37. COMPARATIVE STUDY OF ROCKS FROM DEEP SEA DRILLING PROJECT HOLES 467, 468, AND 469 AND THE SOUTHERN CALIFORNIA BORDERLAND[1]

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INTRODUCTION

Miocene and Pliocene sedimentary and volcanogenic rocks drilled in Holes 467, 468, and 469 of Leg 63 resemble rocks of the same age that have been sampled from other parts of the southern California borderland. The purpose of this report is to compare in general terms the composition, thickness, and age of the pre-Quaternary rocks drilled at these sites with rocks from two test wells, seafloor outcrops, and island areas. From these comparisons, inferences are made concerning the developmental history of the borderland. Emphasis is placed on the composition and origin of coarse clastic and volcaniclastic Miocene rocks. Because the stratigraphic sequences on the mainland shelf, in nearshore basins, and on parts of the northern Channel Islands are unlike the sections in the DSDP holes, they are omitted from most of the comparisons.

From the DSDP cores, 275 samples, chiefly coarse-grained Miocene rocks, were selected and examined. Thin sections of 78 of these selected samples were studied. All available seafloor samples of volcanic and volcaniclastic rocks from the borderland north of 32°N (exclusive of the mainland shelf and nearshore banks) were re-examined for this report (Fig. 1). Igneous rocks are classified according to petrographic determination of mineral content and not on geochemical analysis. Chronostratigraphic assignments follow the usage of Bukry (this volume).

The upper Tertiary sections drilled in two deep stratigraphic test wells, one west of Point Conception (OCS-CAL 78-164 No. 1), the other at the southeast end of Cortes Bank (OCS-CAL 75-70 No. 1), are dissimilar in many respects to those in the DSDP holes. Though information on recently drilled deep exploratory wells on the southern part of Santa Rosa-Cortes Ridge and near Santa Barbara Island is proprietary, the location of these holes suggest that they spudded in middle Miocene or older rocks and penetrated stratigraphic sequences that are, for the most part, older than those in the DSDP holes. Stratigraphic sections of Miocene and Pliocene rocks on some of the islands are reviewed, as they provide possible analogues for subsea sequences that ordinarily are represented only by widely spaced, short cores.

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GEOLOGIC SETTING

San Miguel Gap and Site 467

The seafloor geology in the vicinity of San Miguel Gap is summarized in Figure 2A, and was compiled from bottom-sample and geophysical data in reports by Wright (1967), Vedder et al. (1974, 1976), Crouch (1979a), and Junger (1979). The geology of San Miguel and Santa Rosa islands, mapped in detail by Weaver et al. (1969), is not shown on the figure.

The oldest seafloor rocks, which are depicted as basement in Figure 2A, include blueschist, amphibolite, pyroxenite, serpentinite, and altered mafic volcanic rocks south and east of San Miguel Gap, and nonfoliated metasedimentary rocks on the north end of the eastern spur of Patton Ridge (Vedder et al., 1974, 1979, and in press). Most of these rocks are inferred to be partly equivalent to the Franciscan Complex of the California Coast Ranges and possibly are as old as Late Jurassic (Crouch, 1979b). Some of the ultramafic rocks may represent dismembered ophiolite (Howell and Vedder, 1980). Similar rocks are believed to underlie the northern flank of San Miguel Gap and the southwest edge of the Santa Rosa-San Miguel Island platform (Beyer et al., 1975; Junger, 1979).

East of San Miguel Gap, a thick succession of Upper Cretaceous and lower Tertiary strata are exposed on San Miguel Island (Weaver and Doerner, 1969). Correlative strata are known or inferred from well, dart-core and dredge, and geophysical data to underlie the Santa Rosa-San Miguel Island platform (Vedder et al., 1974, 1980). This pre-Miocene sequence, which is more than 3000 meters thick at places, consists of marine strata that were deposited chiefly in outer-shelf to lower-slope environments until the Oligocene, when sea level dropped, and shallow-marine and nonmarine environments prevailed (Howell and Vedder, 1980; Vedder and Howell, 1980, table 1).

The most common rocks on the banks and ridges surrounding San Miguel Gap are marine siltstone and claystone deposited in the Miocene. Folded and faulted lower and lower middle Miocene strata blanket most of the basement rocks as well as the Upper Cretaceous and lower Tertiary rocks east of the gap. Relatively undeformed and areally restricted upper middle through upper Miocene strata unconformably overlie the older Miocene strata and generally are buried beneath Pliocene and Quaternary sediments in basins.

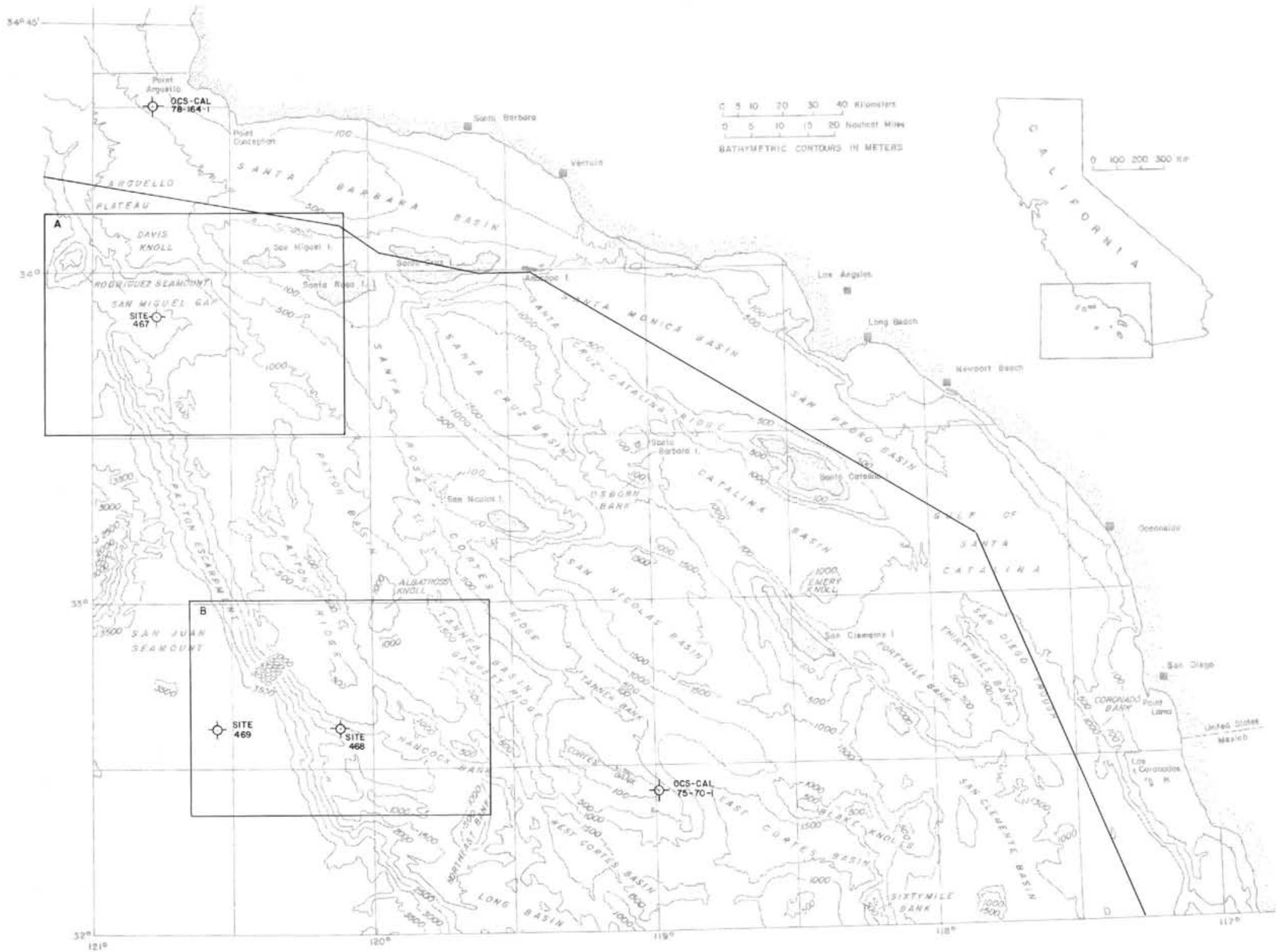

Figure 1. Map of the southern California borderland showing place names, drill-hole sites, and location of large scale maps. (Bathymetric contours are in meters.)

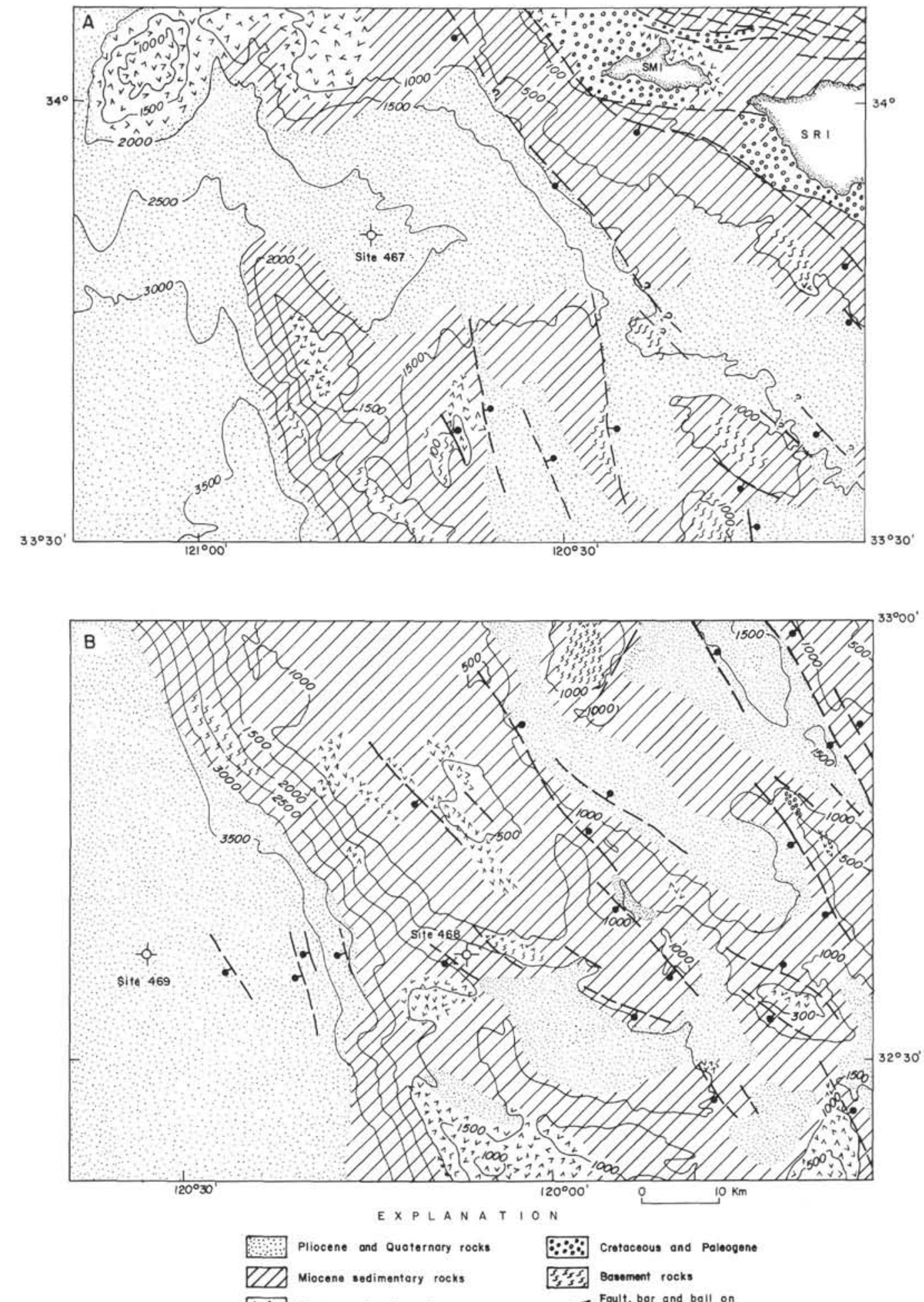

Figure 2. A. Generalized geologic map of the San Miguel Gap area and DSDP Site 467. Faults are interpreted from acoustic-reflection profiles and are projected to the seafloor where covered by Pliocene and Quaternary sediments. This map was compiled and modified from Wright (1967), Vedder et al. (1974, 1976, 1979), Junger (1979), and Crouch (1979a). SMI = San Miguel Island, SRI = Santa Rosa Island. B. Generalized geologic map of the southern Patton Ridge area and DSDP Sites 468 and 469. Faults are interpreted from acoustic-reflection profiles and are projected to the seafloor where covered by Pliocene and Quaternary sediments. This map was modified from Vedder et al. (1974) and Crouch (1979a). (Bathymetric contours are in meters.)

Volcanic rocks exposed in the San Miguel Gap area range in composition from basalt to dacite and are believed to be chiefly Miocene. On San Miguel and Santa Rosa islands, basalt flows and basaltic volcaniclastic rocks are interbedded with lower and middle Miocene strata and possibly interfinger with dacitic and andesitic volcaniclastic rocks (Weaver and Doerner, 1969; McLean et al., 1976). In addition, seafloor samples of lower and middle Miocene siltstone and claystone commonly contain vitric tuff laminae.

Except for a thin veneer (0–20 m) of Quaternary shell sand on the island platform and shallow ridge tops (Greene et al., 1975), Pliocene and Quaternary strata generally are restricted to basins and lower slopes in the vicinity of San Miguel Gap. These deposits consist largely of unconsolidated to semiconsolidated micaceous clay, silt, and sand.

Available marine geologic and geophysical data provide scant information on the structure of San Miguel Gap. Along the southern margin, northwest-trending normal faults (northeast side down) transect Patton Ridge but apparently die out beneath Quaternary sediments that fill the gap. The southeastern and eastern margins are uplifted along major subparallel, high-angle reverse faults. These reverse faults apparently are associated with a major wrench zone that extends southward for more than 100 km along the west flank of the Santa Rosa-Cortes Ridge (Crouch, 1979a).

Southern Patton Ridge and Sites 468, 469

The seafloor geology at the southern end of Patton Ridge (Fig. 2B) is compiled from Vedder et al. (1974, 1976, 1979) and Crouch (1979a). The southern end of the ridge is marked by a reentrant in the Patton Escarpment that is morphologically similar to San Miguel Gap. The known stratigraphy of the two areas is similar. Basement rocks exposed on Patton Escarpment and Albatross Knoll are similar to the Franciscan Complex; these rocks are bordered on the east by a subparallel belt of thick Cretaceous and lower Tertiary strata that underlie Santa Rosa-Cortes Ridge (Vedder et al., 1974; Crouch, 1979b). Lower and lower middle Miocene strata blanket much of the northwest-trending belt of Franciscan-like rocks as well as the Upper Cretaceous and lower Tertiary strata. As in the San Miguel Gap area, this part of the Miocene sequence is intensely faulted and folded and is unconformably overlain by areally restricted and relatively undeformed upper Miocene strata. Truncation of strata older than late Miocene together with the occurrence of coarse-grained volcaniclastic sandstone at the southern end of Patton Ridge, which now is in water deeper than 375 meters, provide evidence of middle Miocene uplift and erosion. Intrusive and extrusive basaltic to andesitic volcanic rocks probably were emplaced during this middle Miocene episode of tectonism.

Landward of Patton Escarpment, faults consistently trend northwest (Fig. 2B) and apparently are related to wrench tectonics. Associated en echelon faults and folds on Patton Ridge die out seaward as they merge with the escarpment (Crouch, 1979a). Along the escarpment, faults and folds generally trend parallel to the slope.

Site 469 is located on Pacific oceanic crust, 20 km seaward from the base of the borderland slope. The site is surrounded by Quaternary hemipelagic sediments on the abyssal plain of the Baja Seamount Province and is separated from the continental slope by several northwest-trending pre-Quaternary normal faults.

STRATIGRAPHY

Pliocene Rocks

DSDP holes. Comparison of Pliocene strata in Holes 467, 468, and 469 with other borderland sections is difficult because seafloor exposures are sparse, thick sequences are buried beneath Quaternary deposits in basins, and island sections are thin and incomplete. Moreover, relating the various sequences is hindered by compositional differences resulting from diverse source terranes and the limited size and wide separation of depositional basins.

The approximately 350-meter-thick Pliocene section (Cores 9–45) drilled in Hole 467 (Fig. 3) is composed largely of silty to sandy clay beds that are diatomaceous in part and that include minor beds of nannofossil clay, dolomite, and dolomitic limestone. About 150 meters of upper Pliocene beds are separated from lower Pliocene claystone beds by an unconformity (Core 25 base). The basal 60 meters of the lower Pliocene section is nearly completely lithified and consists of calcareous claystone and minor beds of siliceous and nannofossil claystone. In Hole 468A (Cores 2–4), approximately 25 meters of lower and upper Pliocene calcareous ooze and minor foraminiferal glauconitic silty sand were drilled. Hole 469 penetrated about 50 meters of clay, nannofossil-foraminiferal ooze, and minor glauconitic silt beds deposited in the early and late Pliocene (Cores 5–11). Noteworthy are the presence of thin, upper Pliocene volcanic ash layers in Holes 467 (Core 14) and 469 (Core 8) and lower Pliocene clay and fine-grained sand containing trace amounts of glaucophane detritus in Hole 467 (Core 40). Neither volcanic ash layers nor glaucophane detritus has been reported from Pliocene dart-core samples on the outer part of the borderland, although pieces of silty ash are mixed with basalt fragments in Pliocene hyaloclastite at Northeast Bank (Hawkins et al., 1971).

OCS-CAL 78-164 No. 1. Approximately 600 meters of interbedded silty clay, sand, and gravel, and underlying calcareous sandstone, siltstone, and shale are assigned to the Pliocene in the Point Conception deep test well OCS-CAL 78-164 No. 1 (Fig. 3) (Cook et al., 1979). Comparison of the thickness, rock types, and clast composition shows little similarity between the DSDP holes and the well section. The proximity of the test well to mainland sediment sources as well as the depositional barrier formed by the southern edge of the Arguello Plateau and the northern Channel Islands platform presumably are responsible for the dissimilar sections in the well and in Hole 467.

OCS-CAL 75-70 No. 1. According to Paul et al. (1976), Pliocene strata are absent in the deep test well at Cortes Bank (Fig. 3), and Pliocene rocks have not been reported from the seafloor in the vicinity of the well.

Basins and ridges. Thick accumulations of Pliocene sediments in the borderland basins contrast sharply with the discontinuous thin veneers and erosional remnants on the ridges and banks. More than 1500 meters of buried Pliocene section is estimated to be present in both the Santa Monica and San Pedro basins (Fig. 3) (Junger and Wagner, 1977). In the relatively shallowly filled Catalina Basin, the Pliocene section generally is 200 to 600 meters thick. None of these basins has been drilled, but it is believed that the Pliocene sequences within them consist largely of turbidites derived from adjoining ridges. Where sampled, Pliocene deposits on the slopes are hemipelagic silt and mud. It seems likely that clayey hemipelagic deposits similar to those in Hole 467 are interspersed with turbidites in the basin sections.

Pliocene deposits on the shallow ridges and banks are areally restricted and generally less than 100 meters thick. Where sampled, these strata are composed chiefly of locally derived foraminiferal mud, silt, and fine-grained sand that contain varying amounts of pelletal glauconite. The only comparable deposits in the DSDP holes are the glauconitic foraminiferal silty sand beds in Hole 468. Basaltic hyaloclastite (tufflike deposit formed by underwater flow and consequent granulation) and volcanic breccia containing shallow-water Pliocene mollusks occur at Northeast Bank, where fission-track and K/Ar dates suggest an age of 4 to 5 m.y. (Hawkins et al., 1971). These are the only known Pliocene volcanogenic rocks on the borderland.

Islands. Pliocene rocks are known from four of the eight Channel Islands, but the stratigraphic sections are thin, and the outcrops are areally limited. On Santa Rosa and Santa Cruz islands, small patches of shallow-marine calcareous sandstone less than 30 meters thick are preserved on the north and east sea cliffs, respectively (Potato Harbor Formation of Weaver and Meyer, 1969; unnamed strata, Vedder and Howell, 1980). Similar beds are present on San Clemente Island and have a maximum thickness of approximately 30 meters (Vedder and Moore, 1976; Susuki and Stadum, 1978). It is believed that all of these strata on the three islands were deposited in the late Pliocene on the basis of their contained molluscan and benthic foraminiferal assemblages; and all were locally derived. Southeast of the isthmus on Santa Catalina Island, unnamed sandstone and granule breccia beds, originating from an adjacent narrow shelf and steep slope, contain a lower bathyal foraminiferal assemblage deposited in the early Pliocene (Vedder, Howell, and Forman, 1979).

The predominantly coarse-grained Pliocene strata in the island sections contrast sharply with correlative pelitic, largely biogenic strata drilled at the DSDP sites. Presumably the shallow-water, high-energy environments at the islands and the distances of the DSDP holes from terrigenous sources contributed to the differences in sediment character.

Upper Miocene Rocks

DSDP holes. The approximately 335 meters of upper Miocene section (Cores 46-80?) drilled in Hole 467 (Fig. 3) consist chiefly of claystone beds interrupted in the lower 60 to 70 meters by a sequence of volcanogenic beds (Cores 74–80). The pelitic beds in the upper part are composed of calcareous claystone and minor amounts of siliceous claystone. Below the drilled depth of 520 meters (Core 56), all siliceous microfossils are absent, and opal-A has been converted to opal-CT (Grechin et al., this volume). Interbedded with the calcareous clayey strata in the lowermost part of the upper Miocene section (Cores 79–80) are tuff, lapilli tuff, and volcaniclastic sandstone and siltstone beds, all of which contain abundant pumiceous material. These volcanogenic beds extend down into the middle Miocene section. Sedimentary structures and upward fining and burrowed topmost beds are characteristic of the lapilli tuff beds, although structures are absent in the lowermost beds. Clayey nannofossil chalk, black chert fragments, and calcareous chert are minor constituents in the lower 50 meters (Cores 76–80).

About 15 meters of upper Miocene interbedded nannofossil ooze and glauconitic sandy clay were drilled in Hole 468B (Cores 2–3), and about 60 meters of correlative foraminiferal and diatomaceous nannofossil ooze are present in Hole 469 (Cores 11–18). Thin layers of glauconitic-foraminiferal sand and vitric tuff occur in the lower part of the upper Miocene section in Hole 469 (Cores 14–17).

OCS-CAL 78-164 No. 1. Paleontologic evidence is weak for assigning ages to the Miocene section in the deep test well west of Point Conception. It seems likely, however, that below 1525 meters, a sequence of fine-grained rocks 500 to 700 meters thick is late Miocene, on the basis of stratigraphic correlations with the Santa Maria Basin and the Santa Barbara Channel (Cook et al., 1979). In the upper part of the section, these rocks are chiefly calcareous shale and siltstone; in the lower part, cherty shale and siltstone. Fine-grained quartzofeldspathic sandstone beds containing a tuffaceous matrix are minor constituents in the upper part.

Upper Miocene strata in the deep test well contain more terrigenous material than those in the DSDP holes and in general are coarser grained. Neither coarse volcaniclastic nor glauconitic material was reported from the well section. In contrast, volcaniclastic material is concentrated in the lower part of the upper Miocene section in Hole 467, and glauconite is common to abundant in the upper Miocene sections in Holes 468A, 468B, and 469. It is probable that the upper Miocene section in the test well is more than twice as thick as equivalent sections in the DSDP holes, although the lack of age-diagnostic fossils in the well prevents direct correlations.

OCS-CAL 75-70 No. 1. Upper Miocene strata were not drilled in the deep test well at Cortes Bank, although upper Miocene foraminiferal and nannofossil claystone is exposed on the flanks and southeastern nose of the bank.

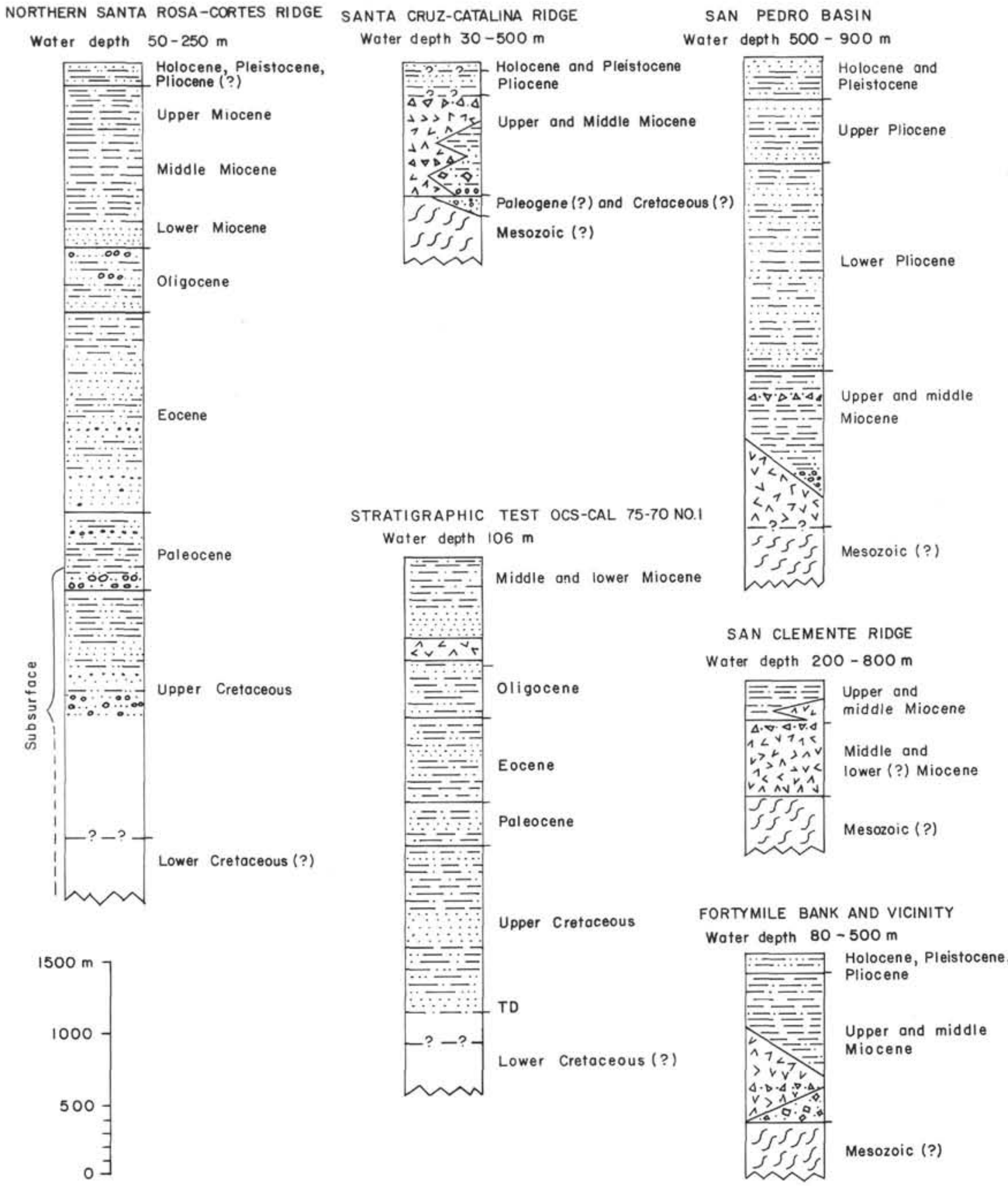

Figure 3. Generalized columns showing time-stratigraphic sequences in DSDP Holes 467, 468, 469, deep test wells, and selected basins and ridges. (Data were compiled and generalized from Paul et al. [1976], Cook et al. [1979], Crouch [1979a], and Vedder et al. [1980].)

Basins and ridges. The thickest sequences of upper Miocene strata in the borderland underlie younger sediments in the basins and are exposed on lower slopes, where the maximum thickness may be as much as 1000 meters and the average, about 300 meters. Thicknesses are variable in the outer borderland basins and range from as much as 850 meters in Patton Basin (Fig. 3) to as little as 150 meters in parts of Catalina Basin.

Upper Miocene rocks have been sampled at numerous places along all of the large borderland ridges. Hemipelagic calcareous claystone and siltstone are the commonest rock types among the samples, and siliceous silty claystone is slightly less common. Vitric tuff laminae are interlayered with these pelitic rocks in many dart cores. Cores of volcaniclastic sandstone and conglomerate are sparse but widespread. Upper Miocene(?) mudstone, sandstone, and pebble conglomerate containing locally derived clasts of basement rocks have been sampled at Albatross Knoll, on an unnamed knoll 15 km northeast of Albatross Knoll, along Santa Cruz-Catalina Ridge, and across the Thirtymile-Fortymile Bank platform. Hornblende from amygdaloidal basalt

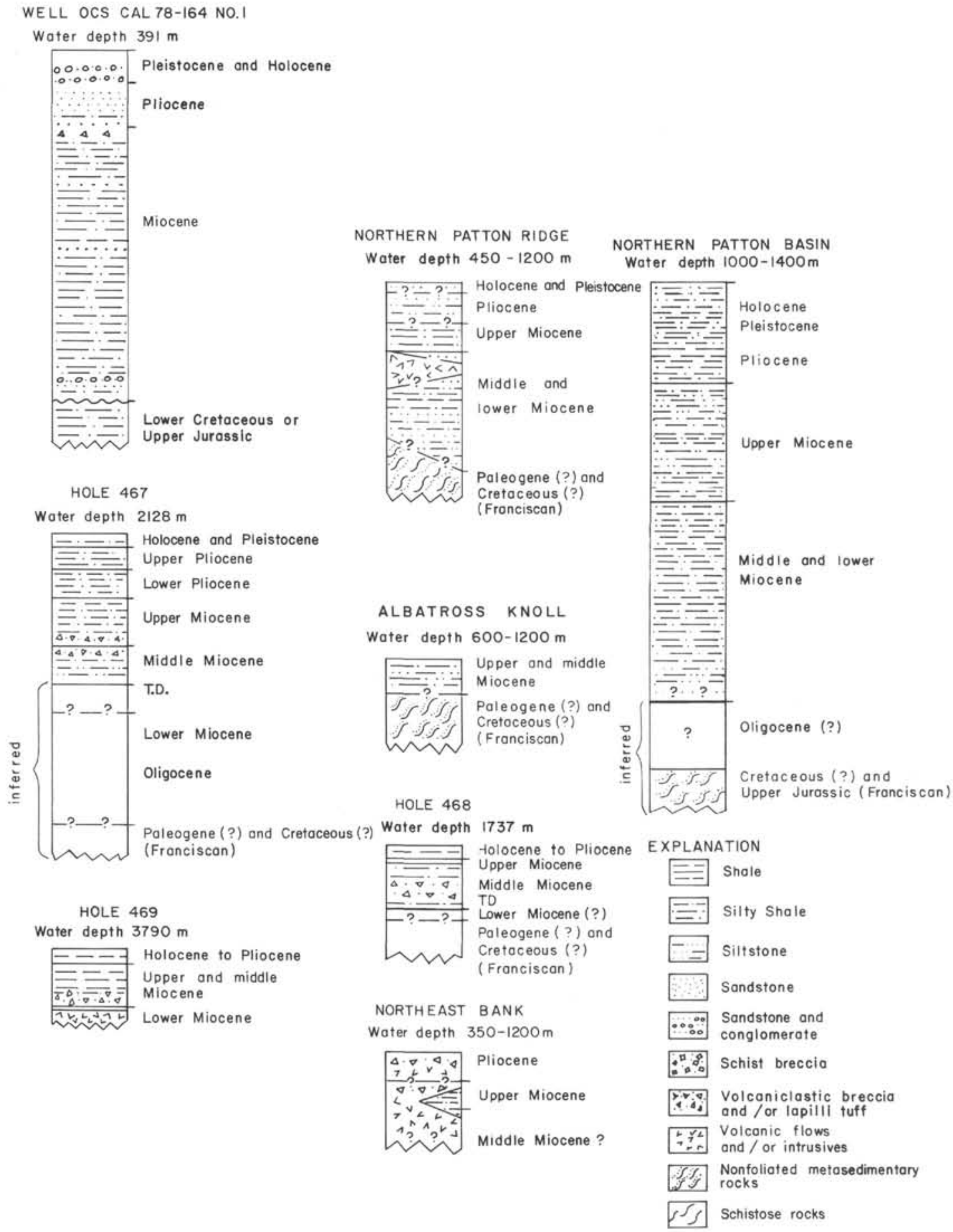

Figure 3. (Continued).

dredged from a low knoll 15 km west of the north end of Northeast Bank yielded a K/Ar age of 6.4 ± 0.5 m.y. (D. Krummenacher, written communication, 1975).

The upper Miocene pelitic rocks along the ridges are similar to those in the DSDP holes. Diagenesis, however, has not affected fossil diatom frustules in upper and middle Miocene seafloor samples from the Santa Rosa-Cortes and Patton ridges (J. Murata, written communication, 1975), whereas opal has been converted to opal-CT in the lower part of the upper Miocene section in Hole 467.

Islands. Rocks of well-documented late Miocene age have been reported only from Santa Catalina (Vedder, Howell, and Forman, 1979) and San Clemente islands (Vedder and Moore, 1976). At Santa Catalina Island, interbedded volcanic and sedimentary rocks include upper bathyal to neritic, calcareous to tuffaceous mudstone and calcarenite, neritic tuffaceous siltstone and sandstone, and andesitic flows and flow breccias. The thickest measured section is less than 20 meters. Correlative rocks on San Clemente Island are predominantly neritic volcaniclastic sandstone in which dacite is the abundant lithic constituent. As on Santa Catalina Island, the rocks are unnamed, and measured sections are less than 20 meters thick. Shallow-water environments, coarse clastic deposits, and volcanic flows typify the island rocks and thus are in direct contrast to the upper Miocene deep-water, predominantly pelitic rocks in the DSDP holes.

Middle Miocene Rocks

DSDP holes. Approximately 275 meters of middle Miocene volcanogenic and sedimentary rocks were drilled in Hole 467 (Cores 81?–110). Volcaniclastic siltstone and sandstone and basaltic to andesitic lapilli tuff beds are concentrated in the upper 60 meters of the middle Miocene section (Cores 81–88). Some of the lapilli tuff beds are graded by upward fining. Underlying beds consist of nannofossil claystone, clayey chalk, and silty claystone and minor interbeds of arkosic wacke and glauconitic sandstone. Below a depth of 984 meters, sandstone beds (Cores 105–108) contain sporadic grains of mica schist as large as 150 μm.

In Hole 468B, a middle Miocene section of about 360 meters was drilled (Cores 4–37), the upper half of which is chiefly claystone; the lower half in both 468 (Cores 12–26) and 468B (Cores 19–37) includes zones of volcanic and volcaniclastic rocks, chiefly of andesitic composition. The pelitic upper section in both 468 and 468B includes calcareous and siliceous ooze, diatomaceous and nannofossil silty to sandy clay, and diatomaceous, calcareous, sandy claystone and silty claystone. The partly volcanogenic lower section in 468B includes vesicular dacite fragments, volcanic lithic wacke, basalt, basaltic andesite, andesite clasts (representing volcanic breccia and sandstone), and hard, laminated dolomitic silty claystone.

The approximately 200 meters of middle Miocene section in Hole 469 (Cores 18?–38?) consist of silty claystone beds in the upper part and volcanic lithic wacke and basaltic to andesitic breccia beds including abundant perlitic glass and pumice fragments in the lower part. Incorporated in some breccia beds are abraded fragments of bryozoans, echinoids, mollusks, and barnacles (Core 33).

OCS-CAL 78-164 No. 1. The sparsely fossiliferous middle Miocene section in the Point Conception deep test well probably is between 500 and 700 meters thick. Most of the drilled sequence consists of laminated cherty shale interbedded with calcareous and dolomitic shale and siltstone. Sandy and tuffaceous siltstone occur in minor amounts (Cook et al., 1979). The sequence contains large amounts of porcellanite and, in general, is much more siliceous and more indurated than correlative sections in DSDP holes.

OCS-CAL 75-70 No. 1. Known middle Miocene rocks in the Cortes Bank deep test well are about 140 meters thick (D. Bukry, written communication, 1976), but at least 90 meters of Miocene section above the dated rocks were not logged (Paul et al., 1976). The rock is predominantly fine-grained silty to clayey arkosic sandstone, in part friable, and includes interbedded claystone and siltstone. Shallow-water megafossils, chiefly barnacle plates, are abundant in some of the coarser-grained beds. Composition of the clasts suggests that the sandstone was derived in large part from nearby outcrops of Upper Cretaceous or Paleogene sandstone and conglomerate beds. This relatively thick sequence of sandstone beds is unusual for Miocene strata on the outer part of the borderland and bears little resemblance to any of the sections drilled in the DSDP holes.

Basins and ridges. Interpretations from acoustic-reflection profiles suggest that middle Miocene rocks range in thickness from about 500 to 900 meters in the outer borderland basins and on the ridge flanks. On the ridges the rocks are predominantly claystone and siltstone that extend downslope beneath younger strata in the basins. Middle Miocene sandy mudstone and sandstone beds are uncommon on the borderland; known seafloor exposures occur at places on Patton Ridge, Hancock Bank, Garrett Ridge, Tanner Bank, the eastern part of Blake Knolls, northern Santa Rosa-Cortes Ridge, and Santa Cruz-Catalina Ridge. Locally derived basement-rock detritus is common in some of these coarse clastic beds and is abundant along the Santa Cruz-Catalina Ridge. Volcaniclastic rocks and basaltic to dacitic volcanic rocks, which include flows, pyroclastics, hyaloclastites, and intrusives, are distributed throughout the borderland (Fig. 4). Dated counterparts on the islands suggest that most of the volcanogenic rocks in the borderland are middle Miocene and fall within an age range of 12 to 15 m.y. Presumably these middle Miocene volcanogenic rocks are directly related to similar rocks in the DSDP holes.

Islands. Middle Miocene rocks probably occur on all of the islands including San Nicolas, where Eocene strata are intruded by middle(?) Miocene diabase and andesite (Vedder and Norris, 1963). On San Miguel Island, about 50 meters of laminated tuffaceous diatomaceous shale including dacite conglomerate and sandstone at the base are assigned to the shale member of the Monterey Formation by Weaver and Doerner (1969). Underlying volcaniclastic strata at the top of the Beechers Bay Member of the Monterey Formation of Avila and Weaver (1969) may be as young as middle Miocene. On Santa Rosa Island, the Monterey Formation of Avila and Weaver (1969) is as thick as 600 meters but probably is middle Miocene only in the uppermost part; the formation includes strata that were assigned to the Blanca Formation by McLean et al. (1976). Characteristic strata of the Monterey and Blanca formations on Santa Rosa Island are interlayered diatomaceous shale and dacitic volcaniclastic sandstone and conglomerate containing varying amounts of blueschist detritus. South of the Santa Cruz Island fault, the Blanca of Rand (1933), Weaver, Griggs, et al. (1969), and Fisher and Charlton (1976) may contain middle Miocene beds at the top of the island section, which consists of volcaniclastic sandstone and siltstone beds and dacite conglomerate (McLean et al., 1976).

Volcanic rocks constitute by far the largest volume of unnamed middle Miocene formations on the southern

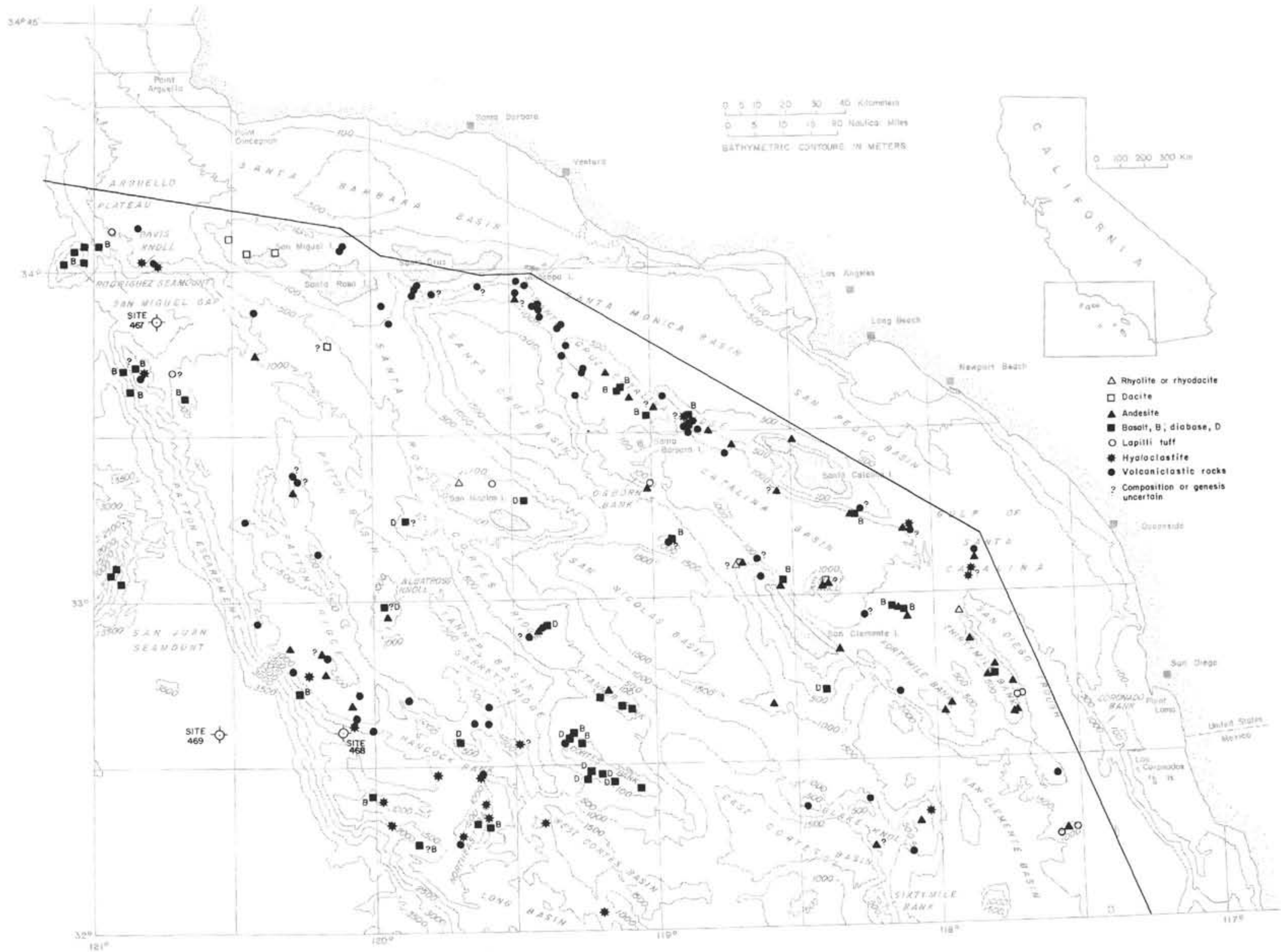

Figure 4. Map showing distribution of available volcanic and volcaniclastic rock samples on the southern California borderland. (Although few of these samples have been dated, most of them probably correlate with Miocene rocks on the islands. Numerous samples of similar rocks from the islands and landward from the boundary line are not shown. [Compiled from Vedder et al., 1974, 1976, 1979, and in press.])

group of Channel Islands; sedimentary rocks are subordinate. At Santa Barbara Island, basaltic to andesitic flows and lapilli tuff are interbedded with minor amounts of hayloclastite and upper bathyal, calcareous, clayey siltstone (Vedder and Howell, 1976). Complex stratigraphic relations typify the middle Miocene volcanic and sedimentary rocks on Santa Catalina Island, where subaerial to shallow-water andesitic flows are interlayered with lenticular lapilli tuff, schist breccia, and neritic diatomaceous siltstone and claystone beds (Vedder, Howell, and Forman, 1979). At San Clemente Island, dacitic to rhyolitic flows K/Ar-dated as 13 to 16 m.y. old (Turner, 1970; Merifield et al., 1971; Hawkins and Divis, 1975) are interstratified with and overlain by middle and upper Miocene volcaniclastic sandstone, laminated silty claystone and shale, and lapilli tuff beds that were deposited in environments that range from neritic to upper bathyal (Vedder and Moore, 1976).

Meager fossil evidence indicates that most of the rocks that constitute the San Miguel Volcanics of Weaver and Doerner (1969) and the Blanca Formation are older than the volcaniclastic strata in the DSDP holes. Although the youngest parts of these formations presumably are correlative with the middle Miocene tuffs, hyaloclastites, and volcanic sandstones in the DSDP holes, compositional differences suggest local rather than island sources for the drilled rocks.

Lower Miocene Rocks

Chalk, claystone, and minor dolomitic and volcanic sandstone and clay beds in the lowermost part of the drilled sedimentary section in Hole 469 (Cores 38?–43) are the only lower Miocene rocks recorded among the three sites. These largely pelagic beds overlie 55 meters of pillow basalt and hyaloclastite (oceanic crust) at the bottom of the hole (Cores 43–51) and, except for one clayey volcanic sandstone bed near the bottom (Core 38), are lithologically unlike any known seafloor samples of lower Miocene sedimentary rocks in the borderland. However, pieces of reddish brown dolomitic claystone, which occur between fragments of the basalt (Core 43), lithologically resemble parts of the Rincon Formation of Avila and Weaver (1969) on Santa Rosa Island and the Rincon Formation of Bereskin and Edwards (1969) on Santa Cruz Island (D. Bukry, written communication, 1980). A diabase sill nearly 20 meters thick (Cores 40–42) interrupts the sedimentary section above the pillow basalt sequence.

SIGNIFICANCE OF THE MIOCENE COARSE CLASTIC AND VOLCANIC ROCKS

Origin

The coarse clastic material in the middle and upper Miocene sections in all three holes was derived chiefly from basaltic and andesitic rocks. Genetic relations of some of these rocks are difficult to recognize in cores because fragmental volcanic rocks such as flow breccia, lapilli tuff, and hyaloclastite are indistinguishable from some volcaniclastic sandstone and breccia beds. All of these rock types are widely distributed in the borderland (Fig. 4) and generally have the same age, although lower Miocene and lower Pliocene volcanic rocks are locally present.

In Hole 467, the vitric tuff and volcaniclastic beds are basaltic to andesitic in composition and are interlayered with claystone beds that are assigned to the upper and/or lower parts of the *Discoaster variabilis* Zone. Sedimentary structures, including upward fining and rip-up clasts, in many of the volcaniclastic sequences suggest that most of these layers are turbidites and regional relations imply a slope–basin depositional setting. Tuffaceous mudstone and sandstone layers occur intermittently; some of these contain abundant quartzofeldspathic grains mixed with volcanic rock fragments, and mica schist clasts are present in arkosic sandstone layers low in the section. The source of the mica schist fragments, as well as of sparse glaucophane grains high in the section, is not known; possibly they could have been derived from basement terranes east of San Miguel Gap or redeposited from lower Miocene schist breccia beds.

The volcanic and volcaniclastic section drilled in Holes 468 and 468B is about 130 to 165 meters thick, respectively, and the upper part is assigned to the *Sphenolithus heteromorphus* Zone. Included are basaltic to andesitic volcanic breccia, lapilli tuff, and volcanic lithic wacke that are interlayered with dolomitic, silty claystone beds. Owing to diagenesis, the lower part of the same section in both holes is unfossiliferous but presumably is middle Miocene.

In Hole 469, a 60-meter-thick section of middle Miocene volcanic and volcaniclastic rocks is interlayered with siltstone and claystone beds assigned to the *Sphenolithus heteromorphus* and *Helicosphaera ampliaperta* Zones. The volcaniclastic rocks are lithic wacke and pebble breccia composed chiefly of basaltic and andesitic detritus. Sporadic grains of gabbro, chert, epidote, and micaceous arkosic sandstone, some of which are foliated, indicate minor contribution of sediment from sources other than volcanic rocks. A diabase sill intrudes the lowermost part, and pillow basalt representing oceanic crust is present at the base of the section.

All three DSDP holes are within 30 km of mapped outcrops of andesitic and basaltic rocks (Vedder et al., 1974, 1976; Crouch, 1979a) that could have been local sources for the middle and upper Miocene volcaniclastic detritus. Site 467 is bordered on the northwest and north by Rodriguez Seamount and Davis Knoll, which are composed of basalt and basaltic andesite together with hyaloclastite of similar composition. The northwestern spur of Patton Ridge, which protrudes into San Miguel Gap, consists of the same rock types. Altered diabase and amphibolite(?) of unknown age on a steep slope and plateau 27 to 30 km southwest of Santa Rosa Island form part of the east edge of San Miguel Gap and could have contributed clastic material to the basin beneath the gap. The San Miguel Volcanics of Weaver and Doerner (1969) on southern San Miguel and Santa Rosa islands are chiefly basaltic in composition[3] and were

[3] We believe that the dacite plug and associated dacitic rocks on and around San Miguel Island are in part older and may not be genetically related to the San Miguel Volcanics. A sample of porphyritic dacite from Prince Island near San Miguel Island yielded a K/Ar date of 24.4 ± 3.0 Ma on plagioclase (D. Krummenacher, written communication, 1975).

deposited in the early to middle Miocene. The volcaniclastic rocks in Hole 467 are younger than the volcanic rocks on San Miguel and Santa Rosa islands. Furthermore, a postulated major fault zone, along which there may have been tens of kilometers of post-middle Miocene cumulative right slip, may separate San Miguel Gap from the island platform. The abundance of dacitic and andesitic detritus in the lower and middle Miocene Blanca Formation on Santa Cruz and adjoining islands precludes this volcaniclastic unit from being a source.

Hole 468 is adjacent to volcanic and volcaniclastic rocks that are exposed on the southern end of Patton Ridge. These seafloor outcrops include basaltic andesite, andesite, and hyaloclastite that presumably are syngenetic with similar rocks in Hole 468 (Crouch, 1979b). Sparse sedimentary rock fragments in some of the middle Miocene volcaniclastic sandstone beds in the hole may represent material eroded from nearby sources composed of Franciscan-like rocks. Serpentinite grains were not detected in the core samples, even though seafloor exposures lie less than 7 km east of Site 468. At places along the flanks of Patton Ridge, Miocene sedimentary rocks contain locally derived basement detritus, which includes fragments of serpentinite, argillite, and metasandstone, suggesting that parts of the ridge were high-standing when the sediments were deposited. Admixed neritic benthic foraminifers in middle to upper(?) Miocene mudstone and sandstone wedges that flank Albatross Knoll together with its surf-truncated and tilted upper surface indicate that it too was at or near sea level at the time these Franciscan-detritus sands were being deposited. Similar conditions are manifested on the unnamed knoll 15 to 18 km northeast of Albatross Knoll.

Even though Hole 469 lies nearly 20 km seaward from the base of Patton Escarpment, some of the constituents in the middle Miocene volcanic-pebble breccia beds imply derivation from the Patton Ridge area. The sparse occurrence of nonfoliated and foliated sedimentary rock fragments and epidote grains together with andesitic rock fragments seems to rule out adjacent, purely basaltic seamounts as a source. Inasmuch as some of the granule and pebble beds contain abraded pieces of barnacles, mollusks, and bryozoans, a shallow-water and perhaps a partly subaerial source and downslope transport are inferred. Glauconitic sandstone layers (some of which are graded) in the middle and upper Miocene sections also imply derivation from upper slopes and ridges.

Conclusions

When combined with regionally assembled dart-core and outcrop information, the Leg 63 drilling off southern California indicates that volcanic rocks, chiefly middle Miocene and of andesitic composition, are present throughout much of the southern California borderland. Prior to Leg 63 and recent U.S. Geological Survey sampling cruises (Vedder et al., 1979; Vedder et al., in press), it was generally believed that borderland volcanic rocks of this type were concentrated on a bifurcating ridge system that included Santa Cruz, Santa Barbara, and San Clemente islands (Vedder et al., 1975). Moreover, the composition and landward distance of these rocks from the base of the continental slope (100–150 km) led several investigators to suggest that these rocks are vestiges of an island-arc sequence, which was derived from a Benioff zone during the waning stages of Farallon plate subduction off southern California (Crowe et al., 1976; Higgins, 1976). The high alkalinity of these rocks and similar calc-alkalic and calcic volcanic rocks onshore in southern California also have been used to support the contention that the southwestern North American subduction zone steepened from 20° to 40° in the Oligocene and Miocene (Keith, 1978).

Because these volcanic rocks of intermediate composition are widespread in the borderland and because they occur at Patton Ridge anomalously close (< 20 km) to the ancestral Farallon-North American trench, it seems unlikely that they were derived from a subduction zone. Instead, they probably are related to the proximity of the ancestral East Pacific Rise and are the results of mantle plus sediment melting, as suggested by Hawkins and Divis (1975), Yeats (1968), and Marshak and Karig (1977). Furthermore, the approximate 17 m.y. age of the oceanic crust off the southern California borderland implies that subduction ceased before emplacement of most of these volcanic rocks 15 to 12 m.y. ago.

In addition to helping establish timing of volcanism, Leg 63 drilling results off southern California aid in documenting middle Miocene uplift and erosion in the outer borderland. The large size and angularity of clasts that compose the middle Miocene volcanic breccias in Holes 468 and 469 indicate that they were derived from nearby sources, probably from intrusive and extrusive volcanic rocks exposed along the southern crest of Patton Ridge.

Volcanism, uplift, and erosion in the outer borderland can be linked to middle Miocene (ca. 16–10 Ma) wrench-style folding and faulting throughout the borderland (Crouch, 1977, 1979a; Vedder, Howell, and Forman, 1979). This episode of wrench-tectonics closely corresponds to a transition from subduction to transform faulting along this segment of the eastern Pacific margin.

REFERENCES

Avila, F. A., and Weaver, D. W., 1969. Mid-Tertiary stratigraphy, Santa Rosa Island (Calif.). *In* Weaver, D. W., Doerner, D. P., and Nolf, B. (Eds.), *Geology of the Northern Channel Islands: Am. Assoc. Pet. Geol.: Soc. Econ. Paleontol. Mineral. Pacific Sec. Spec. Publ.*, pp. 48–67.

Bereskin, S. R., and Edwards, L. N., 1969. Mid-Tertiary stratigraphy, southwestern Santa Cruz Island (Calif.). *In* Weaver, D. W., Doerner, D. P., and Nolf, B. (Eds.), *Geology of the Northern Channel Islands: Am. Assoc. Pet. Geol.: Soc. Econ. Paleontol. Mineral. Pacific Sec., Spec. Publ.*, pp. 68–79.

Beyer, L. A., Sasnett, N. B., and Pisciotto, K. A., 1975. Interpretation of gravity and magnetic surveys of the California Continental Borderland. *Am. Assoc. Pet. Geol. Pacific Sec. Abstracts with Programs*, p. 8. (Abstract)

Cook, H. E., (Ed.), 1979. Geologic Studies of the Point Conception deep stratigraphic test well OCS-CAL 78-164 No. 1, Outer Continental Shelf, southern California. *U.S. Geol. Surv. Open-File Rep., 79-1218.*

Crouch, J. K., 1977. Structure of the Outer California Continental Borderland and a possible analogue in the region between the San Andreas and San Gabriel faults. *Geol. Soc. Am. Abstracts with Programs*, 9:407. (Abstract)

———, 1979a. Marine geology and tectonic evolution of the northwestern margin of the California Continental Borderland [Ph.D. thesis]. University of California, San Diego.

———, 1979b. Neogene tectonic evolution of the California Continental Borderland and Western Transverse Range. *Bull. Geol. Soc. Am.*, Pt. I, 90:338–345.

Crowe, B. M., McLean, H., Howell, D. G., et al., 1976. Petrography and major element chemistry of the Santa Cruz Island volcanics. *In* Howell, D. G. (Ed.), *Aspects of the Geologic History of the California Continental Borderland: Am. Assoc. Pet. Geol. Pacific Sec., Misc. Publ.*, 24:196–215.

Fisher, R. L., and Charlton, D. W., 1976. Mid-Miocene Blanca Formation, Santa Cruz Island, California. *In* Howell, D. G. (Ed.), *Aspects of the Geologic History of the California Continental Borderland: Am. Assoc. Pet. Geol. Pacific Sec. Misc. Publ.*, 24: 228–240.

Greene, H. G., Clarke, S. H., Jr., Field, M. E., et al., 1975. Preliminary report on the environmental geology of selected areas of southern California borderland. *U.S. Geol. Surv. Open-File Rep., 75-596.*

Hawkins, J. W., Allison, E. C., and MacDougall, D., 1971. Volcanic petrology and geologic history of Northeast Bank, southern California borderland. *Bull. Geol. Soc. Am.*, 82:219–228.

Hawkins, J. W., and Divis, A. F., 1975. Petrology and geochemistry of mid-Miocene volcanism on San Clemente and Santa Catalina Islands and adjacent areas of the southern California borderland. *Geol. Soc. Am. Abstracts with Programs*, (3):323–324. (Abstract)

Higgins, R. E., 1976. Major-element chemistry of the Cenozoic volcanic rocks in the L. A. Basin and vicinity. *In* Howell, D. G. (Ed.), *Aspects of the Geologic History of the California Continental Borderland: Am. Assoc. Pet. Geol. Pacific Sec. Misc. Publ.*, 24: 216–227.

Howell, D. G., and Vedder, J. G., 1980. Structural implications of stratigraphic discontinuities across the southern California borderland. *In* W. G. Ernst (Ed.), *The Geotectonic Development of California* (Vol. 1): Rubey Colloquium, 535–558.

Junger, A., 1979. Maps and seismic profiles showing geologic structure of the northern Channel Islands Platform, California Continental Borderland. *U.S. Geol. Surv. Misc. Field Studies Map MF-991.*

Junger, A., and Wagner, H. C., 1977. Geology of the Santa Monica and San Pedro Basins, California Continental Borderland. *U.S. Geol. Surv. Misc. Field Studies Map MF-820.*

Keith, S. B., 1978. Paleosubduction geometries inferred from Cretaceous and Tertiary magmatic patterns in southwestern North America. *Geology*, 6:516–521.

McLean, H., Howell, D. G., and Vedder, J. G., 1976. Miocene strata on Santa Cruz and Santa Rosa Islands—a reflection of tectonic events in the southern California Borderland. *In* Howell, D. G. (Ed.), *Aspects of the Geologic History of the California Continental Borderland: Am. Assoc. Pet. Geol. Pacific Sec. Misc. Publ.*, 24:241–253.

Marshak, R. S., and Karig, D. E., 1977. Triple junctions as a cause for anomalously near-trench igneous activity between the trench and volcanic arc. *Geology*, 5:233–236.

Merifield, P. M., Lamar, D. L., and Stout, M. L., 1971. Geology of central San Clemente Island, California. *Bull. Geol. Soc. Am.*, 82:1989–1994.

Paul, R. G., Arnal, R. E., Baysinger, J. P., et al., 1976. Geological and operational summary, southern California deep stratigraphic test OCS-CAL 75-70 No. 1, Cortes Bank area offshore southern California. *U.S. Geol. Surv. Open-File Rep., 76-232.*

Rand, W. W., 1933. The geology of Santa Cruz Island, California [Ph.D. thesis]. University of California, Berkeley.

Susuki, T., and Stadum, C. J., 1978. A Neogene section, northeastern San Clemente Island, California. *Natural History Museum of Los Angeles County, Contributions in Science No. 299.*

Turner, D. L., 1970. Potassium-argon dating of Pacific Coast Miocene foraminiferal stages. *In* Bandy, O. L. (Ed.), *Radiometric Dating and Paleontologic Zonation: Geol. Soc. Am. Spec. Paper 124*, pp. 91–129.

Vedder, J. G., Arnal, R. E., Barron, J. A., et al., in press. Composition and correlation of bedrock and sediment cores, R/V *Sea Sounder* Cruise S3-79-SC, May 1979, California Continental Borderland. *U.S. Geol. Surv. Open-File Rep.*

Vedder, J. G., Arnal, R. E., Bukry, D., et al., 1979. Descriptions of dart core samples R/V *Samuel P. Lee* Cruise L2-78-SC, May 1978, California Continental Borderland. *U.S. Geol. Surv. Open-File Rep., 79-936.*

Vedder, J. G., Beyer, L. A., Junger, A., et al., 1974. Preliminary report on the geology of the continental borderland of southern California. *U.S. Geol. Surv. Misc. Field Investigations Map MF-624.*

Vedder, J. G., Crouch, J. K., Scott, E. W., et al., 1980. A summary report of the regional geology, petroleum potential, environmental geology, and operational considerations in the area of proposed lease sale No. 68, offshore southern California. *U.S. Geol. Surv. Open-File Rep., 80-198.*

Vedder, J. G., and Howell, D. G., 1976. Neogene strata of the southern group of Channel Islands, California. *In* Howell, D. G. (Ed.), *Aspects of the Geologic History of the California Continental Borderland: Am. Assoc. Pet. Geol. Pacific Sec. Misc. Publ.*, 24:80–106.

———, 1980. Topographic evolution of the southern California borderland during late Cenozoic time. *In* Power, D. M. (Ed.), *The California Islands: Proceedings of a Multidisciplinary Symposium:* Santa Barbara, California (Santa Barbara Museum of Natural History), pp. 7–31.

Vedder, J. G., Howell, D. G., and Forman, J. A., 1979. Miocene strata and their relation to other rocks, Santa Catalina Island, California. *In* Armentrout, J. M., Cole, M. R., and TerBest, H., Jr., (Eds.), *Cenozoic Paleogeography of the Western United States: Soc. Econ. Paleontol. Mineral. Pacific Sec. Coast Paleogeogr. Symp.*, 3:239–257.

Vedder, J. G., and Moore, E. J., 1976. Paleoenvironmental implications of fossiliferous Miocene and Pliocene strata on San Clemente Island, California. *In* Howell, D. G. (Ed.), *Aspects of the Geologic History of California Continental Borderland: Am. Assoc. Pet. Geol. Pacific Sec. Misc. Publ.*, 24:107–135.

Vedder, J. G., and Norris, R. M., 1963. Geology of San Nicolas Island, California. *U.S. Geol. Surv. Prof. Paper 369.*

Vedder, J. G., Taylor, J. C., Arnal, R. E., et al., 1976. Map showing location of selected pre-Quaternary rock samples from California Continental Borderland. *U.S. Geol. Surv. Misc. Field Investigations Map MF-737.*

Vedder, J. G., Taylor, J. C., Wagner, H. C., et al., 1975. Seafloor bedrock patterns from Patton Escarpment to the mainland shelf of southern California. *Am. Assoc. Pet. Geol. Pacific Sec. Abstracts with Programs*, Long Beach, California, April 23–26, p. 7. (Abstract)

Weaver, D. W., and Doerner, D. P. 1969. Mid-Tertiary stratigraphy, San Miguel Island. *In* Weaver, D. W., Doerner, D. P., and Nolf, B. (Eds.), *Geology of the Northern Channel Islands: Am. Assoc. Pet. Geol.: Soc. Econ. Paleontol. Mineral. Pacific Sec. Spec. Publ.*, pp. 80–84.

Weaver, D. W., Doerner, D. P., and Nolf, B. (Eds.), 1969. *Geology of the Northern Channel Islands: Am. Assoc. Pet. Geol.: Soc. Econ. Paleontol. Mineral. Pacific Sec. Spec. Publ.*

Weaver, D. W., Griggs, G., McClure, D. V., et al., 1969. Volcaniclastic sequence, south central Santa Cruz Island. *In* Weaver, D. W., Doerner, D. P., and Nolf, B. (Eds.), *Geology of the Northern Channel Islands: Am. Assoc. Pet. Geol.: Soc. Econ. Paleontol. Mineral. Pacific Sec. Spec. Publ.*, pp. 85–94.

Weaver, D. W., and Meyer, G. L., 1969. Stratigraphy of northeastern Santa Cruz Island. *In* Weaver, D. W., Doerner, D. P., and Nolf, B. (Eds.), *Geology of the Northern Channel Islands (California): Am. Assoc. Pet. Geol.: Soc. Econ. Paleontol. Mineral. Pacific Sec. Spec. Publ.*, pp. 95–104.

Wright, F. F., 1967. Marine geology of San Miguel Gap off Point Conception California [Ph.D. thesis]. University of Southern California, Los Angeles, California.

Yeats, R. S., 1968. Southern California structure, seafloor spreading, and history of the Pacific basin. *Bull. Geol. Soc. Am.*, 79:1693–1702.