THE CONTINENTAL MARGIN OF NORTHERN AND CENTRAL CALIFORNIA *

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The geology of the continental margin offshore from northern and central California, though actively studied in recent years, is still very incompletely known. Much of the available data is in the remote sensing category, that is, it consists of measurements made at the ocean surface from which deductions have been made regarding the rocks and structures on the sea floor. The nature of the young sediments on the surface of the sea floor is moderately well known from dredge sampling, though not nearly so well known as in the broad shelf area off the coast of southern California. Bedrock that underlies these sediments has been sampled only by a few dredgings, but is, of course, exposed in a few islands and along the shore. The continental margin of northern and central California is unusually youthful, and thus this area is particularly suited for the study of basic problems of the development of continental shelves and slopes, and of the transition between continental and oceanic crustal rocks and structures.

The onshore limit of the continental margin is outlined by the western front of the California Coast Ranges, which is itself bounded to the south by the complex structure of the Transverse Ranges and to the north by the sharply defined lithologic boundary of the Klamath Mountains. Offshore the western edge of the continental margin is arbitrarily taken to be the 1,600 fm. (3,000-m) contour line, which lies at the foot of the steeper continental slope where it joins the lower declivity of the continental rise. To the north and south the extensive Mendocino and Murray fracture zones limit the morphological unit that constitutes the part of the continental margin to be described in this article. These major fractures trend from west to east towards the continents from the deep-sea oceanic crust and whether they abut directly against the continental crust or pass beneath is critical to understanding the geologic history of western California.

The narrow shelf and steep slope forms a distinctive morphological entity, which is clearly as different from the continental borderland south of the Transverse Ranges as it is different from the less steep and somewhat broader shelf and slope north of Cape Mendocino and opposite the western bulge of the Klamath Mountains (Irwin, 1960). A fundamental genetic association seems to exist between the submerged margin, the Coast Ranges, and the Great Valley by virtue of the very remarkable dimensional relationship of these structures to the major fracture zones of the sea floor (fig.1).

That relatively little data has been collected from the submerged margin in this area is partly because of the difficult working conditions to which ships are exposed offshore. The steep approach on the very narrow shelf offers little surface area upon which storm-generated seas can dissipate their energy. The severe winter storms generated regularly in the north Pacific during the northern hemisphere winter, and in the southern hemisphere during their winter, serve to create continuous heavy swells which peak sharply on this narrow continental shelf of California.

In contrast, a considerable amount of effort has been devoted to the study of the onshore geology because of the local occurrence of oil fields and the interest in the San Andreas fault system. That the geologic relations are still not entirely understood is partly because of the presence of the enigmatic suite of rocks which make up and are associated with the Franciscan assemblage (see for example, Taliaferro, 1943; Bailey, Irwin, and Jones, 1964). The Franciscan is well known for its thick sequence of graywacke, subordinate amounts of shale, chert, and limestone, some thick units of greenstone, and serpentine with and without glaucophane schist, and ultramafics. This great diversity of upper Jurassic through Cretaceous rocks, in addition to its variety, is unusual in that the base has not been observed and therefore the underlying units are unknown. It has been suggested that it represents an accumulation deposited directly on oceanic crust. Intense deformation of the Franciscan has resulted in the formation of major shear zones and much local crumpling, folding, and faulting, which developed a northwesterly trending grain that certainly must extend seaward. The major structural features of the region indicated in figure 2 have been compiled from the onshore studies summarized by Bailey, Irwin, and Jones (1964), and from the offshore studies of Uchupi and Emery (1963), and Curray (1965).

BATHYMETRY

Some conclusions regarding the late geologic history can be drawn from the submarine topography or bathymetry. The basic bathymetric charts of offshore

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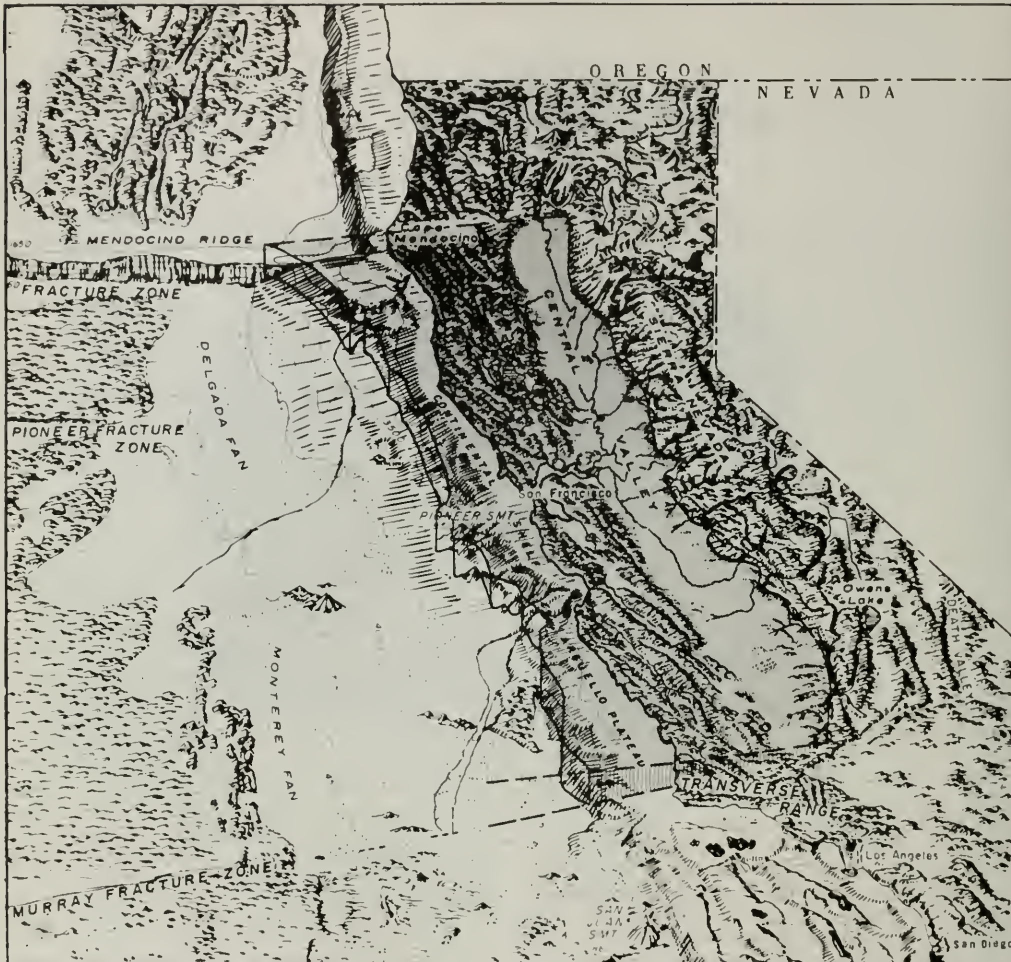


Figure 1. Physiographic setting of the northern ond central California continentol morgin. Modified from Menord (1964); published by permission of McGrow-Hill Book Co.

California have been compiled by Shepard and Emery (1941). They have been incorporated in subsequent maps published by the California Division of Mines and Geology in their Geologic Map Series, and in a shaded relief map with offshore bathymetry shown in fathoms published by the U.S. Geological Survey in cooperation with the State of California. More recently, Uchupi and Emery (1963) have modified these basic charts to incorporate more recent soundings and to show the depths in meters.

The significant features of the northern and central California sea floor are its very narrow shelf with a slope averaging 3°, very steep canyon-cut slope, broad continental rise containing the Delgado and Monterey deep-sea fans, and the broad bank formed on the upper slope west of the Transverse Range. Typical profiles of the continental shelf and slope for various sections off the California coast, compared with the Sierra Nevada escarpment shown on the same scale are illustrated in figure 3.

The widest shelf area is found off the mouth of San Francisco Bay where the small group of Farallon Islands is developed. Width of the slope varies from 50 km off Point Pillar to 30 km west of Cordell bank.

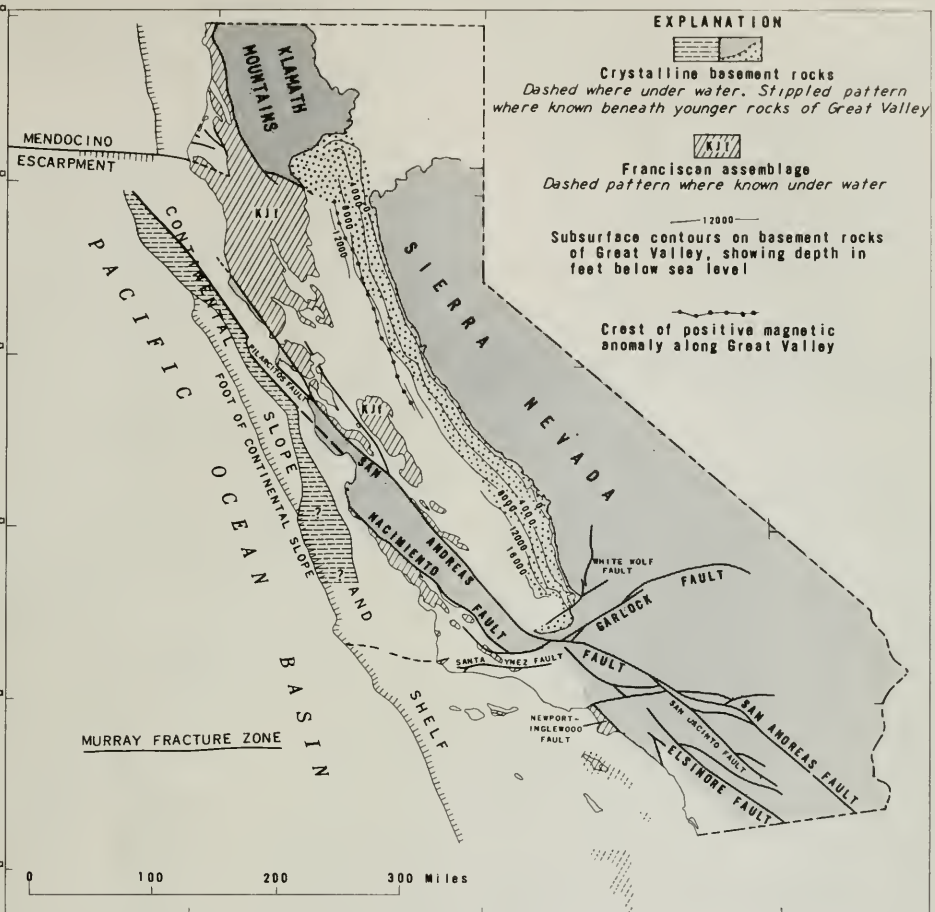


Figure 2: Principal structural features of the California continental margin modified from Bailey, Irwin, and Jones (1964). Offshore crystalline basement rock areas are after Uchupi and Emery (1963) and Curray (1965).

This shelf area is comparable to the still broader Arguello Plateau (fig. 4), which forms a broad bank that should be considered not as a part of the continental shelf but rather as a gentler part of the upper continental slope with an average gradient of 6.5° through its 50 km width (Uchupi and Emery, 1963). The shaded relief map of the State of California (1961) has this area designated as the Santa Lucia Bank and the very steep slope west of it is the Santa Lucia Escarpment.

Profiles of the continental margin at Point Arguello and off San Francisco (fig. 5) demonstrate the variety of surface irregularities on the sea floor. Small pinnacles at the foot of the slope, and locally higher, appear to be volcanic in origin, although most of the surface roughness is thought to be due to slump of sediments or rock.

SEDIMENTS

Sediments of the continental margin include shell sands and glauconitic sands on the shelves and banks, and a range from fine green sands through coarse silts to very fine olive-green silts on the slopes. The sand fraction of the slope deposits normally consist largely of detrital grains of quartz and feldspar with minor amounts of mica. The sand fraction of the Arguello Plateau, however, consists of glaucónite, and phosphorate (see Wilson and Mero, this volume), together with benthonic foraminiferal tests and minor amounts

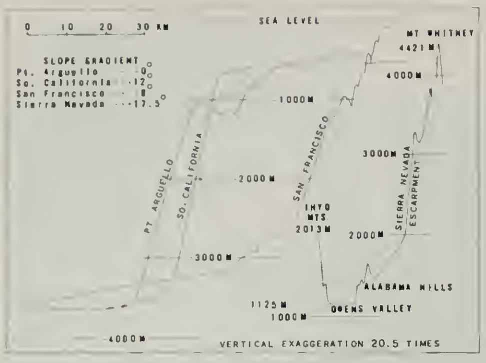


Figure 3. Comparison of three characteristic bottom profiles from the continental shelf, slope, and rise of the California continental margin with a profile of the Sierra Nevada escarpment. Modified after Uchupi and Emery (1963).

of diatoms, radiolarians, and fragments of shells. On the continental rise most of the sand consists of quartz and feldspar with minor amounts of mica, but the outermost lower portion of the rise consists mainly of radiolarians. The lithology of cores collected offshore from San Francisco and Point Arguello has been described by Uchupi and Emery (1963) in considerable detail, and one of their diagrams showing its variation is reproduced as figure 6.

Rates of sediment accumulation recorded for the slope areas are very low, being on the order of 2-6 cm/1,000 years. On the other hand, the shelves have been exposed to repeated periods of extensive wave planation, especially during the fall of eustatic sea level during the Pleistocene, with the result that the shelf areas are now largely nondepositional terraces mantled with only a thin veneer of winnowed materials (fig. 7, Moore and Shumway, 1959; Moore, 1960).

The Monterey, Delgado, and the Arguello deep-sea fans on the continental rise have gentle slopes that grade imperceptibly into the Deep Plain with a gradient of about 1°. These fans are associated with deep channels and with submarine canyons, which probably debouch turbidite deposits regularly to form these "deltas" or "deltalike" features (Menard, 1955, 1960). Recent studies of the Monterey Canyon and related fan deposits (Wilde, 1965; Martin, 1964; F. P. Shepard and R. F. Dill, oral communication, 1965) clearly demonstrate the depositional character of the deep-sea fans and their origin by turbidity currents. Shepard and Dill have recently recognized a well-developed meander at the base of Monterey Canyon which had been believed previously to represent two separate drainage channels for turbidity currents. Constructional levees about 25 m high border the channel, and, because of the Coriolis force induced by the earth's rotation, the right-hand levee is the higher of the two (Menard, 1955). The general absence of thick unconsolidated sediments on the shelf and slope, together with the presence of many outcrops of Miocene and older rocks, indicates that the bulk of sediment stripped from the continents in post-Miocene time has been deposited on these fans.

BEDROCK

Knowledge of the bedrock exposures on the continental margin is limited by the relatively small number of dredgings. Most of the dredge samples came from the area west of San Francisco, but a few samples have been recovered from Monterey Canyon (Shepard and Emery, 1941; Uchupi and Emery, 1963) and from the Rodriguez Seamount and Davis Seaknoll (Palmer, 1965) off the Arguello Plateau. Bedrock exposures are especially well known by subbottom acoustical-reflection techniques. One such profile for the Arguello Plateau and upper slope, as reported by Palmer (1965), is shown in figure 8. This section clearly indicates the general thickness of the unconsolidated sediments; it also reveals the attitude of the underlying semiconsolidated deposits of probable Miocene age (Uchupi and Emery, 1963). A similar cross section obtained from the San Francisco region by Curray (1965) shows considerable slumping of probable Miocene deposits (see dredge samples described by Uchupi and Emery, 1964) and several spurs of basement highs considered by Curray to be quartz diorite, because of proximity to known outcrops in the Farallon Islands. The relationship of sea-floor surface irregularities to underlying structure can be seen clearly here (see fig. 4 in Curray, this volume). The acoustical profile should be compared with the appearance of an adjacent bathymetric profile illustrated with a different vertical exaggeration in figure 5, profile 7.

Evidence from the Farallon Islands (Hanna, 1951, 1952; Chesterman, 1952) and adjacent banks demonstrates that Cretaceous granitic ridges paralleling the onshore structural grain form at least part of the basement offshore. Similarly, dredge samples from the lower slopes, especially the pinnacles, knolls, and seamounts (Uchupi and Emery, 1963), suggest that much of the area is underlain by a basement of volcanic origin that may represent offshore equivalents of greenstone units found in the Coast Range. Detailed sampling and chemical analyses will be required to describe adequately the general distribution of rock types and structures and to learn their relationships to onshore features. Curray (1965) suggests, for example, that a basement ridge of granite underlies the outer shelf and upper slope from a point south of Cape Mendocino for a distance of about 550 km, or to about 100 km south of Monterey. In keeping with the known structures onshore, W. P. Irwin suggests (oral communication, 1964) that the evidence available indicates a northwesterly continuation offshore toward the Farallon Islands, of the granite body lying between

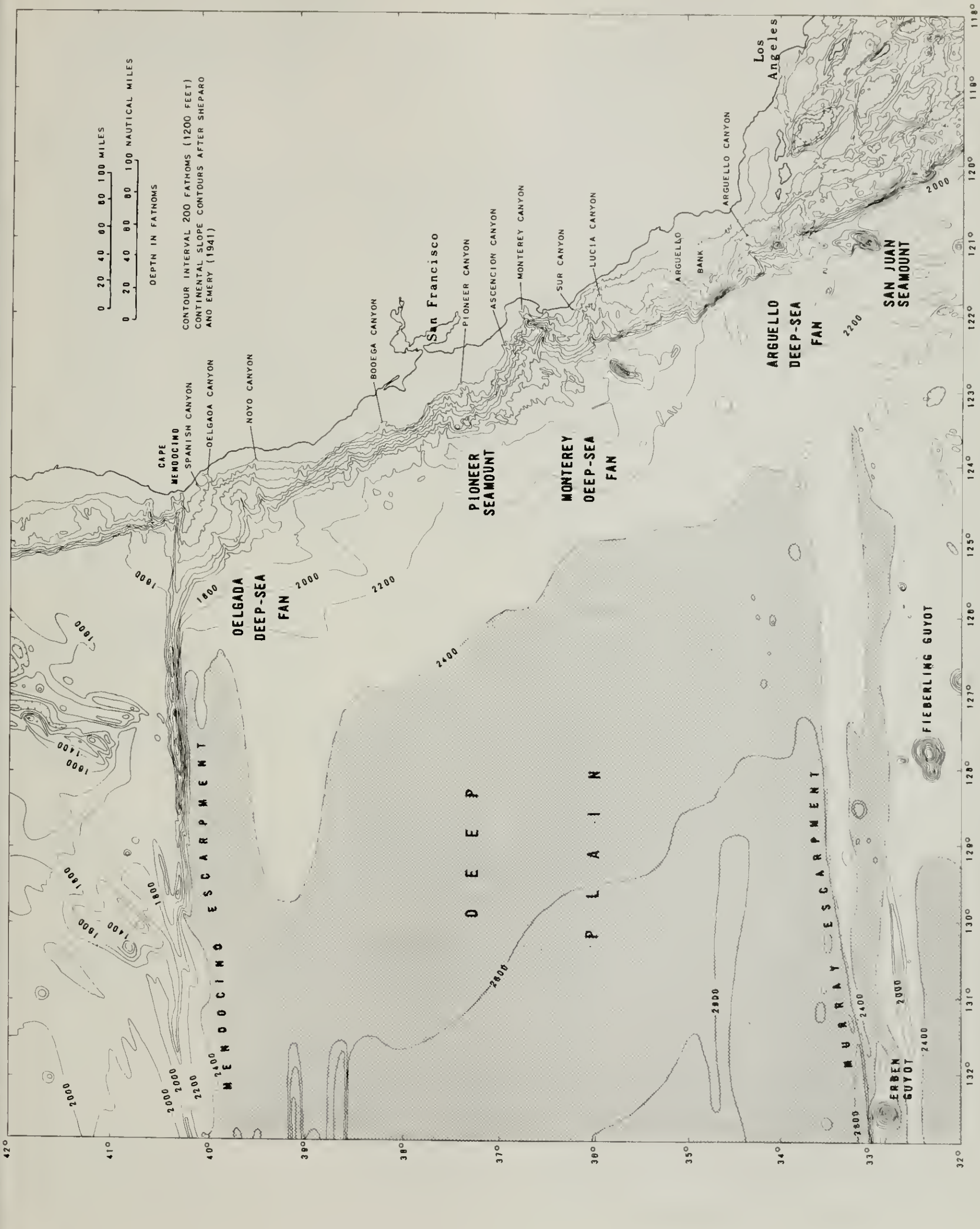


Figure 4. Sea floor bathymetry off California showing the distribution of principal morphological features, after Shepard and Emery (1941).

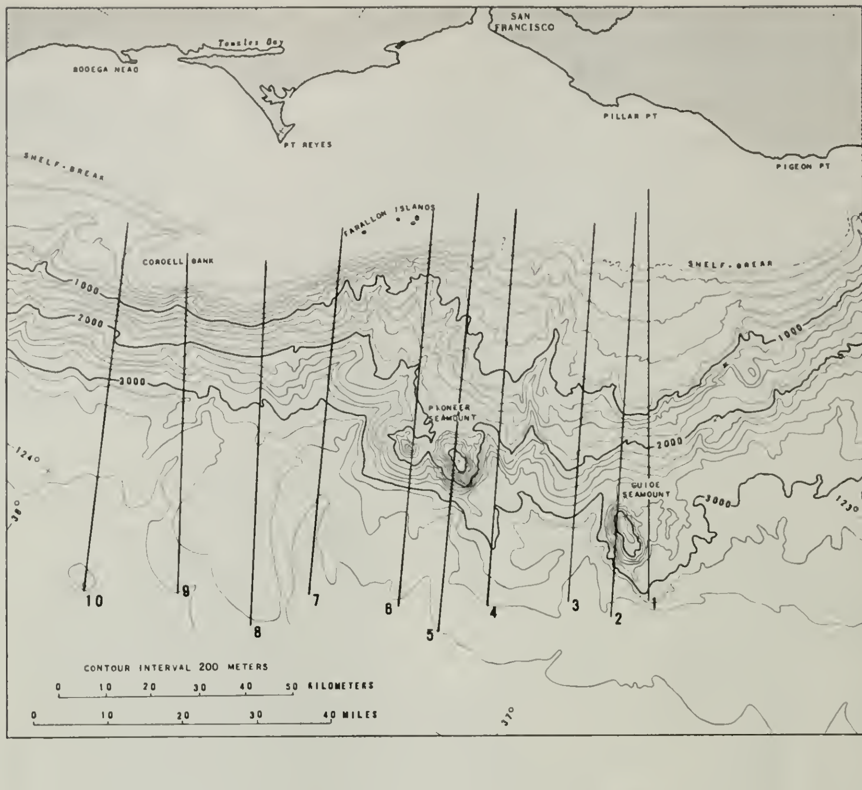


Figure 5. Bottom profiles of the sea floor off San Francisco, California, after Uchupi and Emery (1963).

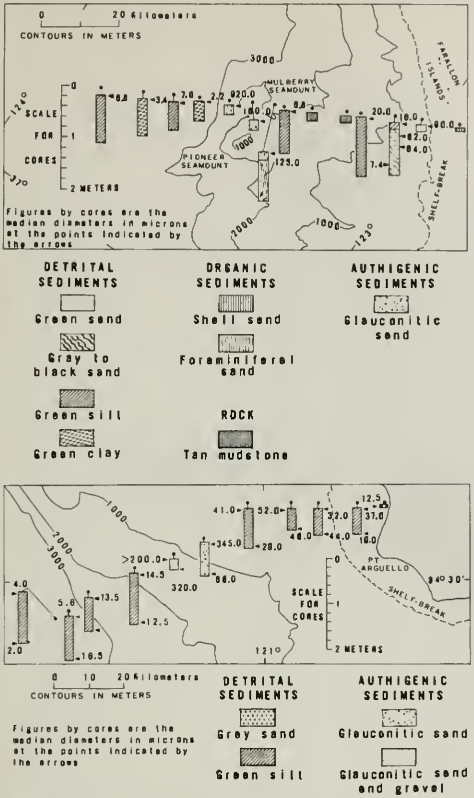
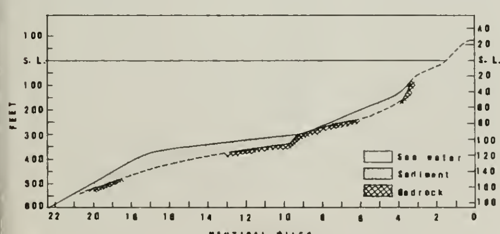


Figure 6. Lithology of surficial deposits off San Francisco (top) and Point Arguello (bottom) as described from cores by Uchupi and Emery (1963).

the Nacimiento and San Andreas faults on the San Francisco Peninsula, in which case no granite would lie near the continental slope south of San Francisco. On shore, granitic units are exposed in the Montara, Ben Lomond, Gabilan, and Santa Lucia mountains, all of which lie between the San Andreas and the Nacimiento faults.

Figure 7 (below). Thickness of unconsolidated sediments off Pigeon Point, California, as compiled by Moore and Shumway (1959) from acoustic-reflection profiles.



REGIONAL GEOPHYSICS

Geophysical data sufficiently detailed to allow a three-dimensional presentation and analysis for most of the area within the continental margin are not yet available. However, some data do provide considerable insight into the geologic structures hidden beneath the ocean in this area. The most complete body of data relating to the geophysics of the margin is based on local measurements of the magnetic field, and the mapping of anomalies in it. The intensive shipboard magnetometer surveys analyzed by Menard and Vacquier (1958), Vacquier, Raff, and Warren (1961), and Mason and Raff (1961) have been summarized by Menard (1964) who related the resulting interpretations to the geology of the eastern Pacific. Figure 9 illustrates the striking north-south pattern of magnetic anomalies associated with the deep-sea floor off the Pacific Coast from central California to Canada. Specific signature characteristics in the magnetic anomalies suggest very large horizontal displacements along the major faults of this area. Menard (1964) then included the sense and amount of lateral displacements in his discussion of the evolution of the crustal flexure of the East Pacific Rise and the subsequent lateral displacement of large east-west crustal units of the sea floor. The sense of motion along the Mendocino, Pioneer, and Murray fracture zone as shown in figure 10 is of particular interest here. It is inconceivable that east-west lateral movements measured in hundreds of kilometers could occur in the crust of the offshore area without disturbing the continents as well. However, it also seems that very little effect of the faults has been identified on the continent except for the seaward displacement of the continental crust south of the Mendocino scarp, where the continental slope has an inferred right-lateral offset of 100 km. Because the inferred movement along the Mendocino fault in its oceanic segment is left lateral, and because other relationships of continental crust tectonics have not been demonstrated, the exact nature of the associations between oceanic and continental segments is unclear.

Neither gravity studies nor seismic investigations in this area have shed much light on the relation between continental crustal movements and oceanic crustal movements. Possibly, an intensive magnetometer survey of the continental shelf and slope would be of help. Local magnetometer surveys around the San Francisco Bay area show only expected correlations with the known magnetic characteristics of the outcrops, according to Andrew Griscom (oral communication, 1965). Measured lateral displacements of continental rocks appear to be restricted to the northwest-southeast motions related to the structural grain of the San Andreas system. Bailey, Irwin, and Jones (1964) have suggested, however, an explanation of the struc-

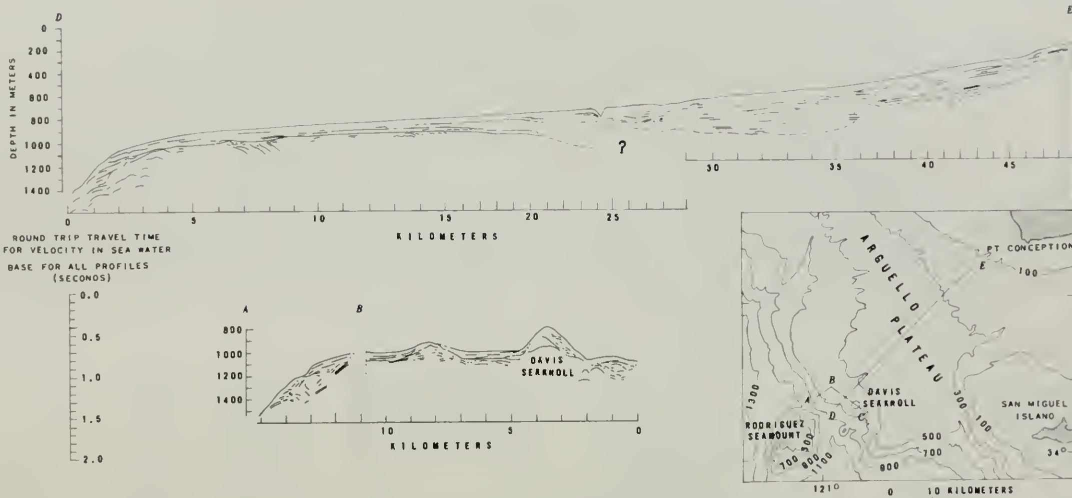


Figure 8. Acoustic-reflection profiles compiled by Palmer (1965) from "ARCER" records across the Arguello Plateau and Davis Seaknoll. Tracing from original records depicts better the stronger acoustical reflectors. Relatively thin, horizontally bedded sediments are in unconformable contact with underlying bedrock. The volcanic Davis Seaknoll is exposed through the thin cover of sediment on the Arguello Plateau. From Palmer (1965).

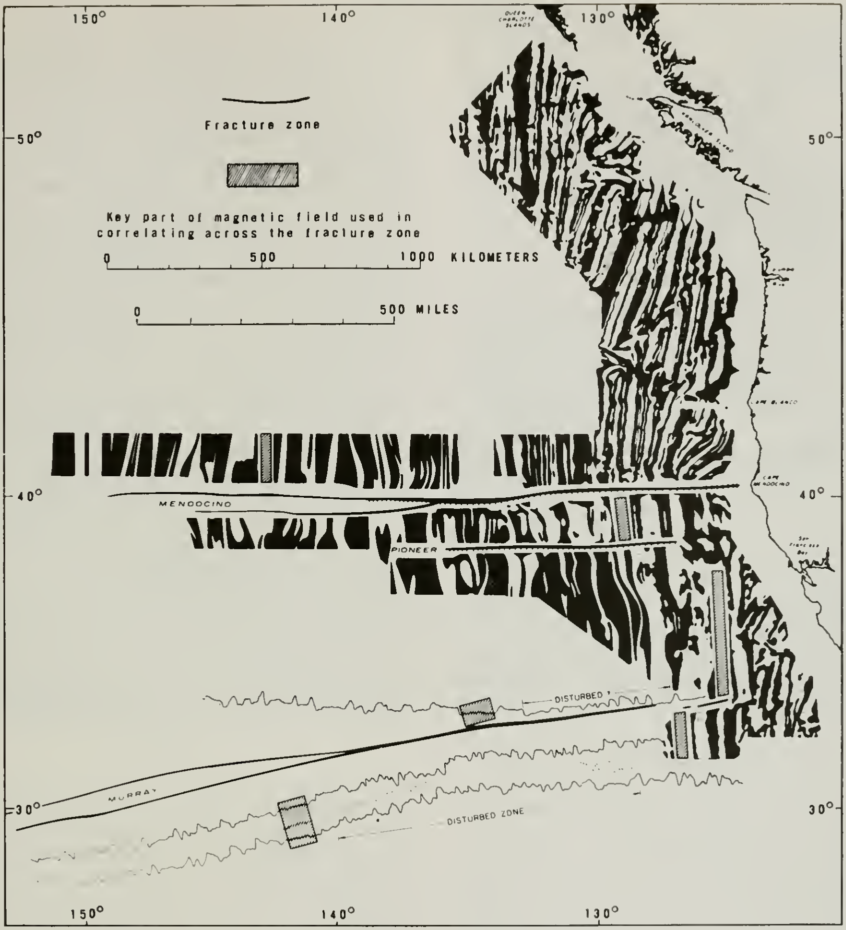


Figure 9. Pattern of magnetic anomalies showing major offsets in the Mendocino, Pioneer, and Murray fracture zones. From Menard (1964); published by permission of McGraw-Hill Book Co.

tural complexity in the northern California Coast Ranges and the Great Valley based on major westward migration of a block of continental-crustal material bounded on the east by an ancestral San Andreas fault. A similar explanation has been used by Rusnak and Fisher (1964) to explain the development of the Gulf of California and the origin of the continental borderland of southern California and Baja California, Mexico. An oblique-motion hypothesis was proposed by King (1959) for the Transverse Ranges which lie between these two areas.

Gravity measurements and seismic refraction studies compiled by Thompson and Talwani (1964a, 1964b) have provided information on the crustal structure of the continental margin (see fig. 4). It is especially noteworthy that the continental shelf east of the Farallon Islands has a mass deficiency similar in magnitude to the anomaly known to be correlated with the great thickness of sedimentary rocks in the Great Valley. This large negative anomaly on the shelf near San Francisco (Orlin, Fanning, Jones, and Garoutte, 1962) also seems to be related to a similar thick section of sediments of low mass, as suggested by the sub-bottom acoustical profile described by Curray (1965, and fig. 4).

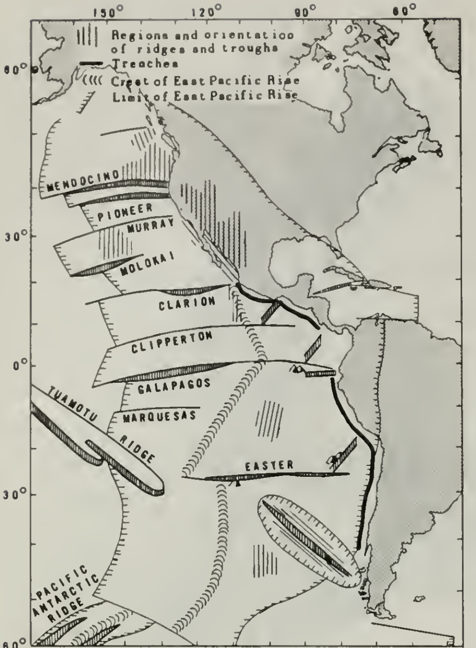


Figure 10. Interpretation of the history of development of the East Pacific Rise and its segmenting along major fracture zones. After Menard (1964); published by permission of McGraw-Hill Book Co.

The anomalies here may be compared with those reported for the Salton trough (Biehler, Kovach, and Allen, 1964) and the north end of the Gulf of California (Harrison and Mathur, 1964); these have been attributed to the crustal thinning that accompanied the westward lateral migration of Baja California following detachment from the mainland of Mexico (Rusnak and Fisher, 1964). The implication is that the similarity in style of the northern and central California continental margin to the Salton trough and the Gulf of California suggests a similar mechanical origin; thus, accounting for the absence of basement reported by Bailey, Irwin and Jones (1964) and strengthening their argument for lateral migration. The question of whether or not the Coast Range units are detached from the western edge of the Sierras must remain open until additional data become available.

The comparison of these two regions further suggests that the San Andreas fault follows the east face of the granitic core that makes up the Gabilan and Santa Lucia Ranges and is similar to the Sierra Juarez-San Pedro Martir-Sal si Puedas escarpment of the Gulf of California (Rusnak and Fisher, 1964). The conclusion of this argument would be to extend the San Andreas Fault seaward along the east face of the basement granite core from the Santa Lucia, Gabilan, Ben Lomond, and Montara mountains on shore past the Farallon Islands and northward to the Mendocino escarpment. One would then have to consider the fault traces drawn by Curray (1965, and this volume) as subsidiary faults of the San Andreas system, similar to those forming the fault pattern observed in the northern Coast Ranges. The question that arises is, if the argument is correct, what are the tectonics involved? The argument demands that two distinct tectonic motions be called upon: (1) westward lateral migration of Coast Range units away from the Sierra Nevada, followed by (2) strike-slip faulting towards the northwest along the San Andreas-Nacimiento-Hayward group, due to a northerly component of motion acting on the competent granitic core.

Two events have been postulated to explain the development of the Gulf of California by Rusnak and Fisher (1964). A double-event tectonic mechanism seems to satisfy equally well the suggestions made by Bailey, Irwin and Jones (1964), King (1959), and Benioff (1962) for the inferred tectonic motions derived from geologic and seismic analyses.

CONCLUSION

Although our knowledge of the northern and central California continental margin is still very fragmentary, the data give a broadly generalized picture of the geology and point to several working hypotheses that might explain the geological history of this complex area. Many questions have been raised by students of the continental margin; few have been answered. The data obtained from offshore studies, however, cannot be disregarded by those working on the mainland. The most intensive analyses of the puzzling geological associations of the central and northern California region, including much that is applicable to the continental margin, have been summarized recently by Bailey, Irwin, and Jones (1964).

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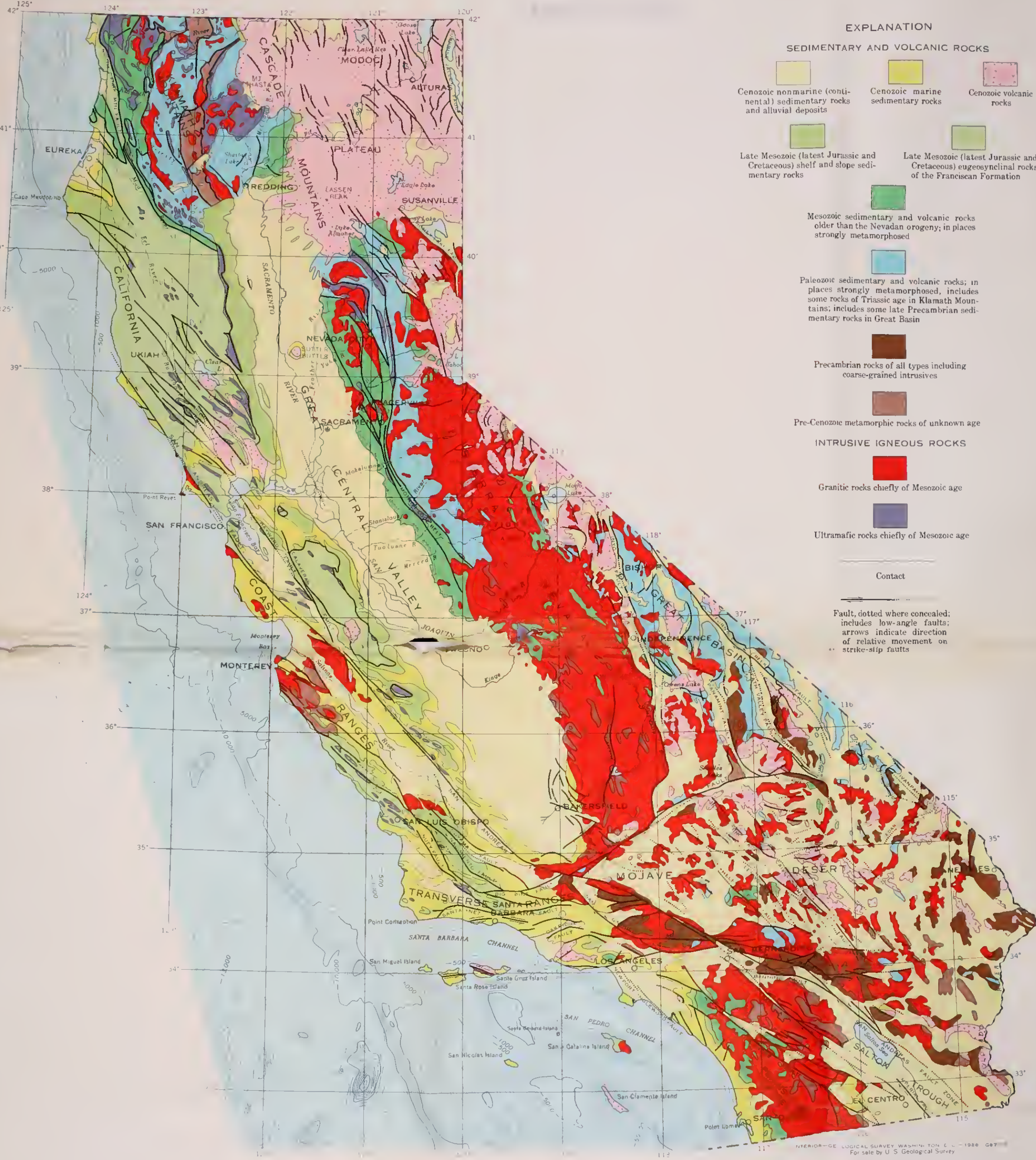
UNITED STATES GEOLOGICAL SURVEY

MISCELLANEOUS GEOLOGICAL INVESTIGATIONS
MAP I-512



EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

Cenozoic nonmarine (continental) sedimentary rocks and alluvial deposits

Cenozoic marine sedimentary rocks

Cenozoic volcanic rocks

Late Mesozoic (latest Jurassic and Cretaceous) shelf and slope sedimentary rocks

Late Mesozoic (latest Jurassic and Cretaceous) eugeosynclinal rocks of the Franciscan Formation

Mesozoic sedimentary and volcanic rocks older than the Nevadan orogeny; in places strongly metamorphosed

Paleozoic sedimentary and volcanic rocks; in places strongly metamorphosed, includes some rocks of Triassic age in Klamath Mountains; includes some late Precambrian sedimentary rocks in Great Basin

Precambrian rocks of all types including coarse-grained intrusives

Pre-Cenozoic metamorphic rocks of unknown age

INTRUSIVE IGNEOUS ROCKS

Granitic rocks chiefly of Mesozoic age

Ultramafic rocks chiefly of Mesozoic age

Contact

Fault, dotted where concealed; includes low-angle faults; arrows indicate direction of relative movement on strike-slip faults

INTERIOR—GEOLOGICAL SURVEY WASHINGTON, D. C.—1966
For sale by U S Geological Survey

GEOLOGIC MAP OF CALIFORNIA

COMPILED BY U.S. GEOLOGICAL SURVEY
AND CALIFORNIA DIVISION OF MINES AND GEOLOGY

SCALE 1:2 500 000

0 50 100 MILES

SUBMARINE CONTOUR INTERVALS 500 AND 1000 FEET DATUM IS SEA LEVEL

1966