50. TECTONICS AND GEOLOGICAL HISTORY OF THE PASSIVE CONTINENTAL MARGIN AT THE TIP OF BAJA CALIFORNIA[1]

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ABSTRACT

The three-site Leg 64 Deep Sea Drilling transect at the tip of the Peninsula of Baja California straddled the transition from continental to oceanic crust. The outer site, 474, penetrated mainly mud turbidites and bottomed in "middle" Pliocene oceanic crust about 3 m.y. old. Two sites on the lower continental slope penetrated hemipelagic muddy sediments, a thin section of low-oxygen, phosphoritic, and glauconitic sediments, and a metamorphic cobble conglomerate; one of the sites, 476, bottomed in deeply weathered granite. The oldest marine sediments at this site are early Pliocene, about 4.5 m.y. old. Depth indicators in these holes suggest that all sites were in almost 1000 meters of water by the time oceanic crust was first generated and sea-floor spreading began. Block faulting, subsidence, and deposition of marine sediments on continental crust had preceded the start of sea-floor spreading.

Close examination of lineated magnetic anomalies demonstrates that the transition from continental to oceanic crust in this region is diachronous, as early as 4.9 m.y. in some places, but as young as 3.2 m.y. along the line of the transect. We propose a geological history scenario which involves termination of subduction along the western margin of Baja California at 12.5 Ma, a period of transform motion between the Pacific and North American plates along the Tosco Abreojos Transform Fault zone along the west side of Baja California, and a jump of the Pacific–North American plate edge to the alignment of the Gulf at 5.5 Ma. Between 5.5 Ma and about 3.2 Ma, separation of the blocks occurred locally by sea-floor spreading, but elsewhere by "diffuse extension," largely involving listric normal faulting and thinning of the continental crust, accompanied by subsidence and marine inundation. Thus, the plate edge system in the mouth and southern part of the Gulf evolved as early as 5.5 Ma, but the transition from rifting to drifting was diachronous, starting only 3.2 Ma along the line of the transect.

INTRODUCTION

Many versions of a model of rift origin and evolution of passive continental margins exist in the geological literature (see, for example, Heezen, 1960; Dewey and Bird, 1970; Falvey, 1974; Curray, 1980; Bally, 1981). These models are all based on a presumed evolutionary link between intracontinental rifting and sea-floor spreading, as exemplified by the East African Rift System, evolving to young, passive, continental margins such as are found in the Red Sea, the Gulf of Aden, the Gulf of California, and the Andaman Sea, and finally evolving to old-age, or mature, passive continental margins as exemplified by those on either side of the Atlantic Ocean. This general model and the evolutionary link are accepted by most workers in the field. Actual demonstration of the evolutionary link is, however, rather difficult. Most study of passive continental margins has been devoted to the old-age, mature margins of the Atlantic Ocean type. Study of youthful, passive, rift-origin continental margins has in fact led to some confusion because of the extreme variability of the few modern examples. A prudent general conclusion might then be that the model holds, but with rather variable local and/or regional conditions, which have in turn introduced extreme variability into the system. Some of this variability is hidden by the subsequent massive amounts of sedimentation in mature margins.

One of the objectives of drilling in the Gulf of California, as discussed by Moore and Curray (this volume, Pt. 1), was to attempt further to establish this evolutionary link. The advantage of studying young continental margins by geophysical means and by drilling is that thick sediments may not have concealed details of the basement morphology, structures related to the rifting and drifting stages, and the continent–ocean transition. This should enable us to be more effective in delineating the transition, understanding the structure, dating events, and matching to the conjugate margin.

The problem is important. Unless we understand the processes and variability of tectonic conditions in young passive continental margins, how can we interpret the geological history of older, more mature passive continental margins? Such understanding is necessary to trace the origin of intracontinental rifting and separation, the environmental conditions of rifting, margin formation, the birth of oceans, and the exploration and exploitation of economic materials.

The present pattern of spreading axes and transform faults involved in the formation of the Gulf of California (Fig. 1) is commonly thought to have been initiated at about 3.5–4.0 Ma (Moore, 1973). Most recent investigators have concluded that a different tectonic regime in middle to late Miocene time formed what has been called the proto-Gulf. These earlier ideas have

[1] Curray, J. R., Moore, D. G., et al., *Init. Repts. DSDP*, 64: Washington (U.S. Govt. Printing Office).

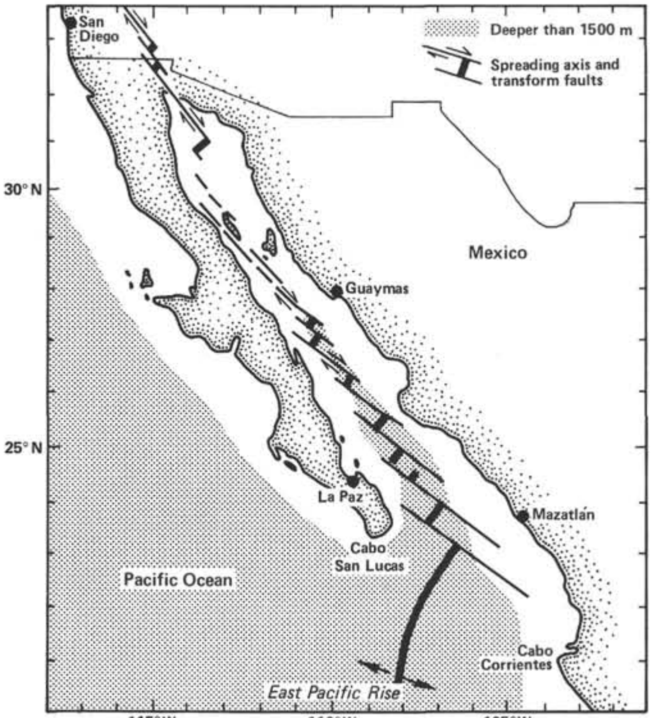

Figure 1. Simplified tectonics of the Gulf of California.

been reviewed in various chapters in this volume. Our new ideas, based on all the previous work, site surveying for this drilling leg, and results of the drilling information, are reviewed by Moore and Curray elsewhere (this volume, Pt. 2) and will be repeated here only as they pertain to specific results of this drilling transect across a segment of youthful passive continental margin at the tip of the Peninsula of Baja California. Neither this chapter nor the overview of the origin of the Gulf can be definitive. We believe that these studies are substantial advances, but we lack sufficient information in some of the critical areas to resolve all of the major points of controversy. We can only expect that through our present efforts we are gradually converging on an understanding of the mechanisms and geological history of this region.

Much land geology and marine geological and geophysical surveying had been done before Leg 64, and plans for the leg were based on syntheses of all that work. The bathymetry around the tip of the Baja California Peninsula (Fig. 2, back pocket, this volume, Pt. 2), is based in part on the pioneering work of Shepard (1964). The geophysical control on which this chapter is based is shown in Figure 3. This includes some data not available before the drilling leg, such as processing of the multichannel reflection lines across the margin.

REGIONAL GEOLOGIC AND GEOPHYSICAL SETTING

The Peninsular Range forms the backbone of Baja California. Geologically, the basement of this range is equivalent to the Peninsular Ranges of Southern California, the Coast Range of central California, and the Sierra Nevada. The granitic batholith, the root of a Mesozoic volcanic arc, is locally capped with preintrusive metamorphics. Lying to the west, in the Great Valley of California and in the Sebastián Vizcaíno Desert of central Baja California, is what is interpreted by many as an old forearc basin, flanked farther to the west by a Mesozoic Franciscan-equivalent accretionary prism.

The southern part of the Peninsula of Baja California is separated into two structural blocks by the generally north-south-trending La Paz Fault (Fig. 4). West of the La Paz Fault are generally flat-lying Tertiary sediments, grading to the northwest into the thick Mesozoic and Tertiary section of a presumed forearc basin. Granitic rocks crop out only locally, in the Magdalena Bay area and near Loreto, approximately 200 km to the northwest of the cape block. Basement underlying the isthmus of the Peninsula west of the La Paz Fault is unknown.

The block east of the La Paz Fault consists of granitic rocks, locally veneered with preintrusive metamorphics. Sense of displacement and age of the La Paz Fault are unknown, but we believe that it is probably a southernmost expression of the Miocene Basin and Range style of tensional faulting. A considerable component of down-to-the-west offset must exist, because the cape block clearly stands higher than the isthmus to the west. Some strike-slip component may also exist, but the evidence for sense of motion is contradictory (Normark and Curray, 1968). Other faults east of the La Paz Fault also produce a generally north-south-trending horst and graben system. Anticlines and synclines trending east-northeast are reported north of La Paz (J. Minch, pers. comm., 1979), but the relationship to the La Paz Fault is unknown. Granitic rocks of the cape block have been dated by Gastil et al. (1976) as ranging from 54–88 m.y.

Structure and geology offshore from the tip of the Peninsula were first interpreted by Normark and Curray (1968). Utilizing the new survey lines run since that time, including some multichannel lines run during site surveys, we have revised and updated their structural map (Fig. 4). The edge of continental crust and transition to oceanic crust as interpreted from geophysical data and confirmed by drilling on this leg are shown in this figure. Rock dredge samples (Table 1) also generally confirm this delineation of the edge of continental crust but imply that considerable volcanism must have occurred through this now subsided continental crust during and following rifting.

The structure within the submerged continental crust (Figs. 4, 5A, B) is dominated by northeast to north-northeast-trending normal faults. Some of these clearly form horsts and grabens; others preferentially dip seaward, and we presume that they are listric, decreasing in dip and soling out seaward. A prominent half graben overlies a terrace and depression in the middle part of the slope behind Cabrillo Seamount, in which the sediment section may attain a thickness as great as 1000 meters. Lying upslope from this half graben is an apparently very thick fill of sediment, well displayed in only one processed multichannel seismic line (Fig. 5A). Further high-quality multichannel seismic would be necessary to delineate this feature, which contains a sediment fill possibly as great as 2000 meters.

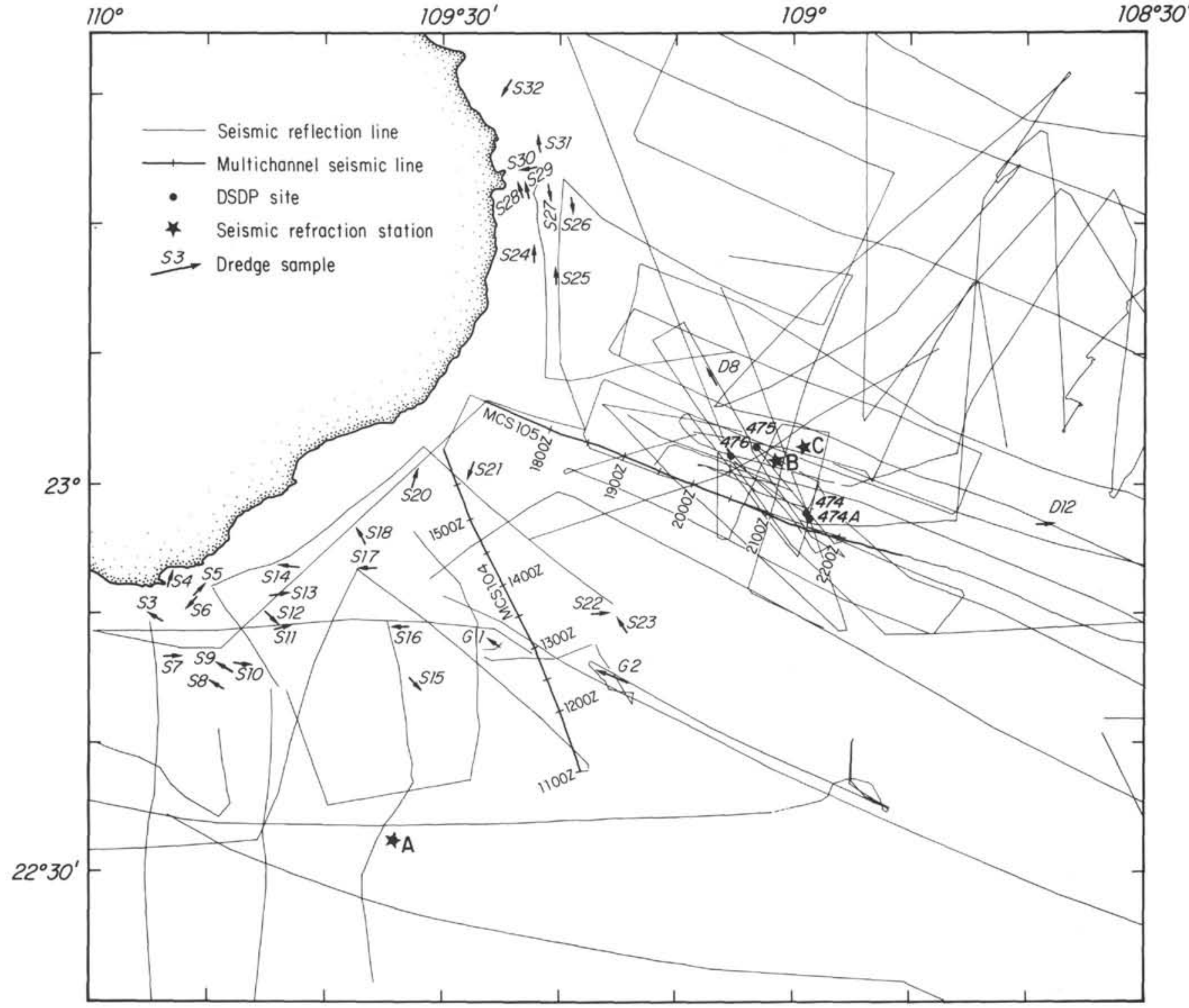

Figure 3. Geophysical tracks of the region of study with available seismic reflection records, showing drilling and dredge sites, refraction stations, and locations of multi-channel digital lines used for line drawings of Figure 5A, B.

At the northern edge of this area and on the southwestern flank of the tip of the Peninsula the structure is less clear. The available survey data and extrapolation from escarpments and canyon trends, however, suggest a continuation of the generally northeast-southwest-trending normal fault system. We believe that the contrast between the generally north-south-trending horst and graben system on land and the north-northeast, south-southwest-trending isochrons and axis of the East Pacific Rise offshore is important. As pointed out previously by Normark and Curray (1968), the structure of the submarine part of this youthful continental margin appears to display extensional tectonics of the kind that commonly exist in rift-origin segments of passive continental margins. The horsts and grabens on land are probably a southernmost manifestation of Miocene Basin and Range extension that occurred before the Gulf of California existed (Dokka and Merriam, 1982).

Sediment thicknesses (Fig. 6) are generally not great overlying continental crust. The thicker sediments overlying oceanic crust at the foot of the continental slope, in contrast, constitute the coalesced deep-sea fans or continental rise of the cape region.

The age of the oldest oceanic crust lying offshore from the continental crust was first interpreted from magnetic anomalies by Larson et al. (1968) and Moore and Buffington (1968) to be approximately 4 m.y. Magnetic anomalies have subsequently been interpreted by other workers as generally confirming this maximum age at about 3.5 m.y. (see, for example, Lewis et al., 1975; Mammerickx, 1980; Ness et al., 1981). A new compilation of selected magnetic anomalies is shown in Figure 7. Clearly, the transition from continental to oceanic crust is diachronous. The model that places initiation of the present phase of opening of the Gulf of California at 3.5 m.y. is, therefore, an oversimplifica-

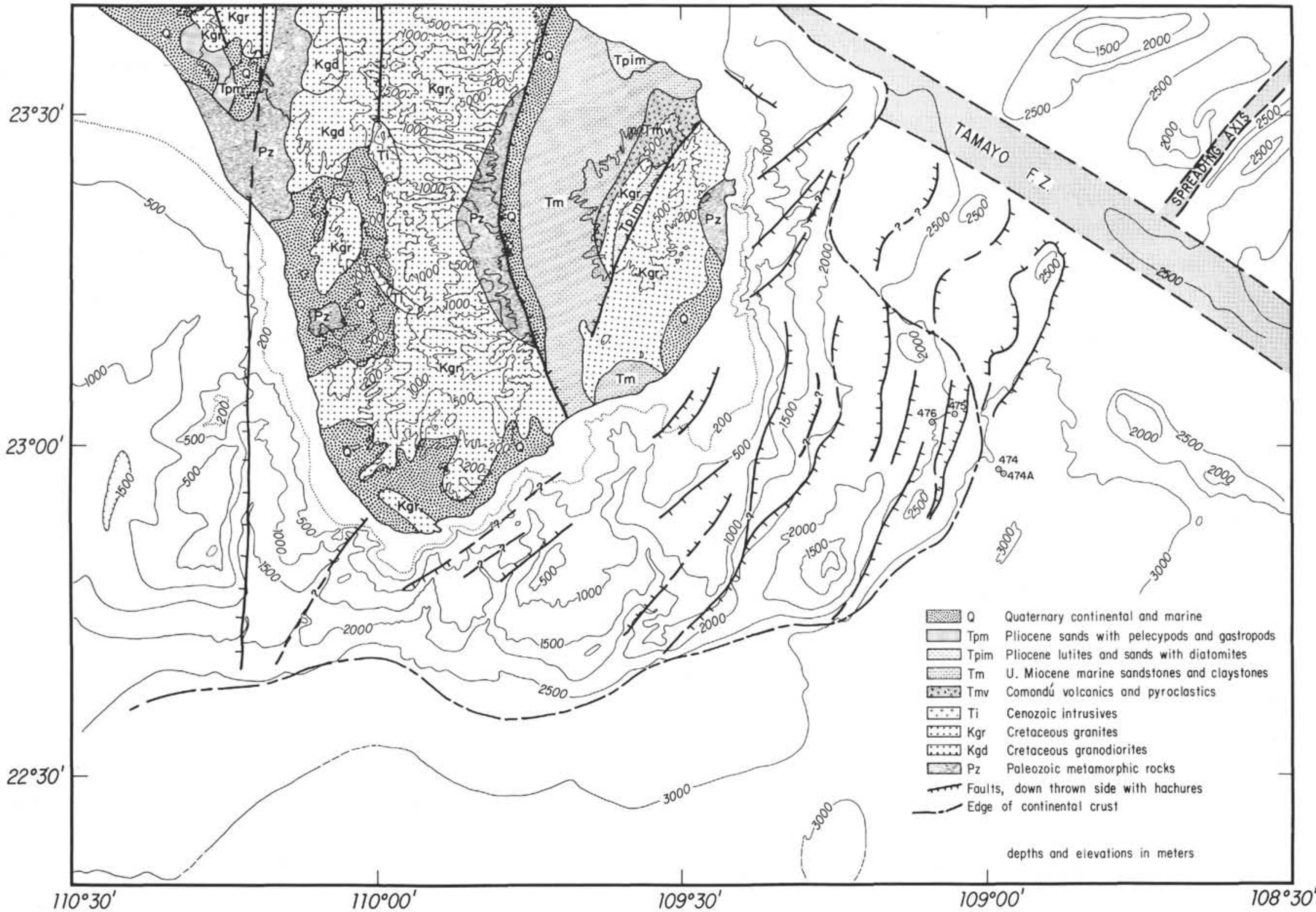

Figure 4. Geology and structure of the region of the tip of Baja California. Land geology adapted from Lopez Ramos (1973 and 1976).

Table 1. Rock dredge samples from the Gulf of California.

S-3.	BAC 61	Weathered granite with manganese; also some fresh granite
S-4.	BAC 63	Granite from outcrop
S-5.	LF 27	Fresh granite, mylonite, slickensides
S-6.	VSS 23	Brecciated granite
S-7.	BAC 20	Shale, granite, porphyritic andesite
S-8.	CAB 1	Granitic rock broken from outcrops
S-9.	VSS 19	Granite broken from wall
S-10.	LF 20	Bottom of dredge full of fresh granite, top full of volcanics
S-11.	VSS 18	Numerous rocks, including granite
S-12.	BAC 58	Large igneous rocks
S-13.	BAC 11	Claystone, cobbles of granite, dacite, and basalt
S-14.	LF 24	Mudstone, basalt
S-15.	SL 2	Basalt
S-16.	BAC 56	Igneous rock, shale with angular fragments
S-17.	LF 19	Granitic cobbles
S-18.	BAC 55	Weathered igneous rock
S-20.	SL 8	Mudstone
S-21.	SL 16	Granite block broken off
S-22.	BAC 17	Highly brecciated granite?
S-23.	BAC 59	Highly fractured granite
S-24.	BAC 19	Granite outcrops
S-25.	BAC 45	Granite, partly weathered
S-26.	BAC 44	Granite outcrop, manganese coating
S-27.	LF 23	Granite and volcanic boulders
S-28.	CAB 17	Angular blocks of weathered granite and pectens, probable Pliocene age
S-29.	SL 9	Angular biotite granite, rounded volcanics
S-30.	BAC 22	Shale fragments, stratified sands, pectens
S-31.	SL 15	Fractured volcanics?
S-32.	BAC 24	Volcanics
D-8.		Basalts, some weathered, some vesicular; sediments, dark, partly consolidated material, some evidence of deformation
D-12.		Basalts, some vesicular, glassy margins; breccia of mud and volcanic fragments; sediments, loosely consolidated
G-1.		Granodiorite and diabase
G-2.		Granodiorite, manganese crusts, and felsic volcanic cobbles

Note: S samples: numbers from Normark and Curray (1968), and original numbers and descriptions from Shepard (1964) and other unpublished descriptions. D samples: from Lewis et al. (1975). G samples: from Moore et al. (1978).

tion, because some oceanic crust was formed at the foot of the continental slope off Baja California prior to this time. The implications of this phenomenon and the modification of the models of formation for rift-segment passive continental margins constitute a major part of the discussion in this chapter.

Geophysicists at the Oregon State University have run a large number of gravity and magnetic survey lines on the west side and at the tip of the Peninsula of Baja California in recent years. Gravity has been compiled for the cape region by Huehn (1977), and part of a more recent compilation (G. Ness, pers. comm., 1981) is reproduced in Figure 8. This compilation shows a gravity minimum of about −40 mg, which Ness et al. (1981) interpret as marking a fossil subduction zone lying off the tip of the Peninsula. Among our reasons for rejecting this subduction hypothesis are, first, that we believe the gravity anomaly is an edge effect of the transition from continental to oceanic crust; second, that a −40 mg anomaly would not be sufficient to indicate a fossil subduction zone; and third, that an even larger anomaly of −50 mg lies northeast of the tip of the Peninsula where Ness et al. do not suggest the presence of a fossil subduction zone. We later discuss the possibility that subduction occurred beneath the cape block and offer other reasons for rejecting it as contrary to existing data.

DRILLING RESULTS: LITHOLOGIES AND PALEOENVIRONMENTS

Simplified lithologies and ages from drilling at Sites 474, 475, and 476 are shown in Figure 9. Descriptions are contained elsewhere (e.g., see the site chapter, this volume, Pt. 1), but we will here present some details of the sedimentology of the basal sediments not discussed elsewhere, and we have revised the lithologic columns on the basis of newer information and interpretations. Most of the sediment section drilled at Sites 474, 475, and 476 comprises rapidly deposited diatomaceous mud turbidites or hemipelagic diatomaceous muds. The basal sections are, however, most critical for understanding the early rifting history. Any scenario of geological history of this transect must be consistent with the environment of deposition for these sediments.

Estimates of bulk composition of some of these samples are listed in Table 2.

Site 474

Most of the section of Site 474, Holes 474 and 474A, is mud turbidites rich in diatoms and nannofossils. These sediments are typical of the distal parts of the coalesced fans of the cape region, the San Lucas Fan (Shepard, 1964; Normark and Curray, 1968), with terrigenous constituents derived from the submarine canyons of the southern Peninsula. Nannofossils continue to near the base of the section, but the proportion of siliceous microfossils decreases in the lower part of the section.

The base of the section encountered several dolerite sills and pillow basalt flows (Figs. 9 and 10). The oldest sediment datable, early Pliocene NN16, was recovered from Core 41 between the upper two dolerite sills, at a depth of about 540 meters sub-bottom.

A redeposited slump-debris flow-turbidite (Unit II) was recognized in the upper part of the section from 21 to 87 meters; it consisted of coarse sand and conglomerate, with evidence of warmer, shallow-water fauna. This is interpreted as a complex Pleistocene slide mass which came from the submarine canyons and a fan valley on the southeast tip of the Peninsula (Moore et al., this volume, Pt. 2).

Sediment recovery of basal mudstones (Figs. 9 and 10) from Hole 474A was rather good because of the state of compaction and lithification, resulting from the depth of burial (470–540 m) and possibly also from effects of intrusion by the dolerite sills. The sediments are light to moderately dark olive brown, with frequent evidence for multiple turbidites. Muddy graded sands are common, and bed tops are defined by burrowing structures. The composition of most coarser sands is arkosic, indicating rapid denudation of a granitic terrain. Almost no volcanogenic debris is present. Particularly coarse-grained sandstone occurs in Sections 474A-38-1 and 474A-40-1, intruded by the uppermost dolerite sill and cemented by calcite as a contact effect. It contains some volcanogenic components and rock fragments. In thin section, the polygenetic mixture includes angular quartz fragments, slightly weathered feldspars, biotite, rare pyroxene, hornblende, benthic foraminifers, and clasts of basalt, quartz-siltstone and "wormy" metamorphic quartzite. These sandstones are presumably the basal portion of thicker turbidites.

Upsection to Core 474A-34 (Figs. 9 and 10), sandy turbidites are common but we perceive a trend to less

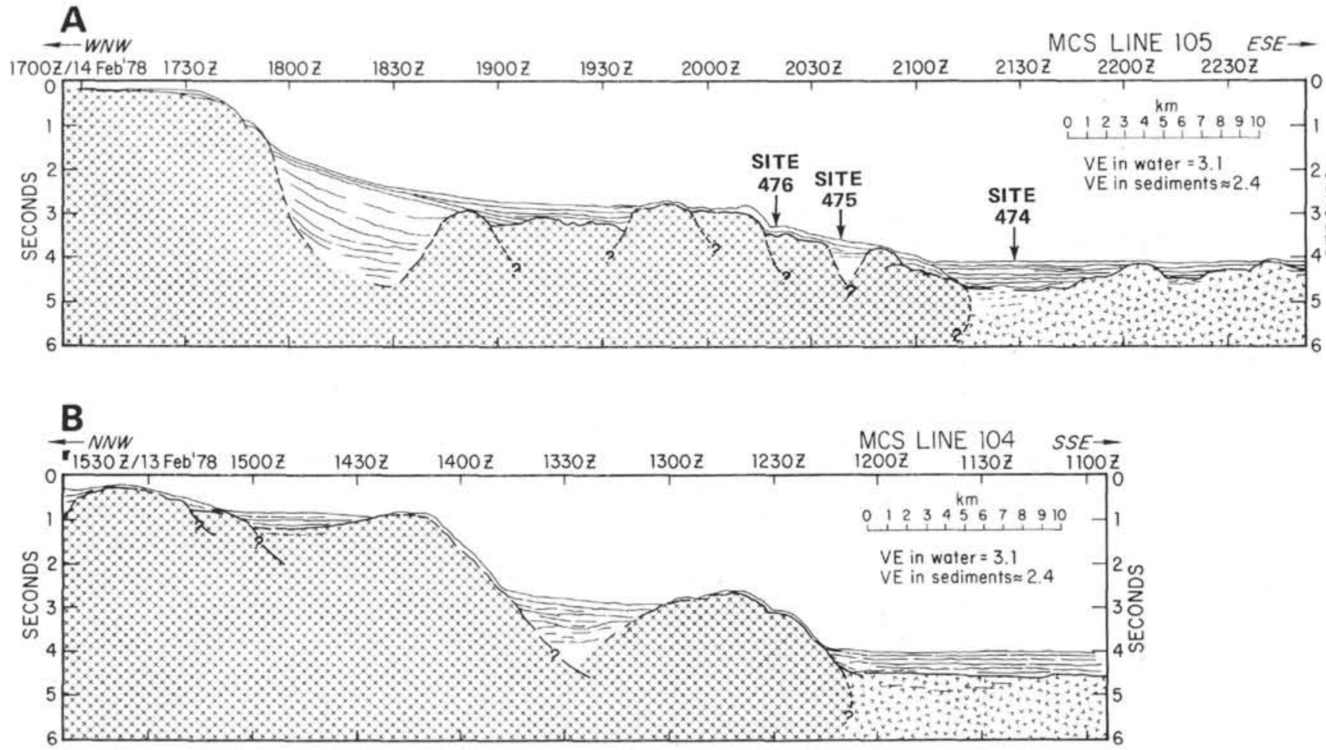

Figure 5. Line drawings of multichannel digital seismic reflection lines, run during Guaymas Expedition, SIO, 1978. See Figure 3 for locations. A. Line 105, with Sites 474, 475, and 476 projected onto the line. B. Line 104.

coarse debris. Pieces of wood and coal fragments occur repeatedly. An abundance of clinoptilolite in X-ray diffractograms is construed as evidence of former siliceous microfossils which have been converted to cristobalite and quartz, but we cannot estimate in what quantities.

There is no clear evidence of redeposition from shallow-water environments. Less conclusive evidence of environment is contained in olive to black-colored mudstone between sill and basalt "basement" Cores 474A-40 and 474-41, and in vermillion-colored siltstone intercalated within deeper basalt flows in Core 45. Almost all fossil evidence has been obliterated. Recovery of the sediments sandwiched between the sill and basalt flow is poor and sand infrequent, but faint bedding characteristics still indicate a sequence of many thin-graded beds. The sediment shows signs of heavy bioturbation, but there are several signs of restricted to anoxic conditions: a piece of lignite and scattered pyrite concretions. Thin, hard calcareous beds (e.g., Sample 474A-41-3, 44 cm) are mudstone cemented by dolomite, cristobalite, and clinoptilolite (Table 2). Barite concretions may be associated with contact hydrothermal effects on anoxic sediment. The sediments are unusually rich in dissolved organic carbon (Michaelis et al., this volume, Pt. 2), which is another sign that they have been deposited in an anoxic, restricted basin concomitant with the early stages of ocean floor development.

We conclude that at the time of intrusion of the upper sills, sometime after the late Pliocene basement prediction of 3.2 m.y., the site was already a rather deep ocean basin receiving turbidites in a distal fan setting similar to the narrow basins of the Southern California Borderland.

The igneous rocks of Site 474 include eight lithologic units (Saunders et al., this volume, Pt. 2). The uppermost sill from ~521–530 meters is underlain by about 10 meters of principally mudstone, but only thin intercalations of sediment were recovered below the top of the second sill at about 540 meters. The first pillow basalt was at 563 meters. The lowermost sediment recovered was a 3-cm piece of baked claystone at the top of Core 45, at 572 meters. Nannofossils *Reticulofenestra* cf. *R. pseudoumbilica* and *Sphenolithus abies* were found in this piece of claystone (Aubry, this volume, Pt. 2). These are possible indicators of Zone NN15, early Pliocene, but Aubry does not make an age assignment.

Saunders et al. (this volume, Pt. 2) argue on the basis of more-HYG/HYG element ratios (hydromagmatophile elements) that Igneous Units 1 and 2 (Fig. 10) were intruded off the spreading axis, whereas Units 4 through 8 formed at or near the spreading axis and are up to 1.4 m.y. older. Furthermore, subsequent examination of the multichannel seismic line near the site (Fig. 5A), processed after the drilling, and comparison with airgun refraction measurements made over the site lead us to suggest the possibility that as much as another 0.8 s of crudely stratified rocks underlie the bottom of Hole 474A. This section could be sediments rapidly deposited in a narrow, early, nascent stage of the Gulf, with intrusion of sills by the same mechanism that we have demonstrated in the Guaymas Basin spreading rifts (see site chapter, Guaymas Basin sites, this volume, Pt. 1).

Clearly the age relations at this site are somewhat contradictory: (1) magnetic anomalies suggest a basement age of about 3.2 m.y.; (2) oldest sediment assigned an age is NN16, possibly as old as 3.2 m.y. according to

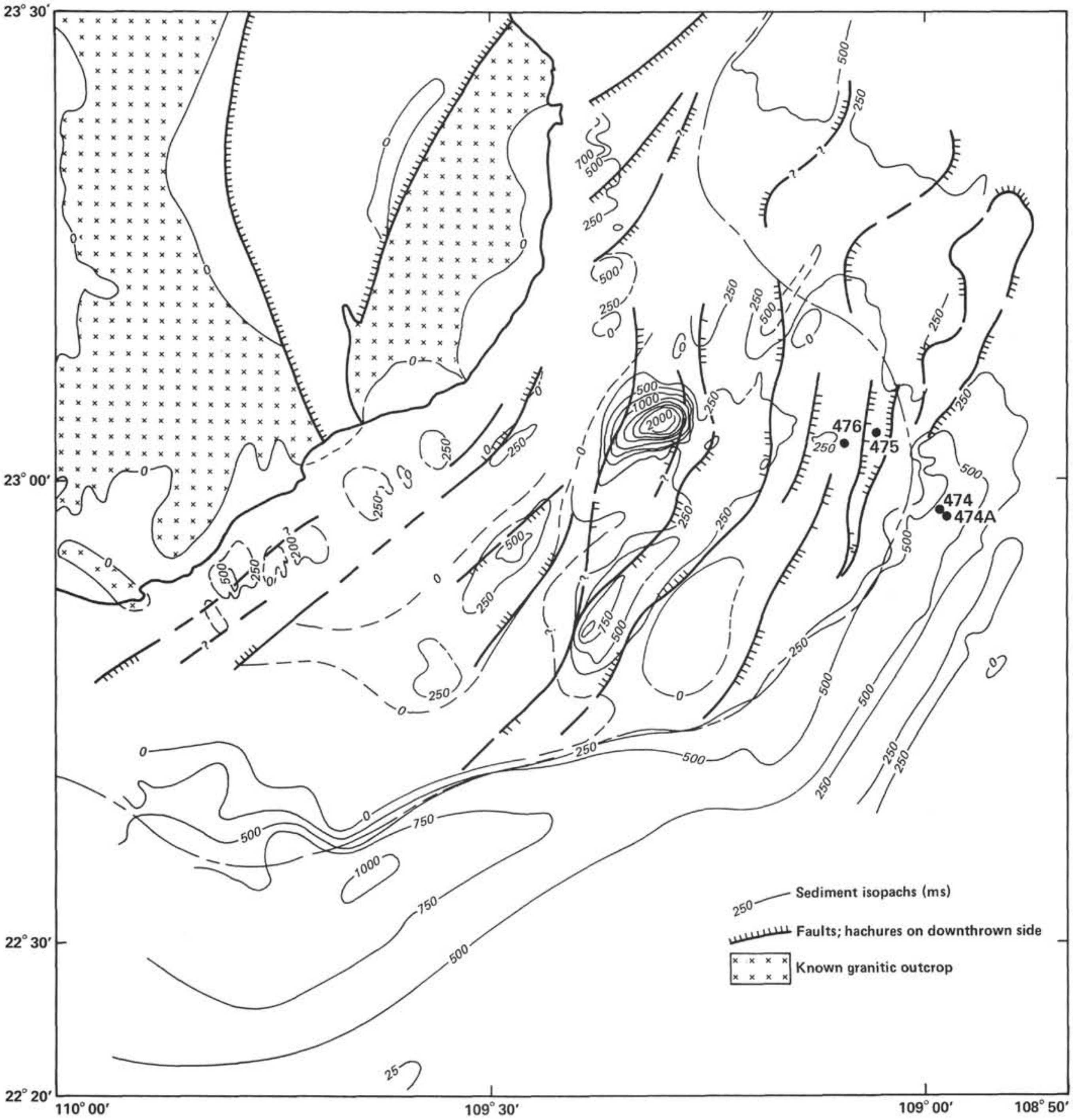

Figure 6. Simplified isopachs of total sediments, contoured in milliseconds. Compiled and contoured by F. J. Emmel.

the chronologies used in the site chapter; (3) older sediment was recovered, possibly NN15; (4) the older sills and flows penetrated may be as much as 1.4 m.y. older than the oldest dated sediment; and (5) possibly as much as a km or more of interbedded sediments, flows, and sills underlies the bottom of Hole 474A.

On the basis of these age relationships and apparent contradictions, we suggest that the oldest dated sediments recovered at this site (NN16) are less than 3.2 m.y. old. It was decided early in the work at sea on Leg 64 to accept a chronology of nannoplankton zonation with the NN16 zone extending back to 3.2 m.y. In fact, most absolute age assignments to the Martini (1971) scale extend NN16 only from about 2.5 to 2.8 m.y., and NN15 from about 2.8 m.y. to 3.0 m.y. By reassigning an age of a maximum of only 2.8 m.y. (if the oldest sediment is NN16) or a maximum of 3.0 m.y. (if indeed some NN15 sediments were recovered), the age contradictions are minimized, and the underlying stratified material could be very rapidly accumulated alternating

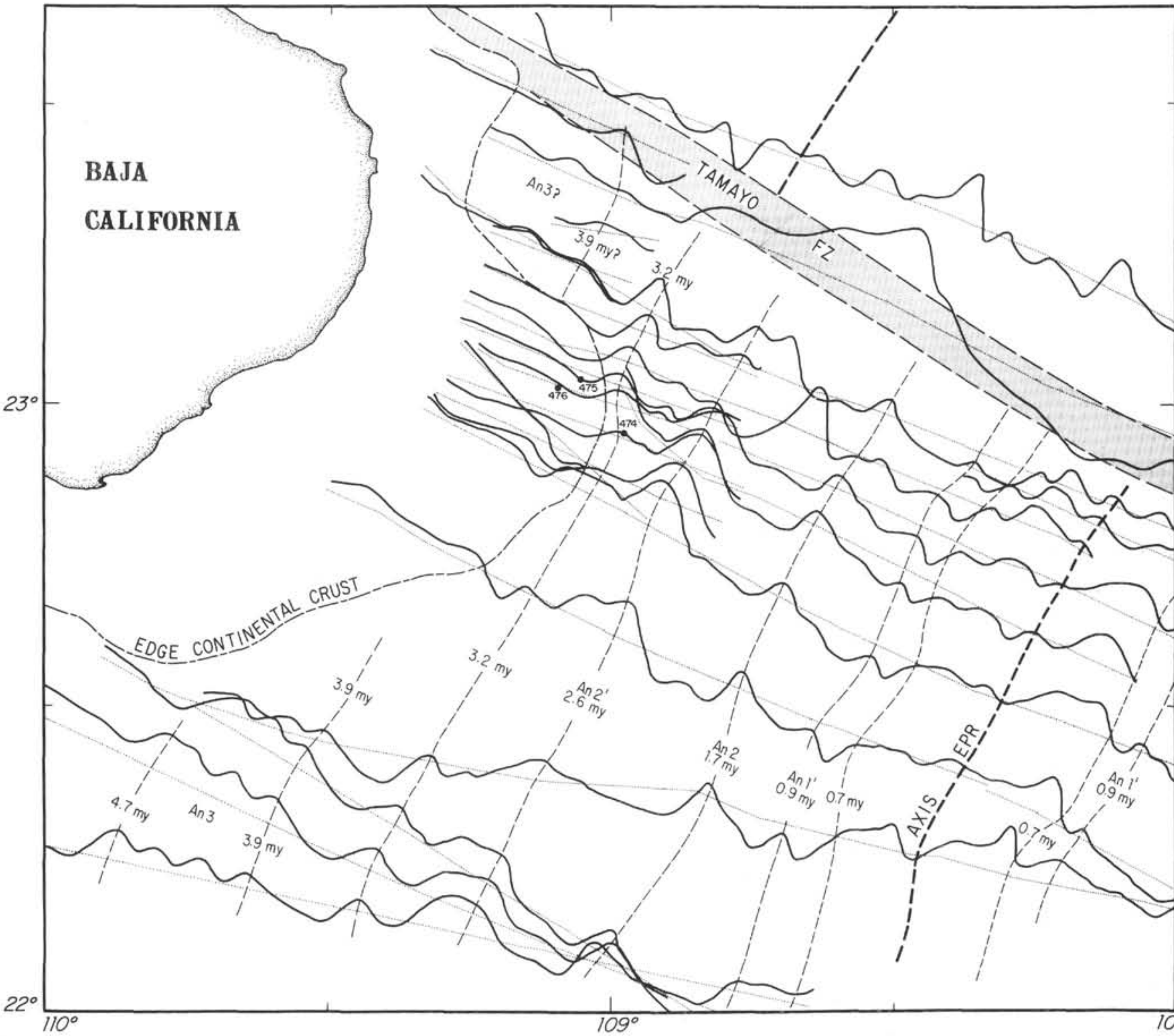

Figure 7. Magnetic anomalies (An) for selected survey lines. Data from Lewis et al. (1975) and unpublished SIO surveys.

sills and flows, with thin intercalations of sediment from the earliest stage of sea-floor spreading. We will consider this possibility in later discussions.

Sites 475–476

These sites share a similar overall stratigraphy that suggests parallel evolution. They can be roughly correlated within the diatomaceous hemipelagic muds on the basis of calcium carbonate content (see site chapter, this volume, Pt. 1). The basal hundred meters (Figs. 9 and 10) include enigmatic unfossiliferous conglomerates and an association of organic claystone, glauconite, phosphorite, and dolomite. We have used standard sediment petrologic methods to examine these samples for clues to their environments of deposition.

No datable nannofossils older than 3.7 m.y. were found at either site (Fig. 9), but the diatoms *Cosmiodiscus insignis* and *Nitzchia jouseae* were found at Site 476 in Core 19 at about 180 meters, giving an age of 4.4 to 4.5 m.y. (Schrader, this volume, Pt. 2). Extrapolations further back on the basis of expected accumulation rates of the basal series are compatible with this date and with $^{40}Ar/^{39}Ar$ and K/Ar dates on a rhyolitic ash bed (Fig. 16) and glauconite (M. Lyle, pers. comm.). These basal units will be described in more detail later.

Weathered Granite (Unit VI)

Site 475 did not penetrate to basement because of technical difficulties in the drilling, but Site 476 was successful in penetrating into granitic rocks. The probable base of the metamorphic cobbles (Unit V) and top of the granite was encountered at 256 meters, but in 29 meters of subsequent penetration we recovered only a little more than one meter of sample. We conclude, however, that this is a deeply weathered granitic terrain, perhaps in part "granite wash," or coarse arkosic sand

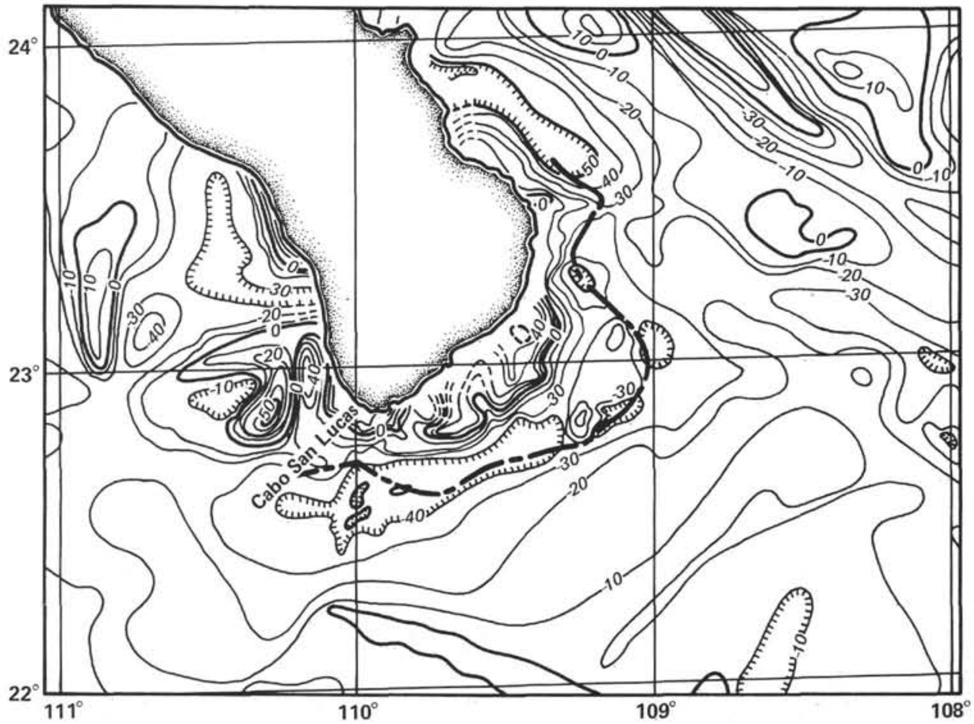

Figure 8. Free air gravity for the region. Reproduced from part of a compilation by Ness et al. (G. Ness, pers. comm., 1981). Values in milligals. Edge of continental crust shown from Figure 4.

overlying less weathered bedrock. The fresh samples recovered are a biotite- and hornblende-bearing, medium-grained, light gray granite with about 40% quartz (Saunders and Fornari, this volume, Pt. 2). It is probably very similar to some of the granites of Cabrillo Seamount, on land on Baja California, on the Tres Marias Islands, and on the mainland of Mexico at Cabo Corrientes (Fig. 1).

Metamorphic Cobbles (Unit V)

A conglomerate of polygenetic pebbles and cobbles forms the basal 65 meters above weathered granite at Hole 476 and constitutes a layer at least 40 meters thick above a basement that is presumed to be granitic at Hole 475. Definitive statements about these sediments are hindered by the extremely poor recovery: only a few pieces were retrieved for each 9 meters cored (Fig. 10).

We can conclude from the behavior of the drill string while drilling these conglomerates—frequent jamming, chatter, high pump pressures, sudden loss of circulation, and sudden thrusts—that the series comprises unconsolidated beds, some softer and with little or no fine-grained matrix. Some of the components may be boulder size, judging from the shape of some cored samples. Most specimens are crushed or broken by drilling, suggesting abundant sizes between 5 and 15 cm. The suite is characterized by a predominance of cobbles from a metamorphic source terrain, and includes compact lithologies from both metasediments and metavolcanics. The samples from Hole 475 are similar to Hole 476 but show more abundant volcanics. The rock types for numbered pieces are listed in Figure 10. Quartzites and metasiltstones are not particularly diagnostic of source areas, but welded tuffs (Fig. 11), metaquartz sandstones (Fig. 12), rhyolite, conglomerates, graywacke, and metabreccias (see site chapter, this volume, Pt. 1) are very similar to the rock suite we encountered in scattered land outcrops we visited during subsequent excursions along the southern perimeter of Baja California. These have been mapped (Fig. 4) as a Paleozoic metamorphic basement which was intruded by Cretaceous granite.

The few granitic pebbles encountered seemed highly weathered or altered (Fig. 13). Thus it is possible that these rocks may also occur in the sequence, but are underrepresented because they were crushed by the drill bit.

We encountered no evidence of cements, but did note traces of iron-hydroxide patina or staining. A single, thin, disturbed bed of plastic, light gray mud was recovered in Section 476-26-1, which consists almost entirely of well-crystallized illitic clay with minor kaolinite, such as might derive from granite weathering. It contains shattered fragments of clear quartz, probably from drill-crushed rock. We believe that the conglomerate of Unit V was a subaerial fluvial plain deposit, perhaps deposited by sheet floods at the mouth of large arroyos. Conditions of semiarid weathering similar to those existing today in the coastal areas of the region tend to decompose granitic components *in situ* while concentrating more compact lithologies downstream. The entire sequence could have been deposited during a very brief period, but subsequently a considerable time span must be assumed to have elapsed between subaerial deposition, separation from source areas, perhaps by faulting, and subsequent subsidence into an offshore environment protected from further clastic input. Many questions remain open and perhaps require a detailed

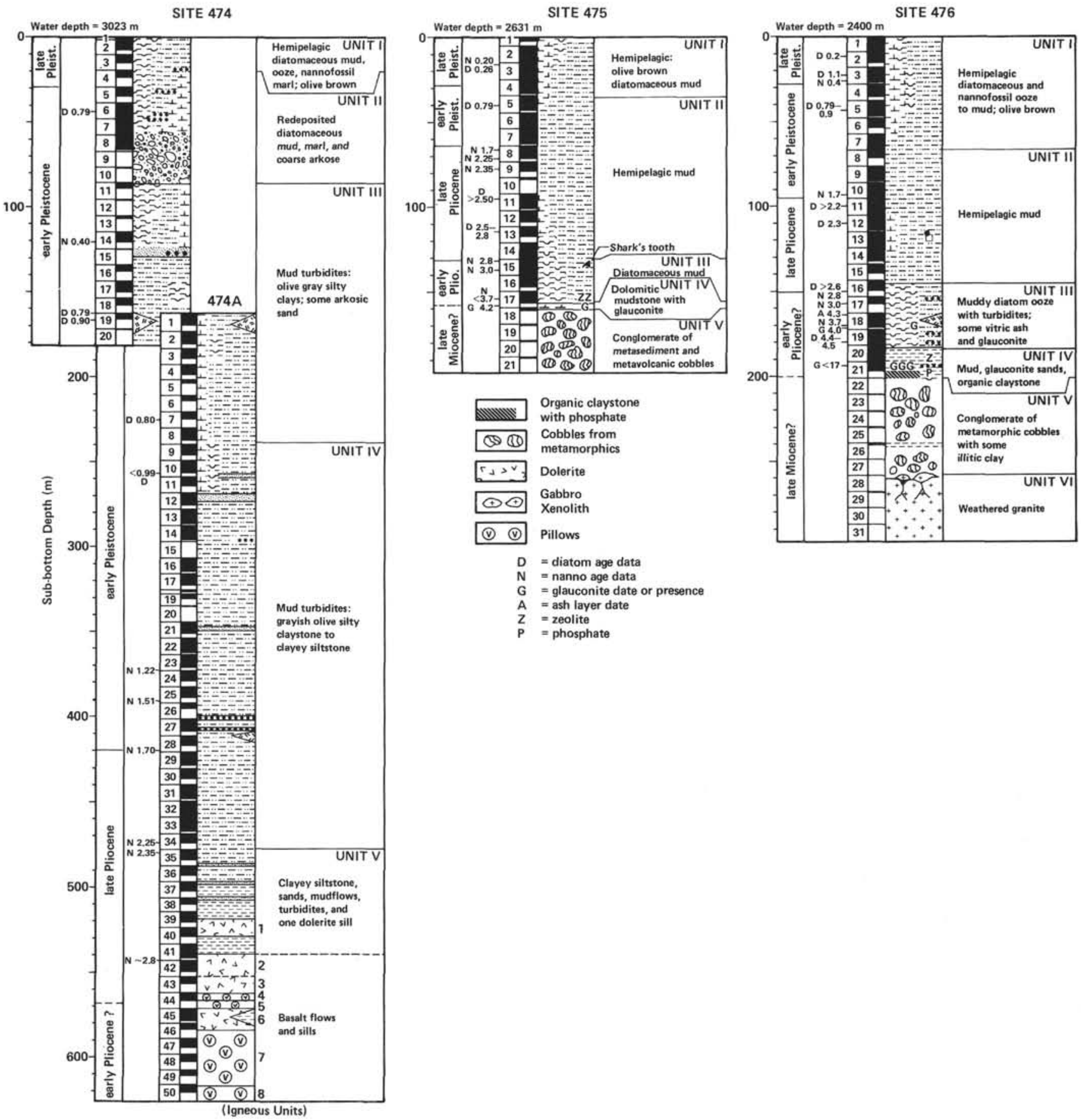

Figure 9. Simplified lithologic summaries for Sites 474, 475, and 476, with ages from biostratigraphic information (see site chapter, this volume, Pt. 1; Aubry, this volume, Pt. 2; and Schrader, this volume, Pt. 2). These columns have been revised from those of the site chapter.

correlation of the components with outcropping lithologies in the region. The age of the conglomerate is unknown, but we speculate that it may be late Miocene.

Some corroborating evidence is provided by a 10.2 ±2.1 m.y. $^{40}Ar/^{39}Ar$ date (Mitchell Lyle, pers. comm.) from a fresh basalt cobble recovered at shallow subsurface depths in Hole 475B, which did not penetrate to the cobble unit. The exact relation of this basalt to the conglomerate unit is unknown, but it may be associated with the postdepositional faulting phase. It is also possible that the cobble unit does not exist at the location of Hole 475B, and that the basalts could be older than the cobble unit (see site chapter, correlation with seismic, this volume, Pt. 1).

Unit IV

Petrological examination of the first glauconitic marine deposits recovered above the conglomerates at both Sites 475 and 476 confirm our interpretation of a period of slow accumulation in protected offshore environ-

Table 2. Bulk composition of some basal sediments from southern Baja margin transect.

Sample	Quartz[a]	Calcite	PLG	K-Fe	Clays	Other
474A-38-2, 15–17 cm Cemented sandstone	115	32	39	—	Illite asymmetric 18, kaolinite + chlorite 11	Mg-calcite shoulder
474A-41-3, 44 cm Sandstone	134	79	27	—	Minor illite, smectite	Dolomite 19, pyrite tr., cristobalite 10
475-11-6, 28–30 cm Hemipelagic mud	96	16	54	19	Mixed broad peak 11–14 Å	Clinoptilolite 9
475-13-2, 1 cm Hemipelagic mud	100	17	70	24	Broad illite, smectite, chlorite	Mg-calcite tr.
475-17-5, 11 cm Dolomitic mudstone	191	—	62	21	Broad illite 6, smectite–chlorite	Dolomite 32, pyrite 11, clinoptilolite 8
475-17-5, 115 cm Dolomitic mudstone	97	—	27	22	Broad illite 11, smectite–chlorite	Dolomite 34, pyrite 3, Mg-calcite 2, smectite–clinoptilolite 21, mixed feldspars
476-10-4, 125–127 cm Hemipelagic mud	87	6	66	17	Illite 19, chlorite–smectite	Clinoptilolite 7, pyrite tr.
476-21-4, 2 cm Phosphorite–glauconite crust	44	—	9	—	Broad asymmetric peak 8.7–10.0 Å	9.3 Å glauconite/apatite, collophane(?)
476-21-4, 16 cm Pyrite	32	—	—	—	—	Pyrite 132
476-21-4, 65 cm Black, laminated mudstone	181	—	56	—	Broad illite 9, chlorite 6	Pyrite 6

Note: Numbers are relative peak heights in mm. PLG is plagioclase, K-Fe is potassium feldspar.

ments. The thin dolomitic mudstone 156 meters subbottom at Site 475 is overlain by 2 meters of compact zeolitic mudstone and glauconite sands. At Site 476, a thin, glauconitic, pyritic, black, laminated claystone, rich in organic carbon and with phosphorite laminae (Fig. 15), is overlain by glauconite sand and about 10 meters of unfossiliferous zeolitic mudstone.

A. Dolomite

X-ray analysis (Table 2) shows that the dusky yellow, massive, burrowed bed (e.g., Sample 475-17-5, 11 cm) consists of a terrigenous quartz–feldspar–clay mixture with about 30% dolomite and accessory clinoptilolite and pyrite. Thin sections (Fig. 14) show that the dolomite occurs in the form of equigranular (20 μm) limpid rhombs as matrix (40%), supporting abundant pellets of glauconite and organic matter debris. Dark high-relief centers in these analyses show low iron content.

This dolomite above conglomerates has originated through early diagenesis in a low-oxygen environment, rather than in an evaporite-related setting. Textural evidence suggests it is an *in situ* cement. There is no sign of a precursor carbonate; nor is there any evidence for redeposition by mud flows. Carbon-13 isotopic values of −11.85‰ are clear evidence for a biogenic source of bicarbonate in conjunction with the breakdown of organic matter by metabolic sulfate reduction or oxidation (Kelts and McKenzie, this volume, Pt. 2). An oxygen-18 isotopic value of −3.90 could be interpreted as warm (25–30°C) marine water or as a signal from meteoric ground waters. This cannot be resolved from one sample, but we suspect a possible relationship with percolating hydrothermal waters from early rifting stages.

B. Glauconite

The glauconite occurs as unbroken rounded grains, some enclosing quartz–feldspar grains. Results of microprobe analysis are given in Table 3 (Mitchell Lyle, pers. comm.). The uniform composition of the glauconite suggests a single source.

Dates were run on some of the glauconites by Mitchell Lyle (pers. comm.). Samples from Core 475-17 gave 4.2 m.y. and from Core 476-18 gave 4.0 m.y. A sample from Core 476-21 yielded an apparent age of 17.7 m.y., but the gas release pattern suggests that it may have adsorbed old Ar released by alteration of the underlying granite. Its real age of formation is probably nearer to 5 m.y.

C. Organic Claystone

In Hole 476 we did not encounter dolomitic beds, but the 50 cm of laminated claystone, rich in organic matter and laced with glauconite and pyrite framboids or concretions (Fig. 15A, B), occur at a stratigraphically equivalent level and are rich in quartz silt. Niemitz (this volume, Pt. 2) registered a significant phosphate anomaly within this bed, as well as MgO and FeO enrichment (pyrite and dolomite?). A K_2O anomaly derives from glauconite. A 2 mm-thin, chestnut-colored, transparent, brittle lamina (Sample 476-21-4, 2 cm) consists of hydroxy-apatite. The fracture-surface microtexture of this piece (Fig. 15C) is curiously botryoidal, although energy-dispersive X-ray analysis confirmed that it is phosphorous-rich. Possibly this is evidence of a very shallow, early diagenetic precipitate.

This curious organic claystone has a petroliferous odor and contains up to 7.5% organic carbon, including many blue-green algal threads. The organic geochemical signatures indicate an uncommon mixture of marine algal and terrigenous sources such as might be found in lagoonal or shallow offshore, low-energy environments (Kendrick, this volume, Pt. 2; Simoneit et al., this volume, Pt. 2). A lack of associated carbonate would seem to preclude the first possibility.

D. Glauconite Sands and Firm Zeolitic Clays

Muddy to well-sorted sands of loose glauconite pellets and quartz grains occur as discrete beds up to 2 meters thick at both Sites 476 and 475. Benthic foraminifers are rare. In part, these seem graded, but some sorting during flushing of the drill hole is possible, since drilling disturbance is excessive in these firm clays. We suspect, however, that the glauconite sands are lag deposits. Sporadic horizons with glauconite continue up-

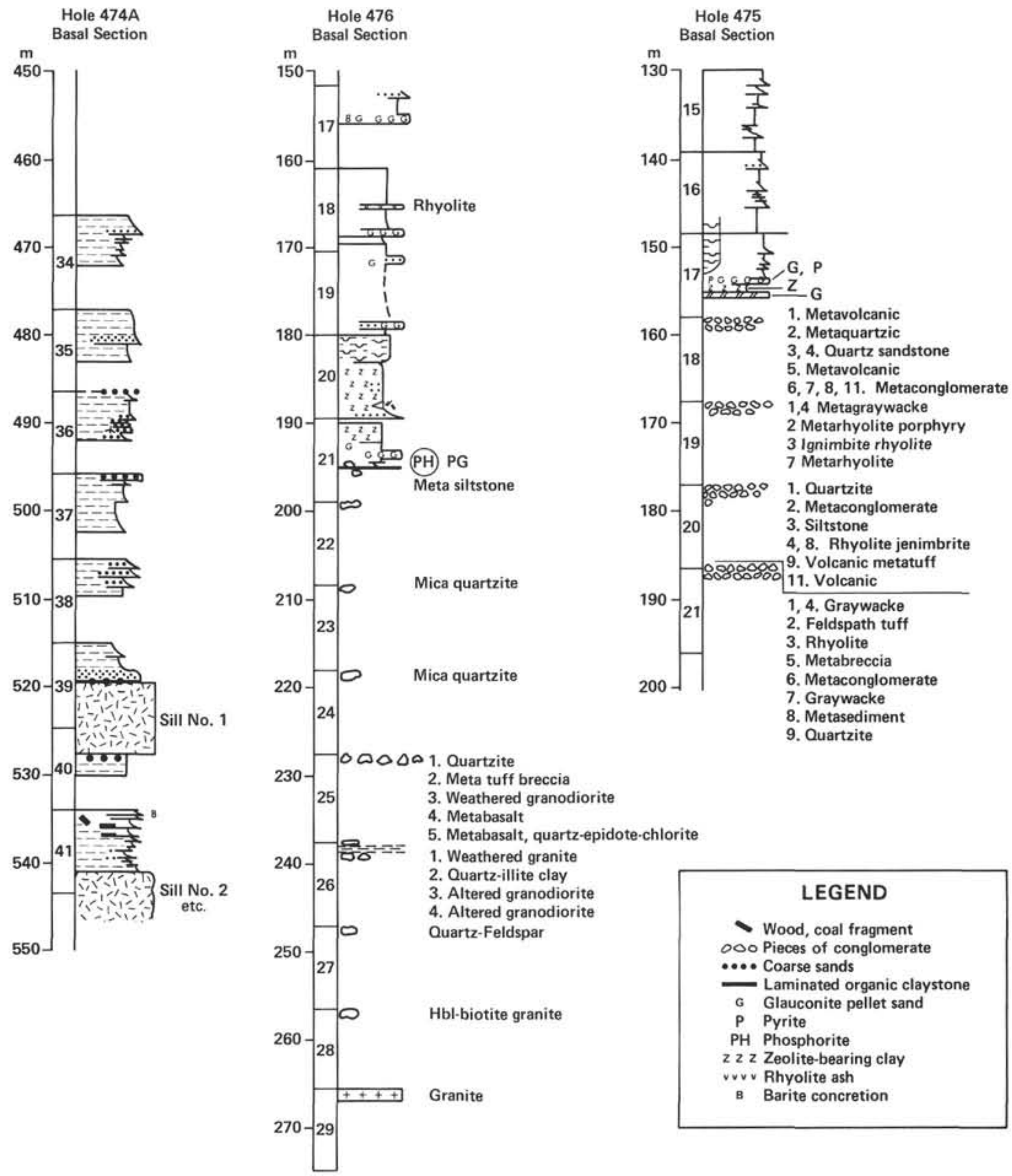

Figure 10. Detailed core lithology of basal sediments at Sites 474, 475, 476. Rock type is listed for each pebble recovered in Unit V.

section for several meters in a sequential fashion. The unfossiliferous, firm, brown clay to claystone associated with and overlying the thickest glauconite beds, for example Cores 476-20 and 21 or Sections 475-17-1 to 475-17-3, are noncalcareous and are characterized by abundant scattered, small (~ 10 μm) zeolite crystals identified as clinoptilolite (Fig. 15D). These sediments show rhythmic patterns of color grading but not size grading. Little is known about the possible rates of formation associated with the early diagenesis of sediments rich in biogenic silica, such as the diatomaceous muds immediately overlying this lithologic unit.

E. Glauconite-Phosphate-Dolomite Association

Phosphorite is found in modern environments along coastal margins associated with intense upwelling, such as offshore from the west coasts of North and South America (see, for example, Emery, 1960). Such areas commonly have laminated sediment, rich in organic matter, in a zone of intersection of an oxygen minimum caused by high productivity in surface waters. Phosphorites may form at either the upper or lower boundary, but in our situation an association with glauconite suggests depths of less than a few hundred meters. Glauconite and diagenetic dolomite are also closely associated with modern phosphorites, although usually in more mildly reducing environments. Their co-occurrence suggests fluctuating paleoceanographic conditions.

Combining the lithologic evidence, we interpret the Unit IV sequence as evidence for deposition on an isolated offshore bank at a depth of 100–400 meters, within an oxygen-minimum zone beneath an active upwell-

Figure 11. Thin section photomicrograph, crossed nicols, Sample 475-20-1, 11 cm, ocher-colored welded tuff with anhedral and euhedral quartz, plagioclase, and K-feldspar phenocrysts in fine groundmass.

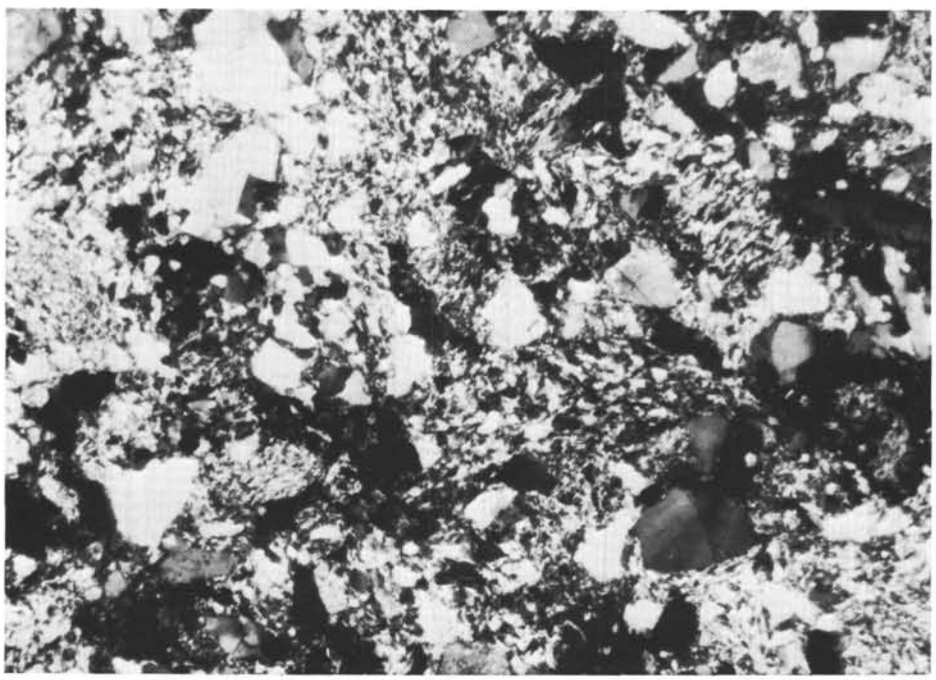

Figure 12. Thin section photomicrograph, crossed nicols, Sample 476-23,CC. Coarse metasandstone with stressed quartz, serrated relicts, and plagioclase in a micaceous matrix.

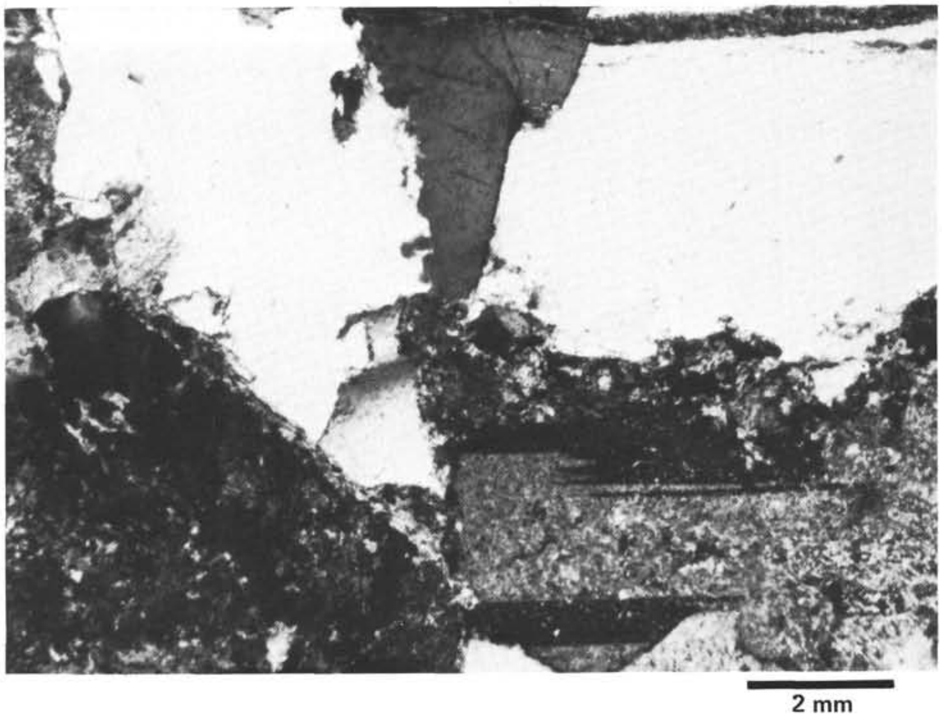

Figure 13. Thin section photomicrograph with crossed nicols, Section 476-25-1, Piece 3, altered granodiorite with large clear anhedral quartz, K-feldspar (dark), and altered plagioclase with partial sericitation. Very little mica. Some other pieces show cataclasis.

ing zone. This bank or terrace must have been protected from influx of terrigenous sediments. There is evidence for a sequential development, gradually more oxic for the zeolitic clays, with intermittent episodes of winnowing which concentrated glauconite sands. Eventually the site subsided below the zone for glauconite formation.

It is difficult to estimate the duration of this phase of the margin evolution. A gray ash layer with very fresh-looking rhyolite shards occurs at 165 meters (Sample 476-18-3, 135 cm; Fig. 16). Dates on this ash layer (M. Lyle, pers. comm.) of 4.38 m.y. by K/Ar and of 4.30 m.y. by $^{40}Ar/^{39}Ar$ are compatible with other age information (Fig. 9). The slow accumulation rates common when glauconite–phosphorite–dolomite associations occur can be used to argue that the few meters in Holes 475–476 represent at least a million or more years.

Units III, II, and I

These units consist predominantly of diatomaceous hemipelagic muds, deposited in a subsiding continental slope environment. The lower parts of Section III contain decreasing amounts of glauconite and zeolitic clays (Figs. 9 and 10).

Since preparation of the site chapter for this drilling transect, new information has become available through studies of the foraminifers at Site 475 by James C. Ingle (pers. comm., 1982). He evaluated the benthic biofacies, the proportion of low-oxygen foraminifers, the percentage of displaced shallower-water species, and considered the evidence for subsidence of this site.

No foraminifers are present below about 140 meters (Core 16 in Unit III). The first forams that are found above this level are of a shelf and upper bathyal facies, with a very high proportion of low-oxygen indicators. At about 135 meters, or Core 15, there is an abrupt increase in the proportion of upper bathyal facies, which Ingle marks as a questionable unconformity. Aubry (this volume, Pt. 2) also suggests a brief hiatus at this level at both Sites 475 and 476. By about 107 meters sub-bottom (Core 12), the low-oxygen indicators are absent, a very high proportion of displaced foraminifers is present, and the fauna is predominantly middle to lower bathyal. At this level is the first appearance of *Melonis pompiloides*, a lower bathyal foram with a minimum depth of about 1500 meters. Thus, by about 2.5 Ma the site had subsided to almost its present depth of water. Ingle also noted a pulse of displaced foraminifers at about 25 m, which would appear to correlate the time of the debris flow in Site 474.

Summary and Rates of Accumulation and Subsidence

Rates of accumulation of sediment for Sites 474, 475, and 476 are illustrated in Figure 17. These compilations are different from those in the site chapters; they are based on additional information and on the reconsideration of absolute age assignments to some of the biostratigraphic zones. Correlation between rates of accumulation and environments of deposition at these three sites will be considered briefly here, but correlation with tectonics and the geological history of the opening of the Gulf of California will be discussed more fully in the following section. Subsidence curves (Fig. 18) will also be considered briefly here and again in the following section.

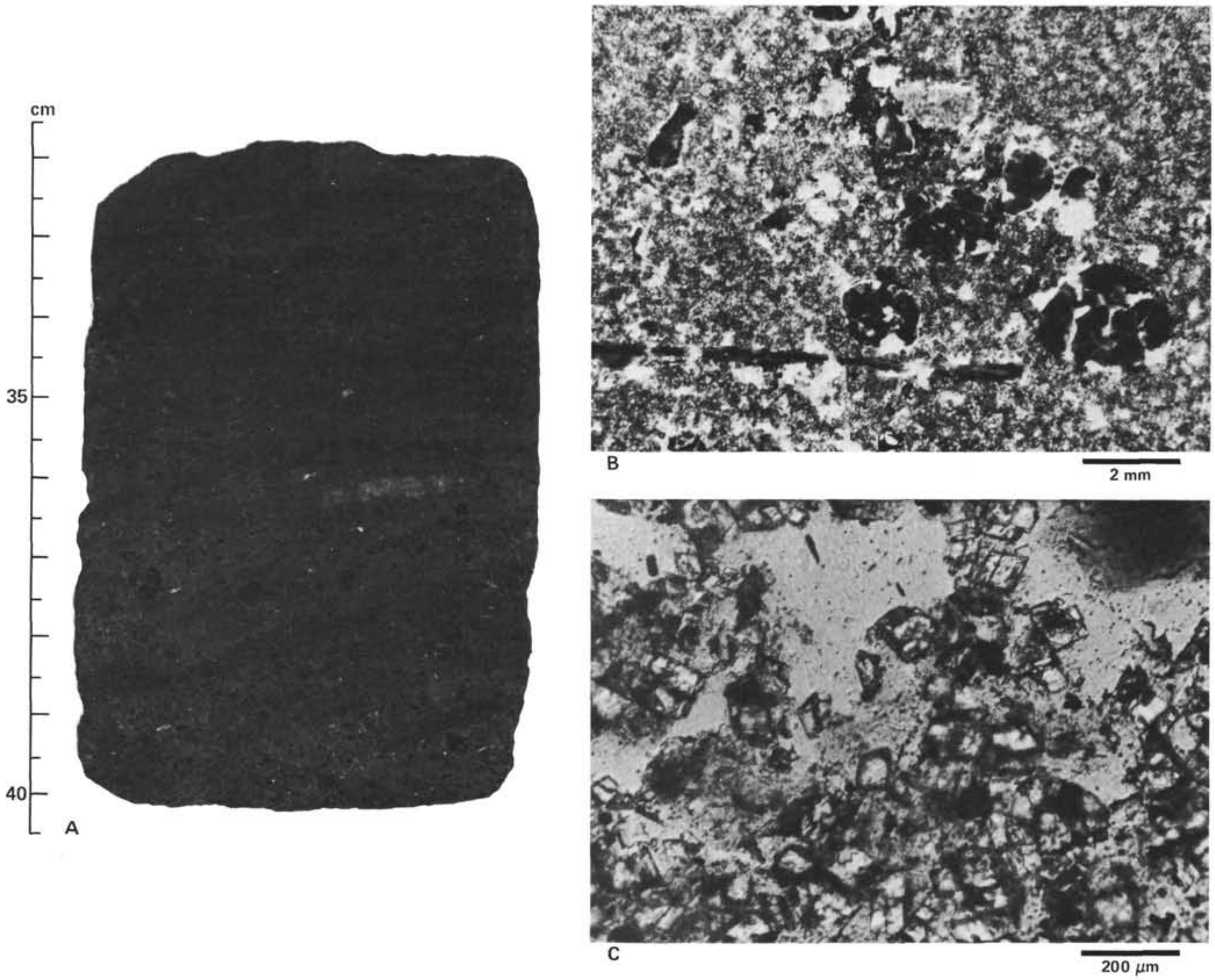

Figure 14. Basal dolomitic mudstone with glauconite pellet clasts, Site 475. A. Macroscopic view of slab, Sample 475-17-5, 30–40 cm. B. Thin section photomicrograph, Sample 475-17-5, 121 cm, crossed nicols, green glauconite pellets, quartz, silt, and a long piece of lignin set in a micritic matrix of dolomite. C. Detail of matrix with equant, limpid dolomite rhombs, some with dark centers.

Sediment accumulation started during and following emplacement of the pillow basalts recovered at the base of Hole 474A. We can only speculate on the nature and significance of the stratified section underlying the base of this hole, but we suggest that interstratified sills and flows might contain thin intercalations or pockets of sediment dating back to the time that sea-floor spreading began at this site, 3.2 Ma. Following emplacement of the last sill, mud turbidites accumulated at a modest rate of 100 m/m.y. The data points suggest a significant increase in rate at about 1.25 Ma. This may really correlate with the early Quaternary fluctuations of sea level and better development of the submarine canyons existing off the cape. These canyons may, in fact, have existed prior to this time as subsided subaerial canyons, but lowered sea level apparently significantly increased the amount of sediment transported through them. We assume that emplacement of the debris flow, Unit II, Figure 17A, took place essentially instantaneously on this time scale, at about 0.5 Ma. The subsequent rate of accumulation has been slow and very nearly the same as at Sites 475 and 476.

Sites 475 and 476 show very similar histories for the rate of accumulation of sediments. We have no way of knowing when or at what rate the fluvial outwash cobbles accumulated, but we have shown termination of this phase as about 5.5 Ma, the time when we believe the plate edge between the Pacific and North American plates entered the mouth of the Gulf and jumped inboard of the present Peninsula. At this time, rifting and diffuse extension were initiated (Moore and Curray, this volume, Pt. 2), and subsidence of this environment below sea level must have occurred immediately. These sites then subsided through the surf zone, probably as erosional or nondepositional areas. By about 4.5 Ma, they had become isolated offshore banks, and zeolitic clays, glauconite, dolomite, and phosphorite started accumulating. Along this particular transect, organized sea-floor spreading had not yet started, and only rifting and thinning of continental crust were occurring. Laterally,

Table 3. Glauconite analyses (Sample 475-17-5, 11 cm).

Element	G3 (wt.%)	G4 (wt.%)	G5 (wt.%)
Fe_2O_3	21.6	20.3	19.22
SiO_2	54.2	54.8	51.59
MGO	4.15	4.09	4.76
MnO	0.04	0.04	0.05
K_2O	7.45	5.50	6.68
Al_2O	5.14	6.33	7.04
Na_2O	0.11	0.11	0.08
CaO	0.17	0.14	0.30
Total[a]	92.90	91.35	89.75

[a] Typical glauconite water content is 8%.

The approximate compositional formulas are thus:

G3 $(K_{1.341}\ Ca_{.025}\ Na_{.025})\ (Mg_{.875}\ Al_{.513}\ Fe_{2.55})\ (Al_{.34}\ Si_{7.66})\ O_{20}(OH)_4$

G4 $(K_{.989}\ Ca_{.021}\ Na_{.024})\ (Mg_{.857}\ Al_{.774}\ Fe_{2.39})\ (Al_{.278}\ Si_{7.722})\ O_{20}(OH)_4$

G5 $(K_{1.237}\ Ca_{.047}\ Na_{.025})\ (Mg_{1.03}\ Al_{.695}\ Fe_{2.334})\ (Al_{.511}\ Si_{7.489})\ O_{20}(OH)_4$

however, both to the northeast and southwest, sea-floor spreading was occurring, and lineated magnetic anomalies were generated (Fig. 7). By about 4 Ma, these offshore banks were too deep for accumulation of glauconite. Organized sea-floor spreading started along this transect at about 3.2 Ma, and the rate of subsidence probably increased. At about the same time, the rate of sediment accumulation increased at both of these sites, but in both a brief hiatus at about 3 Ma (Aubry, this volume, Pt. 2 and by J. Ingle [pers. comm., 1982] for Site 475) could mark a period with increased exposure to tidal currents as the Gulf was developing. Subsequently, the rate of accumulation of hemipelagic slope facies sediments increased at both of these sites for the next 0.5 to 1 m.y. A decrease in rate occurred at approximately 2.25 Ma in both sites. The timing of this decrease is not well constrained, and it could represent establishment of a Quaternary pattern of distribution of sediments. More sediment was transported through submarine canyon conduits and less reached the continental slope. Shelves were wider as a result of Pleistocene fluctuations in sea level. These modest rates of accumulation, very nearly the same as subsequently developed at Site 474, continued apparently to the present day.

Modern equivalents of the depositional environments of all varieties of basal lithologies occurring in these Baja California margin transect sites can be found in nearby localities. An exception is, perhaps, the thin zeolite-bearing clays from Unit IV of Sites 475 and 476. If these are a diagenetic feature from dissolution of diatom frustules, then we do not have a satisfactory explanation for the abrupt transition to overlying diatom muds. They may correlate with the brief hiatus described above, or else these muds indeed represent a long period of very slow accumulation of clay at intermediate water depths.

Subsidence curves are shown for Sites 474, 475, and 476 in Figure 18. Because benthic foraminifers were examined only in Site 475 samples, our evidence of paleodepth is rather tenuous and indirect in the other sites. The parts of Figure 18 older than about 5.5 Ma will be discussed later. It appears that Sites 475 and 476 started at approximately sea level at about 5.5 Ma, at the termination of the time represented by deposition of the cobble conglomerate. These sites lay in shallow water and shelf depths and gradually subsided to become isolated offshore banks with deposition of the glauconites, phosphorites, and zeolitic clays. By the time when the drilling record at Site 474 begins, approximately 3 Ma, subsidence was presumably rapid. As indicated by the benthic foraminiferal record, all of these sites must have attained nearly their present depth by about 2.5 Ma, or shortly thereafter.

GEOLOGICAL HISTORY

The geological information on land, the structural information from geophysical surveying, and the environmental interpretations of the drilling data appear to be compatible with many features of the commonly accepted models of the rift origin of passive continental margins discussed previously. We present such a scenario in section and in plan views in Figures 19 and 20, respectively, and a compilation of subsidence and rates of sediment accumulation in Figure 18. The scenario of geological history is illustrated on interpreted structure from the line drawing of Figure 5A of the multichannel seismic reflection profile across the margin, extended on shore across the cape block. The reconstructions in plan view approximately match those of Moore and Curray (this volume, Pt. 2).

Rifting, Diffuse Extension, Sea-Floor Spreading, and Drifting

Most commonly accepted scenarios for formation of rift-origin segments of continental margins identify separate and distinct stages of rifting and drifting, with preceding and sometimes overlapping volcanism and doming. It is clear from studies of many passive margins, however, that these distinct and separate stages are not always present, nor is the time relation always consistent between the volcanism, doming, and rifting stages.

One of the anomalous features of many passive continental margins is the existence of a magnetic quiet zone, or area of the sea floor adjacent to the margin, without correlatable lineated magnetic anomalies. Various explanations have been offered, usually *ad hoc* to the margin being studied. Cochran (1981a, b) has recently offered an explanation of the magnetic quiet zone bordering the Gulf of Aden that, he suggested, can be extrapolated to other margins, including the Gulf of California. His concept of "diffuse extension" envisions stretching of continental crust as the principal mechanism of diffuse extension and creation of an "ocean floor" without existence of lineated magnetic anomalies. As a secondary mechanism he invokes the extension of original continental crust by injection of dikes, an old concept recently revived by Royden et al. (1980) for a quantitative treatment of continental mar-

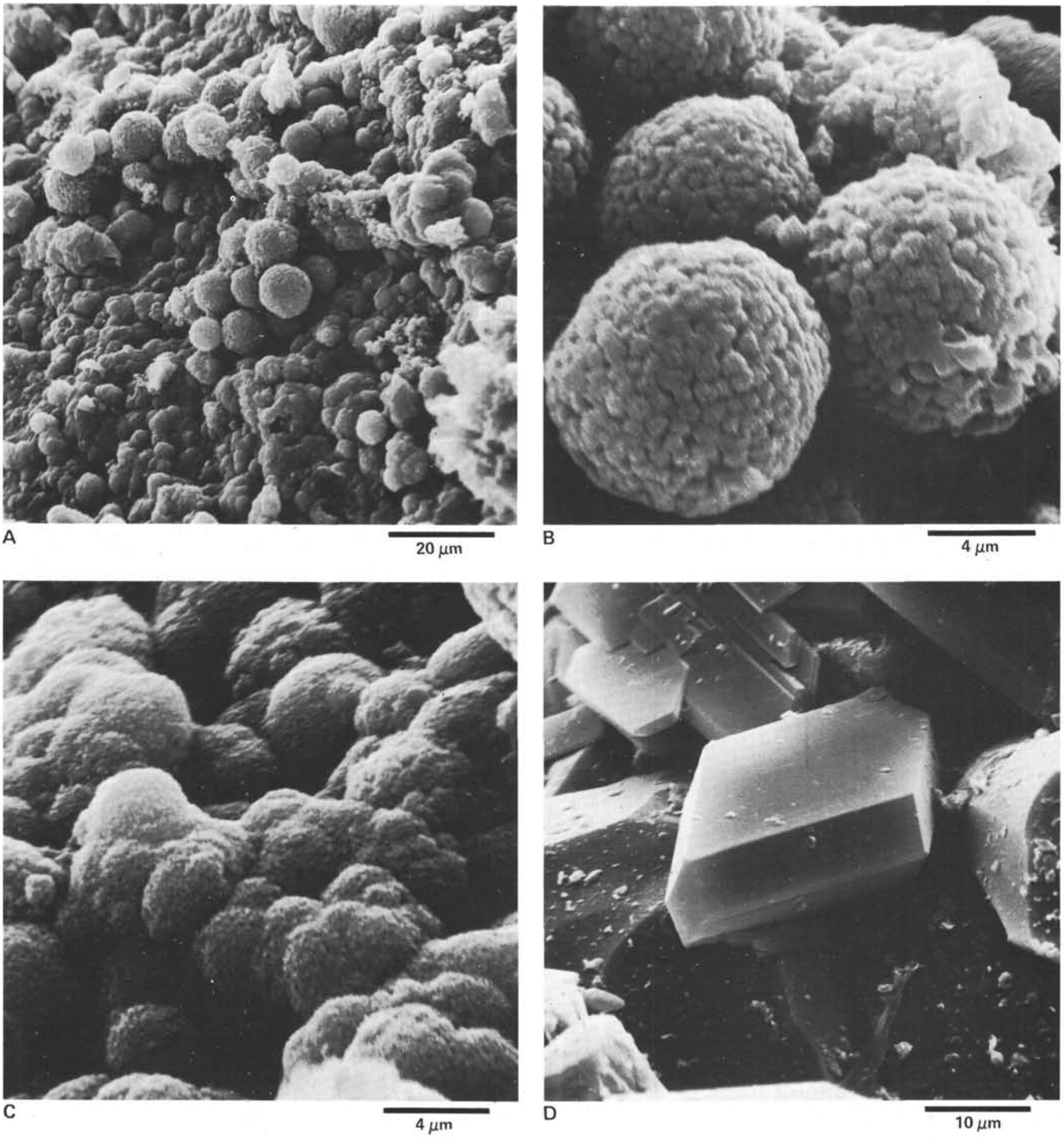

Figure 15. Scanning electron micrographs for basal organic claystone from Core 476-21. A, B. Sample 476-21-4, 2 cm. Pyrite framboids from the broken surface of a concretion. C. Sample 476-21-4, 2 cm. Broken surface of a brittle phosphorite lamina shows botryoidal microtexture. D. Sample 476-21-4, 16 cm. Clinoptilolite and several other authigenic phases.

gin subsidence. Based in part on our experience with Leg 64 drilling in the Gulf of California, we envision four different mechanisms of diffuse extension (see also Moore and Curray, this volume, Pt. 2):

1) block faulting and listric normal faulting and/or ductile stretching and thinning of continental crust (Cochran's principal mechanism);

2) dike injection (Cochran's secondary mechanism and Royden et al.'s mechanism), or in the extreme, slivering of continental crustal fragments between zones of newly generated ocean crust with uncorrelatable magnetic anomalies;

3) generation of new ocean crust in an environment where deposition rates are high by dike and sill injection

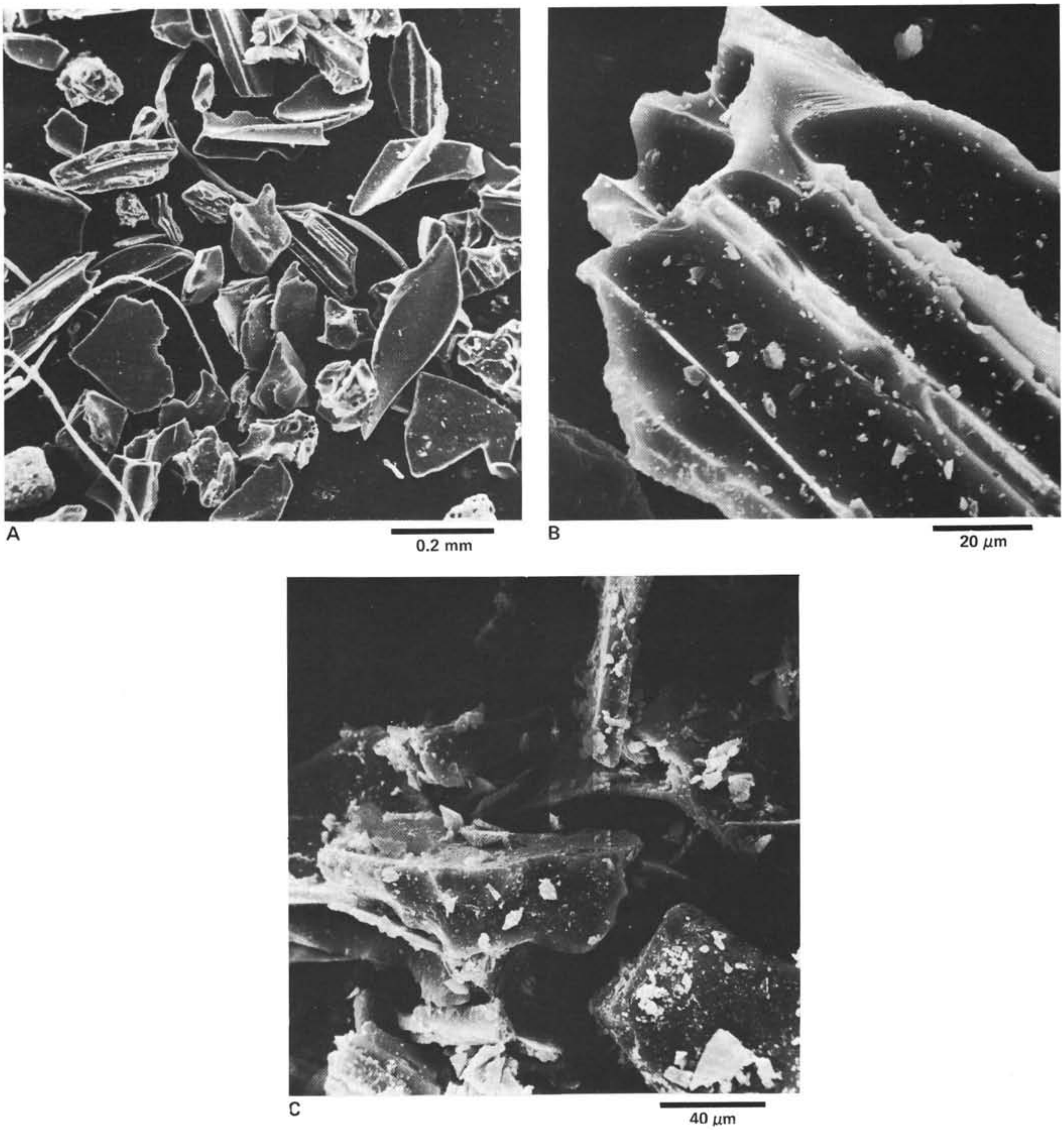

Figure 16. Scanning electron micrographs from rhyolite ash beds. A, B. Sample 476-18-3, 135 cm. Overview and detail of unaltered shards radiogenetically dated as 4.2 m.y. C. Sample 479-18-1, 80 cm. Altered rhyolite shards from late Pleistocene diatom oozes of Site 479 for comparison.

into soft, young sediments, without creation of lineated magnetic anomalies (the Guaymas Basin mechanism);

4) generation of new ocean crust with magnetic anomalies that are uncorrelatable because of frequent short-distance rearrangements of the plate edges. This is the mechanism Sharman (1976) invoked for some of the basins of the Gulf of California.

Of these four processes, we suggest that there exist examples of at least Types 1 and 2 within the mouth of the Gulf. Stretching of continental crust by normal faulting and possibly also by ductile stretching of the lower crust (Type 1) is the principal mechanism for thinning of the crust beneath the continental slope of the transect studied in this chapter, but dike-injection ex-

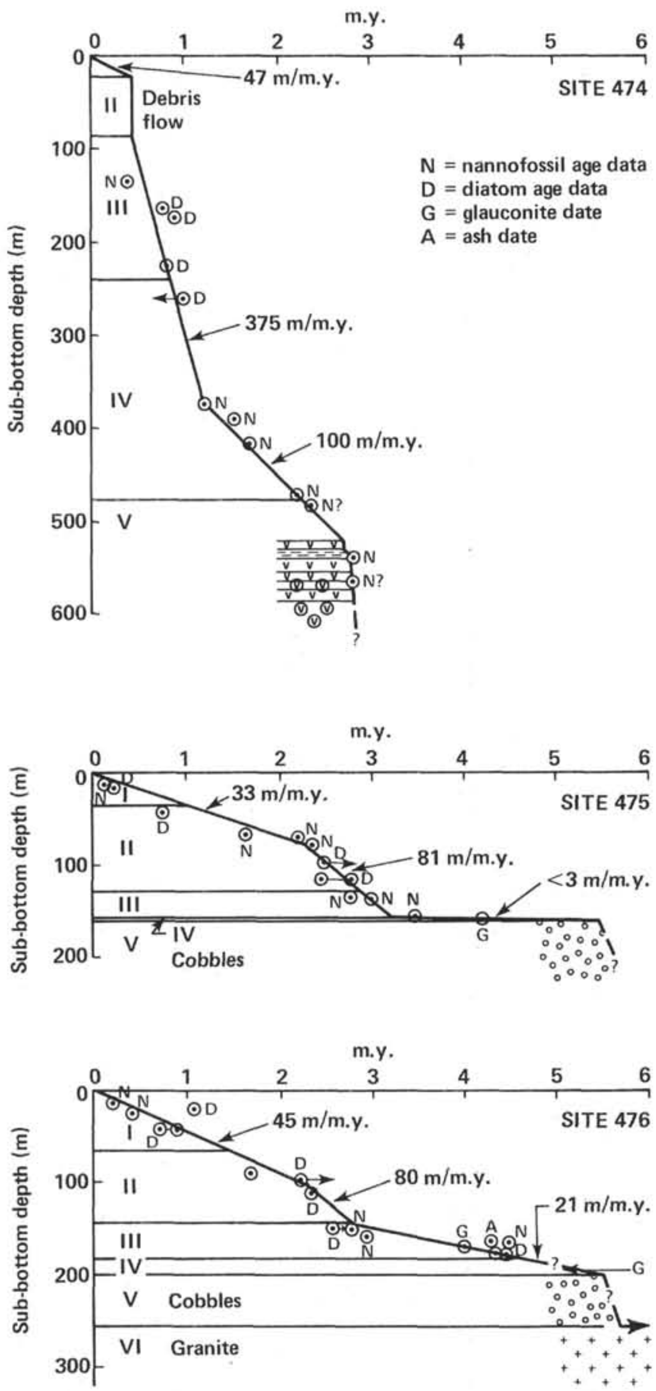

Figure 17. Rates of sediment accumulation, Sites 474, 475, and 476, as revised from site chapter (this volume, Pt. 1) by addition of new data.

tension must also have occurred. The region southeast of the 3.5-m.y.-old magnetic anomaly on the southeast flank of the East Pacific Rise, the Maria Magdalena Rise (Fig. 20E), is, we believe, an example of Type 2. This region was described as proto-Gulf by Moore and Buffington (1968). Subsequently, Ness et al. (1981) correlated magnetic anomalies in that region, but other workers (see, for example, Mammerickx, 1980, and Klitgord and Mammerickx, in press) have not accepted those correlations. As we will explain later, we believe that this may represent an area of stretched, thinned, former continental crust heavily injected with dikes and perhaps broken into slivers, surrounded by younger oceanic crust, and subsided to nearly oceanic depths.

Thinning of continental crust has long been a part of explanations for the origin and subsidence of continental margins. Many specific mechanisms have been suggested: subcrustal erosion; supracrustal erosion; tensional or extensional faulting, by either listric down-to-the-basin faults or horst and graben faults; dike injection; and ductile stretching, flowing, or "hot creep." In addition, subsidence has also been attributed to alteration of the density of continental crust by dike injection or subcrustal metamorphism caused by the thermal anomaly which underlies the incipient margin. With the exception of subcrustal erosion, all of these mechanisms and others not listed are still generally considered as parts of the overall process of subsidence of continental crust. Recently, McKenzie (1978) and Le Pichon and Sibuet (1981) have dealt with the problem of thinning and subsidence more quantitatively. If the surface area of a unit of continental crust is increased by a factor β, the crustal thickness will be reduced by that same factor. Rates and amounts of subsidence can then be calculated on the basis of various assumptions of thermal conditions. Estimates of the value of β for the northern Bay of Biscay continental margin may exceed 3 (Le Pichon and Sibuet, 1981), and estimates for the Gulf of Aden (Cochran, 1981b) are as high as 3.5.

The thickness of the continental crust at the isthmus of the Peninsula of Baja California west of La Paz has been estimated from gravity calculations at about 21 km (Huehn, 1977). No information exists for the thickness of the thinned crust in the transect area in the vicinity of Sites 475 and 476. Le Pichon and Sibuet (1981) and Le Pichon et al. (1982) suggest the relationship

$$Z = 3.6\ (1 - 1/\beta),$$

where Z is the amount of subsidence. Applying this to the region of Sites 475 and 476 would suggest a β value as high as 4. Rates of subsidence are, however, much more rapid than those calculated by McKenzie (1978) and Sawyer et al. (1982). The evidence for extension of continental crust by mechanisms other than just stretching is, however, very strong. The dredge hauls (Table 1) collected by Shepard (1964) and others show the presence of large quantities of basalt in what we have mapped as continental crust (Fig. 4). Dike injection must have been an important part of the process of extension of continental crust here.

Lacking other information, we suggest that the continental crust near Sites 475 and 476 in the transect area may have been extended by a factor of at least 2 and perhaps more. This estimate has been used in the diagrams of Figures 19 and 20.

Scenario of Geological History

A. Middle Miocene, before 12.5 Ma

The scenario starts (Figures 19A and 20A) in middle Miocene time before about 12.5 Ma, before the existence of a marine embayment overlying the present site

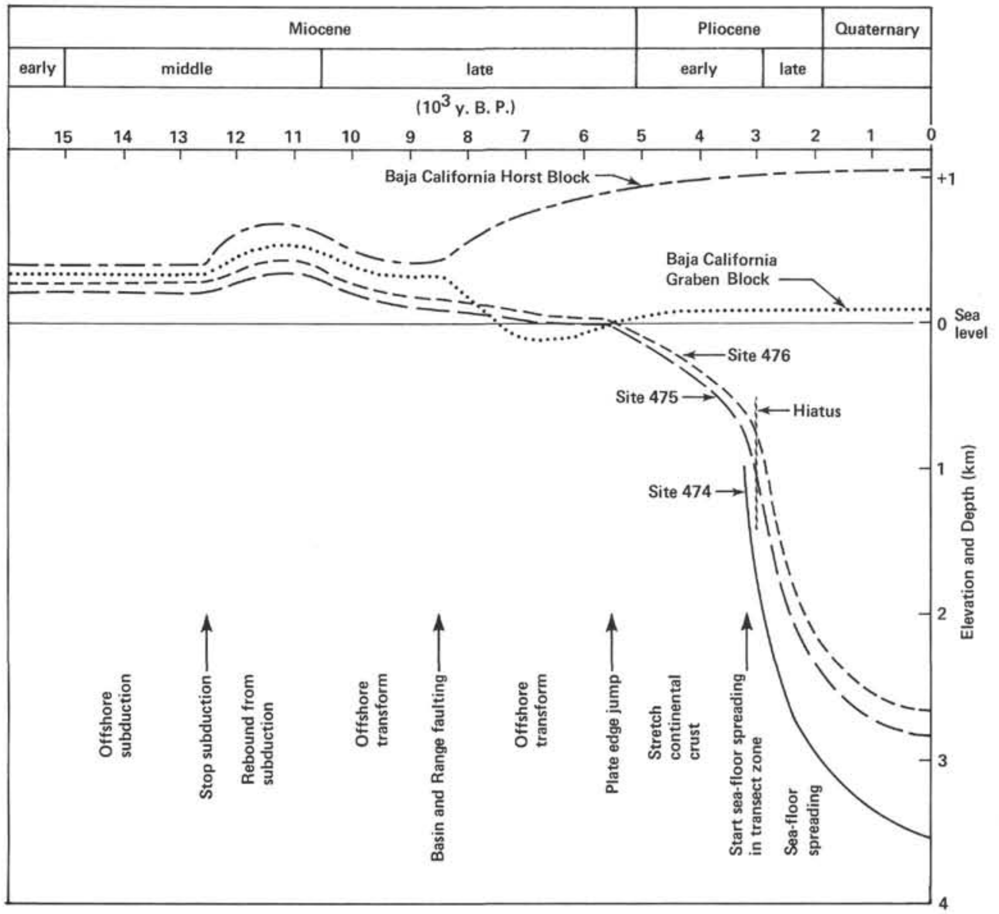

Figure 18. Rates of subsidence.

of the Gulf. A subduction zone lay at the foot of the continental slope west of Baja California where the young Farallon Plate was being subducted beneath the North American Plate. Andesitic volcanism was probably still occurring approximately along the present axis of the Gulf of California, although the main episode of andesitic volcanism along that alignment was from about 22–17 Ma (Gastil et al., 1979). The apparent decrease in subduction-related volcanism may have resulted from the close proximity of the spreading axis offshore and subduction of very young sea floor. The Cretaceous batholithic terrain, the roots of Mesozoic subduction-related volcanism, lay seaward of the active volcanism at the time. This Cretaceous granite now crops out in the Peninsular Ranges of Baja California, in the Tres Marias Islands, and on the mainland coast of Mexico near Cabo Corrientes (Fig. 1). Basin and Range extension was occurring in the western United States, perhaps in response to a slab window mechanism (Dickinson and Snyder, 1979).

The reconstructions of Figures 19 and 20 accept recent evidence for approximately 300 km of offset along the San Andreas Fault system in Southern California (see, for example, Matthews, 1976; Crowell, 1981; and Ehlig, 1981) and 300 km of total opening of the Gulf of California (Gastil et al., 1981). Problems of other related faults to the west and the problem of a proto-San Andreas (i.e., Cretaceous and Paleogene) are not considered here. The 300-km offset along the San Andreas and opening of the Gulf are compatible with data presented here and appear to create satisfactory reconstructions.

Timing of this 300-km/offset is perhaps less precise. We have assumed that it has occurred in the last 5.5 m.y. Estimates from study of the San Andreas Fault in Southern California (Crowell, 1981, and Ehlig, 1981) do not constrain that total offset into quite so short a period: they infer that it has occurred within the last 8–10 m.y. Our estimate of 5.5. m.y. appears to be more compatible with the history of the Gulf, especially considering results from study of this passive margin transect, than these longer time estimates.

The problem of finding the conjugate margin has been mentioned previously. All models for rift origin of a passive continental margin involve intracontinental rifting and drifting apart of pre-existing continental crust, resulting in the creation of two passive continental margins. Restoration of the Peninsula of Baja California toward the mainland of Mexico, however, results in both geologic and geometric problems (Moore and Curray, this volume, Pt. 2). The best reconstruction we can make is constrained by the bathymetric trends of transform faults, some of which may mark the edge of continental crust, and which appear to have formed early in the rifting and/or drifting stage of the formation of the Gulf. Reconstruction cannot violate these transform fault trends. The reconstruction we suggest (see also Moore and Curray, this volume, Pt. 2) brings the tip of the Peninsula of Baja California adjacent to the Tres Marias Islands block off the mainland coast of Mexico. This restoration leaves us with the problem that the conjugate margin of continental crust cannot be confidently identified. Several possibilities exist. First, could this be a situation where no conjugate margin existed immediately prior to the rifting and drifting stages? Second, could the continental terrain of the conjugate margin have gone into the subduction zone off the Tres Marias Islands? Third, could this reconstruction be totally erroneous, with the tip of the Peninsula of Baja California belonging either farther to the southeast, adjacent to the continental margin off Cabo Corrientes, thereby exceeding the 300-km maximum opening of the Gulf, or farther to the east, lying north of the Tres Marias Islands, thereby violating the constraint of transform fault escarpments? Fourth, could the conjugate margin continental block still be present in the area to the southeast of the tip of the Peninsula and the present East Pacific Rise, broken up and subsided to almost oceanic depths as the Maria Magdalena Rise? As will be explained later, we favor this last solution.

B. Late Miocene, 2.5–5.5 Ma

By about 12.5 Ma (shown at 8 Ma in Figs. 19B and 20B), subduction had ceased (Klitgord and Mammerickx, in press), and the plate edge between the Pacific and North American plates was the Tosco-Abreojos Transform Fault (Spencer and Normark, 1979; and Moore and Curray, this volume, Pt. 2). Basin and Range extension probably commenced in the northern Gulf at about 10–15 Ma (Dokka and Merriam, 1982), with occurrence of the first definitely marine sediments (Gastil et al., 1979), but the extension had not reached the latitude of the mouth of the Gulf until perhaps 8 Ma. We suggest that the La Paz Fault and the other onland graben faulting in the cape block were a part of this Basin and Range phase. We believe, however, that the marine embayment in the northern Gulf at this time was not a proto-Gulf of California, but was probably part of the Basin and Range Province, perhaps with connection to the Pacific Ocean through Southern California. Volcanism, probably associated with Basin and Range extension, included rhyolitic to basaltic volcanism on both sides of the northern Gulf, basaltic Comondú volcanism in central and southern Baja California, and rhyolitic-to-basaltic volcanism in Nayarit on the mainland (Gastil et al., 1979). Minor amounts of extension of the present land area may have occurred in an east–west direction associated with Basin and Range faulting, but we have no way of knowing whether any of the terrain now offshore was also subjected to east–west extension. Uplift may have occurred through two possible mechanisms. First, cessation of subduction should result in the edge of the North American Plate rebounding; and second, Basin and Range faulting would have resulted in differential uplift and subsidence. We suggest that the deep subaerial weathering of the granite observed in Site 476 occurred during uplift immediately following the cessation of subduction (Fig. 18), and we suggest that the cobble conglomerate formed as an outwash alluvial deposit after that uplift and before rifting and drifting began.

C. Early Pliocene, 5.5–3.2 Ma

By our scenario, the plate edge jumped inboard of the Peninsula of Baja California at about 5.5 Ma (Moore and Curray, this volume, Pt. 2). In this regard, the rift origin of this particular segment of passive continental margin deviates from the commonly accepted scenario, in that the jump of the plate edge inland straightened out the transform margin between the Pacific and North American plates; it jumped to a structural zone of weakness, possibly caused by the earlier Basin and Range extension. This jump of the plate edge took place abruptly; precursor events such as doming and thermal expansion did not occur in this crustal zone.

This jump in the plate edge marked the commencement of rifting by one of the mechanisms we have termed "diffuse extension"; locally, however, it may also have marked the onset of drifting or sea-floor spreading, although no lineated magnetic anomalies of this age are known within the Gulf. At this time the present alignment of the San Andreas (or San Jacinto) Fault system in southern California was forming. An extensional plate edge formed into the mouth of the Gulf, connecting the East Pacific Rise with the incipient rift–transform system of the Gulf itself, although oceanic crust was not being formed along that plate edge. The first alignment of the Tamayo Fracture Zone and of the other fracture zones of the Gulf occurred at this time (Fig. 20C). As pointed out by Moore and Curray (this volume, Pt. 2), the formation of these fracture zones appears to date to this early time of extension in the Gulf, clearly before 3.5 Ma, the date commonly cited as the beginning of the present phase of opening of the Gulf.

The delineation of the transition between continental and oceanic crust (Fig. 4) and the trends and identifications of magnetic anomalies (Fig. 7) are of great significance. It is apparent from examination of the first delineation of magnetic anomalies in this region by Larson et al. (1968) that that transition is diachronous. The oldest oceanic crust in the drilling transect (labeled the "Transect Zone", Fig. 20E) is about 3.2 m.y. old. To the southwest, in the "San Lucas Zone" (Fig. 20E), Magnetic Anomaly 3, with almost 5-m.y.-old crust, borders the probable edge of continental crust. The small region between the Tamayo Fracture Zone, the edge of continental crust, and the alignment of the 3.2-m.y.-old magnetic anomaly (Figs. 4 and 7) labeled as the "Los Frailes Zone" in Figure 20E had previously been ignored in small-scale plan-view representations and in the two-dimensional cross-sectional studies of this margin. Although few magnetic profiles have been run in this segment, there may exist lineated magnetic

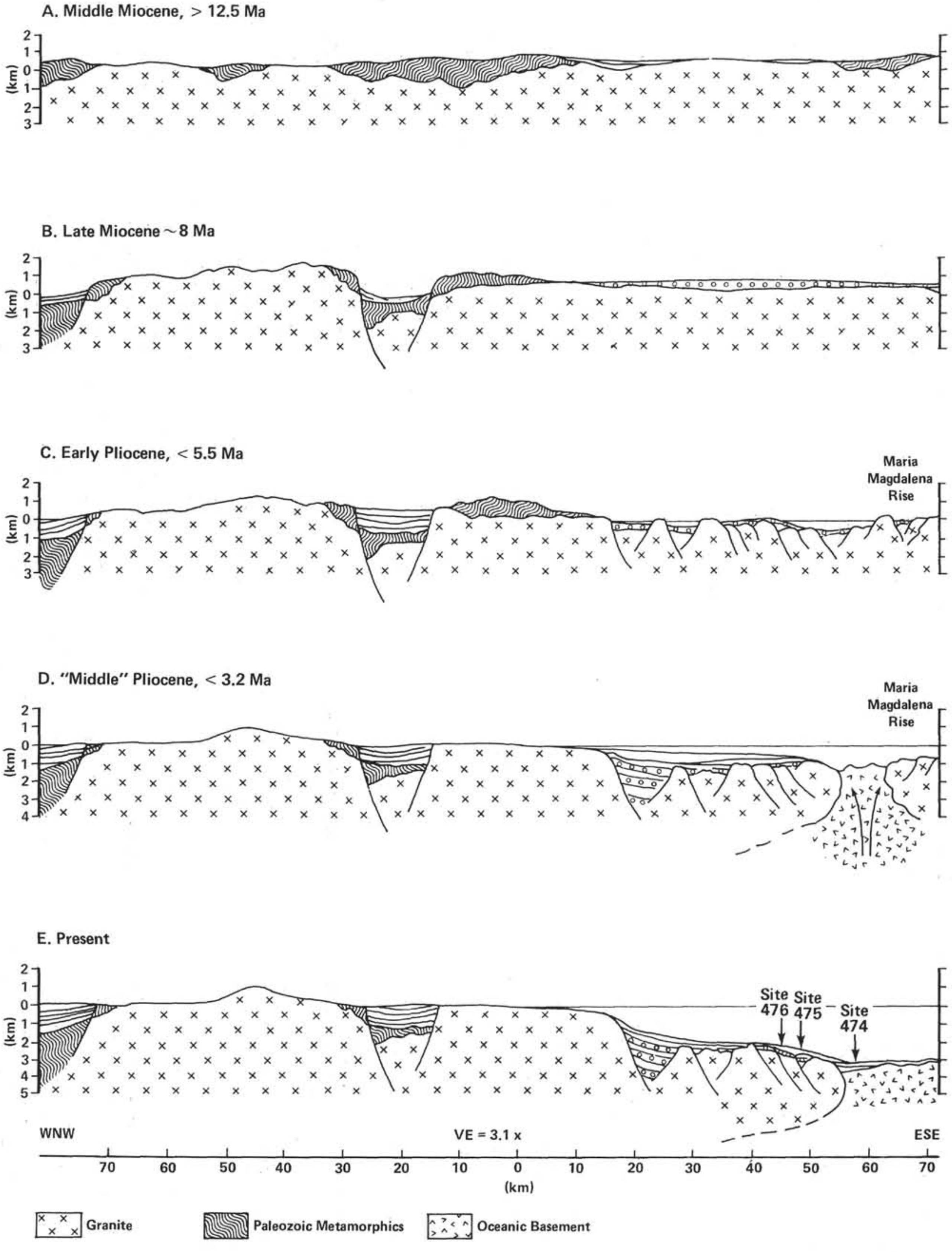

Figure 19. Geological history scenario of the Baja California Margin Transect, illustrated in section view as based on and extrapolated from MCS Line 105, Figure 5A. Location indicated on Figure 3 and extended across the Peninsula. Each section matches a plan view diagram of the same age in Figure 18. A. Middle Miocene, >12.5 Ma. B. Late Miocene, ~8 Ma. C. Early Pliocene, <5.5 Ma. D. "Middle" Pliocene, <3.2 Ma. E. Present structure and tectonics.

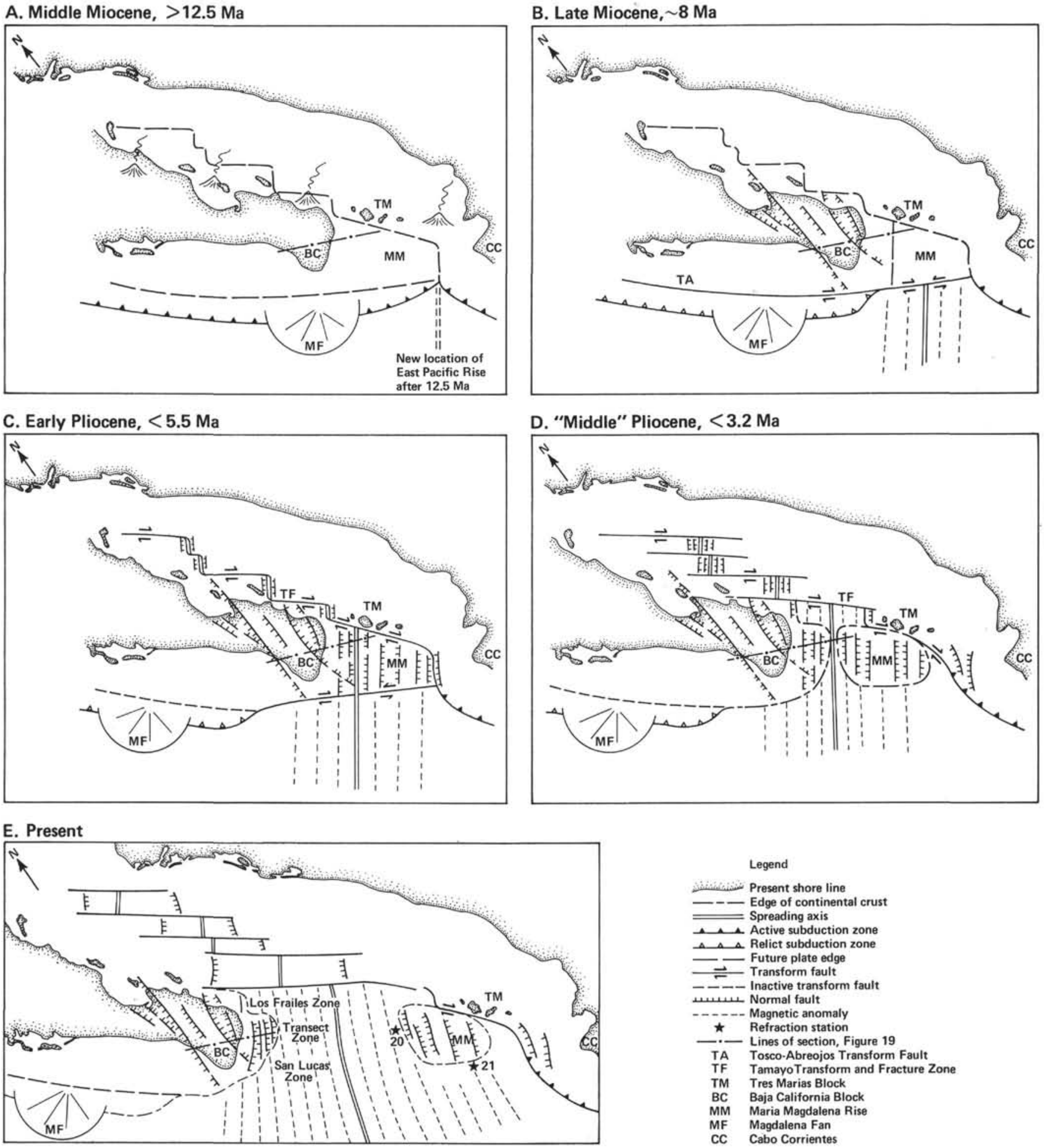

Figure 20. Geologic history scenario of the Baja California Margin Transect, illustrated in simplified plan view. Reconstructions are compatible with those of Moore and Curray (this volume, Pt. 2) and each diagram matches a section in Figure 19 of the same age. A. Middle Miocene, >12.5 Ma. B. Late Miocene, ~8 Ma. C. Early Pliocene, <5.5 Ma. D. "Middle" Pliocene, <3.2 Ma. E. Present structure and tectonics, greatly simplified.

anomalies which represent the start of Anomaly 3, or about 4+ Ma. Thus the transition from continental to oceanic crust may be diachronous also in this direction, that is, to the north of the drilling transect.

Thus, although extension and opening of the mouth of the Gulf started about 5.5 Ma, diffuse extension continued, in the drilling "transect zone" in the form of listric faulting, dike injection, and probably also ductile stretching of lower continental crust until about 3.2 Ma. At that time, normal sea-floor spreading and formation of linear magnetic anomalies commenced in this zone, aligned with the anomalies to the northeast and southwest (Fig. 20D). At the time of Figures 19C and 20C—early Pliocene, just less than 5.5 Ma—no sea-floor spreading was yet occurring in the transect zone.

Deposition of outwash gravels terminated at about 5.5 Ma with the start of rifting. Sites 475 and 476 sank below sea level and gradually subsided through the depth of the surf zone to become offshore banks isolated from influx of terrigenous sediment (Fig. 18C and 19C). Erosion probably occurred during the time of exposure to surf action, followed by very slow deposition of organic claystones, dolomite, phosphate, and glauconite (Figs. 9 and 17). We do not have precise indicators of depth, but we estimate that the glauconites were formed within a range of 100–400 meters water depth and that the association of facies suggests the possibility of a shallow oxygen minimum. As subsidence continued, however, the bank tops became too deep for glauconite formation after about 4 Ma.

D. "Middle" and Late Pliocene, 3.2–1.8 Ma

A major change occurred at about 3.2 Ma—completion of the sea-floor spreading axis from the open Pacific through to the Tamayo Transform Fault (Fig. 19D and 20D). Throughout the evolution of the mouth of the Gulf, we believe that the Maria Magdalena Rise was also undergoing diffuse extension by listric faulting, dike injection, and probably also ductile stretching of lower continental crust. At the same time, a dextral transform fault lay between the Tres Marias–mainland Mexico block and the Maria Magdalena Rise. Thus, as the Peninsula of Baja California moved northwestward relative to mainland Mexico, the Maria Magdalena Rise also moved somewhat more slowly away from the mainland of Mexico, trailing behind the Baja block. Finally, at about 3.2 Ma, the spreading axis of the Los Frailes Zone came into alignment with the spreading axis breaking through from the open Pacific through the San Lucas and the transect zones. As these axes came into alignment, organized sea-floor spreading was occurring all along them, terminating the diffuse extension of the transect zone (Figs. 19D and 20D). It was at this time that the sea floor beneath Site 474 was formed. Hole 474A may not have penetrated through the oldest sediments, sills and flows at the site. Conditions during this first phase of sea-floor spreading may have been similar to conditions in the Guaymas Basin at Sites 477 and 481. Rapid influx of sediment may have prevented rising magmas from reaching the sea floor, resulting in emplacement of sills and feeder dikes.

In the meantime, the slope sites were also subsiding rapidly and had attained a depth intermediate on the continental slope (Fig. 18). Rate of accumulation of sediment increased markedly at approximately 3 Ma at both sites (Fig. 17). These were normal hemipelagic sediment facies of the continental slope. It is interesting that at approximately 3 Ma, or immediately prior to this marked increase in rate of accumulation, Sites 475 and 476 both show a brief hiatus (Aubry, this volume, Pt. 2 and J. Ingle, pers. comm., 1982). Water depth was probably less than a kilometer at the time (Fig. 18). The hiatus could possibly have represented an increase in the velocity of the tidal currents with the opening of the incipient Gulf of California. As the volume of the Gulf as a long, narrow embayment increased, tidal currents at the mouth could temporarily have achieved high enough velocities, from standing-wave resonance, to lead to erosion.

By 3.2 Ma the period of diffuse extension off the tip of Baja California had ended, although diffuse extension may have been continuing in the Maria Magdalena block, either in the form of normal faulting and dike injection, or as major breaking up of the former continental block into narrow slivers of continental crust. We do not know the total amount of extension which occurred either in the tip of the Peninsula of Baja California or in the Maria Magdalena Rise, but we have arbitrarily shown approximately two times extension for the slope of the transect and a somewhat greater amount for the Maria Magdalena Rise (Figs. 19D and 20D).

E. Quaternary, 1.8 Ma to Present

This is the period when most of the sediments penetrated in the three drilling sites of the transect accumulated (Figs. 19E and 20E). Rates of accumulation for the two slope sites, 475 and 476, continued to be fairly high until approximately 2.25 Ma, at which time they both decreased to a very modest rate (Fig. 17). In contrast, the rate of accumulation for Site 474 increased at approximately 1.25 Ma, in early Pleistocene time. These changes in rate of accumulation could represent the onset of Quaternary conditions—wider continental shelves and better-developed submarine canyons. The submarine canyons of the cape block could have existed before this time as subsided subaerial canyons. With Quaternary fluctuations of sea level, these canyons could have been flushed out and enlarged, to become more effective conduits for the transport of sediments bypassing the continental slope to be delivered to the base of the slope as coalesced deep-sea fans, thus resulting in an increased rate of accumulation of sediments at Site 474. The debris flow, Unit II in Site 474, represents a very rapidly deposited, single episode of mass transport of sediment, probably also resulting from the changed environmental conditions related to the fluctuating Quaternary sea level.

Present tectonics are represented diagrammatically in Figure 20E. Lineated magnetic anomalies extend all the way across this area to the Tamayo Fracture Zone and continue to form today at the East Pacific Rise.

Very little is known about the Maria Magdalena Rise. It is only because of our need to find a conjugate margin for the tip of the Peninsula of Baja California that we have suggested that the Maria Magdalena Rise may be broken-up, extended, altered, and subsided continental crust. Other less satisfactory alternatives are, first, that no conjugate margin ever existed and that a marine embayment existed before this continental margin formed, or, second, that the continental crust of the conjugate margin was somehow subducted beneath the Tres Marias block.

Two reversed seismic refraction stations were published by Phillips (1964) near the Maria Magdalena Rise

(Fig. 19E). The southerly shooting run for Station 20 lay at a bearing of approximately 150° from the station; the northerly shooting run for Station 21 lay at a bearing of approximately 320° from that station. Hence, both of these shooting runs extended partly across the Maria Magdalena Rise, although the stations and the opposite shooting runs lay outside of the rise. Results of these refraction runs, which were considered by Phillips to represent typical deep-water oceanic crust stations, were Layer 3 velocities ranging from 6.46 to 6.87 km/s; mantle arrivals ranging from 7.83 to 7.92 km/s; and total thickness to mantle ranging from 7.92 to 10.11 km/s. Thus these stations do not confirm our suggestion that this represents subsided altered, broken-up, formerly continental crust. Nevertheless, we suggest that extreme diffuse extension which we postulate for the Maria Magdalena Rise might in fact so severely thin and fragment the former continental crust as to make it indistinguishable from normal oceanic crust in such a test as this, located outside of the Rise. Moore and Curray (this volume, Pt. 2) have reproduced seismic reflection profiles run by Moore (1973) from the Maria Magdalena Rise, showing the quite anomalous character of the basement rocks in this area as compared with normal oceanic crust. Clearly, to test this hypothesis more careful, better placed marine geophysical work and rock dredging should be attempted in the Maria Magdalena Rise to determine the nature of the crust.

DISCUSSION AND CONCLUSIONS

General Comments

The advantages of geophysical study and drilling on young passive continental margins were stressed earlier in this volume and during discussions on drilling in the Gulf of California. They are obvious: the sediment column is not too thick to penetrate, either geophysically or by drilling. The disadvantage, not previously mentioned, is that if the sediment section is very thin, the sedimentary record of events may be meager. For the tip of the Baja California Peninsula, the only prerift sediments recovered are nonfossiliferous cobble conglomerates, and the synrift sediments are essentially a starved section. Only the postrift section is well represented. Thus our resolving power is rather imprecise. Our interpretations are, therefore, not absolutely compelled by the data.

Study of the details of a short segment of passive rift-origin continental margin in three dimensions and large scale has proved extremely valuable. Only through these means did we realize some important characteristics of this margin that had been missed in previous studies. Principal among these is the observation that the transition from continental to oceanic crust is diachronous, and thus the transition from rift to drift stage is time-transgressive. The degree of such differences and their importance in other margins is not known.

Regional Implications

The Gulf of California is an important part of the tectonic system of western North America and the eastern Pacific. Interaction between the North American, Pacific, and other plates has given this region an exceedingly complex geological history that will never be fully understood until we can delineate each individual aspect of the overall system. We believe that this and the companion papers in this volume, especially that by Moore and Curray on the tectonics of the Gulf, clarify previous confusion over some points of origin of the Gulf and thereby contribute to our understanding of the region.

The concept of a proto-Gulf of California has been in the geological literature since at least 1968 (Moore and Buffington, 1968) and has dominated many of the models of origin. The concept was first proposed by Moore and Buffington specifically for the region discussed in this chapter in the mouth of the Gulf. They pointed out the apparent asymmetry of the position of the East Pacific Rise within the mouth and a region to the southeast of the East Pacific Rise which appeared to have different basement characteristics and more sediment cover. Subsequently, much more attention has been given to proto-Gulf terrain farther up in the Gulf, flanking the deep young basins in which sea-floor spreading can be demonstrated. Various mechanisms had been proposed for origin of this proto-Gulf, including backarc extension (Karig and Jensky, 1972). Determination of the age and basement characteristics of the proto-Gulf was a high priority for proposed drilling within the Gulf, although depth limitations, safety considerations, and time constraints precluded any possibility of really solving those problems.

As an alternative to the two-stage formation model, we now believe that the Gulf was formed during a single, continuous period of opening, but in two time-transgressive phases. This period of opening commenced at about 5.5 Ma, with a jump of the plate edge inboard of the present Peninsula of Baja California. The two phases we refer to are first, diffuse extension by stretching of continental crust, and second, normal sea-floor spreading whether or not lineated magnetic anomalies are generated. Rates, directions, and alignment of transform faults were the same during these two phases of a single process. Of especial significance in this study is the demonstration that the transition from Phase 1 of diffuse extension to Phase 2 of normal sea-floor spreading is diachronous. It occurred as early as about 4.9 Ma in some places, but as late as 3.2 Ma along the transect. Time of the transition from Phase 1 to Phase 2 and hence location of the transition from oceanic to continental crust farther up in the Gulf cannot yet be resolved because we lack lineated, correlatable magnetic anomalies.

The other complication which has contributed to confusion over a proto-Gulf stage is the relationship to earlier Basin and Range, east–west extension, subsidence, and the existence of a marine embayment. Adjacent to and within the central and northern part of the Gulf there are marine sediments related to this Basin and Range period of middle to late Miocene time. We do not, however, consider this to be a proto-Gulf, because it resulted from quite a different tectonic event.

What are the alternatives to this explanation? First, we might suggest the possibility that the dispute over the proto-Gulf and its relationship to present tectonics is largely semantic. If the marine Miocene sediments in the region of the northern Gulf are to be called proto-Gulf, then in a sense the proto-Gulf of California extended well north of the present Gulf region into the southern Basin and Range Province of the United States. This would also imply that the Gulf formed diachronously from north to south, as had been previously suggested by Normark and Curray (1968). Another possibility for diachronous formation of the Gulf is through the mechanism of a propagating rift coming in from the southern end at the Pacific margin (Richard Hey, pers. comm.). For the moment, however, we reject both of these alternatives and favor a distinct Basin and Range stage quite unrelated to formation of the modern Gulf of California.

The problem of the conjugate margin has long been apparent, but has escaped consideration in the literature. Various reconstructions had been suggested, including tucking the tip of the Peninsula in toward the continental margin of mainland Mexico north of the Tres Marias Islands. Such a reconstruction is, however, geometrically very difficult and violates topographic trends of the transform faults, which appear to cut well back into continental crust on both sides of the Gulf. As an alternative, the tip of the Peninsula of Baja California could have lain adjacent to the continental margin near Cabo Corrientes. Such a reconstruction requires either from 400 to 500 km of opening of the Gulf, or fragmentation of the Peninsula by means of transpeninsular faults during its northwestward transport. Such faults have been considered by many investigators but have not yet been convincingly demonstrated. Lacking such evidence, we reject the possibility and favor the reconstructions we have shown. With these reconstructions, identification of a conjugate margin of continental crust is an enigma. The alternative we favor is that the Maria Magdalena Rise does indeed represent broken-up, subsided, altered continental crust which has moved in a right-lateral sense away from the Cabo Corrientes margin along the Tres Marias Transform Fault as a part of the Rivera Plate.

Ness et al. (1981) have proposed an identification of the magnetic anomalies continuously from the East Pacific Rise southeastward across the Maria Magdalena Rise. In order to explain the asymmetry of the position of the East Pacific Rise in the mouth of the Gulf and older ages on the southeast flank than on the northwest flank, they have suggested that from about 9 Ma to 4 Ma northwestward subduction of young oceanic crust occurred beneath the tip of the Peninsula of Baja California. We reject this model of subduction for the following reasons. First, the structure of the tip of the peninsula of Baja California shows no evidence of a buried trench. Instead, the oceanic crust can be followed in the many seismic reflection lines in the area to the toe of the continental slope and the apparent transition to continental crust. The structure of the margin, in fact, appears to demonstrate the block and listric normal faulting commonly associated with rifted passive margins. Second, the free air gravity low they suggest as evidence of a buried trench is strongest northeast of the tip of the Peninsula where they do not propose existence of a subduction zone. Third, we, like others, do not accept their correlation of magnetic anomalies over the Maria Magdalena Rise, as discussed previously in this chapter. Fourth, their model would require a reconstruction placing the tip of the Peninsula against the continental margin of Cabo Corrientes, a reconstruction which we have just rejected. Fifth, subsidence history as interpreted from the drilling information demonstrates that both Sites 475 and 476 lay very near to sea level until about 4 Ma. If a subduction zone had lain beneath this margin, these sites would have been low on the continental slope, immediately above the trench, until the cessation of subduction at 4 Ma. Sixth, their model requires recent movement on a trans-Mexican fault zone, a suggestion rejected by Moore and Curray (this volume, Pt. 2). And seventh, the Maria Magdalena Rise is clearly an anomalous area in that it is shoaler than normal sea floor of that age. Mammerickx (1980) suggested a scenario involving a jump of the spreading axis to explain the anomalous bathymetry. In conclusion, we reject the subduction model of Ness et al. (1981) as being perhaps the least plausible of the many models suggested for the geological history of the mouth of the Gulf.

Finally, one of the major contributions of Leg 64 has been demonstration of the nature of basement rocks in a narrow, young, spreading ocean, where influx rates of terrigenous and biogenic sediments are high. The crust being formed in the Guaymas Basin is quite dissimilar to that which we are accustomed to consider as typical oceanic crust, as formed at an East Pacific Rise or Mid-Atlantic Ridge type of environment. Instead, the extrusives brought up at the spreading axis do not extrude on the ocean floor, but intrude into the soft, wet, young sediments as intrusive bodies of undefined shape, to which we have referred as sills. The possibility exists that the stratified material underlying maximum depth of penetration at Site 474 is of this nature, and represents up to a few hundred thousand years of sediment and intrusive accumulation.

Testing the Model

Models of geological interpretation, history, or evolution are very useful for classifying, synthesizing, and generalizing geological thought. Models should, however, be used only as working hypotheses and should not be accepted without thorough testing against observations. The rift origin of passive continental margins is such a model, and one of the objectives of study and drilling of the Baja California passive margin has been to test it.

Study of the few examples of youthful passive continental margins in the world has led to confusion because of the extreme variability of the modern examples. The Gulf of California is certainly no exception, and we might ask at this stage if our observations and conclusions from the study of this margin are really applicable to testing the model. The model was formulated to explain the evolution from true intracontinental rifts to formation of Atlantic-type continental margins. The Gulf of California is clearly not such a case. It resulted from a complex history, first of subduction, then of transform motion along the margin, Basin and Range extension, and finally an abrupt, surprise jump of the plate edge inboard of the present Peninsula of Baja California. We might, therefore, not expect to find evidence for many of the events commonly thought to be precursor to the rifting and drifting stages; and we might instead expect to find a heritage from subduction and Basin and Range tectonics.

Let us examine certain specific aspects of the model and compare them with our observations on the passive continental margin at the tip of Baja California.

Volcanism is generally thought to precede, or at least accompany the doming and rifting stages. Volcanism has indeed been common in this region, but with a complex history and variable causes. First, volcanism accompanied subduction when the Farallon Plate was subducting beneath the North American Plate. Second, volcanism accompanied Basin and Range extension across the Gulf. Only subsequently did volcanism related directly to rifting and formation of this margin occur, as was demonstrated by dredging the submerged portion of the margin and by recovery of basalt in Hole 475B.

Doming and subaerial, prerifting erosion have not occurred as a part of the evolutionary sequence of all passive margins. Here, a prerift or rift-onset unconformity can be identified as the weathered surface of the granitic basement at Site 476, but doming may have occurred when subduction ceased, quite unrelated to any thermal anomaly underlying this margin as a precursor to rifting.

Rifting and drifting in this margin are not separated in time as distinctly as the model would require. Instead, when the plate edge jumped inboard of the present Peninsula of Baja California, rifting probably occurred everywhere subparallel to present spreading axes, but the transition from rifting to drifting was diachronous and of short duration. Whereas most models (Falvey, 1974) suggest as much as several tens of millions of years between rifting and drifting, the maximum difference in this area is about 2 m.y. Furthermore, we find no compelling evidence for a breakup unconformity (Falvey, 1974). Although we have pointed out that a minor hiatus occurred at about 3 Ma in Sites 475 and 476, there is no evidence of uplift associated with this hiatus.

Finally, subsidence is commonly thought to commence with the drifting stage (Montadert et al., 1979). In this transect, subsidence clearly started earlier, at about 5.5 Ma, with the initiation of the rifting stage. Furthermore, subsidence here has been much more rapid than could be predicted by existing models. Sedimentation has been closely related to this subsidence and changes of environment at the three sites. Because of the lack of prior doming, drainage was not diverted away from this young ocean basin, and quantities of terrigenous material poured into the narrow incipient ocean. No starved environment or evaporite basin ever existed. Instead, a special kind of oceanic crust was created immediately adjacent to the transition to continental crust.

In conclusion, the evolution of the young passive margin at the tip of Baja California apparently fits some parts of the commonly accepted evolutionary model of passive continental margins but deviates in many other aspects. This margin is indeed atypical of the early stages of formation of most ocean basins and Atlantic-type continental margins. At the same time, that model of formation must be considered oversimplified because it excludes this and some of the other examples of young margins in the world today.

Even though its origin is atypical, what are the chances of this young ocean and its continental margins ever evolving to maturity? Because of its highly oblique nature, it will never evolve into an ocean like the Atlantic or Indian Oceans without major reorganization of plate motion direction and poles of rotation. If the present tectonic regime persists, however, the Gulf of California will ultimately become a part of the eastern Pacific Ocean as southwestern California and Baja California move toward the Aleutian Trench. If this occurs, then the margin at the tip of Baja California will have a life expectancy of at least 50 m.y. and will evolve to maturity as a passive continental margin.

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