The Geology of West-Central Baja California Sur, Mexico

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By HUGH McLEAN, B.P. HAUSBACK, and J.H. KNAPP

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The Geology of West-Central Baja California Sur, Mexico

By Hugh McLean, B.P. Hausback, *and* J.H. Knapp

Abstract

The western slopes of the Sierra de La Giganta in the central part of Baja California Sur are composed of Cenozoic sedimentary and volcanic rocks. Pre-Cenozoic granitoid rocks underlie the Sierra, but are not exposed at the surface on the western slopes of the range. No evidence of mineralization was observed within the stratified sequence. The oldest rocks are middle Eocene marine sandstone, siltstone, and minor diatomite of the Bateque Formation. Late Oligocene strata of the San Gregorio Formation (formerly named the Monterey Formation) consist predominantly of diatomite and subordinate phosphatic sandstone, vitric tuff, and porcellanite. Late Oligocene K-Ar ages from the tuffs correlate closely with ages determined by diatom and coccolith assemblages. Early and middle Miocene time is represented by the Isidro Formation, a shallow marine sequence that contains an abundant and diverse assemblage of mollusk fossils in beds of coquina and massive bioturbated silty sandstone; the fossils indicate an age of early to middle Miocene. The area is dominated, however, by a sequence of nonmarine arc-derived volcaniclastic sandstone, conglomerate, agglomerate, and breccia named the Comondú Formation that thins and becomes progressively younger from east to west. Near the crest of the Sierra, the Comondú sequence was intruded by stocks of hornblende andesite porphyry, locally dated at 19 Ma. On the western coastal plain, 12- to 14-Ma flows are interbedded with the nonmarine sequence. In this region alkaline basalts that range in age from 14 Ma to about 7 Ma directly overlie the Comondú Formation. Quaternary volcanism is represented by cinder cones and flank flows, small rounded capping flows, and a few small canyon-filling flows.

Perennial supplies of fresh water along the western slopes of the Sierra are restricted to wells and springs that flow from the nonmarine sedimentary rocks of the Comondú Formation; the largest springs lie close to the center of the Baja peninsula and may be controlled more by fracture systems than by the distribution of individual permeable beds. Water flowing from springs and wells in marine strata are saline.

INTRODUCTION

The geography of Baja California Sur is dominated by an assymetrically sloping northwest-trending mountain range known as the Sierra de La Giganta. The crest of the range lies relatively close to the coast of the Gulf of California and has an average elevation of about 1,000 m with peaks as high as 1,800 m. Steep east-facing slopes drop precipitously to the Gulf coast, whereas the western slopes grade gently down to the Pacific coastal plain (figs. 1 and 2).

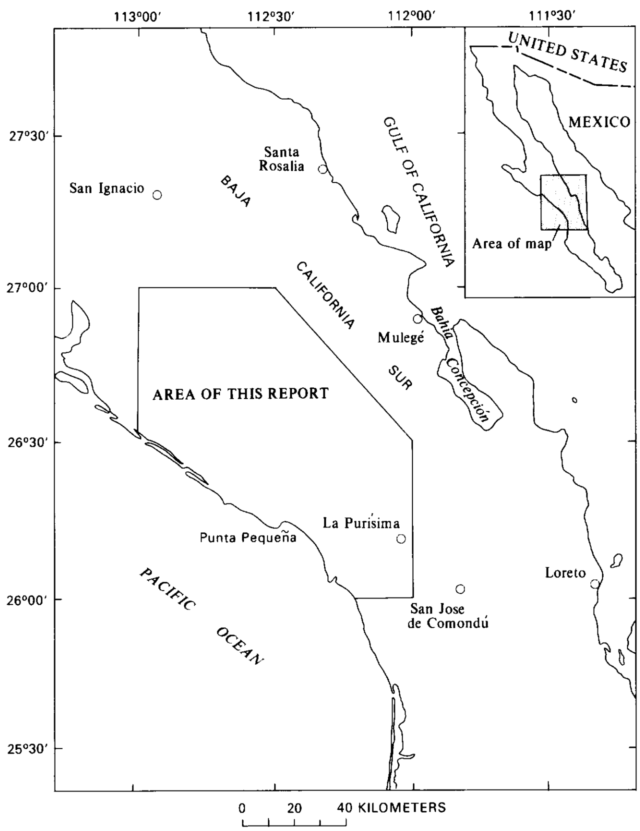

Figure 1. Index map of study area.

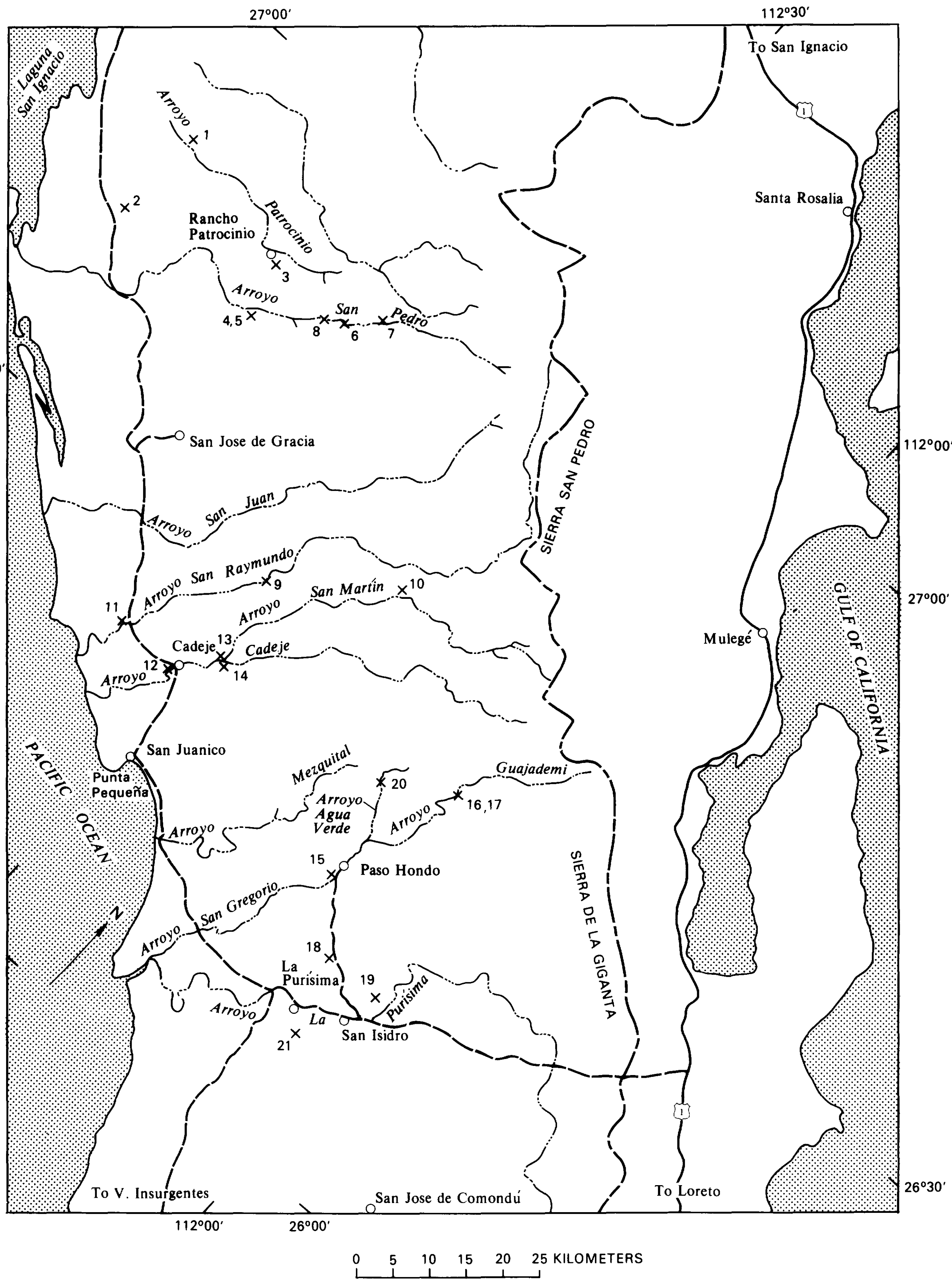

Figure 2. Location of major arroyos, roads, and communities in the study area. Dashed lines are graded roads. Numbers correspond to K-Ar localities on table 1.

This report describes the geology of the lower western slopes of the Sierra de La Giganta between latitudes 26° and 27° N. Southwest-trending arroyos (fig. 2) deeply incise the westward-sloping plateaus, creating excellent laterally continuous exposures of slightly deformed Cenozoic sedimentary and volcanic rocks. Approximately 5,500 km^2 were mapped during three field seasons from 1982 to 1984; the work focused on the regional distribution of Tertiary sedimentary and volcanic units, on age relations, and on sedimentology. The geology was mapped at a scale of 1:50,000 on provisional topographic maps provided by SPP (Secretaria de Programación y Presupuesto). Maps were used in conjuction with 1:70,000-scale black and white aerial photographs, and Landsat color images. Our work was part of a program to determine the framework geology and mineral potential within Baja California Sur. Geologic mapping in the area prior to 1982 was highly generalized because accurate topographic base maps were not available and access by vehicle was difficult.

This report provides newly acquired radiometric ages for volcanic flows and tuffs that range in age from 21 Ma to as young as 0.7 Ma (table 1). Paleontological data from marine fauna and flora provide new age assignments for Eocene, Oligocene, and Miocene strata. The effects of local structural features, as well as geologic history, and geologic control of ground-water distribution are also discussed. We found no outcrops of pre-Cenozoic crystalline rocks west of the crest of the Sierra de La Giganta or any evidence of mineralization associated with intrusions into the Cenozoic rocks. We consider the metallic mineral potential of the area to be negligible.

Previous Work

Previous geologic reports that involve parts of the present area contain descriptions of rock types and stratigraphic relations that we found to be generally accurate. Many of the early workers traveled with pack animals and their mapping was restricted by the sparse distribution of water. Reports that describe parts of the geology of our study area were published as early as 1882 by Willian M. Gabb; followed later by Darton (1921), Heim (1922), Beal (1948), Mina (1957), McFall (1968), Chavez (1978), Gastil and others (1979), and Sorensen (1982). Our field observations confirm many of the ideas presented by the previous workers. Our geologic mapping connects the area to the north and east mapped by Sawlan and Smith (1984), and the area to the south mapped by Hausback (1984). Geologic maps that cover much of the area described in this report have been recently published by McLean and Hausback (1984), and by McLean and others (1985), and are essential adjuncts for readers of this report; many of the geographic names used in this report are located on the two maps referred to above.

Acknowledgments

Mapping and sampling were done under the auspices of a cooperative agreement between the Consejo de Recursos Minerales of Mexico and the U.S. Geological Survey that was initiated in 1981. We thank David G. Howell for his persistence in initiating the Baja Project, and we appreciate his support of our efforts. The senior author thanks B.P. Hausback and J.H. Knapp for their help, companionship, and scientific expertise in the field, with special thanks to Brian Hausback for outstanding work in radiometric age dating. We greatly appreciate the valuable paleontological work of John A. Barron, David Bukry, Gerta Keller, Kristin A. McDougall, and Judith Terry Smith. We also acknowledge James G. Smith, John C. Dohrenwend, and Brent Turrin for sharing their unpublished K-Ar ages, and also R.W. Kistler for the Rb-Sr analyses. Tracy L. Vallier helped select chemical analyses and also helped to evaluate the chemical data.

DESCRIPTION OF ROCK UNITS

Bateque Formation (Eocene)

Distribution

The Bateque Formation (fig. 3) of Mina (1957) crops out continuously from the type area near Rancho del Bateque southeastward for 70 km to Batequi de San Juan. Isolated outcrops in major arroyos extend farther southward for another 45 km to the mouth of Arroyo Mezquital. Petrography and sedimentology of the Bateque Formation for the area between Laguna San Ignacio and Arroyo El Cuarenta were discussed by Sorensen (1982), but continuous outcrops which extend southward from El Cuarenta for 25 km have not been studied previously. The reconnaissance geologic map of McLean and others (1985) shows the distribution of the Bateque Formation, as well as the geographic points of reference, and is a recommended adjunct to the reader of this report.

Lithology

Fine-grained sandstone and coarse-grained siltstone compose most of the Bateque Formation; mudstone is rare. Color is mainly yellowish brown to grayish brown, and induration ranges from moderate to friable. The formation is easily eroded where not capped by basalt. The petrographic study done by Sorensen (1982) indicates that the sandstones are texturally immature, moderately to poorly sorted, and range from arkose to lithic arkose; the average composition is $Q_{12}F_{65}L_{23}$, where feldspar (F) is mainly plagioclase and lithic fragments (L) are mainly silicic and intermediate-composition volcanic rocks. Most grains are angular, indicating that the sediments were only minimally exposed to stream- and wave-dominated environments enroute to the site of deposition, although some of the angularity might be due to secondary porosity. A granitic source terrane for the sandstone is inferred mainly from the presence of grains of plagioclase which lack oscillatory zoning, but display intergrowth twinning and are similar to plagioclase in granitic rocks of the peninsular

Table 1.--Potassium-argon ages of volcanic rocks, Sierra de La Giganta, Baja California Sur, Mexico

[* K-Ar age determination by J.G. Smith; **, K-Ar age determination by John Dohrenwend and Brent Turrin. Ages calculated using the following constants: λ_ϵ = 0.581 x 10^{-10}yr, λ_β = 4.962 x 10^{-10}yr]

Map No.	Sample No. locality	Rock type	Material dated (W.R., whole rock)	Percentage potassium ± standard deviation	^{40}Ar x 10^{-11} mol/g	Percentage ^{40}Ar	Age in million years before present, ±2 standard deviations	Stratigraphic and location comments
1*	83BSJ241 26°51'08"N. 112°59'55 W.	Basalt	W.R.	0.129 ±0.0025	0.1827	7.0	8.1±0.4	Capping flow, Mesa El Yeso
2*	83BSJ244 26°43'40"N. 112°59'15"W.	Basalt	W.R.	0.146 ±0.0026	0.2655	24.0	10.5±0.4	Capping flow, Mesa Las Gallinas
3**	384-6-1 26°48'05"N. 112°46'07"W.	Basalt	W.R.	4.07 ±0.064	6.08	16.3	8.6±0.7	Canyon-filling flow, Arroyo Patrocinio
4**	384-6-2 26°44'52"N. 112°45'40"W.	Basalt	W.R.	2.82 ±0.054	3.61	45.8	7.4±0.3	Small capping flow, Mesa El Bule
5**	384-6-3 26°45'00"N. 112°45'55"W.	Basalt	W.R.	0.052 ±0.009	0.233	11.4	8.8±1.2	Canyon-filling flow, Arroyo San Pedro
6**	384-7-1 26°51'20"N. 112°36'58"W.	Basalt	W.R.	1.728 ±0.039	3.975	78.7	13.2±0.6	Interbedded flow, Arroyo San Pedro
7**	384-7-2 26°52'35"N. 112°34'18"W.	Andesite	W.R.	1.360 ±0.032	3.265	74.4	13.8±0.6	Monomict breccia clast, Arroyo San Pedro
8**	384-8-1 26°49'21"N. 112°39'16"W.	Basalt	W.R.	1.57 ±0.036	2.855	36.8	10.4±0.5	Capping flow, Arroyo San Pedro
9	384-13-3 26°31'02"N. 112°30'00"W.	Tuff	Glass	4.48 ±0.866	1.17	73.5	21.9±0.8	Tuff of San Gregorio Formation, Arroyo San Raymundo
10	384-15-1 26°34'22"N. 112°24'51"W.	Basalt	Plag.	1.158	2.61	71.3	12.9±0.7	Interbedded flow, Arroyo San Martin
11**	384-11-3b 26°22'45"N. 112°36'12"W.	Pillow basalt	W.R.	0.250 ±0.013	4.658	50.7	10.7±1.14	Pillow flow, Arroyo San Raymundo
12*	26°22'18"N. 112°30'58"W.	Data incomplete						Canyon-filling flow, Arroyo Cadeje
13**	101983-4 26°25'00"N. 112°29'00"W.	Basalt	W.R.	1.410	0.188	94.4	0.7±0.1	Small capping flow, Arroyo Cadeje, west side
14**	101983-3 26°25'00"N. 112°27'56"W.	Basalt	W.R.	1.638	0.292	88.7	0.9±0.08	Small capping flow, Arroyo Cadeje, east side
15	383-11-1 26°18'41"N. 112°10'11"W.	Transitional alkalic basalt	W.R.	1.267 ±0.052	3.189	57.4	14.5±1.2	Interbedded flow, Arroyo San Gregorio
16	383-10-1B 26°29'08"N. 112°07'40"W.	Alkalic basalt	W.R.	1.803 ±0.041	3.492	56.9	11.1±0.8	Canyon-filling flow, Arroyo Guajademi
17	383-10-1A 26°29'08"N. 112°07'40"W.	Calc-alkalic basalt	W.R	0.948 ±0.013	2.052	55.5	12.4±0.4	Basal capping flow, Arroyo San Gregorio
18	383-9-1 26°15'32"N. 112°05'58"W.	Alkalic basalt	W.R.	2.585 ±0.042	3.747	56.2	8.3±0.3	Capping flow between Paso Hondo and La Purísima
19	383-8-1 26°16'36"N. 112°02'18"W.	Alkalic basalt	W.R.	2.176 ±0.092	0.3270	4.6	0.8±0.1	Cinder cone flank flow, west of La Purísima
20	383-10-3 26°27'57"N. 112°13'18"W.	Alkalic basalt	W.R.	2.13 ±0.09	2.234	11.0	0.6±0.06	Canyon-fill flow, Arroyo Agua Verde
21	383-17-4 26°09'56"N. 112°01'02"W.	Basalt	W.R.	1.658 ±0.038	4.253	63.8	14.7±0.7	Capping flow south of Arroyo La Purísima

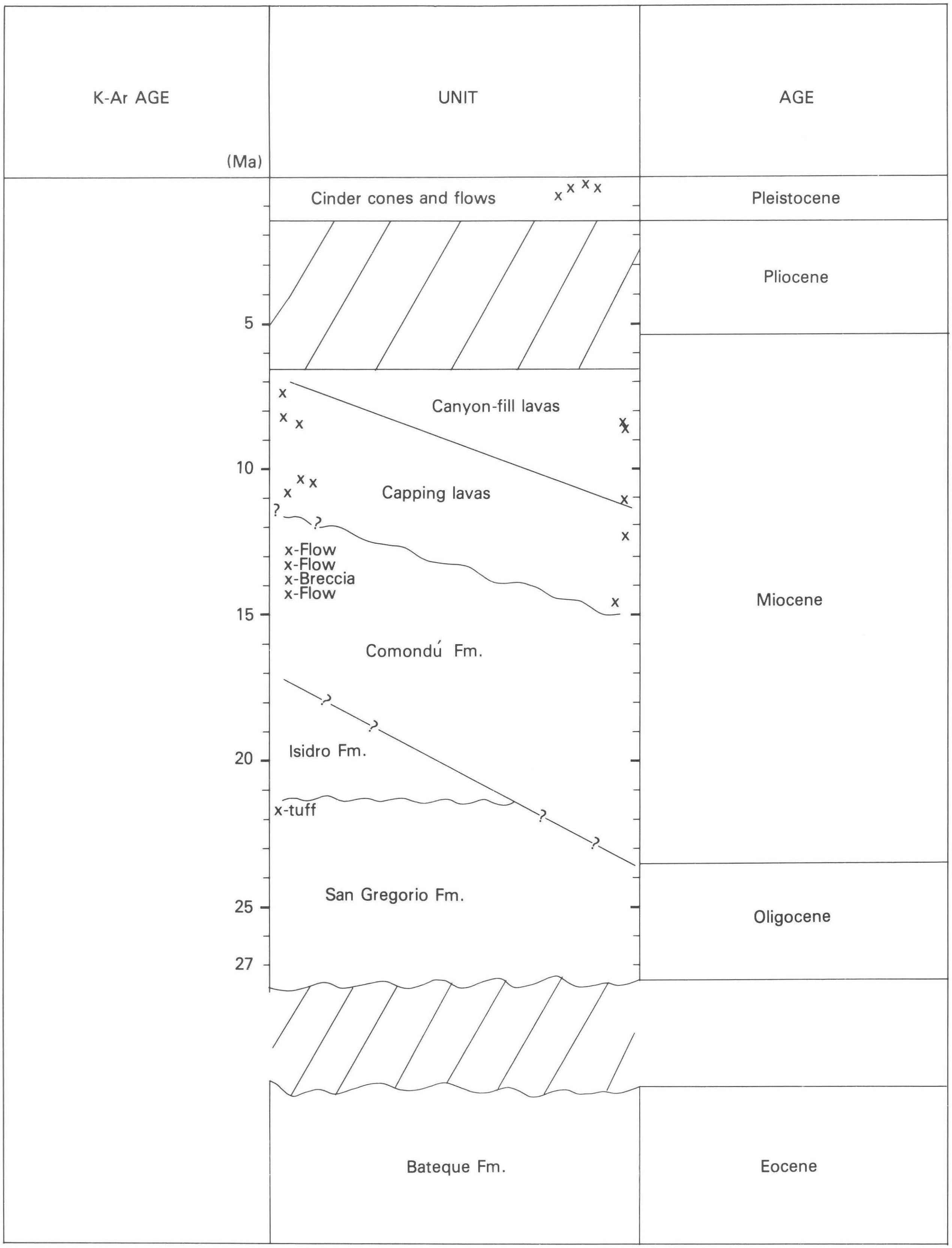

Figure 3. Generalized stratigraphic relations and K-Ar ages of Tertiary rocks of Baja California Sur. Dated samples shown by an x.

batholith. Microcline (also a granitic component) is present in small percentages.

Diatomite is found in isolated outcrops in Arroyo San Raymundo, about 2 km north and 200 m south of La Ballena (a small ranch). Here, grayish-white laminated diatomite and siliceous shale overlie yellowish-brown fine-grained arkosic sandstone. Diatomite samples studied by J.A. Barron indicate a late middle Eocene age; this diatomite represents a new facies of the Bateque Formation. Eocene diatomite also crops out in the south bank of Arroyo Patrocinio and along coastal bluffs a few kilometers north of the mouth of Arroyo Patrocinio.

The diatom assemblage from Arroyo San Raymundo strongly resembles the flora of the Kreyenhagen Formation exposed near Coalinga, California (McLean and others, 1985). The Bateque Formation in Arroyo San Raymundo lies north of latitude 26°15' N. and is the southernmost outcrop of Eocene diatomite known along the west coast of North America. The outcrop latitude corresponds closely to the southern limit of modern diatoms along the Pacific coast. The presence of late middle Eocene diatomite in central Baja California Sur may provide a geologic constraint for postulated post-Late Cretaceous northward movement of the Peninsular terrane that is suggested by the paleomagnetic data of Hagstrum and others (1985).

Previous work by Mina (1957) and Sorensen (1982) indicates that the age of the Bateque Formation based on the foraminiferal assemblage ranges from early Eocene at the base, to middle Eocene near the top. Mixed shallow- and deep-water faunas indicate middle- to upper-bathyal water depths. Shallow-water megafossils also suggest downslope transport of sediment (Sorensen, 1982).

The geologic map of Mina (1957) shows flat-lying, yellowish-brown, fine-grained sandstone and Discocyclinid-bearing siltstone exposed on the south side of the mouth of Arroyo Mezquital, as the Tepetate Formation of Eocene age (fig. 4). We suggest that these beds should be mapped as the Bateque Formation, because the nearest outcrop of the Tepetate Formation is more than 200 km to the south (Knappe, 1974).

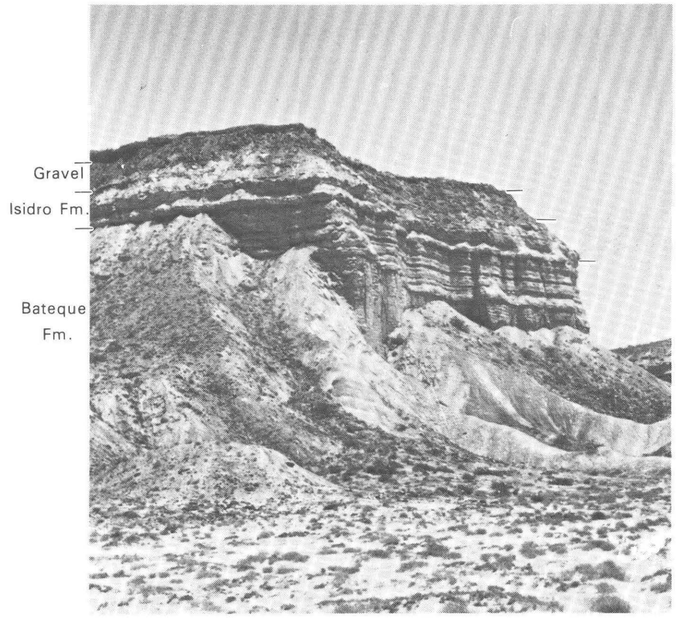

Figure 4. Eocene siltstone of the Bateque Formation overlain by fossiliferous beds of the Isidro Formation and capped by alluvial gravel. Outcrop shown is located 2 km upstream from mouth of Arroyo Mezquital.

Thickness and stratigraphic relations

The total exposed thickness of the Bateque Formation is probably between 500 and 800 m. Most dip angles are less than 5° and nowhere exceed 10°. In the northernmost part of the the San Isidro 1:250,000 quadrangle (north of Mesa El Yeso), the Bateque Formation is overlain by basalt-rich gravels of late Tertiary or Quaternary age. But at the mouth of Arroyo Patrocinio the Eocene strata are overlain by the Isidro Formation consisting of 5 to 10 m of light-gray coquina and calcareous shallow-marine sandstone of early or middle Miocene age, which is in turn capped by laterally extensive basalt that yields K-Ar ages of about 8.1 Ma (table 1, No. 1). At the bottom of Arroyo San Raymundo, the Bateque Formation is locally overlain by siliceous and phosphatic shale, diatomite, and tuff of the late Oligocene San Gregorio Formation. Most outcrops of the Bateque Formation, however, are overlain by the Isidro Formation, indicating that the San Gregorio was extensively eroded prior to deposition of the shallow-marine Miocene beds of the Isidro Formation. The tectonic significance of these stratigraphic relations is discussed in a later section.

San Gregorio Formation (Oligocene)

Distribution

The San Gregorio Formation of Beal (1948) is characterized by small outcrops along the banks and stream bottoms of the largest arroyos between Arroyo San Raymundo in the north and Arroyo La Purísima in the south (figs. 5, 6, and 7). A thickness of 72 m was measured in the bottom of Arroyo La Purísima near the base of El Pilón, just upstream from the town of La Purísima. Laminated, white-weathering diatomite, porcellaneous shale with brown fish scales, and dark gray phosphatic shale are interbedded with pelletoidal phosphatic sandstone and white vitric tuff. Phosphatic rocks weather white, but are dark gray on fresh surfaces and release a fetid petroleum-like odor when broken. X-ray analyses of siliceous porcellanite indicates that the silica phase is opal-CT (cristobalite-tridymite), rather than quartz. These rocks were first named "Monterey-beds" by Darton (1921), and then Monterey Formation by Heim (1922) based on the

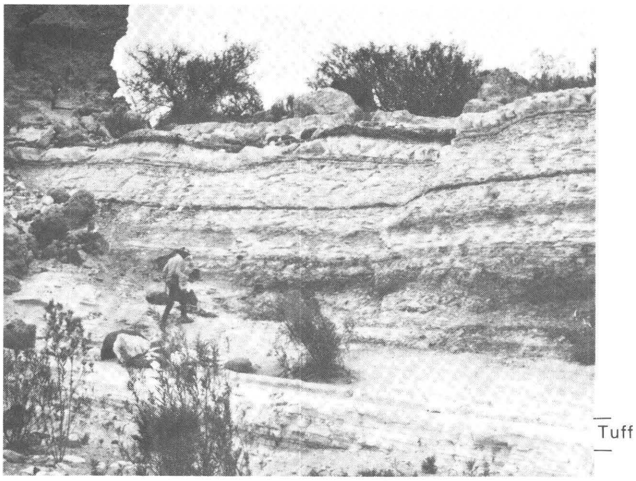

Figure 5. Porcellaneous shale, diatomite, and vitric tuff of the San Gregorio Formation. East bank of Arroyo La Purísima 16 km downstream from La Purísima.

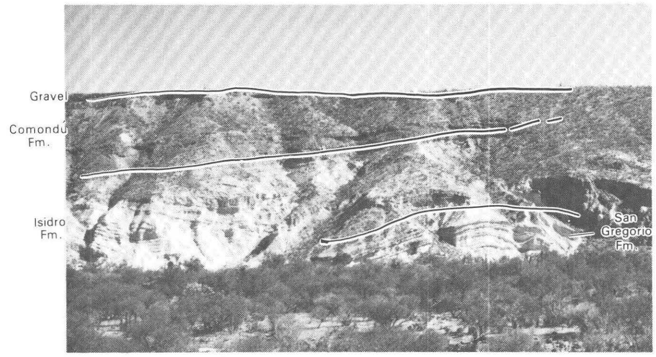

Figure 7. Folded porcellaneous shale and white vitric tuff of the San Gregorio Formation unconformably overlain by light-colored shallow-marine sandstone of the Isidro Formation and incised by a channel filled with nonmarine sandstone and conglomerate of the Comondú Formation. East bank of Arroyo San Raymundo about 16 km upstream from the main road to San Jose de Gracia (table 1, No. 9).

superficial resemblance to the Miocene Monterey Formation of California. Strata correlated with the San Gregorio Formation also crop out about 300 km south of La Purísima at San Hilario and along the west side of the Bay of La Paz at San Juan de la Costa (Hausback, 1984).

Age

Diatoms and nannofossils both indicate a late Oligocene age for the San Gregorio Formation. K-Ar ages from tuff interbeds range in age from 27 to 22 Ma and correspond to the ages of the fossils (McLean and others, 1984). The K-Ar age for the youngest tuff indicates that the formation may extend into early Miocene time (table 1, No. 9).

Diatom assemblages identified by J.A. Barron contain Rocella gelida (Mann) Bukry, indicative of a late Oligocene age. The diatom Rocella gemma reported in the San Gregorio Formation by Hanna (1930) is synonymous with R. gelida. Benthic diatoms and resting spores increase upward through the section exposed at the type locality in Arroyo San Gregorio, indicating possible shoaling of the section as deposition proceeded. The concept of late Oligocene shoaling is supported by the inferred shallow water depths of the overlying Isidro Formation, whose age is probably early Miocene at its base.

Rare molds of planktic foraminifers were found (probably Globigerina bulloides, or G. ouachitaensis); although they are not age diagnostic, they may be indicative of either a late Eocene or Oligocene age. However, the assemblage suggests upper bathyal water depths of 200-1,500 m. The residue of most samples processed for extraction of forams contains a few gastropods, ostracods, glauconite, and phosphate nodules (G. Keller and K.A. McDougall, written commun., 1983).

Coccoliths from the type locality of the San Gregorio Formation on the east bank of Arroyo San Gregorio are sparse and moderately etched, but the assemblage contains seven genera, including Discoaster. These coccoliths indicate a late Oligocene age and open marine conditions (D. Bukry, written commun., 1982).

The distribution of late Oligocene strata in Baja California Sur provides some insight into the paleogeography of the time. Open marine conditions are indicated by the rocks in the La Purísima and San Hilario areas (fig. 2), whereas shallow marine and nonmarine conditions are indicated by strata exposed

Figure 6. San Gregorio Formation on east bank of Arroyo La Purísima between towns of La Purísima and San Isidro.

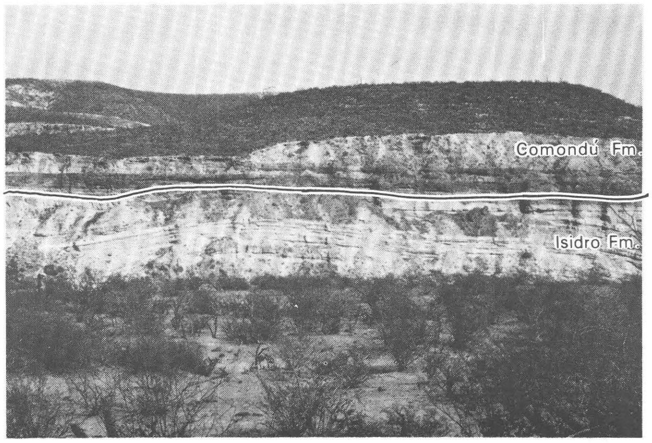

Figure 8. Gentle folds in light-colored Isidro Formation and basal part of the Comondú Formation, unconformably overlain by younger fluvial gravels of the upper part of the Comondú Formation. Location is 8 km downstream from La Purísima; viewed toward the southeast.

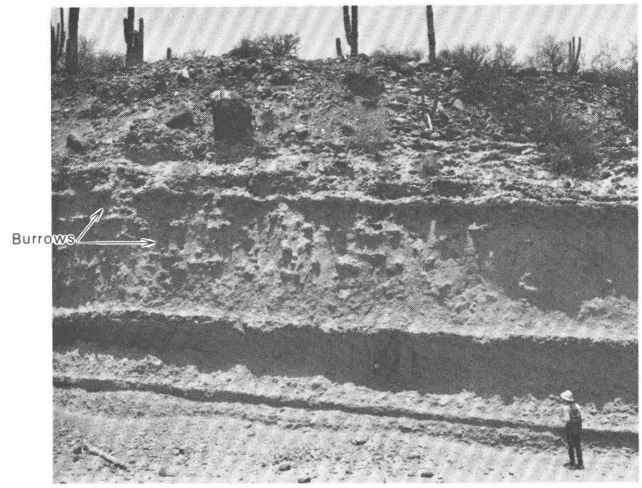

Figure 9. Heavily bioturbated sandstone and coquina of the Isidro Formation. West bank of Arroyo La Purísima at road crossing approximately 6 km northeast of La Purísima.

along the east side of the southern Sierra de La Giganta at San Juan de la Costa (lat 24°20' N.) (Hausback, 1984). Subaerial ash-flow tuffs at Punta San Telmo (lat 25°15' N.) and on the west side of the Bahía Concepción peninsula yielded K-Ar ages of 28 Ma (McFall, 1968; Hausback, 1984). The distribution of these rocks indicates westward deepening of the late Oligocene basin between 25° N. and 26°30' N. latitude, and that a shoreline may have trended northwest nearly coincident with the present crest of the Sierra de La Giganta.

Structure

The structure of the San Gregorio Formation is locally disharmonic with respect to overlying and underlying formations. Attitudes vary from gentle open folds to locally complex small-scale slump folds with steep near-vertical dips (figs. 5 and 6). The irregular distribution of the complex folding and the absence of folding in underlying strata suggests a nontectonic origin. The deformation may be related to compaction resulting from silica-phase changes during diagenesis of diatomaceous sediment (Issacs, 1981).

Isidro Formation (Miocene)

Distribution

The Isidro Formation of Heim (1922), informally named the "Yellow beds" by Darton (1921), is easily distinguished from other formations in the area by its light-yellowish-gray (almost white) color, and by massive, commonly bioturbated sandstone and white coquina containing abundant shallow-marine mollusks. From the type locality in Arroyo La Purísima (figs. 8 and 9), the Isidro Formation extends to the northwest and southeast. To the north, the formation apparently interfingers with the slightly younger San Ignacio Formation of Mina (1957) and Smith (1984). To the east, yellowish Isidro beds interfinger with brownish and grayish nonmarine siltstone and sandstone of the Comondú Formation, a predominantly nonmarine volcanic-derived sequence widely exposed throughout the Sierra de La Giganta. Marine beds of the Isidro Formation interfingering with nonmarine beds of the Comondú Formation are well-exposed at Purísima Vieja in Arroyo San Gregorio (fig. 10). Outcrops of the Isidro are also reported far to the southeast in the San Juan de la Costa area and

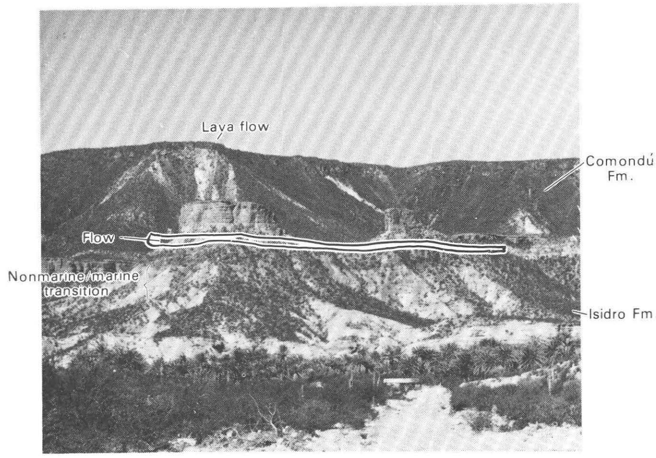

Figure 10. Basalt flow interbedded with Comondú Formation at Purísima Vieja, Arroyo San Gregorio. K-Ar age of flow is 14.5±1.2 Ma (table 1, No. 15). Light-colored marine beds at base of section belong to the Isidro Formation.

near Punta San Telmo on the Gulf coast (Beal, 1948; Escandon 1978; Hausback 1984).

In the northern part of the study area, between Arroyo Patrocinio and Batequi de San Juan, the Isidro disconformably overlies the Eocene Bateque Formation and is capped by late Miocene basalt flows that yield K-Ar ages of 8 and 10 Ma (table 1, Nos. 1 and 2).

Composition

Typical lithologies of the Isidro Formation include calcareous sandstone and siltstone, light-grayish-green porcellaneous shale, white coquina, and yellowish pebble conglomerate. Because sandstone beds in the Isidro Formation are in part derived from older strata, the composition varies from arkosic to volcanic lithic. North of Arroyo San Raymundo, the sandstone composition reflects reworking of the underlying Bateque Formation, but the Isidro Formation sandstone is readily distinguished petrographically by rounded bone fragments and phosphatic grains that are recycled from sandstone of the San Gregorio Formation. Reworking of Eocene and Oligocene sedimentary detritus into the Miocene sandstones indicates uplift and erosion of pre-Miocene beds in earliest Miocene time. Also in Isidro time, active volcanism to the east shed volcaniclastic debris westward that was locally incorporated into beds of the Isidro Formation. The diversity in sandstone composition reflects a lithologically diverse provenance.

Age

Several species of Pecten and Turritella are the most abundant molluscan fossils in the Isidro Formation, in addition to a large assortment of less numerous bivalves and gastropods. Other fossils include echinoids (sand dollars), small shark teeth, rare large shark teeth (Charcharodon megalodon, related to the great white shark), teeth and dense tusk-like bones of Desmostylus (a marine mammal that resembles the modern sea cow), and a variety of barnacles. Much data on the molluscan paleontology of the Isidro Formation have been published over the past 60 years. Most workers suggest that the fossil assemblage indicates an early to early middle Miocene age (Hertlein, 1925; Hertlein and Jordan, 1927; Smith, 1984). For an excellent summary of paleontologic reports prior to 1927, refer to Hertlein and Jordan (1927, p. 613-615).

Radiometric ages of tuff beds in the underlying San Gregorio Formation and of the overlying basalt flows indicate an early Miocene age for the Isidro Formation in the La Purísima-Cadeje area. The K-Ar data are consistent with the paleontologic age assignments. For example, the youngest tuff in the San Gregorio Formation is about 22 Ma, whereas the oldest of the overlying basalt flows are about 14 Ma (table 1, No. 15). In the Patrocinio area, the oldest capping basalts are 8 to 10 Ma. The marine fossil assemblage in the San Ignacio Formation (north of the study area along the Arroyo San Ignacio) appears to be slightly younger than the assemblage in the type area of the Isidro Formation (Smith, 1984).

Sedimentology

The assortment of lithofacies and assemblage of fossils in the Isidro Formation are consistent with an open estuarine environment, an environment that might have closely resembled that of the present Laguna San Ignacio. The diverse molluscan fauna of the Isidro Formation indicates a tropical shallow-water environment, and extensive bioturbation in sandstone and siltstone beds attests to a highly active bottom-dwelling infauna (fig. 9). Beds locally contain upright burrow casts that are as large as 3 cm wide and 9 cm long. Many of the molluscan species have tropical or Caribbean affinities, and some have north-Pacific affinities (Smith, 1984).

Coquina beds vary widely in fossil content and each bed tends to contain a dominant genus. Some beds consist mainly of Pecten shells that in turn overlie a bed of mainly Turritella, which in turn overlies a bed that contains mainly oyster shells. Unbroken shells in beds of coquina indicate subdued wave and current action, in certain areas. A second type of coquina consists of comminuted fossil hash in laminated planar beds, an assemblage that may reflect a beach environment.

Comondú Formation (Miocene)

Distribution and Thickness

The Comondú Formation, named by Heim (1922) for exposures of sedimentary rock in the walls of Arroyo Comondú near the town of San Jose de Comondú, is the most widely exposed Neogene formation in Baja California Sur and the Sierra de La Giganta. Comondú strata in the study area consist of diverse lithofacies, including fluvial sandstone and conglomerate, lacustrine mudstone, sedimentary breccia (volcaniclastic debris flows), volcanic breccia, and rare ash-flow tuffs. The lithofacies interfinger and each may be locally predominant, with the exception of the mudstone and tuffs. North of Mulegé and south of San Ignacio, rocks that are coeval with the Comondú Formation consist of andesitic volcanic breccia and lava flows (Sawlan and Smith, 1984). In the western part of the study area, the formation interfingers locally with marine beds of the Isidro Formation (fig. 11). In two localities, Comondú sandstone and mudstone is interbedded with flows of basalt (4 km south of Paso Hondo in Arroyo San Gregorio, and in Arroyo San Martin 20 km north of the confluence with Arroyo Cadeje, figs. 10 and 12; table 1, Nos. 10 and 15). Much of the Comondú Formation is overlain by basalt flows that tend to increase in number and thickness eastward toward the crest of the Sierra de La Giganta. The thickness of the Comondú Formation increases from a feather-edge in the west to at least 1,800 m along the crest of the Sierra. McFall (1968) reported a total thickness for his Comondú Group of more than 13,000 feet (4,000 m) in

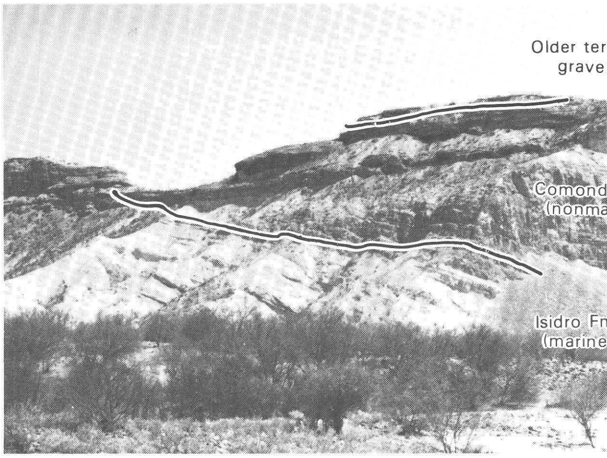

Figure 11. Gently dipping marine beds of the Isidro Formation grading upward into brown nonmarine beds of the Comondú Formation and unconformably overlain by younger flat-lying fluvial sandstone and conglomerate of the Comondú Formation. West bank of Arroyo La Purísima 5 km downstream from town of La Purísima.

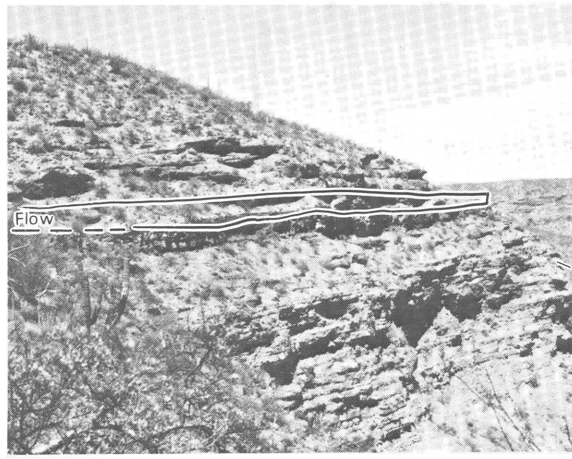

Figure 12. Basalt flow about 3 m thick, interbedded with nonmarine strata of the Comondú Formation; the flow has a K-Ar age of 12.9±0.7 Ma (table 1, No. 10). West bank of Arroyo San Martín 21 km upstream from its confluence with Arroyo Cadeje.

the Bahía Concepción area. His geologic cross sections, however, show only about 8,000 feet (2,500 m), and if allowances are made for interfingering stratigraphic relations, total thickness would decrease to approximately 2,000 m. Bed thickness, overall coarseness, and the ratio of conglomerate and breccia to sandstone increase eastward toward the core of the volcanic arc that produced the voluminous volcanogenic debris that composes the Comondú Formation. The volcanic core of the Comondú is a zone of coarse-grained andesitic breccia, flows, and coeval hypabyssal intrusives that trend approximately north-south along the crest and eastern margin of the Sierra de La Giganta (Hausback, 1984).

Previous workers do not agree on whether the volcanic rocks (mainly capping and canyon-fill flows of andesite and basalt) are part of the Comondú Formation or are part of separate formations. Different aspects of the nomenclature problem associated with the Comondú Formation and the volcanic flows are discussed by Hausback (1984), and Sawlan and Smith (1984). We prefer to follow the nomenclature suggested by Hausback (1984), that the name Comondú be restricted to "the Miocene arc-derived silicic and intermediate-composition volcaniclastics that make up the bulk of the Sierra de La Giganta and excludes the late middle and late Miocene and younger capping flows related to post-arc rifting" (Hausback, 1984, p. 226). However, the lithologic complexity of coeval rocks in the Bahía Concepción area supports the nomenclature used by McFall (1968) in the Bahía Concepción area. McFall elevated the name Comondú to group status and subdivided the group into several formations. Reconnaissance photogeology of the north part of the study area indicates that sedimentary strata of the Comondú are interbedded with monomict breccia that Sawlan and Smith (1984, p. 239) would probably include in their informal unit called the andesite of Sierra Santa Lucia.

Sedimentology

Sedimentary facies of the Comondú Formation show rapid lateral and stratigraphic variation; lenticular sandstone and conglomerate often grade into evenly bedded tabular sandstone and conglomerate (figs. 13 and 14). Lenticular sandstone and conglomerate dominate the exposures of Arroyo La Purísima near the town of La Purísima. In the same arroyo, however, about 8 to 10 km upstream from the community of San Isidro, the Comondú is mainly composed of tabular-bedded sandstone and conglomerate with laterally persistent wedge-shaped beds; these beds probably represent deposition by streams that flowed from an alluvial fan onto an alluvial plain with an estuarine embayment. Massive beds composed of poorly sorted matrix-supported conglomerate and andesitic breccia are well-exposed in the upper part of Arroyo San Pedro in the northern part of the area (fig. 15). The thickness and large clast sizes reflect proximity to active volcanic centers probably located east of the Sierra crest near the latitude of Mulegé.

Flow directions determined from cross stratification and channel orientations suggest southwest paleoflow along a system of coalescing alluvial fans. Environments of deposition include braided and meandering streams, as well as massive debris flows, or lahars. Breccia of both sedimentary and volcanic origin is also present in the Comondú section.

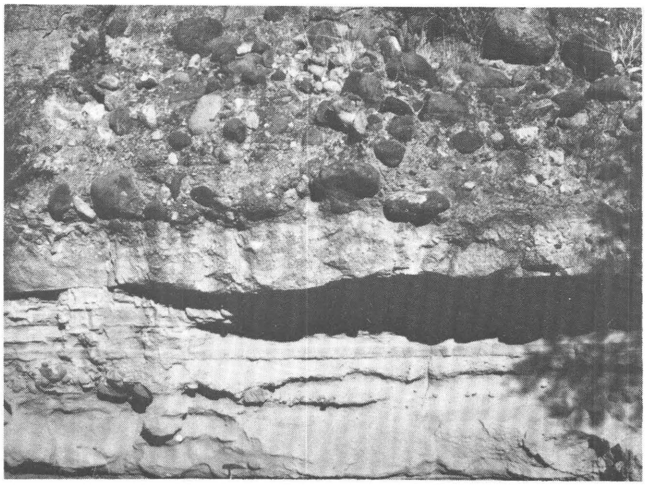

Figure 13. Example of facies variation in the Comondú Formation. Volcanic boulder conglomerate overlying tabular sandstone and conglomerate stringer illustrates variation in sedimentary facies within the Comondú Formation; hammer for scale at bottom of photograph. Outcrop shown is in Arroyo San Martín, 11.5 km upstream from its confluence with Arroyo Cadeje.

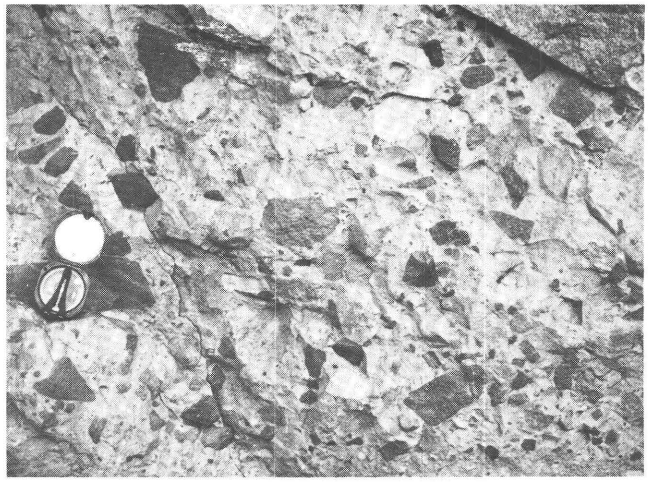

Figure 15. Outcrop of polymict andesite-tuff breccia located in Arroyo San Pedro near locality 6 shown on figure 2. Volcanic breccia in the Comondú Formation becomes predominant in highlands of the Sierra de La Giganta.

Composition

Sandstone in the Comondú Formation in the study area is mainly volcaniclastic and is composed of framework grains of distinctly zoned and partially resorbed plagioclase, andesitic and vitrophyric lithic fragments, clinopyroxene (mostly augite), and both green hornblende and oxyhornblende. Also present are small percentages of quartz and phosphatic grains and shell fragments derived from reworked underlying units. The grains are typically subrounded and unaltered, cemented by varying proportions of clay minerals and zeolites.

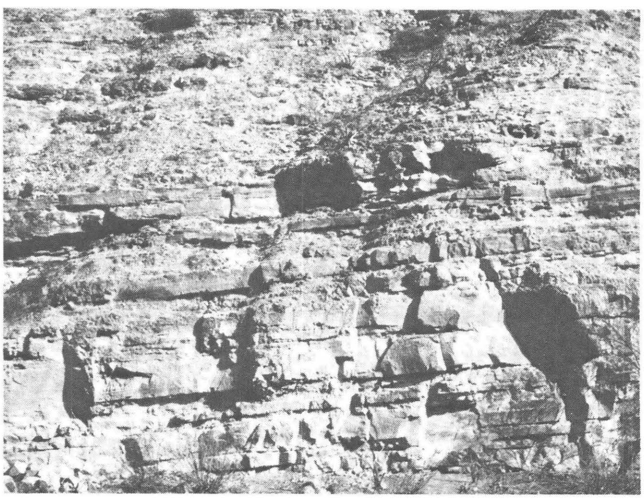

Figure 14. Tabular beds of the Comondú Formation grading upward into lenticular sandstone and conglomerate; interpreted as stream deposits. Section shown is about 16 m thick and is located in Arroyo Cadeje approximately 10 km upstream from the confluence with Arroyo San Martín.

One facies of Comondú sandstone exposed in arroyos Cadeje, San Martín, and San Raymundo has a distinctive bluish gray color that was first noted by Beal (1948, p. 74). The petrography of the sandstone indicates no unusual framework minerals; we suspect that either a clay mineral or mixture of clay and zeolite minerals in the matrix creates the bluish color. The bluish beds lie between brownish sandstone and conglomerate sequences, which results in three recognizable lithofacies of Comondú strata in the Cadeje area.

Age

The age of the Comondú Formation was determined from K-Ar ages obtained from volcanic rocks that underlie, overlie, and are interbedded with nonmarine sedimentary rocks. Hornblende andesite porphyry intrudes the Comondú outside of the study area (between Loreto and San Javier), providing a control for minimum ages. Newly reported K-Ar ages are listed in table 1. These and previously reported ages of Gastil and others (1979) and Sawlan and Smith (1984) provide fresh insight to the areal and stratigraphic-age variation of the Comondú Formation. The picture that emerges from the radiometric data is that the Comondú is as old as 20 Ma and no younger than 8 Ma, and that between 26° and 27° N. latitude the formation is older along the summit of the Sierra de La Giganta than along the Pacific coastal plain, and older in the south than in the north. The long span of time represented by the Comondú is consistent with observed lithologic and stratigraphic complexities, such as interfingering with early and middle Miocene marine strata, and intraformational angular unconformities.

Two basalt flows that are interbedded with sedimentary rocks of the Comondú Formation yield ages of about 13 and 14 Ma (table 1, Nos. 10 and 15). The younger flow is located on the west side of Arroyo San Martín at latitude 26°35' N. and lies stratigraphically in the upper one-third of the exposed Comondú Formation. The older flow is exposed on the west bank of Arroyo San Gregorio at Purísima Vieja (abandoned settlement and palm oasis located 4 km south of the town of Paso Hondo); the flow was dated previously at 13.2 ± 1.9 Ma by Gastil and others (1979). The Purísima Vieja flow is stratigraphically positioned in the lower one-third of the exposed Comondú Formation and lies about 20 m above a fossiliferous sandstone tongue of the Isidro Formation.

The section that includes sandstone, conglomerate, and volcanic-breccia members of the Comondú Formation and forms the escarpment 18 km west of Loreto has a minimum age of 20 Ma established by a K-Ar age assigned to a hornblende andesite porphyry stock that intrudes the section and forms the prominent peak of Cerro de las Parras. Gastil and others (1979, p. 847) report that the section west of Loreto at the base of the grade to San Javier contains hornblende andesite breccia of 17 to 23 Ma but give no analytical data. By comparison, the Comondú section exposed in Arroyo San Pedro near lat 27° N. yields K-Ar ages (from the base of the exposed section) of approximately 13 Ma (table 1, Nos. 6 and 7). Along the Pacific coastal plain, Comondú strata are overlain by capping flows of alkalic basalt that range in age from 8 to 14 Ma (table 1, Nos. 1,2, 18, and 21). The ages of the capping basalts suggest that most of the Comondú had been deposited by late Miocene time. Ages of lavas interbedded with Comondú strata range from 13 to 14.5 Ma and record a time dominated by fluvial sedimentation punctuated by sporadic calc-alkalic and alkalic volcanism (table 1, Nos. 6, 7, 10, and 15).

In summary, the Comondú Formation exposed along the western slopes of the Sierra de La Giganta was formed mainly by sedimentary processes associated with erosion of a calc-alkaline volcanic massif with breccia derived from local vents, and by local alkalic volcanic flows. Ages of andesite breccia and flows of alkalic basalt overlap from about 14 to 12 Ma. Most of the Comondú sequence was deposited before the outpouring of mesa-capping flows between 12 or 13 Ma and 7 or 8 Ma. Radiometric ages of flows that overlie the Comondú Formation on the Pacific coast plain are several million years younger than ages of rocks that intrude the formation along the crest of the Sierra de La Giganta.

Ground Water

Most of the fresh water springs, seeps, and shallow hand-dug wells flow from the Comondú Formation. Traverses along the major arroyos in the region indicate that strata of the Isidro and San Gregorio Formations are relatively impermeable to ground-water flow, and that existing springs and wells are often located close to the basal contact of the Comondú with the underlying formations; examples of this phenomenon are located, from north to south, at Rancho Patrocinio, San José de Gracia, Arroyos San Raymundo, San Martín, Cadeje, Mezquital, and San Gregorio.

The largest fresh water springs are located in the upper parts of Arroyo San Martín and Arroyo La Purísima. Both springs lie close to the geographic axis of the Baja peninsula and flow southwest toward the Pacific Ocean, supplying irrigation water for downstream agriculture.

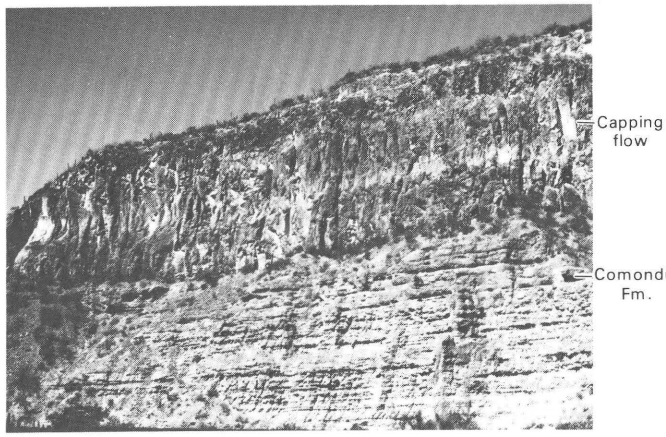

Figure 16. Columnar flow overlying tabular sandstone facies of the Comondú Formation. East wall of Arroyo La Purísima 11 km upstream from San Isidro.

Miocene Volcanic Rocks

Distribution

Lava flows cap much of the highland area of the Sierra de La Giganta, as well as several of the broad mesas in the coastal area, including Mesa El Yeso, Mesa Las Salinas, Mesa Las Gallinas, and Mesa La Cordillera (see McLean and others, 1985, for geographic locations). Most flows overlie sedimentary rocks of the Comondú Formation (figs. 16 and 17) but the coastal mesa-capping basalts also overlie the Isidro and Bateque Formations. In the vicinity of Punta Pequeña, lava flows extend to the shoreline and pillow lava is well exposed in the sea cliffs at the fishing village of San Juanico.

In the highlands of the Sierra de La Giganta, the capping flows reach thicknesses of as much as 400 m. Sections of flow rocks tend to thicken toward the crest of the Sierra, but most flows do not extend eastward as far as the crest. A series of flows appears to have flowed southwest from a source north of Arroyo San Raymundo. South of Arroyo San Martín, another series flowed southwestward from near the crest of the Sierra. Capping flows are absent in the highlands between Arroyos San Raymundo and San Martín; the

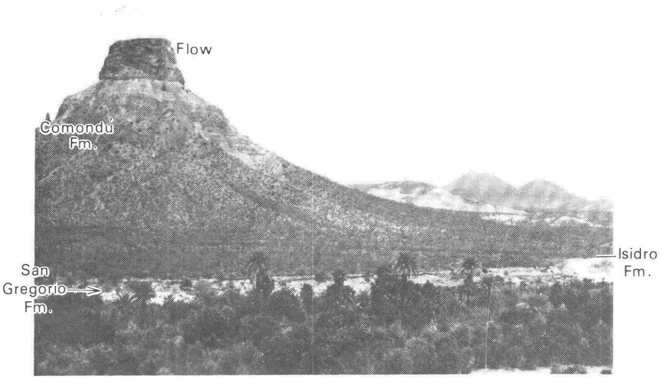

Figure 17. Erosional remnant of a capping flow overlying Comondú Formation on El Pilón in Arroyo La Purísima. Beds of the San Gregorio Formation crop out along the stream bottom behind palm trees.

distribution of flows shows clearly on color Landsat photos of the region.

The steplike distribution of basalt flows along many of the major arroyos gives the impression that the flows are interbedded with the sedimentary rocks of the Comondú Formation. However, close field inspection, confirmed by radiometric ages, indicates that the topographically highest flows are older than the canyon-filling flows at lower elevations. Eruption of the younger flows appears to have occurred after the present arroyo system began to form because the arroyos control the distribution of the flows.

Flows with roughly circular outcrop patterns overlie the Comondú Formation in the northern part of Mesa El Bule. These flows are similar to flows of Pleistocene age near Cadeje that form Cerro La Piedra Rodada (table 1, Nos. 13 and 14), but the Mesa El Bule flows are several million years older with a K-Ar age of 7.4 Ma (table 1, No. 4).

Composition

Chemical analyses indicate that most of the middle and late Miocene flows are alkalic basalts (Demant, 1975; Gastil and others, 1979; Hausback, 1984; and Sawlan and Smith, 1984). Many of the coastal mesa-capping flows are low-potassium tholeiitic basalt (Sawlan and Smith, 1984). Flows in the study area tend to be fine-grained, holocrystalline, and slightly porphyritic. Phenocrysts (without respect to age or chemistry) include zoned calcic plagioclase, pigeonite, augite, olivine, and opaque oxides. Accessory minerals include phlogopite, oxyhornblende, and bronzite (orthopyroxene). Secondary minerals commonly include iddingsite that replaces olivine, zeolites that fill vesicles, and calcite that locally replaces groundmass glass. Some flows have trachytic textures that are highlighted by flow-oriented plagioclase microlites, and some flows have felted textures with randomly oriented microlites.

Age

The oldest mesa-capping flows that we have dated are about 14 Ma. A slightly weathered flow located on the plateau just to the south of San Isidro and Arroyo La Purísima yields a K-Ar age of 14.7 Ma (table 1, No. 21). This age is supported by another K-Ar age (14 Ma) perhaps from the same flow located approximately 3 km farther west (Sawlan and Smith, 1984). A basal flow from the capping sequence exposed on the east wall of Arroyo Guajademi, located about 11 km upstream from San Juan de Guajademi, yields an age of 12.4 Ma (table 1, No. 17) and a topographically lower canyon-filling basalt yields a slightly younger age of 11.1 Ma (table 1, No. 16). Four basalt flows that cap the coastal mesas between Arroyo Patrocinio and Arroyo San Raymundo yield ages that average about 8 Ma (table 1, Nos. 1, 2, 3, and 4).

The distribution of K-Ar ages and the fact that most flows cap Comondú sections indicates that most of the Comondú sedimentary apron was deposited prior to about 14 Ma, and that during the period between 14 and 12 Ma volcanism was contemporaneous with the latest phases of nonmarine (Comondú) sedimentation (fig. 3).

Quaternary Volcanic Rocks

Volcanic rocks of Quaternary age consist of local flows (usually less than 5 km^2) and cinder cones. The flows form topographic highs on mesas and also occur as canyon-filling units. Two prominent cinder cones overlie mesa-capping basalts about 12 km northeast of La Purísima (fig. 17). A flank eruption from the cones yields a K-Ar age of 0.86 Ma (table 1, No. 19).

A canyon-filling flow in Arroyo Agua Verde, about 13 km north of Paso Hondo, yields a K-Ar age 0.60 Ma (table 1, No. 20). Other flows downstream may be coeval. K-Ar ages from two roughly circular flows on the east and west sides of Arroyo Cadeje, located about 6 km north of the town of Cadeje, yield ages of 0.96 Ma and 0.76 Ma (table 1, Nos. 13 and 14); the latter overlies fluvial gravels that unconformably overlie lenticular fluvial sandstone and conglomerate of the Comondú Formation.

The Quaternary flows, which are shown on the geologic map of McLean and others (1985), are located between Cadeje and Arroyo Agua Verde and are aligned along a trend (N. 80° E.) that extends for a distance of more than 30 km and is oriented almost perpendicular to the regional trend of the Sierra de La Giganta.

STRUCTURAL AND STRATIGRAPHIC RELATIONS

The structure of the western Sierra de La Giganta is characterized by flat-lying, gently dipping beds, and distinctive formation boundaries (figs. 18 and 19). But on a local scale this simple picture is complicated by small folds, faults, and gradational contacts (figs. 7, 11, 20, and 21).

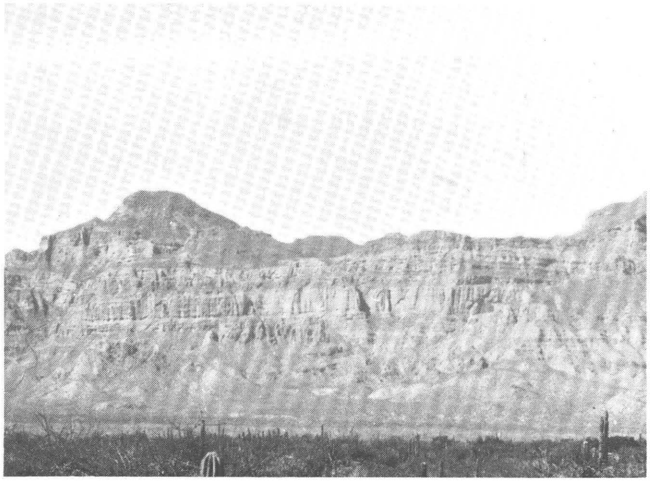

Figure 18. Strata of the Comondú Formation constituting the eastern escarpment of the Sierra de La Giganta about 30 km northwest of Loreto. Elevation of left peak is 1,690 m and rises 1,600 m above plain in foreground.

Folds

A prominent anticline in the Bateque Formation, with gentle flank dips and a northwest-trending axis, lies along the lava-capped coastal mesas. The axis is represented stratigraphically by a paraconformity between the Bateque Formation and the overlying Isidro Formation. The fold axis is also shown on the geologic map of Beal (1948). The absence of San Gregorio strata along the crest and the presence of clasts of ripped-up siliceous shale in basal beds of the Isidro Formation indicate that uplift and erosion occurred in early Miocene time. The axes of smaller-scale open folds in the Isidro Formation also trend northwest. Fold axes are well exposed in the banks of Arroyos San Gregorio and La Purísima. Flank dips die out in overlying nonmarine beds of the basal part of the Comondú Formation (figs. 8, 11, and 21). The relations between these folds and the transition from marine to nonmarine deposition indicates that marine regression was synchronous with folding and regional uplift.

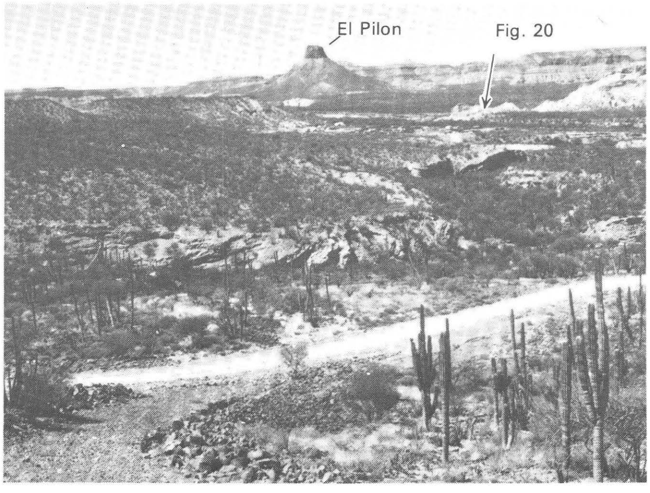

Figure 19. Overview of Arroyo La Purísima looking southwest toward El Pilon, the basalt-capped butte on the horizon. Road in foreground goes south to San Jose de Comondú.

Figure 20. Slump block of brown sandstone of the Comondú Formation in fault contact with light-colored beds of the Isidro Formation; see figure 19 for location. View is toward the north.

Figure 21. Fold in Isidro Formation overturned to the west; located on north bank of sharp bend in Arroyo La Purísima approximately 5 km downstream from La Purísima; folded beds assigned to the Purísima Nueva Formation by Heim (1922, see photograph in plate XXII). In this report the beds are assigned to the Isidro Formation. Flat-lying beds of the Isidro Formation overlie folded beds, indicating that deformation was synchronous with deposition of the Isidro Formation.

Faults

Normal faults as much as several kilometers long that displace capping flows are clearly visible on air photos. Most faults trend northwest and are most visible in the highland area close to the crest of the Sierra de La Giganta. Displacements estimated from air photos and topographic maps range from 20 m to about 100 m. The number of faults and fractures (observed on air photos and during field reconnaissance) increases dramatically east of the crest of the Sierra and may be related to tectonism associated with the opening of the Gulf of California in Pliocene and Pleistocene time.

Slump Blocks

Blocks of Comondú strata several hundred meters long have slumped down along the banks of some of the largest arroyos. Examples of slumping are well exposed along the east and west banks of Arroyo La Purísima about 2 km upstream from the town of San Isidro, where brownish rocks of the Comondú Formation have slumped downward toward the arroyo and now rest discordantly on yellowish beds of the Isidro Formation (fig. 20).

CRYSTALLINE BASEMENT ROCKS

No outcrops of granitic rock or pieces of granitic float were observed west of the crest of the Sierra de La Giganta. However, diorite and gneissic xenoliths were found in a canyon-filling basalt flow in Arroyo La Purísima, located about 6 km upstream from the town of San Isidro. The xenoliths are as much as 10 cm in diameter and are composed of either a two-pyroxene diorite or diorite granulite. Essential minerals include calcic plagioclase, aegerine(?)-augite, hypersthene, and opaque oxides. Measurements of Sr isotopes (by R.W. Kistler of the U.S. Geological Survey) indicate a range of $^{87}Sr/^{86}Sr$ values from 0.70372 to 0.70384; radiometric ages have not been determined for the xenoliths. A granodiorite outcrop on the west side of the Bahía Concepción peninsula has a biotite K-Ar age of 78.4 Ma (McFall, 1968) and a $^{87}Sr/^{86}Sr$ value of 0.70503 (R.W. Kistler, written commun. 1984). The xenoliths in the basalt flow north of San Isidro and the granitoid outcrops described above indicate that most of the Sierra de La Giganta is underlain by crystalline basement rock. Gravity and magnetic models by Coperude (1977) indicate that granitic basement extends westward to a point well beyond the Pacific coastline.

Between lat 24°30' and 28°00' N., Mesozoic granitoid rocks are mostly covered by a veneer of Tertiary sedimentary and volcanic rocks, but on the east side of the Sierra de La Giganta, granitic rocks are locally exposed in several areas, including Arroyo Las Palmas near the town of Santa Rosalia (Wilson, 1948), on the west side of the Bahía Concepción peninsula (McFall, 1968), in the low hills northwest of Loreto (Gabb, 1869; Chavez, 1978), and on several of the offshore islands between Loreto and La Paz (Mina, 1957). The granitic rocks between Santa Rosalia and Loreto may connect the peninsular batholith to the north with the granitoid rocks exposed on several islands north of La Paz and the Sierra La Laguna south of La Paz.

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