, areas that include rocks of these ages involved in subduction-related structural settings still need to be documented.

The close association of the mineralization at Point Delgada with northeast-trending tensional faults conjugate to northwest-trending strike-slip faults implies an origin for the hydrothermal system that is closely linked to right-lateral faulting. Because of this relation, right-lateral motion, possibly associated with a leaky transform, seems to be an unavoidable element in any model for the King Range thermal anomaly, whether or not this anomaly formed at or south of its present position.

San Andreas Transform Model

Our preferred reconstruction for deposition, thermal metamorphism, and translation of the King Range terrane infers transport along the San Andreas transform margin with the offshore Vizcaino block of the Pacific plate (fig. 28). Two important considerations constrain the latitudinal origin of the King Range terrane by this model: (1) the location and nature of igneous heat sources of appropriate age (ca. 14–13 Ma) initiated during propagation of the San Andreas transform (Dickinson and Snyder, 1979; Johnson

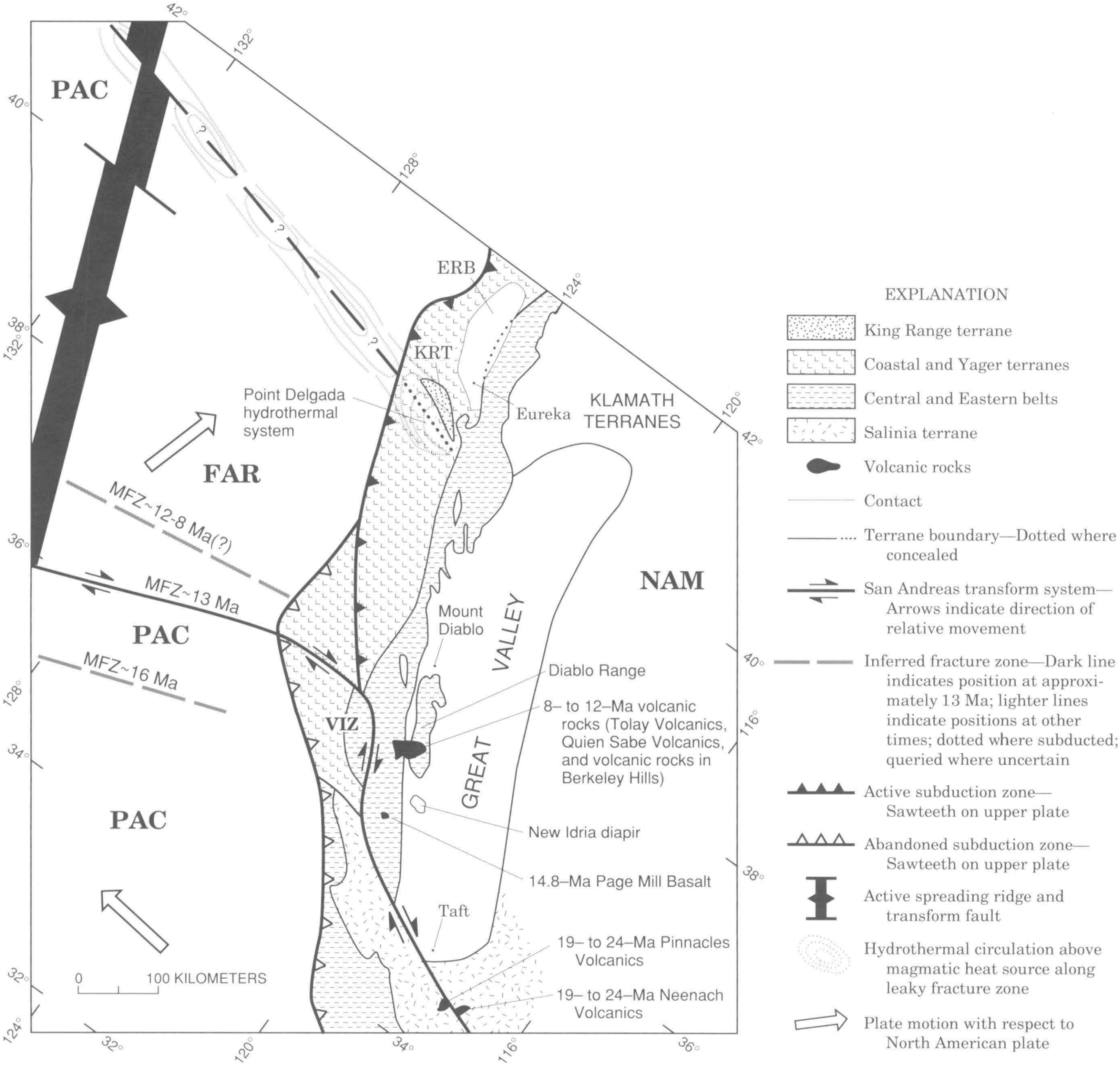
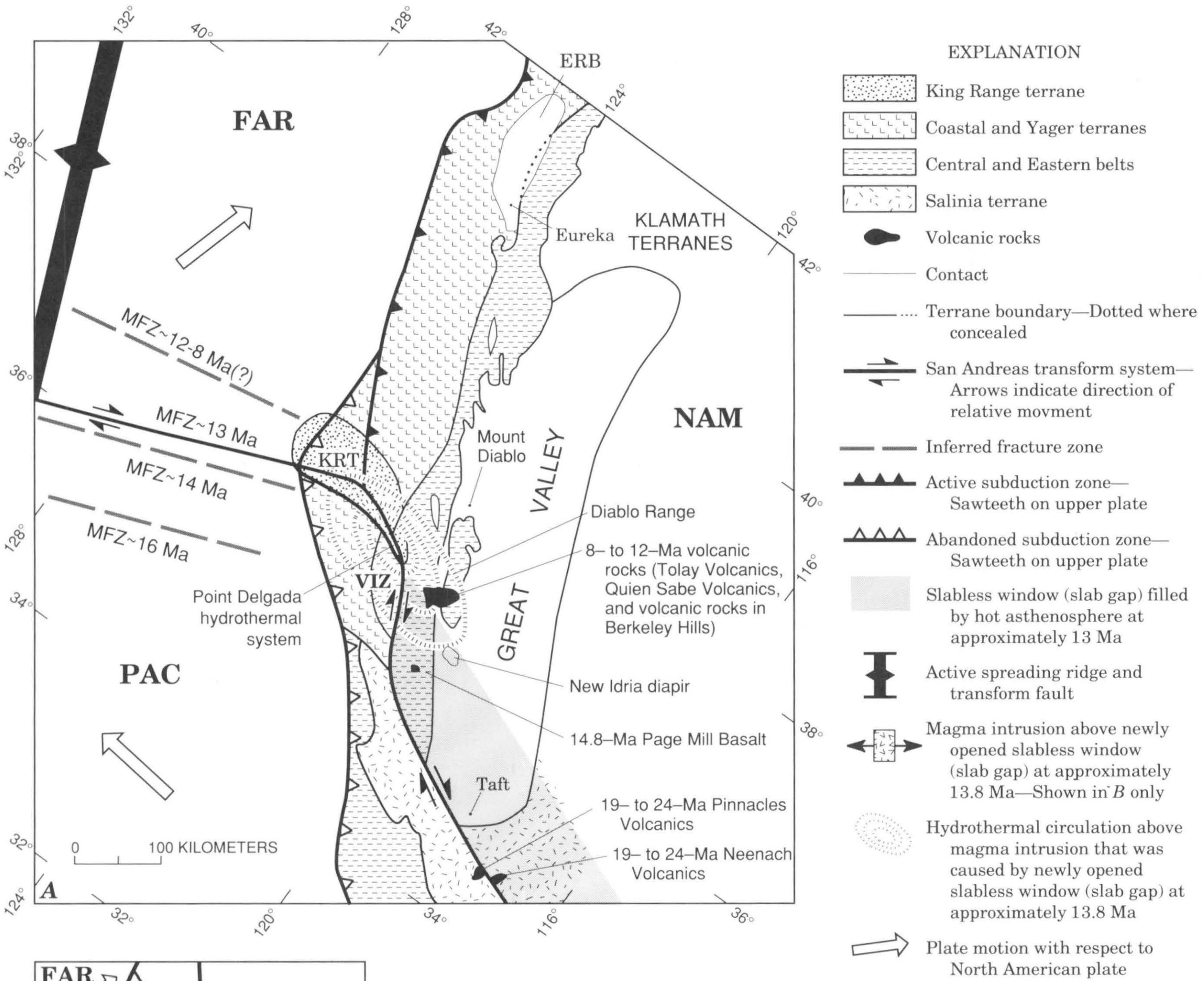


Figure 27. Model for origin of King Range terrane that assumes little or no latitudinal translation, as suggested by Underwood (1989), showing reconstructed North American plate margin at approximately 13 Ma. According to this interpretation, King Range terrane was deposited near its present-day latitude, near Farallon-North American plate subduction margin, and subsequently was "troweled" aside as Mendocino triple junction propagated northward. Thermal anomaly associated with King Range terrane is attributed to hydrothermal circulation caused by shallow magma generated in Farallon plate along partially subducted leaky fracture zone, which has since migrated northward. High geothermal gradient was present in Farallon plate, owing to proximity of spreading ridge to subduction margin. ERB, deposits of Eel River basin; FAR, Farallon plate; KRT, King Range terrane; MFZ, Mendocino Fracture Zone; NAM, North American plate; PAC, Pacific plate; VIZ, Vizcaino structural block.



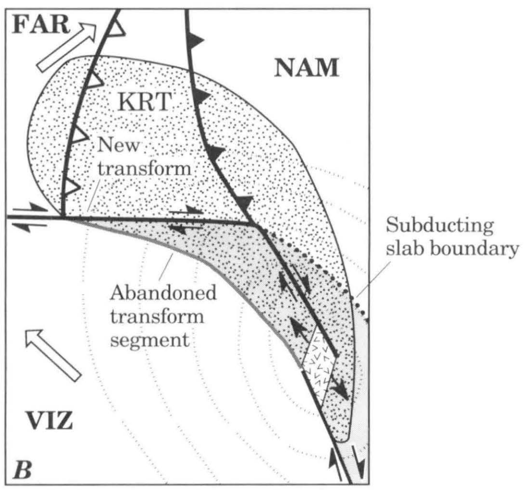


Figure 28. Alternative model for origin of King Range terrane that assumes large-scale translation with Pacific plate, showing reconstructed North American plate margin at approximately 13 Ma. ERB, deposits of Eel River basin; FAR, Farallon plate; KRT, King Range terrane; MFZ, Mendocino Fracture Zone; NAM, North American plate; PAC, Pacific plate; VIZ, Vizcaino structural block. *A*, According to this interpretation, King Range terrane was assembled considerably south of its present-day latitude, along Farallon-North American plate subduction margin, and was accreted to Pacific plate as Mendocino Fracture Zone extended eastward into subduction margin. Point Delgada hydrothermal system was initiated when slabless window (slab gap) opened beneath King Range terrane about 13.8 Ma. King Range terrane was then translated northward with Pacific plate to its present-day latitude, where it was accreted back to North American plate margin as motion between Pacific and North American plates became increasingly transpressive at propagating north end of San Andreas transform. *B*, Enlargement of area of Point Delgada hydrothermal system, simplified from figure 28*A*, showing eastward jump of Mendocino Fracture Zone, realignment of subduction zone, and magma intrusion above newly opened slabless window (slab gap).

and O'Neil, 1984; Fox and others, 1985; McLaughlin and others, 1985b; Stanley, 1987), and (2) the position of the Mendocino Fracture Zone when the King Range terrane was transferred from the North American plate margin to the Pacific plate (Engebretson and others, 1985).

Dickinson and Snyder (1975, 1979) pointed out that the geometric instability created by propagation of the Mendocino triple junction requires a triangular "slabless window" adjacent to the San Andreas transform and east of the Mendocino Fracture Zone. This window beneath the crust is defined on the north by eastward projection of the subducted south boundary of the Gorda plate, on the south by the point along the trailing Pacific-North American plate transform where the East Pacific Rise intersects the North American plate margin, and on the east by a line of intersection at the base of the North American plate connecting the subducted easternmost part of the Gorda plate with the East Pacific Rise-North American plate intersection (fig. 28*A*). Theoretically, the slabless window has opened continuously with northward lengthening of the San Andreas transform and eastward subduction of the Gorda plate, allowing hot asthenosphere to continuously rise upward into the window and heat the overlying crust. Dickinson and Snyder (1979) used this model to explain the relation of magma emplacement to propagation of the San Andreas transform (fig. 28*B*). The same model also has been invoked to explain heat-flow distribution along the San Andreas fault (Lachenbruch and Sass, 1980) and the velocity structure of the crust beneath the Coast Ranges (Zandt and Furlong, 1982). Recently, the concept of a triangular slabless window of asthenosphere has been challenged by Severinghaus and Atwater (in press), who argue that subducted slabs heat up and become incorporated into the asthenosphere over time. The effect of this heating is to obliterate the triangular geometry of the "slabless window" and, instead, produce a large "slab gap" southeast of the triple junction.

Underwood (1987) argued that the appearance of thermal anomalies in the crust of the Coast Ranges lagged behind passage of the Mendocino triple junction by as much as 3 m.y., owing to the time necessary to conductively transfer heat into the crust overlying the asthenosphere-filled slabless window. However, this argument does not seem to apply to the Coast Ranges because initiation of volcanism at 2.6–2.0 Ma in the Clear Lake area lagged behind passage of the Mendocino triple junction by only 0.7 to 1.3 m.y. (Donnelly-Nolan and others, 1981; McLaughlin, 1981; McLaughlin and others, 1985b). This shorter lag may be attributable to the likelihood that thermal anomalies in the upper 10 km of crust above the slabless window (slab gap) are more directly tied to extensional strain adjacent to newly lengthened segments of the transform than to conductive heat transfer. Extensional faulting over the asthenosphere-filled slab gap would establish conduits for upward movement of magma and allow convective hydrothermal circulation to occur above and adjacent to the magma bodies. We have therefore assumed an approximate lag time of 1 m.y. between passage of the Mendocino triple junction and initiation of volcanic activity.

The latitude of origin of the King Range terrane was reconstructed by restoring slip on major faults of the San Andreas system that postdate 16 Ma, and by assuming that the King Range thermal anomaly formed in close proximity to 15–13-Ma volcanism in the Coast Ranges. We consider volcanism of this age and the thermal anomaly to have been initiated over faulted crust above a slabless window (slab gap) shortly after passage of the Mendocino triple junction. In reconstructing the 16–13-Ma California margin, 115 km of Neogene slip are restored on the Hosgri-San Gregorio fault, 28 km on the peninsula segment of the San Andreas fault (Cummings, 1968; Fox and others, 1985), and 102 km on the Pilarcitos fault, amounting to 245 km of combined slip. Restoration of 45 km of slip across the Tolay-Hayward fault and 145 km across the Calaveras fault (for a combined slip of 190 km) are necessary to restore the 12–8-Ma Tolay Volcanics of Morse and Bailey (1935), volcanic rocks in the Berkeley Hills, and the Quien Sabe Volcanics of Leith (1949) to the same pre-12-Ma position (McLaughlin and others, 1990). This reconstruction further restores the 14.8-Ma Page Mill Basalt on the San Francisco peninsula to a position south of the Quien Sabe Volcanics (Johnson and O'Neil, 1984; Fox and others, 1985). The resulting minimum post-16-Ma dextral displacement across the San Andreas system is about 435 km (figs. 26, 28).

Previously discussed structural and stratigraphic relations indicate that between about 17 and 14 Ma, strata in the King Peak subterrane of the King Range terrane were deposited in a lower bathyal trench setting along the Farallon-North American plate subduction margin, north of the Mendocino Fracture Zone. We speculate that this trench or trench-slope depositional setting may have overlapped the Central belt, as well as the Coastal and Yager terranes of the Coastal belt (fig. 28). Deposition of strata in the King Peak subterrane continued until shortly after 15 Ma, when the northward-propagating Mendocino triple junction approached about lat 36.5° N. By that time, the composite Late Cretaceous to middle Miocene Vizcaino block and Point Delgada subterrane had already been accreted to the northwestward-moving Pacific plate. Upper Cretaceous oceanic rocks of the Point Delgada subterrane then were juxtaposed with the King Peak subterrane along an early transtensional fault of the San Andreas regime at about 14 Ma, and hydrothermal circulation was initiated at about 13.8 Ma along normal faults conjugate to the strike-slip system. This hydrothermal event, which affected the entire King Range terrane, most likely resulted from intrusion of magma into the shallow crust above a newly opened partition of the slabless window (McLaughlin and others, 1985b). We postulate that the 14.8-Ma Page Mill Basalt and younger Quien Sabe Volcanics, Tolay Volcanics, and volcanic rocks in the Berkeley Hills are surface manifestations of the magmatic source of the King Range thermal anomaly and that these volcanic rocks were erupted over the slabless window considerably east of the transform margin (fig. 28). We also postulate that the Mendocino Fracture Zone again extended eastward during the episode of crustal extension which accompanied the King Range thermal event, from the northeast corner of the Vizcaino block, into the trench-slope of the North American plate. This eastward propagation of the Mendocino Fracture Zone was accommodated along the trailing transform margin by another eastward jump and slight clockwise rotation of the transform boundary, thus accreting the King Peak subterrane to the east side of the Vizcaino block at 13.8 Ma. Subsequently, the King Range terrane was translated northward with the Pacific plate (fig. 28).

Owing to about 20° of clockwise rotation of the Pacific-Farallon Ridge between 3.7 and 3.4 Ma (Harbert and Cox, 1986), the northern section of the San Andreas fault zone changed direction to a more north-trending orientation north of Point Arena. Since the time of this major reorientation, the transform margin has been dominantly transpressive. This change from dominantly transtension to transpression appears to have prevented magma in the underlying slab window from rising into shallow levels of the crust. Thus, volcanism in the Coast Ranges has not extended north of the Clear Lake area since the Mendocino Fracture Zone propagated past that latitude about 3 Ma. Other tectonic implications of the change from transtension to transpression include (1) major uplift of the northern Coast Ranges; (2) late Cenozoic compressional structures parallel to the San Andreas fault system, which are superposed on earlier transtensional basins; and (3) dominantly north-northeast oriented compression presently occurring at the northeast corner of the Pacific plate south of the Mendocino Fracture Zone.

STRUCTURAL RELATIONS OF THE MODERN MENDOCINO TRIPLE JUNCTION

We now turn to the modern tectonic setting of the Cape Mendocino region and discuss the geologic evidence for the present position of the Mendocino triple junction.

Faults Defining the Configuration of the Triple Junction

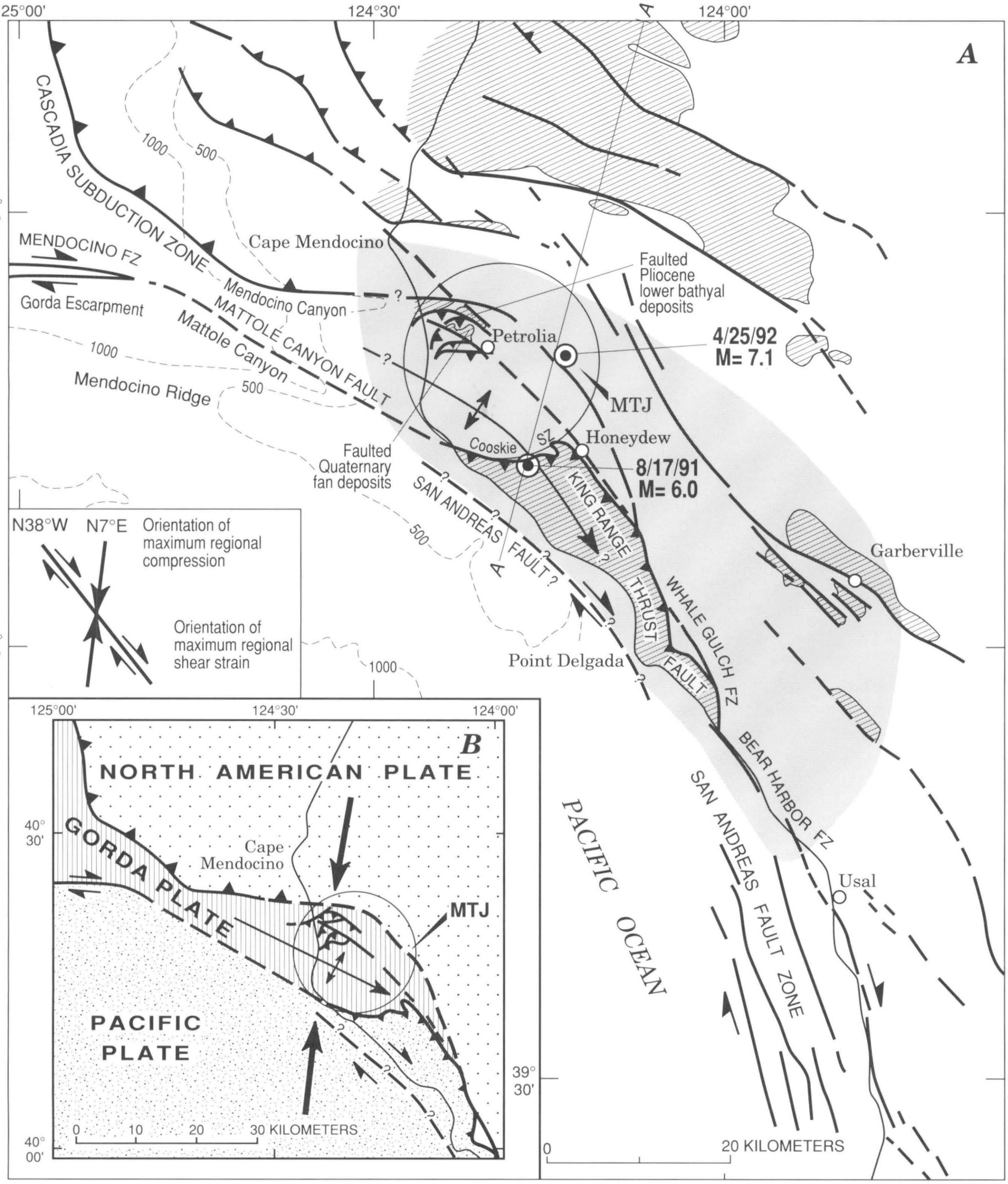
The modern Mendocino triple junction is defined by several major faults in the onshore and offshore areas, with different orientations and senses of slip (figs. 24*A*, 29). Offshore, the modern Pacific plate is bounded to the north by the active Mendocino fault zone. West of long 126° W., the Mendocino fault zone separates oceanic crust of the Gorda and Pacific plates along a prominent, south-facing fault scarp. East of long 126° W., the Mendocino fault zone follows the base of the steep, north-facing Gorda Escarpment, separating the Gorda plate on the north from rocks of the Vizcaino structural block to the south (figs. 24, 29). East of long 125° W., the Mendocino fault zone, if present at all offshore, is difficult to delineate. Onshore, however, northwest of Petrolia, a N. 47° W.-trending fault that truncates the south side of a large Quaternary alluvial terrace projects offshore and aligns with Mendocino Canyon.

Another fault defined in seismic profiles (S.H. Clarke, Jr., oral commun., 1988; Clarke, 1992) branches southeastward from the Mendocino fault at about long 125° W. along Mattole Canyon (figs. 17*A*, 29). This Mattole Canyon fault follows a topographic bench along the base of a prominent escarpment on the northeast side of the Mendocino Ridge. The faulted bench is bathymetrically higher than the base of the escarpment aligned with the more east-west trending Mendocino Canyon.

The Mattole Canyon fault projects shoreward south of the mouth of the Mattole River, to align with N. 69° W.-trending faults that form the northern part of the suture between the King Range and Coastal terranes. The anomalously high and rugged relief of the King Range terrane, which reaches elevations of 1,220 m within 5 km of the coast, aligns closely with that along the crest of the Mendocino Ridge offshore, at the north boundary of the Vizcaino block. Thus, there appears to be structural and physiographic continuity between the northern part of the Vizcaino block and the King Range terrane.

The San Andreas fault has traditionally been projected northward of Point Delgada offshore from the King Range, to intersect with the Mendocino Fracture Zone along the trend of the Mattole Canyon fault (Curray and Nason, 1967; Brown and Wolf, 1972). The San Andreas fault, however, has never been delineated in the offshore area north of Point Delgada (McCulloch, 1987a), and so its presence between Point Delgada and the north side of the King Range terrane is speculative. The east side of the fault zone appears to lie inland along the east side of the King Range terrane, although as-yet-unconfirmed traces of the fault system may also lie offshore, separating the King Range terrane from the east side of the Vizcaino block.

Fold axes and shear fabric in matrix rocks of the Coastal terrane north of Petrolia are oriented northwest-southeast, and foliations in the shear fabric characteristically are inclined northeastward (figs. 17*A*, 29). It also has been shown that the orientation of subduction-related structures (folds and thrusts) in the offshore accretionary prism above the subducted and deformed Gorda plate, including the basal thrust of the Cascadia subduction zone (Clarke, 1988, 1992; McLaughlin and others, 1988b), are coparallel and colinear with onshore structures of the Coastal terrane. Pliocene or


A
B
125°00'
124°30'
124°00'
40° 30'
40° 00'
39° 30'
A'
CASCADIA SUBDUCTION ZONE
MENDOCINO FZ
Gorda Escarpment
Mendocino Canyon
MATTOLE CANYON FAULT
Mattole Canyon
Mendocino Ridge
Cape Mendocino
Petrolia
Faulted Pliocene lower bathyal deposits
4/25/92 M= 7.1
MTJ
Honeydew
Cooskie
SZ
8/17/91 M= 6.0
Faulted Quaternary fan deposits
SAN ANDREAS FAULT ?
KING RANGE THRUST FAULT
WHALE GULCH FZ
BEAR HARBOR FZ
Garberville
Point Delgada
Usal
PACIFIC OCEAN
SAN ANDREAS FAULT ZONE
N38°W
N7°E
Orientation of maximum regional compression
Orientation of maximum regional shear strain
1000
500
0
20 KILOMETERS
NORTH AMERICAN PLATE
GORDA PLATE
PACIFIC PLATE
Cape Mendocino
0
10
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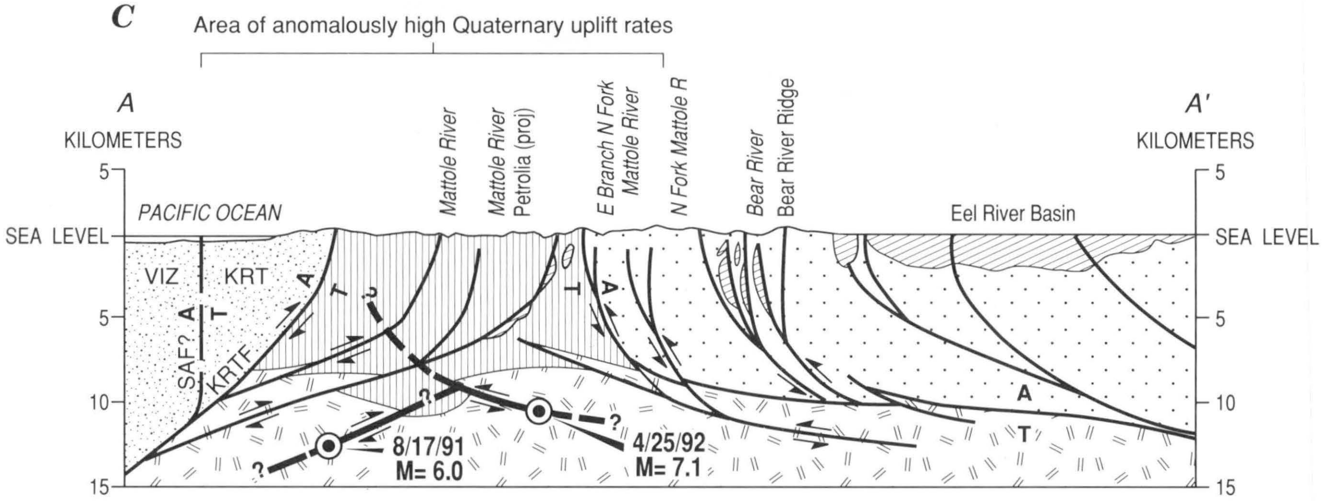
30 KILOMETERS



EXPLANATION

Upper Cenozoic rocks

North American plate—Includes Coastal and Yager terranes

Pacific plate—Includes Vizcaino block and King Range terrane

Gorda plate—Consists of:

Offscraped sedimentary rocks from Coastal and Yager terranes

Oceanic crust

Region of high rate of coastal-terrace uplift and (or) fluvial-terrace incision—At least 1 mm/yr since 120 ka; generally includes area of coseismic uplift of 4/25/92 earthquake

Contact

A T Fault—Dashed where inferred; queried where uncertain. Arrows indicate direction of relative movement. A, away from observer; T, toward observer (shown in cross section only)

Thrust fault—Dashed where inferred. Sawteeth on upper plate

Basal thrust of subduction zone—Dashed where inferred; queried where uncertain. Sawteeth on upper plate

Inferred axis of regional upwarping—Showing direction of plunge. Queried where uncertain

500 Bathymetric contour—In meters

4/25/92 M = 7.1 Epicenter (in cross section, focus) of recent earthquake—Showing date and magnitude (M) of shock

Blind thrust fault (shown in cross section only)—Interpreted from preferred first-motion solution for recent earthquake. Dashed and (or) queried where extent of rupture is inferred from aftershock distribution. Arrows show direction of relative movement

Figure 29. Mendocino triple junction area (MTJ, circled). *A*, Generalized map of faults that define modern Mendocino triple junction, showing area of active uplift associated with compression across triple-junction region, and locations of epicenters of recent earthquakes (Richard Lester, U.S. Geological Survey, oral commun., 1992). Area of uplift deduced from data of Lajoie and others (1982), McLaughlin and others (1982), Bickner (1985), Hagemann (1985), Lajoie (1986), and Merritts (1986). Orientation of maximum regional compression (inset) from trilateration data of Breen and others (1987). FZ, fault zone; SZ, shear zone. *B*, Plate-tectonic model of Mendocino triple junction area. *C*, Schematic cross section across Mendocino triple junction area, showing inferred subsurface geometry of tectonic plates and locations of blind thrust faults associated with recent earthquakes. KRT, King Range terrane; KRTF, King Range thrust fault; SAF, San Andreas fault; VIZ, Vizcaino structural block.

younger strata are cut by faults of this orientation and affected by the folding onshore and offshore. In addition, paleobathymetric data from isolated areas of the Neogene strata affected by these folds and faults onshore show that these strata were deposited at lower-bathyal to abyssal depths, consistent with the offshore setting of the lower part of the accretionary prism. The basal thrust of the accretionary prism strikes nearly east-west and aligns with a steep fault that bounds the north side of a remnant of late Miocene lower-slope strata near the mouth of Davis Creek northwest of Petrolia. In combination with fault relations which suggest that the obducted King Range terrane is part of the Pacific plate, these data suggest that the present-day Mendocino triple junction (the common contact between the Pacific, Gorda, and North American plates) lies onshore between the mouth of Davis Creek and the north side of the King Range terrane (fig. 29).

South of Davis Creek and, notably, in the area between McNutt Gulch and the mouth of the Mattole River, the structural grain in matrix rocks of the Coastal terrane dips south, subparallel to faults bounding the King Range terrane. Lower-bathyal to abyssal Pliocene strata are cut by these thrusts north of Petrolia. We interpret these Pliocene or younger thrusts to be associated with active north-south-oriented compression between the Pacific and North American plates. This association suggests to us that the triple junction may be very close to the hamlet of Petrolia (figs. 17*A*, 29). Thus, the area of imbricated Coastal terrane and lower-slope Neogene sedimentary deposits between Davis Creek and the north side of the obducted King Range terrane may correspond to highly deformed hemipelagic sediment and acoustic basement that are compressed against the Gorda Escarpment at the south side of Gorda Basin offshore (Clarke, 1992). On the basis of this interpretation, these imbricated rocks north of the King Range terrane were scraped off the Gorda plate and squeezed between the North American and Pacific plates, and are currently accreting to the Pacific plate.

Seismicity

Seismic activity is concentrated along the Mendocino fault zone and within the Gorda plate (Bolt and others, 1968; Seeber and others, 1970; Eaton, in press). The depth to the seismogenic zone within the Gorda plate is shallow in the offshore area, but it deepens to below 12 km to the east, where the Gorda plate is subducted beneath the California margin (Jachens and Griscom, 1983). First-motion studies suggest left-lateral slip on northeast-oriented faults within the Gorda plate (Eaton, in press), and right-lateral and up-to-the-north thrusting along east-west-trending faults of the Mendocino fault zone west of long 125° W. These data argue that north-south-oriented compression between the Gorda and Pacific plates, in conjunction with the east-west component of relative motion with North America, has contributed substantially to Gorda plate deformation (Wilson, 1986; Stoddard, 1987) and to its partial coupling to the North American plate. This interpretation is consistent with trilateration data for the region (Breen and others, 1987) which show that maximum compression is oriented about N. 7° E.

Focal mechanisms for earthquakes deeper than 12 km along the Mendocino fault zone east of long 125° W. suggest right-lateral slip between the Gorda and Pacific plates. However, numerous shallow earthquakes occur onshore and are diffusely aligned along the north and east sides of the King Range terrane. These shallow earthquakes define a zone that displays a moderate to steep southwestward dip (Eaton, in press), and are reasonably well constrained as occurring above 10 km (R. McPhearson, oral commun., 1988). No focal mechanisms have been deduced for the shallow earthquakes associated with the King Range terrane boundary, but their southwest-dipping depth distribution suggests that they could be associated with southwest-side-up thrusting—indicative of the relative motion between the Pacific and North American plates.

Quaternary Uplift

Studies of Quaternary marine and inland fluvial deposits (Lajoie and others, 1982; McLaughlin and others, 1983; Bickner, 1985; Hagemann, 1985; Carver and others, 1986; Lajoie, 1986; Merritts, 1986) yield relatively high rates of tectonic uplift of 1 to 4 mm/yr since 120 ka along the coast between Cape Mendocino and the mouth of Whale Gulch southeast of Point Delgada (fig. 29*A*). Comparably high incision rates for fluvial terraces persist inland for at least 50 km along the Mattole River (Merritts, 1986) and may be as high as 1 mm/yr near Garberville (Bickner, 1985). South of Whale Gulch and north of Cape Mendocino, uplift rates diminish to 0.3 mm/yr or less toward the center of the Eel River basin. Thus, Quaternary uplift data are consistent with active northeast-southwest-oriented compression (fig. 29*B*) and suggest that a significant component of the motion between the North American and Pacific plates has been resolved through vertical motion for at least the past 120 ka. This uplift, centered over the King Range terrane (fig. 29), is expressed as a broad regional warp extending northward approximately to Cape Mendocino, southward to Bear Harbor, and eastward to the vicinity of Garberville. Active thrusting along the north and east sides of the King Range probably has contributed to the uplift and warping of this area, in addition to movement along relatively flat, blind thrusts associated with the southern Cascadia subduction zone.

CONCLUSIONS

1. From 90 to 52 Ma, the tectonic setting of the Cape Mendocino region was dominated by oblique dextral convergence between the North American plate and a poorly

defined, fast-moving oceanic plate (McLaughlin and others, 1988a). The dextral component of motion between these plates contributed to the formation and resulted in the northward translation of melange in the Central belt of the Franciscan Complex. This melange includes igneous and pelagic rocks scraped off the fast-moving, northward-translating oceanic plate, as well as slabs and blocks of rock derived from previously accreted and metamorphosed parts of the Franciscan Complex (Eastern belt), the Coast Range ophiolite and overlying Great Valley sequence, and other land-derived sedimentary sequences deposited with and on top of far-traveled oceanic rocks during their northward translation.

2. Between about 60 Ma (late Paleocene) and 52 Ma (early Eocene), the Central belt ceased moving northwestward, was accreted to the northern California margin, was uplifted and eroded, and was depositionally overlapped by nonaccretionary marine littoral, shelf, and slope deposits (McLaughlin and others, 1988a). Simultaneously, the active accretionary margin stepped westward to the Cape Mendocino region, as the North American plate began interacting with the Farallon plate. Between about 55 and 41 Ma, Farallon-North American plate motion was strongly convergent, with a much smaller northward component than before accretion of the Central belt. The Coastal and Yager terranes of the Coastal belt were deposited largely during this time interval on the slope and trench-slope of the Farallon-North American plate margin, north of lat 30° N. A smaller but significant component of the Coastal terrane, consisting of basalt, pelagic limestone, and locally interbedded arkosic sandstone, formed and was deposited at low paleolatitudes on the Farallon plate. The basaltic and pelagic rocks formed between 82 and 69 Ma near the triple junction of the Pacific, Farallon, and Kula plates and north of the Mendocino Fracture Zone. Arkosic sandstones interbedded with the basalts probably were derived from the Late Cretaceous continental margin of northern Mexico and subsequently translated northeastward on the Farallon plate. These strata deposited on the Farallon plate moved at poleward rates of 7.1 to 7.2 cm/yr, until they contacted the California margin near the south end of the Diablo Range at about 49 Ma. Between 49 and 41 Ma, Coastal belt sediment eroded and transported from the North American plate interior and from uplifted, older parts of the Franciscan Complex were deposited on the slope and trench-slope, above the Farallon-North American plate subduction margin. Accretion of the Yager and Coastal terranes of the Coastal belt occurred between the latest Eocene (ca. 40 Ma) and latest Oligocene (ca. 24 Ma). At this time, the subduction margin again stepped westward, as poleward translation of the Coastal terrane slowed to less than 2 cm/yr, and the Coastal and Yager terranes were compressed and uplifted concurrently with westward-directed thrusting of the Central belt along the Coastal belt thrust.

3. After assembly of the Yager and Coastal terranes, the subduction zone between the Farallon and North American plates stepped westward, creating the site of deposition of Miocene clastic strata in the King Peak subterrane. Rocks of the Central belt may partly underlie these clastic strata. Basalt, overlain by radiolarian chert of middle Miocene age, suggests that part of the Farallon plate was incorporated into the King Peak subterrane in the region of the trench. We conclude that the depositional site of strata of the King Range terrane was along the Farallon-North American plate subduction margin and as much as 435 km south of the Cape Mendocino area. According to this interpretation, the King Range terrane was transferred to, and translated with, the Pacific plate beginning about 13.8 Ma, as the Mendocino triple junction propagated northward past about lat 36.5° N. We suggest that at this time, the King Peak subterrane was rifted away from the North American plate margin as magma intruded concurrently and hydrothermal circulation was initiated above a slabless window (slab gap) filled with asthenosphere behind and adjacent to the northward-propagating triple junction. At the time of this rifting and accretion to the Pacific plate, the King Peak subterrane came into contact with the Point Delgada subterrane, which had previously been accreted to the Vizcaino structural block. The transfer of the King Range terrane to the Pacific plate was accommodated by eastward extension of the Mendocino Fracture Zone and a concurrent eastward jump of the San Andreas transform.

4. The Vizcaino structural block represents either the north end of an extinct paleosubduction margin between the North American and Farallon plates, or an extinct convergent margin between the Pacific and North American plates, driven from the southeast by Oligocene extension and rifting above subducted segments of the Pacific-Farallon Ridge system. The Vizcaino block was accreted to the Pacific plate after initial contact of the Pacific-Farallon Ridge with the North American plate between 30 and 28 Ma. Between about 28 and 16 Ma, fragmented remnants of the Farallon plate south of the Mendocino Fracture Zone may have been caught between segments of the Pacific-Farallon Ridge that were becoming extinct, and the North American subduction margin. Alternatively, westward-directed thrusting of the North American plate over the Pacific plate may have begun south of the Mendocino Fracture Zone, as a result of northwest-southeast extension and rifting initiated above the subducted Pacific-Farallon ridge after its collision with the North American plate margin during Oligocene time. Between about 16 and 14 Ma, the Mendocino Fracture Zone extended eastward across this convergent margin, forming the north boundary of the Vizcaino block. Eastward extension of the Mendocino Fracture Zone probably was concurrent with and, possibly, resulted from a reorientation of the Pacific-Farallon Ridge at its point of contact with the

North American plate. This reorientation caused the west edge of the North American plate, including the Vizcaino block, to rift and take up northward motion of the Pacific plate. The modern San Andreas fault system was thereby initiated, connecting the newly extended segment of the Mendocino Fracture Zone to the newly oriented, active Pacific-Farallon Ridge system.

5. The modern-day Mendocino triple junction probably is situated onshore near Petrolia, rather than in the offshore region where it has traditionally been located. The present-day triple-junction region is characterized by high rates of Quaternary uplift (1–4 mm/yr) that define an area of anomalous upwarping extending from Cape Mendocino on the north to Bear Harbor on the south and, at least, to Garberville on the east. This uplift is attributable to north-northeastward-directed blind thrust faults in rocks as young as Pliocene along the north and northeast sides of the King Range terrane, and to more broadly defined regional warping above north-northeast-dipping blind thrust faults north of Petrolia. These features apparently accommodate northeast-southwest compression between the North American and Pacific plates. In addition, north of the hamlet of Petrolia, shear fabric in the Coastal terrane of the Franciscan Complex parallels north-northeast-dipping, northwest-trending active thrusts in the offshore accretionary wedge overlying the subducting Gorda plate. The faulted base of the accretionary prism offshore bends east and trends onshore in the vicinity of Petrolia. Together, these data suggest that the south end of the Cascadia subduction zone is bent eastward to accommodate motion between the North American and Pacific plates and that partial coupling is occurring between the North American and Gorda plates (fig. 29). The Mendocino triple junction is expressed today as a region of northeastward-directed thrusting related to motion between the North American and Pacific plates, superposed on the northwest-southeast-oriented, northeast-dipping, convergent structures resulting from motion between the North American and Gorda plates.

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