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by

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STRATIGRAPHY AND CORRELATION FOR THE ANCIENT GULF OF CALIFORNIA AND BAJA CALIFORNIA PENINSULA, MEXICO

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ABSTRACT

This paper presents the first comprehensive stratigraphic correlation charts for both the Baja California peninsula and the Gulf of California area since Durham and Allison (1960). Forty-five columns show stratigraphic or lithologic units for San Diego, California through western Baja California, Mexico, and the Salton Trough of California to the Islas Tres Marías, Nayarit, Mexico. Correlations are based on published and unpublished stratigraphic, paleontologic and radiometric data. The columns refine the chronostratigraphic context for interpreting the geologic history of the ancient Gulf of California and a series of embayments along the western Baja California peninsula. We summarize upper Mesozoic to Quaternary stratigraphy, but emphasize Tertiary marine units, including those that were described formally in accordance with the North American Stratigraphic Code (1983), informal units that were introduced without full locality and stratigraphic data, and unnamed lithologic units that need further study. The lack of detailed geologic mapping over large parts of the area accounts for much of the variation in formal stratigraphic nomenclature. Periodic reviews are needed to improve age data and constrain events in this structurally complex area, which includes the Basin and Range Province, the San Andreas Fault system, the East Pacific Rise, the Gulf Extensional Province, the Puertecitos Volcanic Province, and the California Continental Borderland. Selected references to paleontologic and radiometric data are listed in Appendix 1. They document the earliest seawater in the northern Gulf of California in late Middle or early Late Miocene time, multiple marine incursions into the Salton Trough of California, and more refined chronostratigraphic ranges for such problematic units as the Imperial Formation, Comondú Formation, Salada Formation and El Cien Formation.

RESUMEN

Se presenta la correlación y la discusión de 45 columnas que representan las unidades litoestratigráficas que han sido empleadas formal o informalmente en el área comprendida entre San Diego, California, EUA a través de la costa occidental de la Península de Baja California, México (Lámina I), y el Salton Trough, California, EUA hasta las islas Tres Marías, Nayarit, México (Lámina II). Estas columnas están basadas en información estratigráfica, paleontológica y radiométrica publicada e inédita y constituyen, después de la publicación de Durham y Allison (1960), una significativa contribución en el contexto cronoestratigráfico para interpretar la geología histórica del antiguo Golfo de California. Se resume la estratigrafía desde el Mesozoico superior hasta el Cuaternario, con énfasis en las unidades marino-terciarias, incluyendo aquéllas que no fueron descritas formalmente de acuerdo con el Código de Estratigráfico Norteamericano (1983), es decir, unidades informales que han sido introducidas sin una adecuada y completa descripción, así como unidades que necesitan ser redefinidas o reestudiadas. La falta de levantamiento geológico detallado en la mayor parte de la región ha fomentado el incremento de la nomenclatura estratigráfica. Será necesario realizar revisiones periódicas con la intención de calibrar la edad y los eventos ocurridos en esta área tectónicamente compleja, que incluye la Provincia de Cuencas y Valles, el sistema de fallas de la Falla de San Andrés, la Cuenca pacífica del Este, la Provincia Extensional del Golfo, la Provincia Volcánica de Puertecitos y el Borde Continental de California. Se ha incluido importates referencias con información paleontológica y radiométrica, documentándose así la presencia de agua marina en la región septentrional del Golfo de California, durante el Mioceno medio tardío o el Mioceno tardío, así como múltiples incursiones marinas en el área del Salton Trough, California. De igual manera, esta información proporciona alcances cronoestratigráficos más confiables para algunas unidades problemáticas como las formaciones Imperial, Comondú, Salada y El Cien.

INTRODUCTION

Heightened interest in the geology and tectonic history of the ancient Gulf of California brought more than 150 scientists from more than ten countries to Baja California and the adjacent islands in the decades from 1970 to the present. The region is an exceedingly complex plate boundary area, and invites models and topical studies in many disciplines. These require a time-stratigraphic framework, early versions of which were established for local basins over the past 80 years without regard to the overall history of the ancient Gulf and peninsula. Beal (1948), Anderson (1950), Mina-Uhink (1957), Durham and Allison (1960), López-Ramos (1973), and Gastil *et al.* (1975) published the most comprehensive correlation summaries of the area's geology. Because any time-stratigraphic context needs periodic review to incorporate new mapping and dating, we update earlier charts by modifying or constructing 45 reference columns based on our best interpretation of available paleontologic, stratigraphic and radiometric data.

Tertiary stratigraphy and biostratigraphy is our emphasis, but we include references to older units and cite studies of Quaternary deposits where available. Batholithic and pre-batholithic units were summarized by Walawender *et al.* (1991) and papers edited by Gastil and Miller (1993). Comments on Cretaceous marine units were provided by LouElla Saul (written communication, 2003).

Pleistocene data are presented in an exhaustive review of terraces along 3,000 kilometers of coastline in the gulf and Baja California peninsula; Ortlieb (1991) related terrace profiles and ages to rates of vertical motion and sea level fluctuations. A review paper by A. G. Smith *et al.* (1990) included mostly Holocene but some fossil records for the land mollusks of the Baja California peninsula, many of which are represented in the collections of the California Academy of Sciences, San Francisco, California. Taylor (1983, 1985) discussed Holocene freshwater mollusks of the lower Colorado River and eastern Salton Trough and related species to drainage patterns.

This paper summarizes current knowledge of the age and extent of important lithostratigraphic units, synthesizing data from published and unpublished sources to refine ages and to improve correlations between marine embayments and structural provinces. Ages are based primarily on paleontological data for Tertiary marine sediments constrained by Tertiary to Quaternary radiometric ages for associated volcanic units.

The geographic extent of this report is shown in Text-figure 1, from San Diego and the northern Salton Trough of California to southern Baja California Sur and the mouth of the Gulf of California. The text is organized in two sections that describe the columns from San Diego and the western Baja California peninsula (Part 1) and those from the Salton Trough, California to the Tres Marías Islands (Part 2). The embayments represented by columns are indicated in Text-figure 2. The peninsula is divided into two states at 28° N: Baja California and Baja California Sur. The last published reconnaissance geologic map for the northern state was by Gastil *et al.* (1975). Beal (1948) and Mina-Uhink (1957) provided the most recent published geological maps for the entire southern state.

Paleogeography

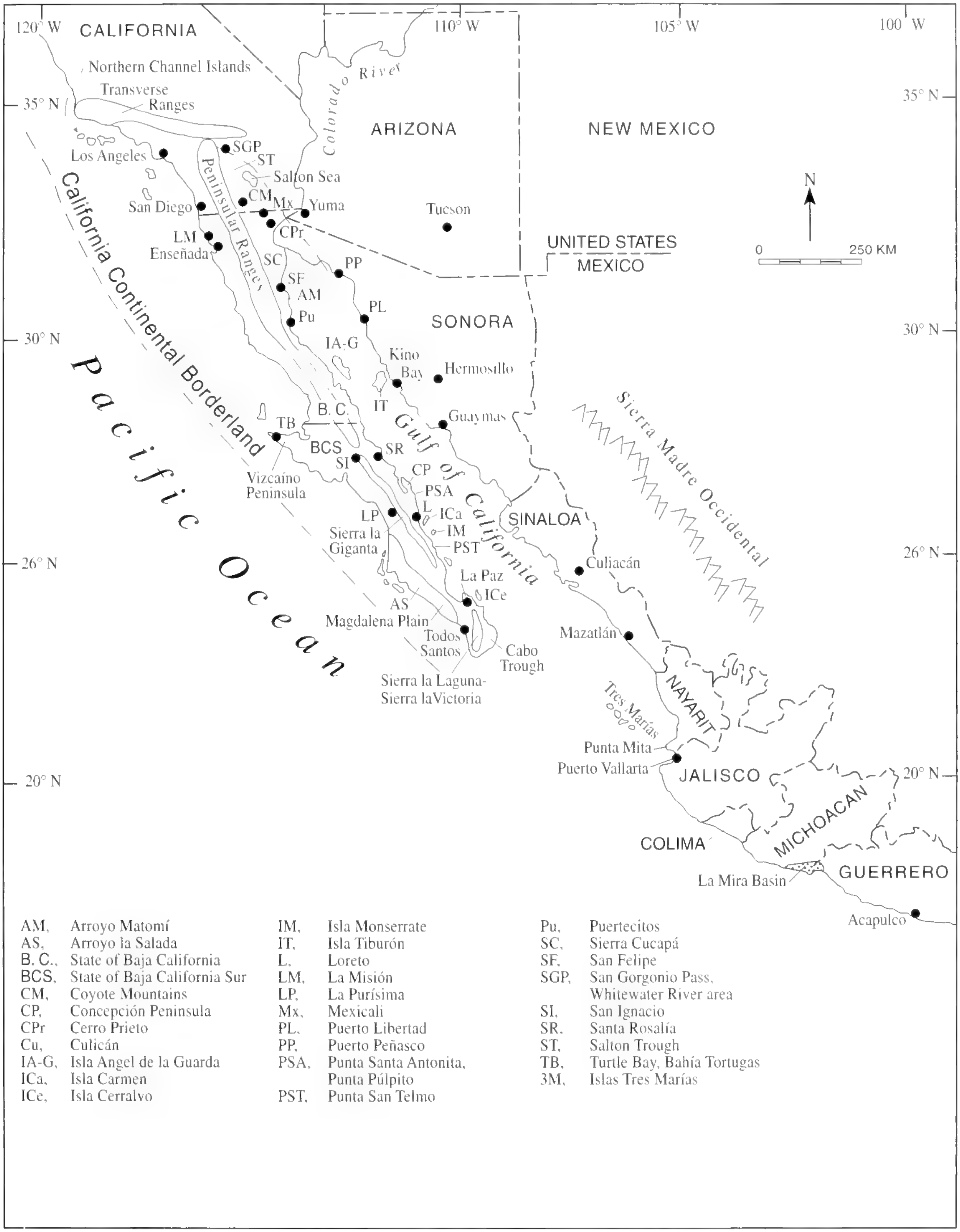
An extensive body of literature documents a time when the Baja California peninsula was attached to mainland Mexico, prior to the onset of spreading and crustal thinning approximately four million years ago (Dauphin and Simoneit, 1991). A volcanic arc occupied the area of the ancient Gulf of California from 24 Ma to 12 Ma (Hausback, 1984a,b; Sawlan, 1991). The first seawater invaded the ancient gulf as early as 12.9 million years ago (Gastil *et al.*, 1999; J. T. Smith, 1991b), before the Pacific/North American Plate boundary shifted from west of the peninsula to inside the present Gulf. The area includes or is near the Basin and Range Province, the San Andreas Fault system, a segment of the East Pacific Rise, and the Gulf Extensional Province. Discrete Neogene basins that developed in the western Gulf of California differ from each other in structural setting and chronostratigraphy; all exhibit a great variety of facies.

The western Baja California peninsula is part of the California Continental Borderland. In contrast to the Gulf side, the area was covered by extensive Cretaceous to Tertiary seas that at times extended as far east as the edge of the present Gulf of California (Text-fig. 35, p. 54). Except for the Vizcaíno peninsula, the southwest coast of Baja California was structurally homogeneous during Tertiary time; sediments were slightly warped or tilted, uplifted, then capped north of the Magdalena Plain by extensive lava flows that emanated from the central part of the peninsula.

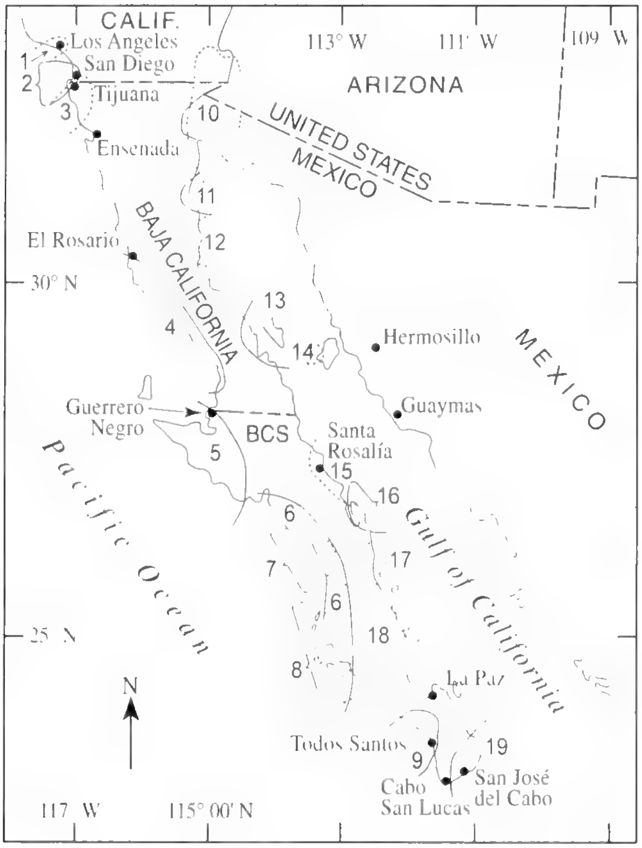
Helenes and Carreño (1999) related the Neogene sedimentary history of Baja California to the 22 structural domains defined by Fenby and Gastil (1991). Those subprovinces included an eastern protogulf from 13 Ma to 5 Ma and a modern system of pull-apart basins that began at approximately 5 Ma (Fenby and Gastil, 1991). Henry and Aranda-Gómez (2000) regarded the Middle to Late Miocene (12–6 Ma) east-northeastern extension in the Gulf, which formed the Gulf Extensional Province, as part of a broader southern Basin and Range extension.

Previous Correlations

Comparative stratigraphic columns for all of Baja California are included in the reports by Beal (1948), Anderson (1950), Durham (1950), Durham and Allison (1960), and J. T. Smith (1991c). Regional correlations were given by Helenes and Carreño (1999), McDougall *et al.* (1999) and McLean *et al.* (1985, 1987), among others. Gastil *et al.* (1975) focused on



Text-figure 1.—Ancient and modern Gulf of California and the Baja California peninsula, index map showing the principal geographic locations cited in this paper. Map modified from J. T. Smith (1991c).



Text-figure 2.—Embayments, map showing southern California, U. S. A. to Cabo San Lucas, Baja California Sur, Mexico. North to south, Plate 1: 1, Los Angeles basin; 2, San Diego embayment (Encinitas, California, to La Joya, B.C.), overlaps 3, Rosarito embayment, including Tijuana and La Misión basins; 4, Rosario embayment; 5, Vizcaíno embayment; 6, Western embayment, which includes Arroyo San Ignacio to Arroyo San Raymundo and 7, Purísima-Iray basin, and 8, Magdalena embayment; 9, Todos Santos North to south, Plate 2: 10, Salton Trough; 11, San Felipe embayment; 12, Puertecitos embayment; 13, Isla Angel de la Guarda embayment; 14, southwestern Isla Tiburón; 15, Boleo basin; 16, Concepción-San Nicolás embayment; 17, Loreto embayment; 18, Arroyo San Carlos to San Juan de la Costa, the easternmost Magdalena embayment; 19, Cabo Trough. Tobias Schwennicke (oral communication, 2003) suggested that southern Magdalena and Todos Santos embayments might once have been connected.

units and correlations for the Santa Ana Mountains, California, through the northern state of Baja California.

Darton (1921), Heim (1922), Beal (1948) and Mina-Uhink (1957) introduced a number of formation names that were subjected to much reinterpretation and in some instances misuse, leading to long periods of faulty correlations of units of different lithology, provenance and age. Because of the international interest in the area and the difficulty in obtaining some reports, this paper provides a chronostratigraphic context as a starting place for further refinement of basic data. Our comments on such problematical formation names as Imperial, Comondú, Salada and El Cien are given in the text for the embayments that include their type sections.

Historical Background

In California, William P. Blake made the earliest sketch map and geological observations of the Salton Trough and the Peninsular Ranges during explorations for the Pacific Railroad (Blake, 1857, *fide* Testa, 1996; 1858). Kew (1914), Mendenhall (1910), and Brown (1923) published early papers that included maps with fossil-collecting areas and some geology. More recent geologic maps are cited in the text that describes each column. The most important papers for early stratigraphic nomenclature in the ancient northern gulf are Vaughan (1917), Hanna (1926), Woodring (1931, 1932), Allen (1957), and Dibblee (1954, updated in 1996a). Dall (1874, 1898) and Arnold (1903) established the San Diego Formation, the first formal lithologic name in the San Diego area.

South of the border, the first traverse of the entire peninsula was made in 1867 by W. M. Gabb, on loan from J. D. Whitney and the California Geological Survey to lead one of the field parties for the J. Ross Browne Expedition. Financed by the New York and Lower California Colonization Company, the explorers went by boat to Cabo San Lucas and zigzagged north along old trails used by the indigenous people and the padres. Later known as a pioneer of California paleontology (Gabb, 1869b), he collected only a handful of paleobotanical fossils during the expedition and did not name any stratigraphic units. His official geologic report was written in June 1867 but published in a Supplementary Appendix to J. R. Browne's "Resources of the Pacific slope" (Gabb, 1869a).

Other early references to Baja California geology are contained in the papers of Lindgren (1888, 1889, 1890), Emmons and Merrill (1894), Willis and Stöse (1912), Darton (1921), and Böse and Wittich (1913). Nelson (1921) provided a good overview of the earliest surveys, natural history, roads, trails and ranchos in his report on the biological survey of 1905–1906. Access for these early Baja California expeditions was by boat and by pack animals; the Transpeninsular Highway (Mexico 1) from Tijuana to La Paz was not completely paved until December 1973.

Formational names for the principal Cenozoic sedimentary sequences of the Baja California peninsula were first proposed in the reports of the following: Darton (1921) for the Sinclair Exploration Company; Heim (1922) for a Swiss Colonization Company; Beal (1948) for the Marland Oil Company; I. F. Wilson (1948), and I. F. Wilson and Rocha (1955) for the Instituto Geológico de Mexico, the U. S. Geological Survey, and the Comité Directivo para la Investigación de los Recursos Minerales en Mexico; Anderson (1950) and Durham (1950) in the volume on the 1940 *E.W. Scripps* cruise to the Gulf of California; and Mina-Uhink (1957) for Petróleos Mexicanos (PEMEX). Other new formational names and members, some formal and some informal, were introduced by Santillán and Barrera (1930), Flynn (1970), Kilmer (1963), Carreño (1981, 1982), Minch *et al.* (1984), Ashby (1989b), Martínez-Gutiérrez and Sethi (1997), Martín-Barajas *et al.* (1997), and Ledesma-Vázquez *et al.* (1999, 2004).

Explanation of Format and Terminology

Representative stratigraphic columns are shown north to south for San Diego, California to southwestern Baja California Sur (Plate 1) and for the Salton Trough to the Islas Tres Marías, Nayarit (Plate 2). Units are plotted on the time scale of Haq *et al.* (1988). Data, in some cases summarized in tables, include author, original reference, status of formation name (formal or informal), type locality if designated, general lithologic description, geographic extent and age; where available, thickness and contacts with adjacent units are also given. Nomenclature reflects ongoing studies as well as published and unpublished reports. Subsequent papers by cited authors should be anticipated and consulted. See Appendix 1 for selected references to papers on paleontology and radiometric ages, and Appendix 2 for a list of quadrangle maps cited herein.

We have grouped the columns by embayment for convenience, realizing there is overlap in some cases; many embayments were at times more extensive and perhaps interconnected. Generally, we use "embayment" for the most extensive features, "trough" for narrower areas commonly delineated by faults, and "basin" for less extensive areas of marine outcrops.

Formally named stratigraphic units are those described in recognized, widely available scientific publications according to the rules of the North American Stratigraphic Code (1983), the most recent guideline for classifying, defining and naming of geologic units. Names that were proposed in theses, mentioned in abstracts or unpublished reports, or that were incompletely described, are included in our columns if they have come into common usage through field trip guidebooks or other regional references. We regard these as informal names of the author in question; their inclusion here does not validate them as formal names. Problems of stratigraphic nomenclature are discussed under the columns containing the type areas of formations. Our cited paleontological references include principal sources of data but are not intended to be exhaustive.

The formal classification of a formation promotes understanding based on a clear concept of the rock unit, unambiguous communication between scientists, and nomenclatural stability, especially when the unit is correlated beyond its type area or across an international boundary (the Imperial and Otay Formations, for example). Observing the rules of priority conserves well-established names and avoids the confusion of multiple formations with the same name, although the North American Stratigraphic Code (1983) advises thoughtful consideration and a clear statement of need before discarding a long-used name for an obscure earlier one. An excellent review of lithologic terminology and basic mapping procedures is given in "Manual of Field Geology" (Compton, 1985); the classic paper by Schenck and Muller (1941) discusses the differences between units of lithology (rocks), age (time), and stage (time-rock). These authors used early, middle and late subdivisions for age, and upper and lower subdivisions for stage names.

Stratigraphic Terminology

Rock units: formation, member, group

The fundamental mappable unit is a formation, whose name is based on a lithologic description and includes a designated type section (also called the stratotype) from a specific geographic locality. In cases where a single section is incomplete, a composite type locality can be designated, as is recommended by Carreño *et al.* (2000) for the Tepetate Formation. A complete description commonly includes lithologic variation, geographic extent, stratigraphic position, the nature of upper and lower boundaries, age, paleontological data if any, and prior nomenclatural history. Names should not be preoccupied by formations elsewhere within the country (North American Stratigraphic Code, 1983, articles 7b and 7c).

A member is part of a formation, a lithologic unit of lesser rank that is always defined as a subunit of a formally named formation. It can be a lens, tongue, or reef, a wedge-shaped extension of the main formation, or a separate facies, such as the Cerro Colorado Member of the El Cien Formation of Applegate (1986). A bed (or beds) is the smallest lithostratigraphic division of a sedimentary rock; it can be a distinctive marker, such as the Capas Humboldt phosphorite bed at San Juan de la Costa, or the Llajas de Palo Verde of Ojeda-Rivera (1979), a local horizon at the top of the Cerro Tierra Blanca Member of the El Cien Formation of Applegate (1986). In volcanic rocks, a flow or a tuff is the equivalent of a bed, such as the Tuff of San Felipe of Stock *et al.* (1999).

Group is the largest category of lithologic unit. It consists of two or more associated formations or a collection of named and undifferentiated lithologic units that are associated or share aspects of age, composition or history. An example from the Vizcaíno embayment is the Valle Group, which is composed of several formations that were laid down in a similar depositional setting between Cretaceous and Eocene time (D. P. Smith *et al.*, 1993a). The Poway Group, La Jolla Group, and Rosario Group of the San Diego area were originally described as formations but raised to Group status to reflect similarities in lithology and origin of the units that comprise them (Kennedy and Moore, 1971). The concept of a Group can be especially useful in small-scale mapping and regional stratigraphic analyses.

Time-rock units: stages and zones

Paleontologists use faunal stages to define packages of rocks and structures such as unconformities that represent a particular increment of geologic time. Faunal or floral assemblages define zones by which stages are recognized. They can be based upon diatoms (Barron, 1985, 1986; Barron *et al.*, 1985); foraminifers and nannofossils (Bolli *et al.*, 1985a,b; Mallory, 1959; Kleinpell, 1938, 1980; Finger, 1990); mammals (Prothero, 1995), or invertebrates (Squires *et al.*, 1988; Saul, 1983). Time-rock units are related to the geologic time scale and recognized by distinctive assemblages of index species that range throughout the given stage. The age of a rock, in contrast to its stage, is the time period, usually measured in millions or hundreds of thousands of years, during which the rock unit was formed; it can be an "absolute" number based on radiometric measures, such as 12.6 Ma for the Tuff of San Felipe, or a general range construed from paleontologic and stratigraphic constraints, such as late Middle to Late Miocene for the Tortugas Formation.

Stages can be provincial, such as the Pacific Coast Molluscan Stages, also called the West Coast Molluscan Stages (for example, the "Capay" Stage for the middle Early Eocene age sections of the Bateque Formation), or the broader European Stages (the Maastrichtian Stage for the Late Cretaceous age Rosario Formation). Vertebrate paleontologists use North American Land Mammal Stages (the Lower Arikareean Stage, Late Oligocene age Otay Formation of the San Diego area, for example). Pacific Coast Molluscan Stage names are not generally used for Neogene formations in Baja California because many of the Mexican species have closer faunal affinities with the Tertiary-Caribbean province than with California Tertiary taxa, and they require further study.

The International Commission on Stratigraphic Nomenclature continually refines global stage correlations based on particular stratigraphic sections. Their web site provides up-to-date information on Global Boundary Stratotype Sections and Points, such as the section near Rabat, Morocco, that was named the standard for the Miocene–Pliocene boundary (Benson and Rakic-El Bied, 1996). Such data are especially useful in refining the ages of a number of formations in Baja California that span the Miocene–Pliocene boundary; these include the Almejas Formation, Tirabuzón Formation, and Carmen Formation.

Stage boundaries commonly do not coincide with age (epoch) or formation (lithologic) boundaries; stages are useful for refining resolution and correlation between two formations, and distinguishing upper and lower units within a formation of a given age. They can indicate time transgressed by a formation that varies in age over its geographic extent. For example, the Bateque Formation is middle Early Eocene in age, "Capay" Stage south of Laguna San Ignacio, and late Middle Eocene age, "Tejon" Stage at its southern occurrence at the mouth of Arroyo Mezquital (Squires and Demetrion, 1992).

Informal lithologic units

We use lithologic names (Pliocene marine sandstone, basalt of Rancho Esperanza, unnamed volcaniclastic sandstone, for example) for units that are undescribed or not yet well understood. Informal names cited in this paper are not officially established by this publication.

Taxonomic Note

Published papers dealing with the taxonomy of microfossils recovered from sedimentary or volcano-sedimentary strata of Baja California are scarce, although some important publications use micropaleontology to assign ages and/or interpret paleoenvironments of the marine strata that contain them. Some of these papers do not indicate a repository for the microfossils, but many were placed in the National Museum of Natural History (*e.g.*, Pessagno, 1979, and Bukry, 1981a) or the California Academy of Sciences (*e.g.*, Hanna, 1930; Hanna and Grant, 1926; Mandra and Mandra, 1972). Microfossils listed in a number of theses were placed in the Micropaleontology Thesis Collection of the School of Earth Science at Stanford University (Boehm, 1982; Helenes-Escamilla, 1980, 1984; Kim, 1987) and at Rice University (Pérez-Guzmán, 1983). Specimens determined by Carreño (see references herein) are housed in the Micropaleontology section of the Paleontological Collection at the Instituto de Geología, Universidad Nacional Autónoma de Mexico, Mexico, D.F., where they have IGM-Microfossil numbers.

Molluscan species cited herein were determined by J. T. Smith from her collections made between 1979 and the present, and from well-illustrated type specimens in the Tertiary marine molluscan literature. Specimens from southern California and the Baja California peninsula were compared with the type and general holdings of the California Academy of Sciences and Leland Stanford Junior University, the University of California Berkeley Museum of Paleontology, Natural History Museum of Los Angeles County, San Diego Museum of Natural History, the University of Chicago, the U. S. Geological Survey, and the National Museum of Natural History. Ongoing systematic research includes redetermining earlier-named taxa that were described from a single or only a few individuals from a particular formation or basin. Many taxa have multiple synonyms that obscure their broader geographic distributions. Current investigations consider variability with growth stage and mode of preservation, refined ages of fossiliferous units with respect to associated radiometrically dated rocks, and species distributions within a broader tectonostratigraphic context. Preliminary results document a number of Tertiary-Caribbean species in Baja California and southern California and permit closer correlation between marine basins.

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The need for an updated correlation chart grew out of biennial meetings in 1991, 1993, 1995, 1997, 2000, and 2002 of the Peninsula Geological Society, or Sociedad Geológica Peninsular, which was founded in 1991 in La Paz, Baja California Sur. Our charts are the result of many collaborations with all who share an interest in the geology of Baja California. Colleagues who provided special encouragement and assistance are: Douglas P. Smith, California State University, Monterey, California; Jorge Ledesma-Vázquez, University of Baja California, Ensenada, Baja California; Sergio Cevallos-Ferriz, Luis Espinosa-Arrubarrena, and Shelton P. Applegate, Universidad Nacional Autónoma de Mexico, Mexico, D.F.; John A. Barron, Kristin McDougall, and James G. Smith of the U. S. Geological Survey; Edward C. Wilson, formerly of the Natural History Museum of Los Angeles County; Arturo Martín-Barajas, Luis Delgado-Argote, and Javier Helenes, CICESE, Ensenada, Baja California; James C. Ingle, Jr., Stanford University, Stanford, California; Tobias Schwennicke, Elvia Plata-Hernández, and Genaro Martínez-Gutiérrez, Universidad Autónoma de Baja California Sur; and Patricia A. Whalen, University of Arkansas.

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Lindsey Groves and Harry Filkorn of the Natural History Museum of Los Angeles County provided type specimen and locality information. Many librarians guided us to hard-to-find literature: Charlotte Derksen and the staff of the Stanford University Branner Earth Sciences Library and Map Collections, Martha Rosen and David Steere of the Smithsonian Institution Libraries at the National Museum of Natural History, and Thomas Carey of the San Francisco History Center, San Francisco Public Library. Natalie E. Smith arranged for copies of rare literature from special collections. We appreciate the advice of Joann Sanner, National Museum of Natural History Department of Paleobiology, and the technical assistance of M. Alcayde-Orraca, Instituto de Geología, Universidad Nacional Autónoma de Mexico. Preliminary text-figures were made by F. A. Vega; final maps were drafted in Adobe Illustrator by James G. Smith. The Dirección General de Asuntos del Personal Académico provided support through UNAM (Universidad Nacional Autónoma de Mexico) grant number IN1102995. Jamie G. Smith consulted on the photographic figures.

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na; and Señor Leonardo de la Toba, Rancho el Médano.

PART I: THE WESTERN BAJA CALIFORNIA PENINSULA

SAN DIEGO, CALIFORNIA, TO TODOS SANTOS, BAJA CALIFORNIA SUR

San Diego embayment

Geographic Overview

The San Diego embayment is an onshore Tertiary marine basin similar to the Los Angeles, Ventura, Santa Barbara, and Santa Maria embayments of southern California. It extends from north of Encinitas through the greater San Diego area and across the international boundary to several kilometers south of Playas de Tijuana and La Joya, Baja California. Structurally, this embayment lies in a graben bounded on the east by the La Nacion-Sweetwater fault system of Artim and Pinckney (1973) and on the west by offshore faults (Deméré, 1983). Cretaceous, Eocene, and Pliocene sediments of at least 1,100 m thickness overlie Mesozoic basement that includes metamorphic and granitic rocks (M. P. Kennedy, 1975; M. P. Kennedy and G. W. Moore, 1971). The Tijuana basin of the northern Rosarito embayment partly overlaps the San Diego embayment. Both embayments lie within the California Continental Borderland structural province. They are bounded on the east by the Peninsular Ranges and underlain by the same basement as the San Diego embayment. Quaternary marine terrace deposits are found along much of the coastal area.

San Diego embayment
Plate 1, Column 1

Rancho Santa Fe, California, to La Joya, Baja California, Mexico
(Text-figs. 2, 3, Table 1, Appendices 1, 2)

Column modified from M. P. Kennedy (1975) and Ashby and Minch (1984). Area shown on Point Loma, La Jolla, Del Mar, Encinitas, Rancho Santa Fe, Escondido, Poway, La Mesa, and National City quadrangles, California, and the Tijuana quadrangle, 111C69 and 111C79, 1:50,000, Baja California. Geologic maps of the area include California Division of Mines and Geology San Diego 2° sheet; M. P. Kennedy (1967), scale 1:24,000; Minch (1967); and M. P. Kennedy and G. W. Moore (1971).

Stratigraphy

Mesozoic to Paleogene basement rocks.—The oldest rocks in the area are the Santiago Peak Formation, metamorphosed rocks of Jurassic age that crop out at Black Mountain in the Poway quadrangle. They were intruded by Cretaceous plutons known collectively as the Peninsular Ranges batholith, which extends from north of San Diego to 28°N.

The Santiago Peak Formation is overlain unconformably by gently folded Late Cretaceous and Early (?) to Late Eocene rocks that are discussed by M. P. Kennedy and G. W. Moore (1971) and M. P. Kennedy (1975). These authors raised a number of formation names to group level, oldest to youngest: Rosario Group, La Jolla Group, and Poway Group. Individual formations, type locality, and age data are summarized in Table 1 and shown in Text-figure 3 and Plate 1, Column 1.

The Rosario Group, named for the Upper Cretaceous Rosario Formation, includes all the postbatholithic Mesozoic units of the San Diego embayment. Oldest to youngest, they are the Lusardi Formation, Point Loma Formation, and Cabrillo Formation. They are unconformably overlain by the Eocene La Jolla Group of six intertonguing marine and nonmarine formations, all nearly flat-lying and described from the coastal San Diego area. From oldest to youngest these are: Mount Soledad Formation, Delmar Formation, Torrey Sandstone, Ardath Shale, Scripps Formation, and Friars Formation. They are overlain by three Late Eocene Poway Group nonmarine formations: the Stadium Conglomerate, Mission Valley Formation, and Pomerado Conglomerate. An angular unconformity separates them from the overlying late Neogene San Diego Formation.

San Diego Formation, Late Pliocene–Early Pleistocene.—The area from Pacific Beach, north of San Diego, to La Joya, south of Tijuana, is underlain by discontinuous outcrops of the San Diego Formation, a fossiliferous marine Pliocene to Early Pleistocene unit named for a section along the sea cliffs at Pacific

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Text-figure 3.—Quadrangles of the San Diego embayment and northern Rosarito embayment (= northern Tijuana basin). Eastern boundary of the San Diego embayment is from M. P. Kennedy (1975). Open circles mark type sections of units described from this area (Table 1): 1, Lusardi Formation; 2, Delmar Formation; 3, Torrey Sandstone; 4, Scripps Formation; 5, Ardath Shale; 6, Mount Soledad Formation; 7, Poway Conglomerate; 8, Pomerado Conglomerate; 9, San Diego Formation; 10, Friars Formation; 11, Stadium Conglomerate; 12, Mission Valley Formation; 13, Point Loma Formation; 14, Cabrillo Formation; 15, "Black Mountain Volcanics"; 16, Otay formation, informal name; 17, Sweetwater Formation.

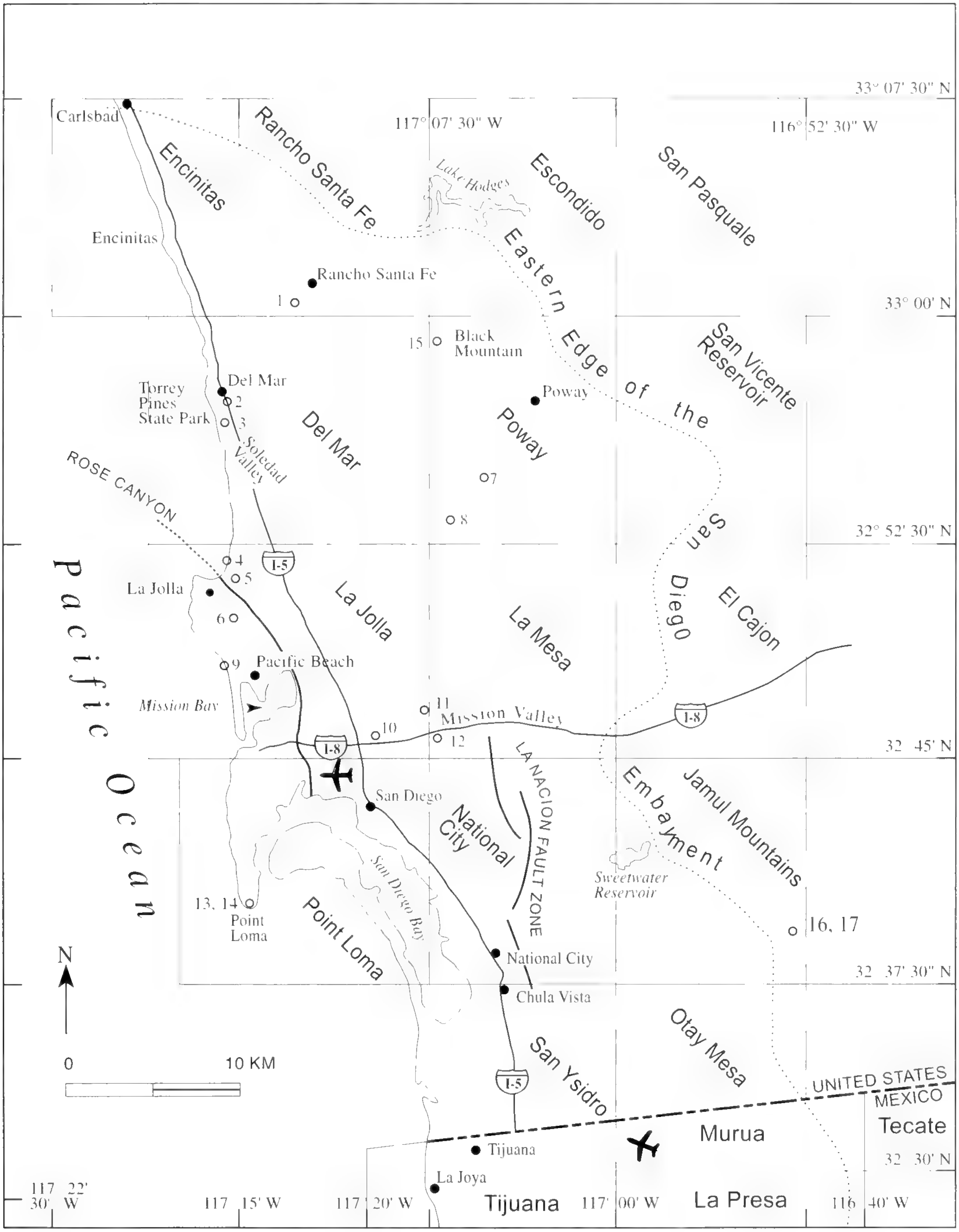

Carlsbad
Encinitas
Rancho Santa Fe
Lake Hodges
Escondido
San Pasquale
Encinitas
Rancho Santa Fe
Eastern Edge of the San Diego Embayment
1
15
Black Mountain
San Vicente Reservoir
Del Mar
Torrey Pines State Park
2
3
Poway
Soledad Valley
Del Mar
Poway
ROSE CANYON
7
8
4
5
I-5
La Jolla
Pacific Ocean
La Jolla
6
La Mesa
El Cajon
9
Pacific Beach
Mission Bay
11
Mission Valley
10
12
I-8
I-8
LA NACION FAULT ZONE
San Diego
National City
Jamul Mountains
Sweetwater Reservoir
San Diego Bay
13, 14
Point Loma
Point Loma
16, 17
National City
Chula Vista
Otay Mesa
San Ysidro
I-5
N
0
10 KM
UNITED STATES
MEXICO
Tecate
Murua
Tijuana
La Joya
Tijuana
La Presa
33° 07' 30" N
117° 07' 30" W
116° 52' 30" W
33° 00' N
32° 52' 30" N
32° 45' N
32° 37' 30" N
32° 30' N
117° 22' 30" W
117° 15' W
117° 20' W
117° 00' W
116° 40' W

Table 1.—San Diego embayment, lithostratigraphic units (Text-fig. 3). Lowercase names indicate informal units that were not established according to the North American Stratigraphic Code (1983).

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
Ardath Shale	M. A. Hanna (1926) named as member of Rose Canyon Shale; M. P. Kennedy and G. W. Moore (1971) raised to formation in La Jolla Group.	Unit is an olive-gray silty shale with thin beds of sandstone, concretions, and molluscan fossils. Type section is 70-m-thick, on the east side of Rose Canyon 800 m south of the junction of Ardath Road and Interstate 5, La Jolla 7½-minute quadrangle. Early Middle Eocene age (Bukry and M. P. Kennedy, 1969).
Bay Point Formation	Hertlein and Grant (1939).	Formation is a widespread fossiliferous marine to nonmarine sandstone described from the coastal San Diego area, California (M. P. Kennedy, 1975). Kern (1971) regarded it as a late Pleistocene (Sangamon) estuarine deposit that intertingers with a nonmarine slope wash. Molluscan index species are Late Pliocene or Early Pleistocene (G. L. Kennedy, 1973).
Cabrillo Formation	M. P. Kennedy and G. W. Moore (1971) named as formation in Rosario Group.	Massive sandstone, thin siltstone beds, and massive crossbedded cobble conglomerate with diorite clasts exposed in 81-m-thick type section on the Point Loma peninsula, 250 m east of the lighthouse, Point Loma 7½-minute quadrangle; also crops out at Pacific Beach and La Jolla. Contains the Cretaceous age, Maastrichtian Stage bivalve, "*Pharella*" *alta* (Gabb) (L. R. Saul *in* M. P. Kennedy, 1975).
Delmar Formation	M. A. Hanna (1926) named the Delmar Sand as member in La Jolla Formation of Clark (1926); M. P. Kennedy and G. W. Moore (1971) raised to formation in La Jolla Group.	Unit is a lagoonal deposit of sandy claystone interbedded with coarse-grained sandstone and well-indurated brackish-water oyster beds composed of *Ostrea idriaensis* Gabb. Described from a canyon two kilometers south of the Del Mar railroad station in the Del Mar 7½-minute quadrangle, and mapped from the subsurface as far north as Carlsbad (M. P. Kennedy, 1975). Partly equivalent to the overlying Torrey Sandstone. Middle Eocene, Domengine West Coast Molluscan Stage.
Friars Formation	M. A. Hanna (1926) included in Rose Canyon Shale Member of the La Jolla Formation of Clark (1926); M. P. Kennedy and G W. Moore (1971) raised to formation in La Jolla Group.	Formation includes a nonmarine and lagoonal sandstone and greenish-gray claystone described from a 35-m-thick section on the north side of Mission Valley near Friars Road, La Jolla 7½-minute quadrangle. Conformably overlain by the Stadium Conglomerate. Middle to Late Eocene age based on a brontotheriid tooth and the ages of associated members.
La Jolla Group	Clark (1926) named as Formation; M. P. Kennedy and G. W. Moore (1971) raised to group that includes Mount Soledad and Delmar Formations, Torrey Sandstone, Ardath Shale, Scripps and Friars Formations.	La Jolla Formation was described from La Jolla; many of the other units were described by M. A. Hanna as part of his Rose Canyon Shale Member of the La Jolla Formation. Middle Eocene age; these formations correlate with the Delicias and Buenos Aires Formations of the Tijuana basin, Baja California (Flynn, 1970).
Lindavista formation	M. A. Hanna (1926) called a terrace, not a formation; not a formal rock unit.	Nearshore marine and nonmarine terrace deposits of reddish-brown interbedded sandstone and conglomerate with reworked Poway Conglomerate clasts seen along the Lindavista Railroad siding in the La Jolla quadrangle (M. P. Kennedy, 1975). Contact with the underlying San Diego Formation unconformable or gradational, interpreted as a regressive phase of the upper part of the San Diego Formation (Peterson and Jefferson, 1971). Early Pleistocene.
Lusardi Formation	Nordstrom (1970) named as formation; M. P. Kennedy and G. W. Moore (1971) included in Rosario Group.	Unit includes boulder and cobble conglomerates with sandstone lenses exposed in the Rancho Santa Fe quadrangle at the confluence of Lusardi Creek and the San Dieguito River, three kilometers southeast of Rancho Santa Fe, in the quadrangle of the same name (M. P. Kennedy, 1975). Reported from subsurface wells at Point Loma Peninsula and overlain unconformably by the basal Point Loma Formation (G. L. Kennedy and others, 2000). Correlative with the Redondo Formation of Flynn (1970) in northern Baja California (Ashby, 1989a,b). Late Cretaceous.
Mission Valley Formation	M. P. Kennedy and G. W. Moore (1971) named as part of Poway Group.	Formation is predominantly fine-grained fossiliferous marine sandstone with a sandstone layer containing silicified wood and a cobble-conglomerate facies. Type section is exposed on the west side of Highway 163 along the south wall of Mission Valley in San Diego, La Mesa 7½-minute quadrangle. Unit thins from west to east, ends in the eastern Poway and La Mesa 7½-minute quadrangles. Late Eocene megafossils in the uppermost beds (M. P. Kennedy, 1975).

Table 1.—Continued.

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
Mount Soledad Formation	M. P. Kennedy and G. W. Moore (1971) named as part of La Jolla Group.	Unit is marine cobble conglomerate and sandstone named for a type section on Mount Soledad, at the head of an amphitheater 400 m west of the intersection of Ardath Road and Interstate 5 in the La Jolla 7½-minute quadrangle. It crops out at Pacific Beach and south of Mission Bay; it overlies the Cabrillo Formation unconformably. Middle Eocene (Deméré, 1983).
Point Loma Formation	M. P. Kennedy and G. W. Moore (1971) named as formation in Rosario Group.	Type section is marine sandstone and siltstone exposed along sea cliffs at the tip of the Point Loma peninsula, San Diego County. It crops out in La Jolla and correlates with the middle part of the Rosario Formation in northern Baja California (M. P. Kennedy, 1975). Late Cretaceous age, Campanian–Maastrichtian Stage microfossils (Sliter, 1968, 1984).
Pomerado Conglomerate	G. L. Peterson and M. P. Kennedy (1974) named as formation; M. P. Kennedy and G. W. Moore (1971) included in Poway Group.	Unit is a 10-m-thick nonmarine cobble conglomerate named for a type section along Pomerado Road on the divide between Carroll Canyon and Poway Valley, eastern Poway 7½-minute quadrangle. Late Eocene age, based on its relation to the underlying Mission Valley Formation (M. P. Kennedy, 1975).
Poway Conglomerate or Poway Group	Ellis (1919) named; M. P. Kennedy and G. W. Moore (1971) raised to Poway Group, which includes all the rocks above the La Jolla Group and below the San Diego Formation: Stadium Conglomerate, Mission Valley Formation, and Pomerado Formation.	Unit is an alluvial conglomerate, sand and shale described from a section along the south wall of Poway Valley, Poway 7½-minute quadrangle. The Late Paleocene to Late Eocene deposits contain distinctive rhyolite and dacite clasts derived from a source area near El Plomo, Sonora, in northern Mexico (Abbott and T. E. Smith, 1989). Poway clasts are also present in deep marine conglomerates on the Northern Channel Islands, where they are important markers for the reconstruction of the California Continental Borderland (Abbott *et al.*, 1983).
Rosario Group	M. P. Kennedy and G. W. Moore (1971) raised Rosario Formation to Rosario Group, which includes all Late Cretaceous post-batholithic rocks in San Diego County.	Group is based on the Late Cretaceous Rosario Formation formally described from the area of El Rosario, Baja California, 300 km south of the International boundary (Santillán and Barrera, 1930). The Group includes (oldest to youngest) the Lusardi, Point Loma and Cabrillo Formations; it crops out from San Diego to Ensenada, Baja California.
San Diego Formation	Dall (1898) and Arnold (1903), early references to the name; Arnold (1906) refined.	Unit includes a basal pebble to cobble marine conglomerate overlain by gray to yellow sandstone, silty sandstone and conglomerate; above this is a fossiliferous, silty, bioturbated sandstone. Type section is a 74-m-thick package of Late Pliocene fossiliferous sediments (Deméré, 1983) in the sea cliffs at Pacific Beach, La Jolla 7½-minute quadrangle (Arnold, 1903). Dominantly marine sediments crop out from Mount Soledad near Pacific Beach to La Joya, Baja California, and as far east as Otay Mesa (Artim and Pinckney, 1973). Many workers at different locations recognized two members: a lower Late Pliocene fine-grained sandstone and an upper, latest Pliocene to Early Pleistocene sandstone and conglomerate that grades up section to nonmarine sediments. Age ranges from Late Pliocene to Early Pleistocene (Deméré, 1983).
Santiago Peak Formation	Larsen (1948) renamed preoccupied "Black Mountain Volcanics" of M. A. Hanna (1926).	Prebatholithic, slightly metamorphosed volcanic, volcaniclastic, and sedimentary rocks were described from Black Mountain in the northwestern Poway 7½-minute quadrangle. Adams and Walawender (1982) summarized stratigraphic and age data for the unit, which crops out for 130 km from the Santa Ana Mountains in Orange County, California, to central Baja California (M. P. Kennedy and G. L. Peterson, 1975). Latest Jurassic age, Portlandian Stage, based on the index species *Buchia piochii* (Gabb), the belemnoid *Cylindroteuthis* sp., and lead-alpha ages of 150 and 155 ± 10% on a metarhyolite and a metadacite, respectively (Jones and Miller, 1982; Bushee *et al.*, 1963).
Scripps Formation	M. P. Kennedy and G. W. Moore (1971) named, included in La Jolla Group.	Type section is a sandstone with cobble conglomerate and siltstone interbeds described from a kilometer north of the Scripps Pier, north side of Black's Canyon, La Jolla 7½-minute quadrangle. The unit is also exposed from east of Del Mar to south of the mouth of Mission Valley. Middle Eocene (M. P. Kennedy, 1975).

Table 1.—Continued.

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
Stadium Conglomerate	M. P. Kennedy and G. W. Moore (1971) named in Poway Group.	Unit is a massive cobble and boulder conglomerate that contains distinctive slightly metamorphosed volcanic and volcaniclastic Poway clasts. Type section is in the northern wall of Mission Valley (along Interstate 8 near the San Diego Stadium), at the boundary between the La Jolla and La Mesa 7½-minute quadrangles. It crops out from east of Del Mar to south of the mouth of Mission Valley. Middle (?) and Late Eocene (M. P. Kennedy and G. W. Moore, 1971).
Torrey Sandstone	M. A. Hanna (1926) named as Member of La Jolla Formation of Clark (1926); M. P. Kennedy and G. W. Moore (1971) raised to formation of La Jolla Group.	White to light brown arkosic sandstone interfingers with and grades into the overlying transgressive Ardath Shale. Type section is on the Torrey Pines Grade of Highway 101 where it climbs from Soledad Valley to the south, in the La Jolla 7½-minute quadrangle. Middle Eocene, based on its association with the well-dated, interfingering Ardath Shale.

Text-figure 4.—Rosarito embayment, Tijuana basin in the north and La Misión basin in the south. Map modified from Ashby (1989b). Open circles indicate type sections: 1, Otay formation, informal name; 2, Sweetwater Formation; 3, Rosarito Beach Formation; 4, Buenos Aires Formation; 5, Delicias Formation; 6, Redonda Formation. Fault abbreviations: LNF, La Nacion Fault; LBF, Los Buenos Fault; ACF, Agua Caliente Fault. La Gloria is east of the Agua Caliente Fault and west of La Presa.

Beach. Hertlein and Grant (1944) reported a total thickness of 375 m (1,250 ft) for the formation in the Chula Vista and San Ysidro areas; Minch (1967) calculated only 85 to 90 m for the section near Tijuana, the same thickness determined by Deméré (1983) for the basin as a whole. The northernmost outcrops are west of the Rose Canyon Fault; southernmost exposures are north of the Agua Caliente Fault (Deméré, 1983) near La Joya (Text-fig. 4). The unit caps Otay Mesa in southern San Diego County, where it overlies Cretaceous and Eocene marine units of the northern Tijuana Basin.

Early records, geologic setting, paleontological, and lithological data for the San Diego Formation were summarized by Deméré (1983). Several workers recognized two members, a lower Late Pliocene fine-grained sandstone and an upper member of latest Pliocene to Early Pleistocene sandstone that includes cooler water fossils and grades upsection to nonmarine sediments. In addition to mollusks, sand dollars, and microfossils, the lower member has a rich vertebrate fauna that includes whales, dolphins, sea lions, birds, bony fishes, and sharks of the Blancan Land Mammal Stage (Deméré, 1983).

Age and correlation of the San Diego Formation.—Studies at La Joya suggest that the San Diego Formation is Late Pliocene in age (Ashby and Minch, 1984; Aranda-Manteca and Téllez-Duarte, 1989); the section correlates with the "lower member" of the unit in San Diego County as well as to the Niguel Formation of southern California (Deméré, 1983). Many of the lower member megafossils are also found in the upper part of the Almejas Formation of the Vizcaíno Peninsula, 700 km (440 mi) to the south, as well as in Late Pliocene formations in the Los Angeles, Ventura and Santa Maria basins to the north. Representative Pliocene taxa include *Pecten* (*Pecten*) *bellus* Conrad, *Lituyapecten dilleri* (Dall), *Lyropecten cerrosensis* (Gabb), *Miltha xantusi* (Dall), and the colonial barnacle *Balanus gregarius* (Conrad). Deméré (1983) noted that planktonic foraminifers correlated with data from the Deep Sea Drilling Project suggest the San Diego Formation in the Mount Soledad area is as young as the Early Pleistocene *Emiliania annula* Subzone, approximately 1.5 Ma.

Tijuana basin, northern Rosarito embayment
Plate 1, Column 2

EastLake Development, San Diego County, California, through Rosarito to Punta Descanso, Baja California

(Text-figs. 2, 4, Table 2, Appendices 1, 2)

Column modified from Flynn (1970), Ashby (1989a,b), Deméré (1988), and Walsh and Deméré (1991). The area is shown on the Jamul Mountains 7½-minute quadrangle, southwestern San Diego County, California; the Tijuana quadrangle I-11 C69 and I-11 C79; the La Presa quadrangle I-11D71, Baja California, 1:50,000; and the geologic maps of Flynn (1970) and Artim and Pinckney (1973).

Overview

The Rosarito marine embayment (Text-fig. 4) existed from the Late Cretaceous to Late Pliocene; it included the northern Tijuana basin (the EastLake Development, east of Chula Vista, California, to Punta Descanso, Baja California) and the southern La Misión basin, from Punta Ventanita to Punta San Miguel, 10 km northwest of Ensenada (Ashby, 1989b). The stratigraphic units described from these areas are generally correlative, but no member of the Rosarito Beach Formation is present in both basins. Formations, their authors, type sections, and brief descriptions are tabulated in Table 2.

Stratigraphy

Mesozoic units.—Mesozoic prebatholithic metamorphic and volcanic basement rocks and the Peninsular Ranges batholith were discussed by Gastil *et al.* (1975). They are overlain unconformably in northwestern Baja California by the Late Cretaceous Redonda Formation, a massive unfossiliferous conglomerate and breccia (Flynn, 1970), and by unconformable marine sediments of the Late Cretaceous Rosario Formation. Yeo (1984) and Ashby (1989a,b) correlated the Redonda Formation with the Lusardi Formation of the northern San Diego embayment.

Delicias and Buenos Aires Formations, Eocene.—Flynn (1970) mapped the La Gloria-Presa Rodríguez (or La Presa) area southeast of Tijuana, where he described the Early to Middle Eocene Delicias Formation, which correlates with the Del Mar Sandstone of the La Jolla Formation in San Diego County. He also described the unconformably overlying marine Buenos Aires Formation of Middle to Late Eocene age.

Sweetwater Formation, Late Eocene. Otay formation, informal name, Late Oligocene.—Northwest of the Presa Rodríguez-La Gloria region the international boundary area is underlain by the nonmarine Late Eocene Sweetwater Formation and Late Oligocene Otay formation, both described from southern San Diego County (Artim and Pinckney, 1973) and revised by Walsh and Deméré (1991). Although they are nonmarine, they are included in the northernmost Tijuana basin because their type areas lie east of the San Diego embayment.

Before the vertebrate fossil localities were discovered, the nonmarine clastic rocks were mapped together as Miocene sediments. Later, the lower beds were recognized as the Sweetwater Formation of Late Eocene age based on Uintan and/or Duchesnean Stage land mammals (Walsh and Deméré, 1991). The conglomeratic and gritstone facies that were formerly included in the upper part of the section were remapped as disconformable and referred to the Otay formation (informal name). Otay formation vertebrate fossils, termed the "EastLake local fauna" by Deméré (1988), include a number of Late Oligocene age, Lower Arikareean Stage mammals such as the oreodont *Sespia*, a few reptiles, and birds.

Publications prior to 1988 commonly included or correlated the Otay formation with the Miocene Rosarito Beach Formation of Minch (1967), but the "EastLake local fauna" is considerably older. The vertebrates correlate the unit with the Tecuya Formation of the San Emigdio Mountains and the upper Sespe Formation in southern California, and with the John Day Formation of Oregon (Deméré, 1988).

Rosarito Beach Formation, Middle to Late Miocene.—Minch (1967) and Minch *et al.* (1984) described the Rosarito Beach Formation and a number of members from the Rosarito area in the Tijuana basin. Oldest to youngest they are: Mira al Mar, Costa Azul, Amado Nuevo, Las Glorias and Los Buenos Members. Their authors and type sections are listed in Table 2. The Mira al Mar unit yielded Middle Miocene marine fossils, including diatoms (Scheidemann and Kuper, 1979) and mollusks (Minch, 1967) that correlate it with the Los Indios Member of the La Misión basin to the south (Ashby, 1989a,b). The Costa Azul Member includes a basalt with a K/Ar age of 14.3 ± 2.6 Ma (Hawkins, 1970).

Table 2.—Rosarito embayment, Tijuana and La Misión basins, lithostratigraphic units (Text-fig. 4). Lowercase names indicate informal units that were not established according to the North American Stratigraphic Code (1983).

Lithostratigraphic unit/ Basin	*Author, reference*	*Lithologic description, type locality, age*
Amado Nuevo Member/Tijuana basin	Minch (1967) described as member in Rosarito Beach Formation	Unit consists of massive to scoriaceous basalts with a thick ash bed 100 ft above the base. It crops out north of Rosarito Beach approximately 2.5 km south of Escuela Amado, on north slope of large canyon near the Agua Caliente Fault, El Rosarito quadrangle, Baja California. Miocene.
Buenos Aires Formation/Tijuana basin	Flynn (1970).	Formation has two members: a lower 70-m-thick cobble to boulder conglomerate with sandstone and mudstone matrix, and an upper 60- to 80-m-thick white to tan marine fossiliferous sandstone that grades laterally to arkosic sandstone and mudstone. Type section is in the La Gloria-La Presa Rodríguez area southeast of Tijuana (Text-fig. 4, area between La Presa and the Agua Caliente Fault). It is exposed on the grade leading from Valle Cuero de Venado toward Rancho Buenos Aires, La Presa quadrangle. Unit crops out from Rancho Delicias to the mesas of the Sierra Juárez and overlies the Delicias Formation with unconformity. Middle to Late Eocene.
Costa Azul Member/ Tijuana basin	Minch (1967) named as member in Rosarito Beach Formation.	Member consists of basalt and tuffaceous interbeds. Type area is inland from La Joya, Baja California, El Rosarito quadrangle; it extends from 90 m (300 ft) due east of Rancho José to the ridge top, mostly west of the Los Buenos Fault. Miocene, based on a basalt dated at 14.3 ± 2.6 Ma (Hawkins, 1970).
Delicias Formation/ Tijuana basin	Flynn (1970)	Formation has two members, a lower mudstone and an upper sandstone, named from the La Presa quadrangle, Baja California. Type section for the lower member is 4 km southeast of Rancho Delicias on the grade below Rancho Buenos Aires; the upper member was described from an amphitheater south of Rancho Delicias, 5–6 km southwest of Mexico 2 between Tijuana and Tecate, Baja California. Early to Middle Eocene.
Descanso member, informal name/La Misión basin	Ashby (1989a,b) used name informally as part of Rosarito Beach Formation.	Member is a mesa-capping conglomerate that is well-exposed on the northeast corner of Mesa de los Indios northeast of La Misión. Measured type section is well-described in Ashby (1989a) from "... those exposures on the slope near the gate on the road to the top of Mesa de los Indios, just north of Juncalito," Primo Tapia quadrangle. Interbedded with, also overlies, upper part of the Los Indios Member of the Rosarito Beach Formation. Middle Miocene.
La Misión Member/ La Misión basin	Minch *et al.* (1984) named as member of Rosarito Beach Formation.	Basalts and tuffs of the southern outcrop area of the Rosarito Beach Formation were named from a type section on the old Highway 1 grade south of the town of La Misión, Primo Tapia quadrangle. Lower part consists of olivine basalt flows that overlie the Rosario Formation; the upper porphyritic basalt flow was dated at 16.1 ± 2.1 Ma (Gastil *et al.*, 1975). Both facies thin to the east. Early Middle Miocene.
Las Glorias Member/ Tijuana basin	Minch (1967) described as member of Rosarito Beach Formation.	Member consists of tuffaceous sandstones and siltstones interlayered with basalts. Type section is just north of Rosarito Beach near the head of the highway grade, approximately 2 km, 375° W of the town of Las Glorias, El Rosarito quadrangle. Late Middle Miocene.
Los Buenos Member/ Tijuana basin	Minch (1967) named as member of Rosarito Beach Formation.	Unit consists of olivine basalts, pyroclastic, and clastic sediments that include thin sandstone and siltstone interbeds and a tuff layer at the top. Type section is in the El Rosarito quadrangle west of Escuela los Buenos, on the north side of the canyon. The youngest member of the Rosarito Beach Formation is Miocene.
Los Indios Member/ La Misión basin	Minch *et al.* (1984) named as member of Rosarito Beach Formation. Ashby (1989a,b) mapped type area and measured sections.	Member consists of abundantly fossiliferous marine and nonmarine volcaniclastic sediments and tuffs. Type section is in a quarry approximately 6½ km northeast of La Misión at the southwest end of Mesa de los Indios, Primo Tapia quadrangle. Its large, diverse vertebrate assemblage was termed the "La Misión Local Fauna" (Deméré *et al.*, 1984). Middle Miocene, constrained by an overlying volcanic unit dated at 14.3 ± 2.6 Ma (Hawkins, 1970), and a porphyritic basalt flow in the underlying Medio Camino Member dated at 16.1 ± 2.1 Ma (Gastil *et al.*, 1975; Minch *et al.*, 1984).
Medio Camino member, informal name/ La Misión basin	Ashby (1989a,b) used name informally as member of Rosarito Beach Formation.	Type section of tuff, basalt, and sandstone is exposed at Medio Camino along the beach between Punta Mezquite and Cañón El Descanso, Primo Tapia quadrangle. It underlies the Middle Miocene La Misión Member, which contains a porphyritic basalt flow dated at 16.1 ± 2.1 Ma (Gastil *et al.*, 1975).

Table 2.—Continued.

Lithostratigraphic unit/ Basin	*Author, reference*	*Lithologic description, type locality, age*
Mira al Mar Member/ Tijuana basin	Minch (1967) named as member of Rosarito Beach Formation.	Unit is a fossiliferous sandstone, limestone, and breccia. Type section is on the north slope of the second canyon near Rancho Mira al Mar, 8 km (0.5 mi) due south of the rancho, El Rosarito quadrangle. Ashby (1989b) correlated it with the Los Indios Member, the Topanga Formation of the Los Angeles basin, and the Round Mountain Silt of the San Joaquin Valley, California. Middle Miocene.
Otay formation, informal name/Tijuana basin	Artim and Pinckney (1973) did not formally designate a type section. Walsh and Deméré (1991) measured sections and described (oldest to youngest) three informal members: conglomerate, gritstone, and sandstone-mudstone members.	Unit consists of fossiliferous nonmarine volcanic and volcaniclastic rocks that crop out east of the La Nacion Fault and on Otay Mesa in the San Diego embayment and in the northern part of the Tijuana basin. Mapped east of Chula Vista in the Jamul Mountains 7½-minute quadrangle, the formation extends from 13 km north of the international boundary to an undetermined distance south of it. Deméré (1988) listed 24 terrestrial vertebrate taxa, including mammals, reptiles, and birds, as the "EastLake Local Fauna" of Late Oligocene, Early Arikareean Land Mammal Age (approximately 29 Ma). Fossils correlate these rocks with the nonmarine Tecuya Formation and upper Sespe Formation of California and the John Day Formation of Oregon.
Punta Mesquite member, informal name/ La Misión basin	Ashby (1989a,b) used as lowest member of Rosarito Beach Formation.	Breccias and tuffs in the Primo Tapia quadrangle deposits were mapped for 1½ km along the beach south of Punta Mesquite, just south of 32°10′ N and east of 116°55′ W. Late Early or early Middle Miocene, unconformable on basement rocks.
Redonda Formation/ Tijuana basin	Flynn (1970).	Unit is a massive unfossiliferous conglomerate and breccia that was described from northwest of Gran Mesa Redonda in the La Gloria-Presa Rodríguez area, east of the Agua Caliente Fault. Type section is in Arroyo Rosarito, La Presa quadrangle, where it unconformably overlies the Peninsular Ranges batholith and underlies the Rosario Formation. Late Cretaceous.
Rosario Formation/ Tijuana and La Misión basins	Anonymous (1924: 421) used but did not describe; Santillán and Barrera (1930) designated formally.	Unit is a post-batholithic marine sandstone, shale, and conglomerate described from near the coastal town of El Rosario in the quadrangle of the same name (Table 3). Flynn (1970) mapped it in the La Gloria-Presa Rodríguez area as a 75-m-thick lower arkosic sandstone with mudstone interbeds and an upper 45-m-thick gray to green mudstone containing Campanian to Maastrichtian Stage mollusks and microfossils. Late Cretaceous.
Rosario Group/ San Diego to Ensenada, Tijuana and La Misión basins	M. P. Kennedy and Moore (1971) named Group, which includes (oldest to youngest) the Lusardi, Point Loma, and Cabrillo Formations.	Group name based on the Rosario Formation described from the southern Rosario embayment near the town of El Rosario, Baja California (Table 3). Late Cretaceous.
Rosarito Beach Formation/Tijuana and La Misión basins	Minch (1967) described the formation and five members from the Tijuana basin, named five other members from the La Misión basin.	Formation consists of interbedded basalt flows, pyroclastic rocks and clastic sediments that as a whole extends from south of Tijuana to Punta San Miguel, 10 km northwest of Ensenada, and offshore on Islas Los Coronados and Isla Todos Santos. Type section is in the Rosarito area south of Tijuana. Unit is underlain unconformably by Eocene rocks, overlain by Pliocene sandstone and conglomerate of the San Diego Formation. Mostly Middle Miocene in the Tijuana basin, latest Early Miocene to Middle Miocene in the La Misión basin.
San Diego Formation/ San Diego embayment and northern Tijuana basin	Dall (1898) and Arnold (1903) made early references to unit; Arnold (1906) refined (Table 1).	Deméré (1983) reviewed the long history of this Plio–Pleistocene, largely marine unit, whose southernmost outcrops are in the Tijuana basin at La Joya.
Sweetwater Formation, informal name/ Northern Tijuana basin	Artim and Pinckney (1973) mentioned; Scheidemann and Kuper (1979) described a type section; Walsh and Deméré (1991) redefined unit.	Formation at its type section consists of a lower 42-m-thick fluvial and lacustrine mudstone with sandstone lenses that interfingers with a gritstone facies; it is overlain by a 35-m-thick red claystone (Scheidemann and Kuper, 1979). Type section is east of Chula Vista and Otay Mesa, southeastern Jamul Mountains 7½-minute quadrangle. It extends from 33 km north of the international boundary to an unknown distance south. Originally regarded as Miocene and mapped with the other nonmarine sediments, until Walsh and Deméré (1991) identified the fossil vertebrates as Late Eocene, latest Uintan and/or Duchesnean Land Mammal Ages, 37–42 Ma.

San Diego Formation, Pliocene to Early Pleistocene.—Fossiliferous sandstone and conglomerate of the San Diego Formation overlie the Rosarito Beach Formation with angular unconformity. Deméré (1983) regarded its age in the La Joya area as Pliocene–Pleistocene in this area (Table 1).

La Misión basin, southern Rosarito embayment
Plate 1, Column 3

Punta Ventanita through La Misión to Punta San Miguel, Baja California
(Text-figs. 2, 4, Table 2, Appendices 1, 2)

Column from Ashby (1989a,b), Minch *et al.* (1984). Area shown on the Primo Tapia, I11D81, and El Sauzal de Rodríguez, H11B11, quadrangles, 1:50,000; and the geologic map of Ashby (1989a), scale 1:50,000.

Overview

The southern part of the Rosarito embayment extends from Punta Ventanita, 15 km north of La Misión and the Guadalupe River Valley, to Punta San Miguel, 10 km northwest of Ensenada, Baja California. The area is important to the tectonic and sedimentary history of northwestern Baja California because it contains the type sections of Miocene sedimentary units whose source areas alternated from east to west and then east (Ashby, 1989a,b). Basement rocks are the same as in the Tijuana basin; they are overlain by the Rosario Formation, which was described from the next embayment to the south.

Stratigraphy

Rosarito Beach Formation, Early to Middle Miocene.—The La Misión area lies 75 km by toll road south of Tijuana and includes the type sections of five members of the Rosarito Beach Formation, an Early to early Middle Miocene marine unit that was described by Minch (1967) and further discussed by Ashby (1989a,b) and Minch *et al.* (1970, 1984). The five formally and informally described members crop out on or near Mesa de los Indios, east of the coastline and northeast of La Misión, Baja California. They are unconformable on prebatholithic and batholithic basement rocks, and on the Upper Cretaceous Rosario Formation. Berry and Ledesma-Vázquez (1997) recognized a waxy olive gray mudstone containing significant quantities of volcanic ash in the La Misión area; further work is needed to determine whether it is a new formation or a new, lowest member of the Rosarito Beach Formation.

From oldest to youngest, the members of the Rosarito Beach Formation in the La Misión basin are: Punta Mesquite, Medio Camino, La Misión, Los Indios, and Descanso. Some of these are informal names because full descriptions and type section designations are unpublished (see Table 2).

Correlation

The most important members of the Rosarito Beach Formation for correlation are the La Misión Member, which contains a basalt flow dated at 16.1 ± 2.1 Ma (Gastil, 1975) and the Los Indios Member, which contains abundant upper "Temblor" Stage marine megafossils and Luisian Stage benthic foraminifers (15–13 Ma). These fossils include species present in the Topanga Formation of the Los Angeles basin, the Round Mountain Silt of the San Joaquin Valley, California, and the Mira al Mar Member of the Tijuana basin (Ashby, 1989a,b). The Los Indios Member vertebrates represent the Hemingfordian Land Mammal Stage (Deméré *et al.*, 1984). The molluscan index species *Turritella ocoyana* Conrad of authors has been used to correlate the member with the Tortugas Formation, Member A of Helenes-Escamilla (1980), of the Vizcaíno embayment.

Rosario embayment
Plate 1, Columns 4, 5, 6, 7

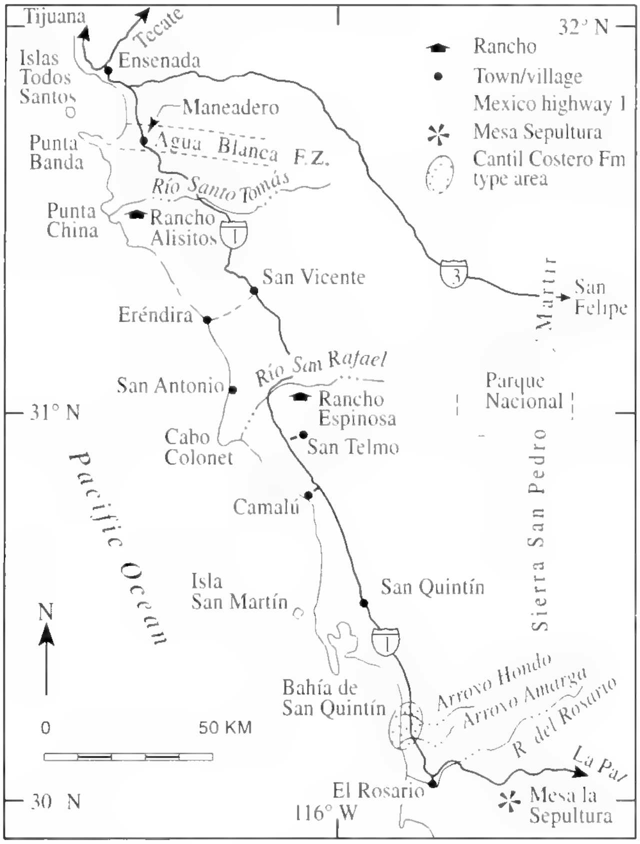
Ensenada to 28° N, state line between Baja California and Baja California Sur
(Text-figs. 2, 5, 6)

Overview

South of Ensenada the Punta Banda Peninsula projects into Todos Santos Bay, a well-known stop on field trips because of the fossiliferous outcrops of the Cretaceous Rosario Formation and La Bufadora, the gigantic blowhole on the southwest side. Punta Santo Tomás, Punta China, and the mouth of Río Santo Tomás are 25 km to the south. The Agua Blanca Fault Zone, which trends northwest on the northeast side of Punta Banda, marks the northernmost occurrence of the Alisitos Formation, an extensive arc-derived volcaniclastic unit in the southwestern part of Baja California.

The Rosario embayment extends almost as far south as the state line between Baja California and Baja California Sur and the boundary with the Vizcaíno embayment.

Fourteen marine terraces can be seen near Ensenada. Ortlieb (1991) studied their ages, rates of uplift, and correlation; uranium-series ages of corals and hydrocorals from Punta Banda ranged from 80,000 to 1.3 Ma. Rockwell *et al.* (1989) and Muhs *et al.* (1992) investigated rates of slip in the active Agua Blanca Fault Zone, which delineates the northern boundary of the Agua Blanca block.



Text-figure 5.—Rosario embayment, northern part, Ensenada to El Rosario, B.C. Santillán and Barrera (1930) named the Alisitos Formation for a section near Rancho Alisitos; they described the Cantil Costero Formation from bluffs between Arroyo Hondo and Arroyo Amarga.

Northern Rosario embayment, Ensenada to Punta China
Plate 1, Column 4
(Text-figs. 2, 5, Table 3, Appendices 1, 2)

Column after Allison (1974) and Beggs (1984). Area is shown on the Ensenada quadrangle, H11B12, Rodolfo Sánchez Taboada quadrangle, H11B22, and the Puerto San Isidro quadrangle, H11B32, scale 1: 50,000; and on the geologic maps of Gastil *et al.* (1975) and Allison (1974).

Stratigraphy

Alisitos Formation, late Early Cretaceous.—Beggs (1984) and Gastil *et al.* (1975), among others, discuss the complex history of relationships between the Alisitos Formation and the Peninsular Ranges batholith. Plutons were emplaced over a long time, some syngenetic with the Alisitos Formation and others predating or postdating it. Gastil *et al.* (1975: table 7) included plutons dated at 90 and 130 Ma.

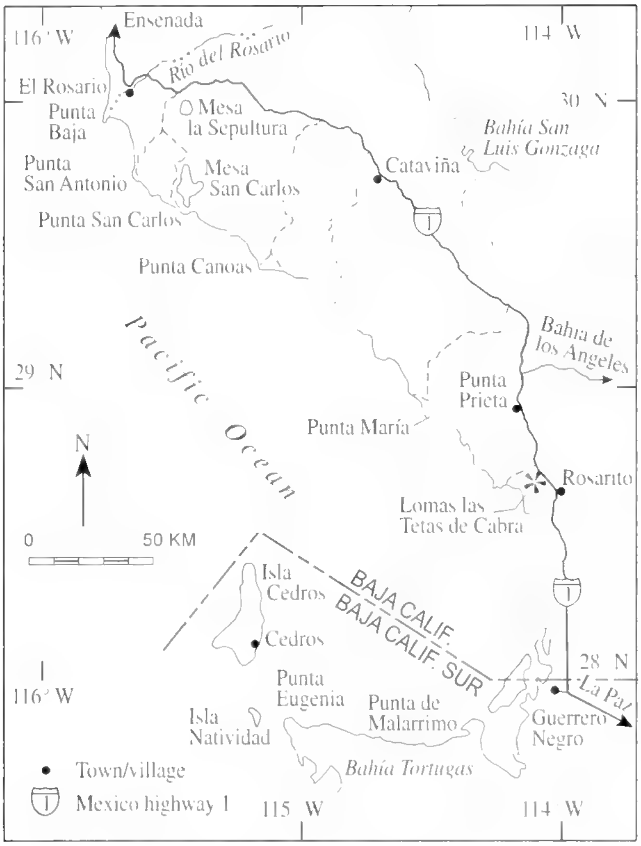
The Alisitos Formation is a sequence of volcanic and marine volcaniclastic rocks and limestones that was described from the Río Santo Tomás valley south of Ensenada. Allison (1974) mapped the type area and reported on the unit's lithologic diversity. He estimated a greater thickness than in the original description, 7,500 m for the formation as a whole, and listed a large number of late Early Cretaceous age, Albian–Aptian stage (120–99 Ma) megafossils. He recognized two facies: a lower mudstone and an upper part containing coarse andesitic breccia, tuffs, and interbedded biohermal limestone with pachydont bivalves and corals in living position.

Rosario Formation, Late Cretaceous.—The overlying Rosario Formation, named from a section in the southern Rosario embayment, crops out extensively for almost 500 km between the San Diego embayment and Punta Canoas (Text-fig. 5). These are the Cretaceous rocks mentioned by White (1885) and Lindgren (1888) that contain biostromes of the Upper Campanian to Lower Maastrichtian Stage rudistid clam *Coralliachama orcutti* White (Marincovich, 1975). Saul (1970, figs. 1–26) illustrated a number of associated shallow-water mollusks, including the gastropods *Homalopoma euryostoma* (White), *Nerita californiensis* White, and *Benoistia pillingi* (White), and the bivalves *Cymbophora* sp. aff. *C. ashburneri* (Gabb) and *Calva varians* (Gabb).

In the coastal areas the section is capped by Pleistocene terrace deposits.

San Telmo Pluton, Cretaceous.—The San Telmo Pluton was described from east of Mexico 1 in the western foothills of the Sierra San Pedro Mártir. Geologic mapping and chronology studies of the granitoid rocks by Delgado-Argote *et al.* (1995) near Rancho Espinosa identified gabbro and diorite of approximately 100 Ma, quartz monzodiorite of 92 ± 4 Ma and 82 ± 8 Ma; Böhnel and Delgado-Argote (2000) published ages of 90 Ma to 100 Ma.

Mesa sandstone, obsolete name.—In 1867, W. M. Gabb, the first geologist to traverse the entire Baja California peninsula, used ". . . mesa sandstone, as I shall call it for convenience" in field notes to describe topography, not lithology. His narrative (Gabb, 1869a) was part of J. Ross Browne's official report on the expedition, and focused on general physiography, trails, and logistics. He did not name or describe any formations, but discussed sizes and roundness of volcanic clasts. Most of the abundantly fossiliferous rocks he saw contained oysters or internal molds that are not readily differentiated from very worn Neogene and Holocene specimens. In some instances the similarities led him to estimate their ages as Pliocene.



Text-figure 6.—Southern Rosario embayment, map showing El Rosario to 28° N, including Mesa la Sepultura, Mesa San Carlos, Punta María, and Lomas las Tetas de Cabra

The mesa-forming sediments Gabb observed between La Paz and Ensenada are now referred to a number of different units, both Mesozoic and Cenozoic, sedimentary and igneous. Early workers, including Lindgren (1888, 1889, 1890), Emmons and Merrill (1894), and Willis and Stöse (1912), attached the name to Cretaceous rocks in the Ensenada area; Darton (1921) used it for rocks overlying the "Yellow beds" in Arroyo la Purísima, but did not call it a formation. Heim (1922: 530) pointed out that the "so-called Mesa sandstone" of the northern peninsula is Late Cretaceous and lithologically different from the Tertiary age "Mesa Sandstone" of the southern peninsula. As such, he concluded, the name could not be applied to a stratigraphic unit; it was neither a useful nor a valid term.

Southern Rosario embayment
Plate 1, Columns 5, 6
(Text-figs. 2, 6, Table 3, Appendices 1, 2)

The main part of the southern Rosario embayment extends from north of the town of El Rosario to Punta Canoas, north of the Baja California/Baja California Sur state line (Text-fig. 6). It is underlain by Late Cretaceous to Paleocene deep marine to nonmarine sediments that have undergone tectonic subsidence and uplift, folding, faulting, and tilting. Busby *et al.* (1998) reviewed the stratigraphic units within the tectonic and depositional settings of the Peninsular Ranges fore-arc basin. Sections at Mesa la Sepultura and Mesa San Carlos were sampled for evidence of the K/T boundary (Abbott *et al.*, 1993b), but it was not found in either sequence. Geologic maps and stratigraphic summaries of selected areas are included guidebook articles such as W. R. Morris and Busby (1996).

San Quintín to El Rosario, Baja California
Plate 1, Column 5
(Text-figs. 1, 2, 5, Table 3, Appendices 1, 2)

Column for San Quintín is from Santillán and Barrera (1930). Area shown on the Venustiano Carranza quadrangle, H11B74, and El Rosario quadrangle, H11B84, scale 1:50,000; and on the geologic map of Gastil *et al.* (1975), scale 1:250,000.

Overview

The San Quintín area, 190 km (119 mi) south of Ensenada, is known for the Quaternary San Quintín Volcanic Field. Luhr *et al.* (1995) studied the basalts, which were dated at 0.73–0.22 Ma by Aranda-Gómez *et al.* (1993). Basement rocks are overlain by the late Early Cretaceous Alisitos Formation to the east and by the Late Cretaceous Rosario Formation. A thin Pliocene marine unit caps the section south of San Quintín.

Stratigraphy

Rosario Formation, Late Cretaceous.—The Rosario Formation includes sandstones, siltstones, shales, and conglomerates that contain abundant Late Cretaceous fossils (Table 3). It crops out west of the Peninsular Ranges batholith.

Cantil Costero Formation, Late Pliocene.—The Cantil Costero Formation extends along the east side of Mexico 1, from Bahía San Quintín to Punta Baja (Johnson and Ledesma-Vázquez, 1993; Ledesma-Vázquez and Johnson, 1994). The type section is a poorly-sorted transgressive marine conglomerate that contains Late Pliocene fossils such as *Pecten* (*Pecten*) *bellus* (Conrad), *Acanthina emersoni* Hertlein and Allison, and clusters of the large barnacle *Balanus gregarius* (Conrad). The barnacle is also known from the latest Pliocene or earliest Pleistocene upper member of the San Diego Formation and from Pliocene strata of the Almejas Formation of the Vizcaíno peninsula (J. T. Smith, 1984). An abrasion platform developed on the underlying Rosario Formation is extensively bored by the Holocene pholad clam *Penitella penita* (Conrad) in concentrations of 200 individuals per square meter (Ledesma-Vázquez and Johnson, 1993).

El Rosario to Mesa la Sepultura, Mesa San Carlos, and Rosarito
Plate 1, Columns 6 and 7
(Text-figs. 2, 5, 6, Table 3, Appendices 1, 2)

Columns after Abbott *et al.* (1993a,b), Abbott *et al.* (1995), W. R. Morris and Busby (1996), Busby *et al.* (1998), and D. P. Smith (written communication, 1998). Area is shown on El Aguajito quadrangle, H11B85, Emiliano Zapata quadrangle, H11D15, Rosarito quadrangle, H11D69, 1:50,000, and on the geologic maps of Gastil *et al.* (1975); Kilmer (1963), Renne *et al.* (1991), and W. R. Morris and Busby (1996).

Stratigraphy

Units exposed in this part of the Rosario embayment are Cretaceous to Paleocene marine and nonmarine fore-arc basin deposits that overlie Late Jurassic to Late Cretaceous Peninsular Ranges plutons. Ages are from D. P. Smith (written communication, 1998).

Informal units of Kilmer (1963), Late Cretaceous.—Kilmer (1963) gave informal names to three Late Cretaceous sedimentary units in the area south of El Rosario and northeast of Punta Baja. Although he did not publish formal descriptions, the names have been used informally in subsequent literature, especially field guidebooks. The formations and members are not shown individually in Plate 1, Columns 6 and 7, because they represent a relatively short time, 73–78 Ma (L. R. Saul, written communication, 2003). Their outcrop areas were mapped by W. R. Morris and Busby (1996: fig. 4).

Brief descriptions and type section locations are given in Table 3 for the following:

"La Bocana Roja formation," Late Cretaceous.—
"Punta Baja formation," Late Cretaceous.—
"El Gallo formation," Late Cretaceous, and its three members: "La Escarpa," "El Disecado," and "El Castillo."

Rosario Formation, Late Cretaceous.—The Upper Campanian to Lower Maastrichtian Stage Rosario Formation overlies the preceding units. In this area it is divided into lower near shore deposits and an upper deep marine sequence (W. R. Morris and Busby, 1996; Busby *et al.*, 1998). A paleosol separates the top of the Rosario Formation from the overlying Sepultura Formation on the northeast side of Mesa de la Sepultura; a disconformity marks the contact at Mesa San Carlos, 40 km to the south. Faunal stage determinations are from Durham and Allison (1960).

Sepultura Formation, Paleocene.—Late Early to early Late Paleocene fan delta to submarine fan deposits of the Sepultura Formation crop out discontinuously between the towns of El Rosario and Puerto de San Carlos. Lesdesma-Vázquez (1991) studied the lower glauconitic member, which contains storm deposits and shallow-marine facies at its base that grade upward to shelf deposits of 200 m depths. Sampling at Mesa de la Sepultura to identify the K/T boundary within the unit indicated that the basal sediments contain abundant younger, Late Paleocene microfossils (Abbott *et al.*, 1993) and Upper Thanetian Stage mollusks such as *Turritella peninsularis* Anderson and Hanna (Squires *et al.*, 1989; Abbott *et al.*, 1995) and *Popenoeum maritimus* Squires, Zinsmeister, and Paredes-Mejía.

Zinsmeister and Paredes-Mejía (1988) reported considerable taxonomic diversity in the mollusks from Mesa San Carlos, ". . . comparable to coeval tropical faunas of the Gulf [of Mexico] Coast Paleocene." They noted exceptional preservation of shells, some with color patterns, and warmer water assemblages than in penecontemporaneous basins in southern California.

Correlation of the Sepultura Formation.—Fife (1968) mapped limestone outcrops at Punta María (29°00′ N, 114°30′ W) that Abbott *et al.* (1995) informally named the Punta María limestone member of the Sepultura Formation. They described the unit as a red-algal biosparrudite containing benthic foraminifers; interfingering sandstone facies bear abundant *Venericardia* and the early Late Paleocene index species *Turritella peninsularis* Anderson and Hanna. The Punta María limestone member correlates with the Los Cuervitos limestone member of the Bahía Ballenas Formation of the Vizcaíno embayment (D. P. Smith *in* Abbott *et al.*, 1995) and the Sierra Blanca Limestone of southern California.

Lomas Las Tetas de Cabra Formation, Eocene.—In the badlands 30 km south of Punta Prieta the Sepultura Formation interfingers with or grades upward to the continental Lomas Las Tetas de Cabra Formation. Novacek *et al.* (1991) described the sediments and Early Eocene vertebrates from a locality known also as Occidental Buttes (Gastil *et al.*, 1975).

Vizcaíno embayment
Plate 1, Columns 8, 9, 10, 11, 12
(Text-figs. 1, 2, 7, 10, Table 4, Appendices 1, 2)

Overview

The Vizcaíno embayment stretches almost 200 km from Isla Cedros across the Vizcaíno peninsula to Punta Abreojos, west of Laguna San Ignacio. It is under-

Table 3.—Rosario embayment, lithostratigraphic units. Ensenada to Mesa San Carlos, Baja California, including Punta China, El Rosario, and Mesa de la Sepultura (Text-figs. 5, 6). Lowercase names indicate informal units that were not established according to the North American Stratigraphic Code (1983).

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
Alisitos Formation	Santillán and Barrera (1930) named; Allison (1974) amplified original description, recognized two members. Beggs (1984) raised to Group, identified seven volcanic and volcaniclastic facies A–G.	Formation is a lithologically diverse, metavolcanic, and metasedimentary unit described from Rancho Alisitos and Arroyo la Cueva, Rodolfo Sánchez Taboada quadrangle. Clastic sediments are finer in the lower part of the section, coarser in the upper part between Punta China and Los Muertos, Puerto San Isidro quadrangle, where they occur with tuffs and interbedded rudistid limestones. Beggs (1984) classified the volcanic facies, their environments of deposition and distributions. Late Early Cretaceous (119–97.5 Ma), Albian–Aptian Stage, based on megafossils (Allison, 1974).
Cantil Costero Formation	Santillán and Barrera (1930).	Formation is a thin, flat-lying marine fossiliferous conglomerate with a sandstone matrix that caps the mesas south of San Quintín, Venustiano Carranza quadrangle. Type section is south of San Quintín and east of Mexico 1, 14–20 km north El Rosario. An abrasion platform developed on the disconformity exposed between Arroyo Hondo, km 35, and Arroyo Amargo, km 41 (Ledesma-Vázquez and Johnson, 1994). Late Pliocene.
"El Castillo member," informal name	Kilmer (1963) named as member of "El Gallo formation."	Member consists of fluvial to shallow marine sediments that crop out discontinuously in the eastern part of the Rosario embayment. They interfinger with the "El Disecado member" north of El Rosario and east of Punta Canoas. Late Cretaceous.
"El Disecado member," informal name	Kilmer (1963) named as member of "El Gallo formation."	Unit is a sequence up to 1,000 m thick of interbedded fluvial to tidal mudstones, sandstones, and minor tuffs (W. R. Morris and Busby, 1996). Exposed north and south of Río del Rosario in both eastern and western margins of the Rosario embayment, it also crops out at Punta San Antonio. The member contains a basal bentonite dated at 74.25 ± 0.07 Ma and an altered tuff higher in the section with K-Ar ages of 73.59 ± 0.9 Ma and 73 ± 2 Ma, respectively (Renne *et al.*, 1991; G. B. Dalrymple *in* W. J. Morris, 1981). Most of the vertebrates collected from the "El Gallo formation" came from this member and the interval between the dated samples. Late Cretaceous age, Upper Campanian Stage.
"El Gallo formation," informal name	Kilmer (1963), also named three informal members: "El Castillo," "El Disecado," and "La Escarpa."	Unit is a mainly nonmarine sequence of fluvial to tidal conglomerates, sandstones and tuffs more than 1,246 m thick (W. R. Morris and Busby, 1996). Its members crop out discontinuously in the eastern and western parts of the Rosario embayment, mostly (except for the "El Disecado" member) south of Río del Rosario, in the El Rosario and Punta Baja quadrangles. "El Gallo formation" overlies the "Punta Baja formation" and is overlain with angular unconformity by the Rosario Formation. It contains fossil vertebrates, including dinosaurs (bones, also casts of scales or skin), mammals and birds (W. J. Morris, 1974a; 1981). Late Cretaceous age, Upper Campanian Stage.
"La Bocana Roja formation," informal name	Kilmer (1963)	Oldest of Kilmer's Late Cretaceous units, the formation consists of more than 1,260 m of gently unfossiliferous folded fluvial sandstones, siltstones, claystones, and conglomerates (W. R. Morris and Busby, 1996). Nominal type section is exposed along the coast east of Punta Baja in the quadrangle of the same name. Unit is unconformably overlain by the "Punta Baja" and "El Gallo" formations. Early Late Cretaceous (W. R. Morris and Busby, 1996).
"La Escarpa member," informal name	Kilmer (1963) included in "El Gallo formation."	Unit consists of 800 m of coarse-grained alluvial fan and braided stream deposits (Renne *et al.*, 1991) that crop out discontinuously south of Río del Rosario as far as Punta San Antonio, El Rosario and Punta Baja quadrangles. Unconformably overlain by the "El Disecado" member. Late Cretaceous age, Campanian Stage, bracketed by $^{40}Ar/^{39}Ar$ dates of 74.87 ± 0.05 Ma for a basal bentonite and 74.46 ± 0.08 Ma for a tuff higher in the section (Renne *et al.*, 1991).

Table 3.—Continued.

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
Lomas las Tetas de Cabra Formation	Novacek *et al.* (1991).	Formation is a red and brown sandstone and siltstone described from an area known as Occidental Buttes or Las Tetas de Cabra, 1–1.5 km west of Mexico 1 and approximately 7 km northwest of Rosarito, in the quadrangle of the same name. Overlain by unnamed coarse-grained sandstone and conglomerate. Early Eocene, Wasatchian Land Mammal Stage, based on vertebrates (Novacek *et al.*, 1991), 57–51 Ma.
"Punta Baja formation", informal name	Kilmer (1963).	Unit is a series of gently undulating deep-marine conglomerates, sandstones, shales, and siltstones described from approximately one mile north of Punta Baja. W. R. Morris and Busby (1996) regarded them as bathyal submarine canyon deposits that overlie the "La Bocana Roja formation" in the western Punta Baja quadrangle. Unit is unconformably overlain by the "La Escarpa member" of the "El Gallo formation." Late Cretaceous age, lower Upper Campanian Stage, 77–74 Ma (based on an ammonite, *fide* L. R. Saul, written communication, 2003).
Punta María limestone member, informal name	Abbott *et al.* (1995) named; Fife (1968) mapped as Sepultura Formation.	Unit is a fossiliferous sandy red-algal biosparrudite and limestone with sandstone interbeds described at Punta María, Punta El Diablo quadrangle. It is regarded as the upper member of the Sepultura Formation and correlated with the Los Cuervitos limestone member of the Bahía Ballenas Formation in the southern Vizcaíno embayment (D. P. Smith *in* Abbott *et al.*, 1995). Late Paleocene.
Rosario Formation	Santillán and Barrera (1930) named; Anonymous (1924) mentioned (Table 2).	Formation was described as a sequence of sandstones, shales, and conglomerates with abundant marine invertebrates. Type section is near the town of El Rosario in the quadrangle of the same name. It is unconformable above the Alisitos Formation, unconformably overlain by the Sepultura Formation. Late Early Cretaceous, no younger than Middle Maastrichtian Stage (L. R. Saul, written communication, 2003).
San Telmo Pluton	Woodford and Hariss (1938).	Unit consists of multiple plutons described from the western foothills of the Sierra San Pedro Mártir, south of Arroyo San Rafael near Rancho Espinosa and San Telmo, Punta Colnet quadrangle. Emplacement could have occurred over a 20 m.y. period (Delgado-Argote *et al.*, 1995). Late Early Cretaceous.
Sepultura Formation	Santillán and Barrera (1930) named; Abbott *et al.* (1993) distinguished two members.	Formation is a marine sandstone alternating with conglomerates and limestones described from Mesa de la Sepultura (30°00′ N, 115°30′ W) approximately 20 km east-southeast of El Rosario, El Aguajito quadrangle. Abbott *et al.* (1993) recognized a lower megafossiliferous glauconitic-clastic member with red-algal rhodolith nodules and an upper deep-water limestone bearing foraminifers and red algae. Late Early to early Late Paleocene age at Mesa la Sepultura. Téllez-Duarte and Helenes (2002) noted a finer facies and absence of carbonates in the unit at Mesa San Carlos, where it is also Late Paleocene.

lain by rocks of Triassic to Pliocene age. It differs from the rest of western Baja California Sur in its tectonostratographic history and in the great thickness, more than 8 km, of its exposed sedimentary section (Boles, 1986; D. P. Smith *et al.*, 1993a,b).

The Vizcaíno peninsula lies west of the Peninsular Ranges and east of the offshore Tosco-Abreojos and San Benito Fault Zones. Coney *et al.* (1980) regarded it as the Vizcaíno terrane. Shallow magnetic inclinations reported in several Cretaceous units in the Vizcaíno embayment suggest 15° of post mid-Cretaceous northward translation with respect to North America (Filmer and Kirschvink, 1989; D. P. Smith and Busby, 1993), but workers continue to explore alternative interpretations to explain the data. Sedlock (1993, 2000) summarized later interpretations that recognize upper and lower convergent margin plates separated by an ophiolite. The upper plate consists of three different oceanic terranes: Choyal, Vizcaíno Norte and Vizcaíno Sur.

Unlike the Tertiary marine embayments to the north and south, the Vizcaíno embayment underwent an abrupt deepening to middle bathyal depths in the late Early Miocene, as documented by stratigraphic and paleontologic studies of the Tortugas Formation north of the town of Bahía Tortugas (Helenes and Ingle, 1979; Helenes-Escamilla, 1980).

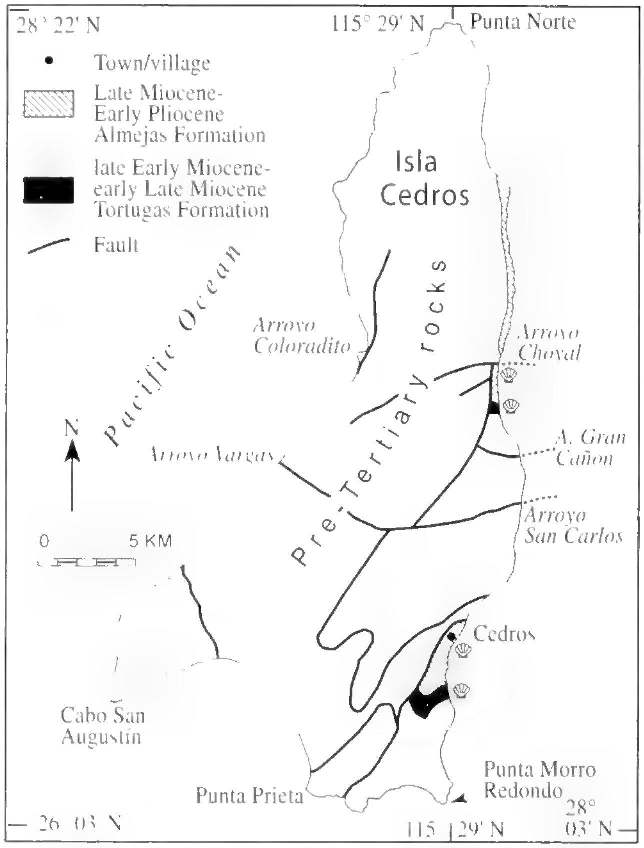
The stratigraphic units of the Vizcaíno embayment include a number of time-transgressive formations, many of which were revised as new mapping was completed. Bottjer and Link (1984), Boehlke and Abbott (1986) and Busby-Spera (1988), among others, discussed these changes.

Basement Rocks of the Vizcaíno embayment.—Metamorphic basement rocks, including a serpentinite-matrix mélange with blocks of blueschist and greenschist, lie in fault contact with ophiolites and volcanic arc-related units (Rangin, 1979; T. E. Moore, 1985, 1986; Kimbrough, 1985; Sedlock, 1988, 1993). Sedlock (1993) summarized the structural units of the Vizcaíno embayment and the islands of the western Magdalena Plain 400 km to the south, as follows: an upper plate (Triassic and Jurassic arc and ophiolitic rocks overlain by Cretaceous turbidites), lower plate (blueschist metamorphic rocks, including red ribbon radiolarian chert), and an intervening fault zone containing serpentinite-matrix mélange consisting of exotic blocks of amphibolite, blueschist, eclogite, greenschist, and ultramafic rocks. This complex is also known as the Puerto Nuevo area mélange complex of T. E. Moore (1986) and the Sierra Placeres mélange of Sedlock (1993).

Stratigraphic Summary

Mina-Uhink (1957) mapped the area and named many of the earliest recognized units, which were subdivided and mapped by a number of graduate students and professors from the 1970s to the present. This work is summarized in the guidebooks of Abbott and Gastil (1979) and Frizzell (1984) and the papers of D. P. Smith *et al.* (1993a,b), and Abbott *et al.* (1995). Some of the new units lack formal type section designations, having been analyzed and discussed in unpublished theses and guidebooks. These are regarded as informal units in Table 4, which lists names, authors, and type areas for the principal formations and members in the area.

D. P. Smith *et al.* (1993a) used data from mapping and basin analyses to refine stratigraphic units of varying rank. They raised the Valle Formation of Mina-Uhink (1957) to a Group and included seven lithologic units as formations within it. Ongoing studies by D. P. Smith, D. L. Kimbrough, T. E. Moore, and others continue to refine the formal stratigraphy of the Valle Group. D. P. Smith, C. Busby, and other workers focus on the relation of Mesozoic units to convergent margin settings and progressive tectonic phases, from extensional to compressional systems. They recognize an early subduction stage at 200–130 Ma and a later one at 140–100 Ma.



Text-figure 7.—Isla Cedros, B.C.S., map showing Neogene marine outcrops and general geology modified from Kilmer (1984). Kilmer (1984) mapped a narrow band of Almejas Formation along the east coast for 8–10 km north and 1 km south of the Arroyo Choyal Fault, and a 20-m-thick white sandstone facies of the Tortugas Formation at the southern end. South of the town of Cedros, Rangin (1979) and Kilmer (1984) mapped 1.5 km of northwest-dipping marine sediments that include the Tortugas Formation and the Almejas Formation vertebrate locality of L. G. Barnes (1992) and L. G. Barnes *et al.* (1997).

Isla Cedros, northern Vizcaíno embayment
Plate 1, Column 8
(Text-figs. 2, 7–10, Table 4, Appendices 1, 2)

Column after D. P. Smith and Busby (1993b) and D. P. Smith (written communication, 2000). Geologic maps include those by D. P. Smith *et al.* (1993b), D. P Smith and Busby (1993b), Sedlock (1988, 1993), and Kilmer (1977, 1984).

Stratigraphy

Mesozoic basement rocks.—The basement of Isla Cedros includes a Jurassic island-arc complex in the north and a Jurassic ophiolite assemblage south of Arroyo Choyal (Kimbrough, 1985). These rocks are structurally underlain by Jurassic to Cretaceous blueschist grade metamorphic rocks of the western Baja Terrane (Kimbrough, 1985; Sedlock, 1988). Kimbrough (1984), Busby-Spera (1988), and Boles and Landis (1984) studied the sedimentary sequences and summarized, after Kilmer (1977), the lower units that crop out on the island: the Cedros mélange and a Middle to Late Jurassic ophiolite (Kimbrough 1982, 1984), the overlying Gran Cañon formation and Coloradito formation (informal names), Eugenia Formation, and a large section referred to the Valle Group. D. P. Smith *et al.* (1993b) distinguished the Late Cretaceous Vargas Formation and the overlying Late Cretaceous Pinos Formation as units within the Valle Group in the central and southern parts of Isla Cedros. The lower parts of the Vargas Formation correlate with the Los Chapunes formation, informal name, of the Vizcaíno peninsula.

Tortugas Formation and Almejas Formation of Isla Cedros, Miocene and Pliocene.—Tertiary marine rocks referred to the Tortugas and Almejas Formations, both described from the Vizcaíno Peninsula by Mina-Uhink (1957), crop out south of the town of Cedros and north of Gran Cañón on the east side of the island (Text-fig. 7). The Late Miocene to Early Pliocene Almejas Formation contains a rich diversity of vertebrates and invertebrates at a locality south of the town of Cedros that has yielded one of the most important sections for vertebrate taxa from this time period in the North Pacific (L. G. Barnes, 1973, 1984, 1992; Aranda-Manteca and Barnes, 1993). Just north of Gran Cañón and south of Arroyo Choyal, approximately 15 km north of the town, the Almejas Formation consists of unsorted megafossiliferous conglomerates that contain reworked Miocene mollusks (J. T. Smith, 1984, 1991a; Kilmer, 1984; Text-figs. 8, 9 herein). Hanna (1927) estimated the thickness of exposed marine Pliocene rocks on the island as 30 m (less than 100 ft).

Northern Vizcaíno peninsula, Punta Eugenia to Bahía Tortugas Plate 1, Columns 9, 10 (Text-figs. 1, 2, 10–12, Table 4, Appendices 1, 2)

Columns after Helenes-Escamilla (1980, 1984), Helenes (1984), and D. P. Smith (written communication, 1998). Area is in the Punta Eugenia quadrangle, G11B17, and the Bahía Tortugas quadrangle, G11B27, 1:50,000. The geology was mapped by Robinson (1975), Rangin (1979), Helenes-Escamilla (1980), Hickey (1984), and Patterson (1984).

Overview

The northern part of the Vizcaíno peninsula mapped by Robinson (1975, 1979a) includes the type section of the Eugenia Formation, which is separated by faults from adjacent units. Age and lithology vary between structural blocks, from latest Jurassic or Early Cretaceous in the west to Middle Cretaceous in the east (Boles and Hickey, 1979).

The late Early Cretaceous Valle Formation was first mapped and named by Mina-Uhink (1957) in the area of Valle Salitral, east and southeast of Bahía Tortugas (Text-fig. 10). Because the focus of this paper is Tertiary stratigraphy, we briefly mention the units that were mapped in the Valle Group, some of which are in contact with Tertiary marine formations (Table 4). Berry and Miller (1984) reported on Jurassic and Cretaceous foraminifers, radiolarians, and calcareous nannoplankton as part of the University of California, Santa Barbara's Vizcaíno Project of the late 1970s and 1980s.

Sedimentology and microfossils reflect a three-stage evolution of the Vizcaíno embayment, beginning in the Early Miocene with rapid subsidence from subaerial to middle bathyal depths. A Middle Miocene uplifting event triggered deposition of turbidites in the deeper part of the basin, followed by Late Miocene subsidence (Helenes-Escamilla, 1980). Such extreme depth changes are not seen in penecontemporaneous embayments elsewhere in western Baja California.

Pleistocene terrace deposits of the Vizcaíno Peninsula were studied by Emerson *et al.* (1981) and Ortlieb (1979, 1991).

Stratigraphy

Mesozoic sediments, latest Jurassic to Early Cretaceous.—Latest Jurassic–Early Cretaceous metamorphic rocks crop out southeast of Punta Eugenia and west of a group of faults referred to the Playa Negra fault zone (Boles and Hickey, 1979)

In the northern Vizcaíno Peninsula Cretaceous sediments were referred to the Eugenia Formation, the informally named Perforada formation of Hickey (1984), the Los Chapunes formation of Patterson (1984), and the undivided Valle Formation, which was regarded as the Valle Group by D. P. Smith *et al.* (1993a). These units are overlain with angular unconformity by the Miocene Tortugas Formation; the contact between the Valle Formation and the Tortugas Formation is well exposed approximately 1.5 km northeast of the Bahía Tortugas harbor (Text-fig. 10).

Tortugas Formation, late Early to early Late Miocene.—Helenes-Escamilla (1980) divided the type section of the Tortugas Formation northeast of the town

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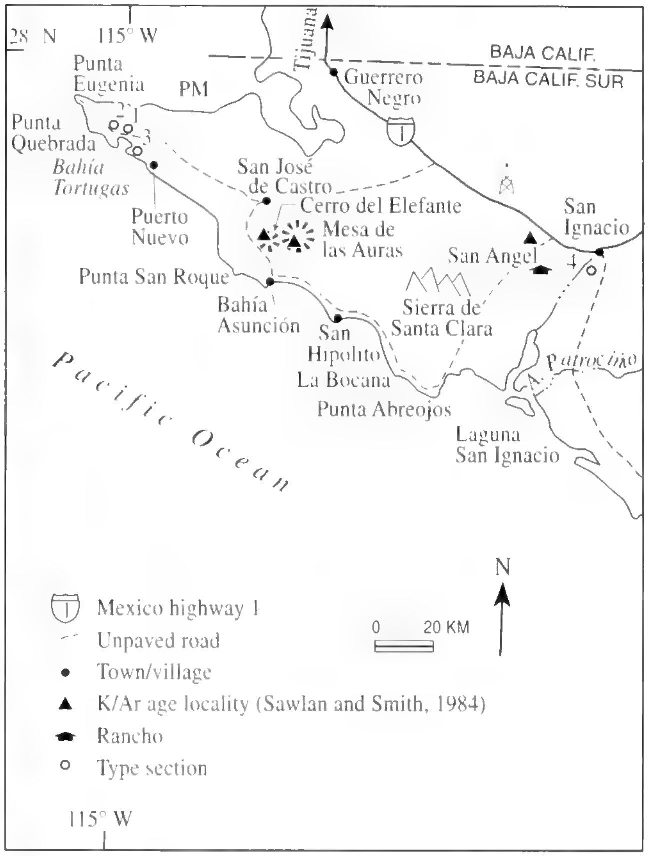

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Text-figure 8.—Arroyo Choyal, northeastern Isla Cedros, area of California Academy of Sciences locality 946 collected by Hanna and Jordan in 1925. Late Miocene, Almejas Formation. Photo, J. T. Smith, 1979.

Text-figure 9.—Arroyo Choyal, outcrop in small canyon to the south with unsorted conglomerates containing disarticulated valves of the Late Miocene pectinid *Lyropecten gallegosi* (Jordan and Hertlein). Photo, J. T. Smith, 1979.

of Bahía Tortugas into two members, A and B, and the section at Punta Quebrada, 10 km to the northwest, into four members, 1–4. He conducted a quantitative analysis of foraminifers, diatoms, and sediments to determine paleoenvironments and basin history, and related local faunal zones to the West Coast benthonic foraminiferal stages of Kleinpell (1938, 1980).

Member A of the type section contains yellow-gray sandstone that weathers to brown and phosphorite with silicified shells of late Early to early Middle Miocene mollusks. Molluscan index species include *Aequipecten discus* (Conrad), *Lucinoma* sp. cf. *L. sanctaecrucis* (Arnold), and *Turritella ocoyana* Conrad (J. T. Smith, 1984). It is a shallower water correlative of Members 1 and 2 that represent Early to Middle Miocene bathyal conditions at Punta Quebrada. Member B at the airfield consists of diatomaceous shales with microfossils that indicate an environment similar to that of Members 3 and 4 at Punta Quebrada (Helenes-Escamilla, 1980). McGee (1967) also reported diatomite in the Tortugas Formation from Isla Cedros (Text-fig. 7).

At the type section, Helenes-Escamilla (1980) referred the lower part of Member A to the Relizian–Luisian Stage, lower Middle Miocene age (15.5–13 Ma) *Cibicides floridanus* local zone. Overlying Member B represents the lower Mohnian Stage, Middle Miocene age (13–9.8 Ma) *Bulimina uvigerinaformis* zone.

At Punta Quebrada the basal section ranges from the upper Saucesian Stage, late Early Miocene to early Middle Miocene *Rectouvigerina mayi* Zone (Member 1) to the upper Mohnian Stage, Early Miocene age *Bolivina girardensis* Zone (Member 4). Intermediate member 2 contains the Relizian to lower Mohnian stages. Middle Miocene age *Cibicides floridanus* and lower *Bulimina uvigerinaformis* zones. Member 3 has lower Mohnian *Bulimina uvigerinaformis* Zone foraminifers and abundant diatoms of the late Middle to early Late Miocene *Denticula hustedtii*/*D. lauta* Zone (13.5–9 Ma).

Correlation

White calcareous sandstone and siltstone near San Ignacio could correlate with the Tortugas Formation, which crops out discontinuously between Punta Quebrada and the town of Asunción. Agatized megafossils from a quarry near Microondas Abulón (km 88 on Mexico 1 and 4.7 km west of the turnoff to San Ignacio; Text-fig. 10) include some of the same taxa as in Member A of the Tortugas Formation.

The Tortugas Formation correlates with the Rosarito Beach Formation, Los Indios Member, of the La Misión area, Baja California. Its megafaunal composition is closer to that of the southern California embayments than to the penecontemporaneous Salada Formation of the Magdalena Plain, 250 km to the south.

Almejas Formation, Late Miocene to Early Pliocene.—Outcrops of the Almejas Formation vary in age from Late Miocene to Early Pliocene, determined by abundant megafossils and constrained by overlying basalts of 6.48 ± 0.23 Ma and 5.7 ± 0.2 Ma (J. T. Smith, 1984). Fossil mollusks, barnacles and echinoids collected from a monadnock 3 km south of town (Text-fig. 12) suggest shallow neritic depths similar to the present Bahía de Almejas. Miocene taxa include *Forreria wrighti* Jordan and Hertlein, *Trophon* sp. cf. *Forreria belcheri* (Hinds) of Durham and Addicott, and *Leptopecten praevalidus* (Jordan and Hertlein). Representative Pliocene mollusks include *Lituyapecten dilleri* (Dall), *Pecten* (*Pecten*) *bellus* (Conrad), *Argopecten percarus* (Hertlein), and "*Ostrea*" *veatchii* Gabb (J. T. Smith, 1984); these species and others are also found in the lower part of the San Diego Formation.

Southern Vizcaíno embayment,
San Roque—Asunción—San Hipólito—
Punta Abreojos
Plate 1, Columns 11, 12
(Text-figs. 2, 10, Table 4, Appendices 1, 2)

San Roque and San Hipólito columns after D. P. Smith (written communication, 1998), Whalen and

←

Text-figure 10.—Vizcaíno embayment, map of Isla Cedros to Laguna San Ignacio, B.C.S. Open circles indicate type sections: 1, Valle Formation; 2, Tortugas Formation; 3, Almejas Formation; 4, San Ignacio Formation. K/Ar ages for basalts capping Cerro del Elefante and Mesa de las Auras are 6.48 ± 0.23 Ma and 5.70 ± 0.20 Ma, respectively (Sawlan and J. G. Smith, 1984). Basalt of Rancho Esperanza has a K/Ar age of 9.72 ± 0.29 Ma west of San Ignacio at the turnoff to San Lino (km 74) (Sawlan and J. G. Smith, 1984). Quarry along Mexico 1 west of Microondas Abulón (km 88) contains agatized *Turritella* sp. and other mollusks also found in the Tortugas Formation. Beal (1948) reported that Marland Oil Company reconnaissance geologists collected extensively near Rancho San Angel, which has abundant identifiable fossils represented by internal molds; the specimens are now at the California Academy of Sciences, San Francisco. PM, Punta Malarrimo.

Text-figure 11.—Martin Lagoe standing on the angular unconformity between brown turbidite sands of the Cretaceous Valle Formation and light-colored pelletal phosphorite and sand facies of the Miocene Tortugas Formation. Area is 1.5 km northeast of the harbor in the town of Bahía Tortugas. Photo, J. C. Ingle, Jr., 1980.

Text-figure 12.—Monadnock of highly fossiliferous Late Miocene Almejas Formation sandstones, 3 km southeast of Bahía Tortugas. This is California Academy of Sciences locality CAS 945 collected by Hanna and Jordan in 1925. Photo, J. T. Smith, 1982.

Table 4.—Vizcaíno embayment, Baja California Sur, lithostratigraphic units (Text-figs. 7, 10). Lowercase names indicate informal units that were not established according to the North American Stratigraphic Code (1983).

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
Almejas Formation	Mina-Uhink (1957).	Formation consists of fossiliferous sandstone, shale, and conglomerate facies; the contact with the underlying Tortugas Formation has not been observed. Type section is in Arroyo Bateque, 15 km southeast of the town of Bahía Tortugas, Bahía Tortugas quadrangle. North of Asunción the Almejas Formation is capped at Cerro del Elefante and Mesa de las Auras by basalts of 6.48 ± 0.23 Ma and 5.7 ± 0.2 Ma, respectively (J. T. Smith, 1984, 1991c). Late Miocene to Early Pliocene, based on fossils and associated volcanic rocks (J. T. Smith, 1984).
Asunción formation, informal name	D. A. Barnes (1982, 1984); D. P. Smith *et al.* (1993) included in the Valle Group.	Unit consists of 800–900 m of coarse-grained tuffaceous and calcarenaceous rocks, reworked carbonate debris, and matrix-supported conglomerate in the southern Vizcaíno peninsula. Chaotic basal sediments contain enormous clasts 25–150 m in diameter; the limestones have large orbitolinid foraminifers. Type section is approximately 17 km north-northwest of Asunción, near Rancho San Andrés on the south side of Cerro del Elefante, Puerto Nuevo quadrangle. Late Early Cretaceous, Aptian-Albian Stage, based on radiolarians and calcareous nannofossils (D. A. Barnes, 1984).
Bahía Ballenas Formation	New name of Abbott *et al.* (1995) for the informally named "Ballenas formation" of Sorensen (1982); D. P. Smith *et al.* (1993b) included in the Valle Group.	Formation is a 2-km-thick bathyal siliciclastic shale that includes a basal breccia, the Los Cuervitos limestone with transported shallow-water marine fossils, and five shell bed layers. Type section is near Rancho el Carrizo, 40 km north of Punta Abreojos, Punta Abreojos quadrangle. Early Paleocene to late Early Eocene (D. P. Smith *in* Abbott *et al.*, 1995).
Bateque Formation (used by some authors in the Vizcaíno embayment)	Mina-Uhink (1957) named and mapped east of Laguna San Ignacio. Sorensen (1982) used "Ballenas formation" for outcrops in the Vizcaíno peninsula; D. P. Smith *in* Abbott *et al.* (1995) proposed a new name for these rocks.	Unit contains fossiliferous marine sandstones and siltstones. Type section is near Rancho Bateque, south of San Ignacio in the Mesa Las Lagunitas quadrangle (Text-fig. 13). D. P. Smith *et al.* (1993a,b) restricted the Bateque Formation to the east side of Laguna San Ignacio and published a new name, Bahía Ballenas Formation, for the Paleogene marine sediments of the Vizcaíno embayment. Middle Eocene.
Cedros ophiolite, informal name	Kilmer (1963, 1977, 1979); also discussed by Kimbrough (1984, 1985) and Sedlock (1993).	Unit consists of blueschists, chert, and volcaniclastic strata that are exposed in fault blocks on Isla Cedros. It crops out in the southern half of the island and along the east coast between Arroyo San Carlos and Gran Cañón. Sedlock (1993) regarded it as part of the upper plate of the Choyal oceanic terrane. Middle to Late Jurassic age.
Choyal formation, informal name	Kilmer (1977, 1979); Kimbrough (1984); Sedlock (1993).	Formation includes marine volcanic rocks and small granitoid plutons that crop out on eastern Isla Cedros from Arroyo Choyal northward. Part of the upper plate sequence of the Choyal oceanic terrane. Jurassic, based on dates of 166–160 Ma (Sedlock, 1993).
Coloradito formation, informal name	Kilmer (1977, 1979); Boles and Landis (1984) and Kimbrough (1984) also discussed.	Unit includes argillite, chert, limestone, sandstone, and a tuff dated at 159 Ma (Gastil *et al.*, 1978; Sedlock, 1993). Well-exposed on both flanks of a syncline in the southern part of Isla Cedros, it is part of the upper plate sequence of the Choyal oceanic terrane (Sedlock, 1993). Middle to Late Jurassic.
Conglomerados los Juncos, informal name	Drake (1995). D. P. Smith *et al.* (1993b) regarded as a formation in the Valle Group.	Unit is a bathyal conglomerate that was deposited in a submarine canyon. Type section in the southern Vizcaíno peninsula is several kilometers inland from Punta Abreojos, in the quadrangle of the same name. Late Cretaceous age, Upper Campanian Stage (Drake, 1995).
Eugenia Formation	Mina-Uhink (1957) named. Boles and Landis (1984) and Sedlock (1993) also discussed.	Formation is a coarse-grained submarine conglomerate and sandstone. Type area near Punta Eugenia, northwestern Vizcaíno peninsula, was not formally specified. It is the uppermost unit of the Vizcaíno Norte oceanic terrane (Sedlock, 1993). Late Jurassic to Early Cretaceous age, Tithonian to Valanginian Stage, based on the Tithonian index fossil *Buchia piochii* (Gabb) and radiolarians (Hickey, 1984).

Table 4.—Continued.

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
Gran Cañón formation, informal name	Kilmer (1963, 1966, 1977). D. A. Barnes (1984), Busby-Spera (1988), Kimbrough (1984), and Sedlock (1993) also discussed.	Unit includes tuff, volcanogenic breccia, and pyroclastic flows described from Gran Cañón, northeastern Isla Cedros (Busby-Spera, 1998; Busby *et al.*, 1998). In depositional contact with the Choyal formation and the Cedros ophiolite, it is part of the upper plate sequence of the Choyal oceanic terrane (Sedlock, 1993). Late Middle Jurassic.
La Costa Ophiolite	T. E. Moore (1983, 1986). See also Sedlock (1993).	La Costa Ophiolite includes chert, limestone, and volcaniclastic sediments. It is the oldest part of the basement complex in the southern Vizcaíno peninsula, part of the Choyal oceanic terrane (Sedlock, 1993), and overlain by the Late Triassic–Early Jurassic San Hipólito Formation. Middle to Late Triassic.
Los Chapunes formation, informal name	Patterson (1984) used name for the lower member of the Valle Formation of Mina-Uhink (1957). D. P. Smith *et al.* (1993a) included in the Valle Group.	Unit is a turbidite deposit described from a composite section (not formally designated) northeast of Bahía Tortugas, in the Bahía Tortugas quadrangle. It also crops out in the southern Vizcaíno peninsula in Arroyo Pitahaya and Arroyo San Lorenzo, east of Punta San Hipólito. Late Early Cretaceous age, Albian Stage, based on foraminifers (Patterson, 1984).
Los Cuervitos limestone, informal name	D. P. Smith *in* Abbott *et al.* (1995) named as member of the Bahía Ballenas Formation.	Member is a 10-m-thick biosparrudite with coarse-grained sand- to pebble-sized clasts that are mainly broken shells. Type section is a ridge near Rancho el Carrizo, at 27°00° N, 26.8 km northeast of Punta Abreojos in the Punta Abreojos quadrangle. Late Early Paleocene to early Late Paleocene, based on fossils.
Malarrimo Formation	Mina-Uhink (1957). Robinson (1975, 1979*a*) and later workers included in the Valle Formation.	Formation is a conglomerate interbedded with sandstone and claystone that crops out along the north coast of the Vizcaíno peninsula west of Punta Malarrimo, and from Arroyo de la Mesita to six kilometers south (Text-figs. 6, 10). Originally regarded as Paleocene–Eocene (Mina-Uhink, 1957), later revised to Cretaceous (Robinson, 1975).
Morro Hermoso ophiolitic complex, informal name	Rangin (1979). Also called the "tuff of Morro Hermoso" of T. E. Moore (1986).	Ophiolites and tuffs were described at Morro Hermoso, between Bahía Tortugas and Puerto Nuevo in the Puerto Nuevo quadrangle. They overlie the Sierra de San Andrés ophiolite. Late Triassic age (T. E. Moore, 1986).
Morro Redondo formation, informal name	Kilmer (1979, 1984) name for part of the Valle Formation of Mina-Uhink (1957). D. P. Smith *et al.* (1993) included as a lithologic unit in the Pinos Formation.	Unit consists of siltstone, sandstone, shale, and fossiliferous marine conglomerate. Type section is exposed in central Isla Cedros in the Punta Prieta and Arroyo Coloradito areas (Kilmer, 1984). Late Cretaceous age, Turonian Stage.
Perforada sandstone, informal name	Hickey (1984). D. P. Smith *et al.* (1993) regarded as a formation in the Valle Group.	Rocks are fine-grained marine sandstones and siltstones named for a section near La Perforada along the La Bamba Fault in the northern Vizcaíno Peninsula, Punta Eugenia quadrangle. Late Early Cretaceous age, Aptian–Albian Stage, based on radiolarians and foraminifers (Hickey, 1984), correlative with the Asunción formation (D. P. Smith, written communication, 1998).
Pinos Formation	D. P. Smith *et al.* (1993a), new name for the upper part of the Valle Group on Isla Cedros. Formation contains five members and the Morro Redondo formation of Kilmer (1984).	Formation is a coarse-grained unit with rapid facies variations and slump deposits, its stratigraphy complicated by syndepositional active faults (D. P. Smith *et al.*, 1993a). Type section is in the central part of Isla Cedros, from Arroyo Choyal to Arroyo Vargas and near Punta Prieta, where it overlies the Vargas Formation and Gran Cañón formation. It is overlain with angular unconformity by diatomaceous beds of the Miocene Tortugas Formation. Early Late Cretaceous age, Lower Cenomanian Stage.
Puerto Escondido tuff, informal name	D. A. Barnes (1982) named as informal member of the San Hipólito Formation. T. E. Moore (1986) included in the tuff at Morro Hermoso.	Unit consists of 200–300 m of tuffaceous chert, limestone, volcaniclastic sandstone and tuff. It is well exposed in the walls of Arroyo Puerto Escondido, also found at Morro Hermoso and to the north at Punta Quebrada. Late Triassic age, upper Middle Norian Stage based on radiolarians, conodonts, and well-preserved *Monotis* sp. from calcareous tuff beds (Dávila-Alcócer and Pessagno, 1986; D. A. Barnes, 1984).

Table 4.—Continued.

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
San Hipólito Formation	Mina-Uhink (1957). Finch and Abbott (1977), and Finch *et al.* (1979) divided into four members.	Formation consists of 2,400 m of sediments and radiolarian chert divided into four members, oldest to youngest: red and green fossiliferous chert, fossiliferous limestone, breccia, and volcaniclastic sandstone with fossiliferous limestone concretions. Type locality, not formally specified, is at the southern end of Punta San Hipólito, approximately 40 km southeast of Asunción, Bahía Asunción quadrangle. Late Triassic, Norian Stage lower members, based on radiolarians and hemipelagic pectinaceans in the genera *Monotis* and *Halobia*. Early Jurassic age, Pliensbachian and/or Toaracian Stage for the uppermost sandstone member, which contains radiolarians and conodonts (Whalen and Pessagno, 1984; Whalen and Carter, 2002).
Santa Clara Formation	Mina-Uhink (1957).	Formation is a 120-m-thick agglomerate and reddish to purple volcanic breccia described from the Sierra de Santa Clara, inland from Punta Abreojos in the southeastern Vizcaíno peninsula. Mina-Uhink (1957) regarded it as equivalent in age and origin to the San Zacarías Formation, which he considered younger than the Eocene Bateque Formation and probably Oligocene or Early Miocene.
Sierra de San Andrés ophiolite, informal name	T. E. Moore (1976, 1986).	Unit consists of ophiolitic rocks including pillow basalts and breccias. Type area of this basement complex is south of Bahía Tortugas in the Puerto Nuevo quadrangle. Part of the Vizcaíno Norte oceanic terrane, these rocks are older than the overlying conformable Late Triassic tuff, chert, and volcaniclastic sandstone (Sedlock, 1993).
Tortugas Formation	Mina-Uhink (1957). Helenes-Escamilla (1980) recognized Members A and B at Bahía Tortugas and Members 1–4 at Punta Quebrada, 10 km to the west-northwest.	Formation is a 400-m-thick marine lithic sandstone overlain by diatomaceous shales. Its type section consists of 45 m of neritic silty sandstones and pelletal phosphorite (Member A) overlain by 95 m of silty, diatomaceous shales (Member B); it is located east of the airfield 2 km north of the town of Bahía Tortugas in the quadrangle of the same name. Late Early Miocene to Middle Miocene (18–15 Ma to 15–10 Ma) at the type area, based on diatoms, benthonic foraminifers, and mollusks (Helenes-Escamilla, 1980; Ingle, written communication, 1984; Smith, 1984). The section at Punta Quebrada ranges from late Early Miocene age, Upper Saucesian Stage to Late Miocene age, Upper Mohnian Stage (18–15 Ma to 9.8–5.5 Ma) (Helenes-Escamilla, 1980).
Valle Formation, Valle Group	Mina-Uhink (1957). Later workers divided into a number of different units. D. P. Smith *et al.* (1993) raised to the Valle Group, including the "undivided Valle Group" (work in progress by D. P. Smith *et al.*, written communication, 1998) and the following: Perforada formation, Asunción formation, Los Chapunes formation, Vargas Formation, Pinos Formation, Conglomerados los Juncos, and Bahía Ballenas Formation.	Formation has various lithologies, including fossiliferous mudstone, siltstone, sandstone, and a massive sandstone with mudstone interbeds. Type area, not formally designated, is in a west-flowing arroyo in Valle Salitral, 4–5 km northeast of Bahía Tortugas in the quadrangle of the same name (Robinson, 1975, 1979*a*). As a Group of formations, the Valle is more than 8 km thick; it is mainly Late Early Cretaceous age, Upper Albian Stage but may range to Early Paleogene in some sections (D. P. Smith, written communication, 2000).
Vargas Formation	D. P. Smith *et al.* (1993). New name for the lower member of the Valle Formation of Kilmer (1984) on Isla Cedros and the Los Chapunes formation of Patterson (1984). D. P. Smith *et al.* (1993) regarded as a formation in the Valle Group.	Formation is a fine-grained, shale-rich unit that attains a thickness of 1,700 m and is conformably overlain by the Pinos Formation. Type locality is on east side of Isla Cedros, along the steep western wall of Gran Cañón. Unit is no younger than early Late Cretaceous, Turonian Stage (D. P. Smith, written communication, 1998).

Carter (2002), Troughton (1974), J. T. Smith (1984), and T. E. Moore (1986). Area is shown on the Puerto Nuevo quadrangle, G11B38, San Roque quadrangle, G11B48, Bahía Asunción quadrangle, G11B49, Estero la Bocana quadrangle, G12A51, Punta Abreojos quadrangle, G12A52, 1:50,000; and the geologic maps of Troughton (1975), Finch and Abbott (1977), T. E. Moore (1983), Whalen and Pessagno (1984), Drake (1995), and D. P. Smith and students (ongoing field work).

Mesozoic stratigraphy

Sierra de San Andrés ophiolite, informal name, Middle to Late Triassic.—The Sierra de San Andrés ophiolite basement complex of T. E. Moore (1976, 1986) described from the Puerto Nuevo area consists of Middle to Late Triassic pillow basalts, cherts, and breccias of the La Costa ophiolite sequence. These rocks are overlain by Late Triassic to Early Jurassic tuff, chert and volcaniclastic sandstone (Sedlock, 1993).

San Hipólito Formation, Late Triassic to Early Jurassic.—Punta San Hipólito lies 40 km to the southeast of Asunción; it is formed of sediments and radiolarian chert of the San Hipólito Formation, which is restricted to this area. Of its four members, the two oldest contain Late Triassic Norian Stage radiolarians and the hemipelagic pectinaceans *Monotis* sp. cf. *M. subcircularis* (Gabb) and *Halobia lineata* of authors (Pessagno *et al.*, 1979; Finch *et al.*, 1979). Formerly regarded as Triassic, the upper volcaniclastic sandstone with limestone concretions contains abundant Early Jurassic age, Pliensbachian and/or Toarcian Stage (195.3–180.1 Ma) radiolarians and conodonts (Whalen and Pessagno, 1984; Whalen and Carter, 2002). The San Hipólito Formation is part of the Vizcaíno Sur terrane that originated in an oceanic island arc setting; it is in fault contact with the overlying Valle Group.

Valle Group, late Early Cretaceous.—The Valle Group unconformably overlies basement rocks of the Sierra de San Andrés-Cedros complex in the area from San Roque to Asunción (Rangin and Carrillo-Martínez, 1978; T. E. Moore, 1984). Mapping and preliminary sedimentological studies in progress between Asunción and Punta Abreojos by D. P. Smith and students will define five new formations within the Valle Group, which attains 6 km of thickness in that area (D. P. Smith *et al.*, 1993a).

One of the units is the Conglomerados Los Juncos, a localized upper Campanian Stage, Late Cretaceous submarine-canyon deposit that is correlative with the Perforada formation, informal name, of the northern Vizcaíno peninsula (D. P. Smith, written communication, 1998).

Bahía Ballenas Formation, Paleocene to Early Eocene. Los Cuervitos limestone member, informal name, Middle Paleocene.—D. P. Smith *in* Abbott *et al.* (1995) provided new fossil data and descriptions for the Middle Paleocene to late Early Eocene Bahía Ballenas Formation. One of its shell beds is the Middle Paleocene Los Cuervitos limestone, which crops out north of Punta Abreojos and correlates with limestones in the Sepultura Formation and parts of the Sierra Blanca Limestone in southern California (Abbott *et al.*, 1995; Saul, 1983). The Middle Paleocene age is based on the molluscan index species *Turritella peninsularis* Anderson and Hanna, *Turritella infragranulata pachecoensis* Stanton, *Venericardia venturaensis* Verastegui, and *Venericardia* sp. cf. *V. nelsoni* Verastegui, which also correlate it with the lower part of the Santa Susana Formation in the Simi Hills of southern California.

Tortugas Formation, late Early to Middle Miocene.—Arroyos north and east of the town of Asunción were mapped by Troughton (1974), who delineated unnamed fine phosphatic beds overlain by diatomite as the Tortugas Formation. Samples of diatomaceous shales from the "Valle de Diatomita" or Arroyo la Chiva (10 km northwest of Bahía Asunción and 2 km east of the road to Punta San Roque, San Roque quadrangle) yielded early Late Miocene (8.9–8.4 Ma) diatoms of *Denticulopsis hustedii* Subzone D and the *D. lauta* Zone (Moreno-Ruiz and Carreño, 1993, locality IGM-2439, 27°11′29″ N, 114°20′55″ W), and Late Miocene *Diartus petterssoni* and *Didymocyrtis antepenultima* radiolarian zones (Pérez-Guzmán, 1985). In this area the unit is also known for shark teeth, fish, and mammals (Applegate *et al.*, 1979).

A localized well-indurated sandstone on the beach at Asunción has different megafossils but seems referable to the lower part of the Tortugas Formation. Mollusks include *Amussiopecten vanvlecki* (Arnold) and large *Turritella* sp.

Almejas Formation, Late Miocene.—D. P. Smith and others have mapped the Almejas Formation in the area of Punta Abrojos, where it overlies the Cretaceous Valle Formation with angular unconformity. Reconnaissance collections of Late Miocene megafossils include *Lyropecten gallegosi* (Jordan and Hertlein) and *Leptopecten praevalidus* (Jordan and Hertlein).

Western embayment, northern part,
Arroyo San Ignacio, Arroyo Patrocinio,
Arroyo San Raymundo
Plate 1, Columns 13, 14, 15
(Text-figs. 2, 13–16, 18, Appendices 1, 2)

Columns modified from Mina-Uhink (1957), McLean *et al.* (1985, 1987), Squires and Demetrion (1992). Area is shown on the San Ignacio quadrangle, G12A34, Mesa las Lagunitas quadrangle, G12A43, El Patrocinio quadrangle, G12A54, San Juan quadrangle, G12A65, San Raymundo quadrangle, G12A75, scale 1:50,000; and the geologic maps of McLean *et al.* (1985), 1:125,000; McLean and Hausback (1984), scale 1:83,000; Mina-Uhink (1957), scale 1:500,000; and Beal (1948).

Overview

The region that includes Arroyo San Ignacio and Laguna San Ignacio is the northern part of an Early Eocene to Miocene embayment that extended from this area of western Baja California to the southern Magdalena Plain. Marine formations that are penecontemporaneous with units in the Magdalena Plain are gently folded, north to south, and capped by extensive Miocene tholeiitic basalts (10–6 Ma) that emanated from near San Ignacio (Sawlan and Smith, 1984; Sawlan, 1991). There are no Mesozoic basement rocks exposed in the western embayment, although McLean *et al.* (1987) noted dioritic and granitic clasts in a basalt flow in Arroyo la Purísima, upstream from San Isidro.

From north to south, significant outcrop areas are exposed by streams flowing west from the crest of the Sierra la Giganta in Arroyo San Ignacio, Arroyo Patrocinio, and Arroyo San Raymundo, among others. The southernmost exposures of Eocene diatomite on the Pacific coast occur in Arroyo San Raymundo.

Arroyo San Ignacio
Plate 1, Column 13
(Text-figs. 2, 10, 13–15, Appendices 1, 2)

Column modified from Mina-Uhink (1957); area is shown on the San Ignacio quadrangle, G12A34 and the Mesa las Lagunitas quadrangle, G12A43, scale 1:50,000; and the geologic maps of Mina-Uhink (1957) and Beal (1948).

Stratigraphy

Bateque Formation, Early Eocene.—The marine Bateque Formation of Mina-Uhink (1956, 1957) is an arkosic sandstone and siltstone. Although a specific outcrop was not designated, it was named for a section near Rancho Bateque, 32 km southwest of San Ignacio, Mesa Las Lagunitas quadrangle (Text-fig. 13). Its age, based on microfossils and megafossils, is Early to late Middle Eocene (Sorensen, 1982; McLean *et al.*, 1987; Squires and Demetrion, 1992; Squires, 1997). The Early Eocene index species *Turritella andersoni* Dickerson identifies the unit in the type area as "Capay" West Coast Molluscan Stage (Squires, 1988). It crops out for 70 km from the east side of Laguna San Ignacio to Batequi de San Juan, and discontinuously as far south as Arroyo Mezquital, east of Punta Pequeña (McLean *et al.*, 1985).

Correlation

The Bateque Formation correlates in part with the upper Tepetate Formation, which crops out 200 km to the south in the Magdalena Plain. Squires and Demetrion (1992) referred the Bateque Formation to the "Capay" West Coast Molluscan Stage at its type area, but to a younger, late Middle Eocene age, "Tejon" West Coast Molluscan Stage at Arroyo Mezquital.

Paleogene marine units of Mina-Uhink (1957): San Zacarías, Santa Clara, Zorra and San Joaquín Formations, Oligocene (?) or Early Miocene.—Southeast of Laguna San Ignacio in the area between Rancho San Joaquín and mesas near Cuarenta the Bateque Formation is overlain unconformably by several Oligocene to Miocene units named by Mina-Uhink (1957): the San Zacarías, Santa Clara, Zorra and San Joaquín Formations. Some might be penecontemporaneous. Of limited geographic extent, they include volcanic breccias and mesa-capping deposits that have not been visited since Mina-Uhink's work. Their type areas were given, respectively, as: Arroyo San Joaquín, near Rancho San Zacarías; mesa tops in the Sierra de Santa Clara, Rancho el Alamo and Casa Blanca (the shallow marine Zorra Formation); and continental deposits near Rancho San Joaquín. A period of erosion or nondeposition separated these units from subsequent shallow marine deposits.

San Ignacio Formation, late Middle Miocene to Late Miocene.—The San Ignacio Formation is a white, fossiliferous, calcareous, and volcaniclastic marine sandstone named by Mina-Uhink (1957) for cliffs along Arroyo San Ignacio. Beal (1948) and later workers regarded the type area as 4–8 km downstream from the town of San Ignacio (Text-figs. 14, 15). Facies include limy marls, coquina, siltstone, and coarse pebbly sandstone.

Abundant shallow-water marine fossils were reported by Hertlein and Jordan (1927), Beal (1948), and J. T. Smith (1984, 1986). Hertlein and Jordan (1927) described, among others, *Thais wittichi, Macron hartmanni, Cymia heimi, Turritella bösei, Chione richthofeni, Sanguinolaria toulai,* and *Amiantis* sp. These taxa

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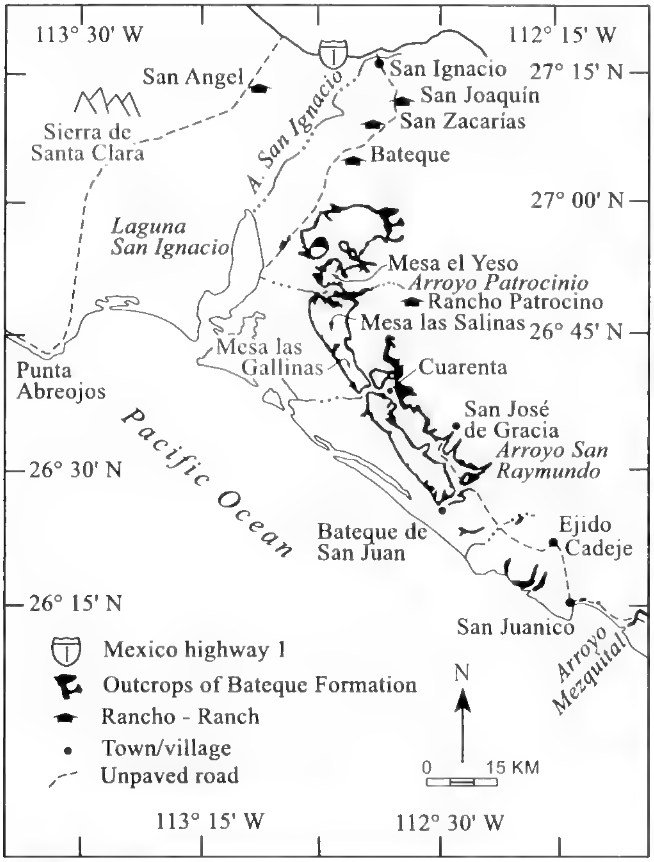

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Text-figure 13.—Western embayment, San Ignacio to Arroyo Mezquital, with outcrops of the Eocene marine Bateque Formation. Map is modified from Squires and Demetrion (1992).

Text-figure 14.—Arroyo San Ignacio, view from Rancho el Estribo at type area of the Late Miocene San Ignacio Formation, 4–8 km downstream from San Ignacio. Photo, T. M. Cronin, 1984.

Text-figure 15. San Ignacio Formation, south wall of Arroyo San Ignacio showing fossiliferous marine sediments overlain by an unnamed volcaniclastic sandstone (possibly the Atajo Formation of Mina-Uhink, 1957) and capped by the Late Miocene basalt of Rancho Esperanza. Photo, T. M. Cronin, 1984.

Text-figure 16.—Mesa el Yeso, north side of Arroyo Patrocinio. White fossiliferous sandstones of the Isidro Formation are overlain by a thin layer of Comondú Formation and capped by basalts with a K/Ar age of 8.1 ± 0.4 Ma. Photo, J. R. Ashby, Jr.

Text-figure 17.—Arroyo Mezquital section of Eocene Bateque Formation siltstones overlain unconformably by the Miocene Isidro Formation. Beal (1948) mapped the units as Eocene Tepetate Formation overlain by the Miocene Salada Formation. Photo, J. T. Smith, 1984.

need to be compared with Tertiary-Caribbean taxa to determine their faunal affinities. The late Middle to Late Miocene age is based on megafossils and a radiometric age of 9.72 ± 0.29 Ma for the overlying basalt of Rancho Esperanza (informal name) exposed along Mexico 1 near the road to San Lino, between Microondas Abulón and the turn-off to San Ignacio (Text-fig. 10, herein; Sawlan and J. G. Smith, 1984; J. T. Smith, 1986). In places the marine beds are overlain by an unnamed volcaniclastic sandstone that is capped by the basalt (Sawlan and J. G. Smith, 1984) (Text-fig. 15).

The San Ignacio Formation crops out from just north of Mexico 1 at San Ignacio to north of Arroyo Patrocinio. Although Mina-Uhink (1957) mapped the formation as far as Mesa Cuarenta, 50 km south of the type area, McLean *et al.* (1985, 1987) interpret the fossiliferous sandstone at Arroyo Patrocinio and to the south as the older Miocene Isidro Formation. Yellowish-brown sandstones and siltstones near Rancho San Ángel, 24 km southwest of San Ignacio, Mesa las Lagunas quadrangle, are probably another facies of the San Ignacio Formation; they contain abundant external molds of marine mollusks (Beal, 1948; J. T. Smith, 1986).

Correlation

Although there are some molluscan fossils in common between the San Ignacio Formation and the Isidro Formation, the former could be younger by several million years. The Isidro Formation is inferred to be Early Miocene to late Middle Miocene on the basis of fossils and the radiometrically dated tuffs in the overlying Comondú Formation; the San Ignacio Formation could be latest Middle to Late Miocene, based on megafossils and the age of the overlying basalt of Rancho Esperanza (Sawlan and J. G. Smith, 1984; Sawlan, 1991; J. T. Smith, 1986). The San Ignacio Formation correlates with the Tortugas Formation of the adjacent Vizcaíno embayment, although the two units differ markedly in lithology, megafaunal composition, and depositional history.

Atajo Formation, Miocene.—Mina-Uhink (1956, 1957) named but did not describe the Atajo Formation as an unconformable volcaniclastic unit in the area north of Cerro San Angel between the Vizcaíno peninsula and San Ignacio. He regarded it as a local equivalent of the Late Miocene Comondú Formation and unconformable above the San Ignacio Formation. The name has not been used or investigated since then, although it may be appropriate for an unnamed volcaniclastic sandstone that overlies the San Ignacio Formation in the eastern wall of Arroyo San Ignacio (Text-fig. 15).

Basalt of Rancho Esperanza, informal name, Late Miocene.—Sawlan (1991) discussed a young tholeiitic basaltic andesite, the basalt of Rancho Esperanza (informal name of Sawlan and J. G. Smith, 1984), which is 3–6 m thick and has a K/Ar age of 9.7 ± 0.29 Ma near San Ignacio. The distinctive, fast-flowing lava erupted in the area of Rancho Esperanza near the Tres Vírgenes volcanoes (Text-fig. 49) and extended southwest as far as the Pacific Ocean, where it formed pillows at Punta Pequeña (Sawlan, 1991, fig. 4).

Arroyo Patrocinio
Plate 1, Column 14
(Text-figs. 10, 13, 16, Appendices 1, 2)

Column is modified from McLean *et al.* (1985, 1987) and Squires and Demetrion (1992). Area is shown on the El Patrocinio quadrangle, G12A54, scale 1:50,000; and the geologic maps of McLean *et al.* (1985), scale 1:125,000; McLean and Hausback (1984); Mina-Uhink (1957); and Beal (1948).

Overview

Marine sections from Arroyo Patrocinio to Punta Pequeña are capped by volcanic units whose Late Miocene dates constrain the underlying sediments. Arroyo Patrocinio is approximately 60 km south of San Ignacio, accessible by a challenging, unpaved, ungraded road famous for sandy "*brincas malas.*" The region contains the northernmost thin outcrops of the Isidro and Comondú Formations described from the Purísima-Iray basin 140 km to the south; the type section of the Eocene Bateque Formation is just north of this area. Mesa el Yeso flanks the mouth of Arroyo Patrocinio on the north, Mesa la Salinas on the south (Text-fig. 16).

Stratigraphy

Bateque Formation, Early Eocene.—The Bateque Formation crops out in Arroyo Patrocinio, where it is unconformably overlain by the Isidro Formation, Miocene capping basalts, or late Tertiary to Quaternary gravels (McLean *et al.*, 1987). In this area it is Early Eocene age, "Capay" West Coast Molluscan Stage based on *Turritella andersoni* Dickerson and other species (Squires and Demetrion, 1992, 1994a).

Isidro Formation, late Middle Miocene.—Described from the area of La Purisíma and San Isidro, the Isidro Formation is a highly fossiliferous shallow-marine clastic unit that thins to the northeast to perhaps a few tens of meters on the north side of Arroyo Patrocinio. It can interfinger with the lower San Ignacio Formation to the north (McLean *et al.*, 1987). The section at Mesa el Yeso is overlain unconformably by a thin layer of the Comondú Formation, also described from the Sierra la Giganta, and by Late Miocene basalt flows whose ages are 8.4 ± 0.30 Ma (J. T. Smith, 1991c, p. 645) and 8.1 ± 0.4 Ma (McLean *et al.*, 1985, 1987). Megafossils and radiometric ages of associated rocks suggest its age in Arroyo Patrocinio is late Middle Miocene, penecontemporaneous with or slightly older than the San Ignacio Formation.

Comondú Formation, Late Miocene.—McLean *et al.* (1985) mapped the northernmost occurrences of the Comondú Formation in Arroyo Patrocinio. A fluvial volcaniclastic conglomerate, the unit has been widely interpreted by many authors to include volcanic rocks and vent facies from eastern Baja California Sur between Santa Rosalía and La Paz. We use a narrower definition for this formation, which we discuss in the section on the Purísima-Iray basin, p. 44. The Comondú Formation is 1,800 m thick at its type area near San Jose de Comondú, but only a few meters thick at Arroyo Patrocinio. Its age is constrained at Mesa las Gallinas by an overlying basalt flow with a $^{40}Ar/^{39}Ar$ age of 10.05 ± 0.4 Ma (Text-fig. 13, herein; McLean *et al.*, 1985, 1987).

Arroyo San Raymundo
Plate 1, Column 15
(Text-figs. 2, 13, 18, Appendices 1, 2)

Column modified from McLean *et al.* (1985, 1987). Area is shown on the San Juan quadrangle, G12A65, and the San Raymundo quadrangle, G12A75, scale 1:50,000; and the geologic maps of McLean *et al.* (1985), scale 1:125,000; McLean and Hausback (1984); Mina-Uhink (1957); and Beal (1948).

Stratigraphy

Bateque Formation, Middle Eocene.—The Bateque Formation in Arroyo San Raymundo consists of brown, thin-bedded arkosic sandstones and siltstones interbedded with white diatomites and siliceous shales that contain cool-water, upper bathyal taxa of latest Middle Eocene age. The diatoms indicate the *Triceratium inconspicuum* var. *trilobata* Partial Range Zone (McLean and Barron, 1988).

Significant outcrops are seen upcanyon from where Arroyo San Raymundo crosses the unpaved road from Cadaje to San José de Gracia. The locality is approximately 20 km north of Punta Pequeña and north of latitude 26°15′ N (Text-fig. 18). According to McLean and Barron (1988), it is the southernmost occurrence of Eocene diatomite known in North America, correlative with the Kreyenhagen Shale of California.

The Bateque Formation is overlain unconformably in Arroyo San Raymundo by the northernmost exposures of the Late Oligocene San Gregorio Formation. Squires and Demetrion (1992) suggested that more detailed mapping might place the diatomite in the lower part of the San Gregorio Formation, whose base is not exposed, rather than in the Bateque Formation.

San Gregorio Formation, Late Oligocene to Early Miocene.—In Arroyo San Raymundo the San Gregorio Formation consists of phosphatic and siliceous shale, sandstone, and an interbedded tuff of 21.9 ± 0.8 Ma (Hausback *in* McLean *et al.*, 1985). Regarded as Oligocene at its type area, these beds are interpreted as Early Miocene middle and outer shelf deposits that are unconformably overlain by shallow water sediments of the Isidro Formation.

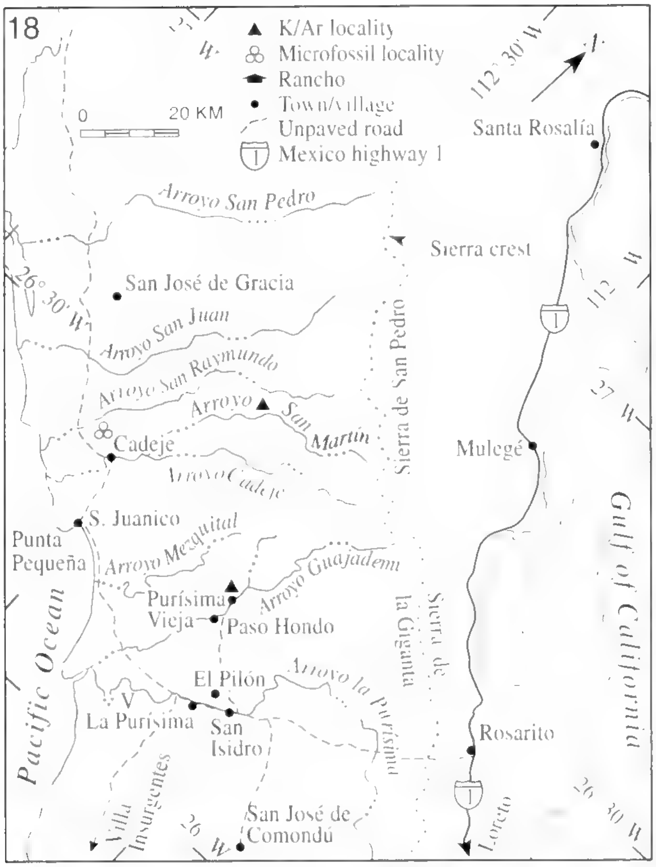
Isidro Formation, Middle Miocene.—Mina-Uhink (1957) named this unit the San Raymundo Formation, but subsequent mappers regard it as the earlier-named Isidro Formation described by Heim (1922) from the village of La Purísima. The grayish-white marine sandstone and siltstone contains well- to poorly-preserved shallow-water to inner-shelf megafossils. It is overlain unconformably by the nonmarine Comondú Formation. Mina-Uhink (1957) mapped the Isidro Formation from the Vizcaíno peninsula to approximately 75 km north of La Paz, noting lateral facies changes from shales to sandstones. More recent mapping limits the formation to outcrops between Arroyo Patrocinio and Arroyo la Purísima.

Comondú Formation, late Middle Miocene.—Described from farther south, the Comondú Formation in this area is a brown to gray, poorly sorted volcaniclastic sandstone and conglomerate deposited by braided streams. An interbedded basalt flow in Arroyo San Martín, the next drainage southeast of Arroyo San Raymundo, yielded a K/Ar age of 12.9 ± 0.7 Ma (McLean *et al.*, 1985; Text-fig. 18 herein). An unconformity separates the Comondú Formation from overlying plateau basalts.

Unnamed plateau basalts, Late Miocene.—Widespread unnamed plateau basalts cap the section over much of the western slopes. McLean *et al.* (1987) reported a K/Ar age of 10.7 ± 1.14 Ma for a pillow basalt in Arroyo San Raymundo.

Purísima-Iray basin, western slopes of the
Sierra la Giganta, Western embayment
Plate 1, Column 16
(Text-figs. 2, 17–23, Appendices 1, 2)

Column modified from McLean *et al.* (1987). Area is shown on the San Raymundo quadrangle, G12A75,


18
K/Ar locality
Microfossil locality
Rancho
Town/village
Unpaved road
Mexico highway 1
0 20 KM
Santa Rosalía
Arroyo San Pedro
Sierra crest
San José de Gracia
Arroyo San Juan
Arroyo San Raymundo
Arroyo San Martín
Cadeje
Arroyo Cadeje
Sierra de San Pedro
Mulegé
S. Juanico
Punta Pequeña
Arroyo Mezquital
Arroyo Guajademi
Purísima Vieja
Paso Hondo
Sierra de la Giganta
El Pilón
Arroyo la Purísima
La Purísima
San Isidro
Rosarito
Pacific Ocean
Gulf of California
Villa Insurgentes
San José de Comondú
Loreto


21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23

Paso Hondo quadrangle, G12A76, San Isidro quadrangle, G12A76, Punta Pequeña quadrangle, G12A85, Comondú quadrangle, G12A87, scale 1:50,000; and the geologic maps of Beal (1948), McLean and Hausback (1984), McLean *et al.* (1985), and Mina-Uhink (1956, 1957).

Overview

The Purísima-Iray basin was named by Mina-Uhink (1956, 1957) for the 16,000 km^2 area from Arroyo la Purísima to La Paz. For convenience we restrict this basin to the area between Arroyo Patrocinio and the vicinity of Colonia Santo Domingo. The western slopes of the Sierra la Giganta are underlain by a flat-lying to gently dipping Middle Eocene to Middle Miocene marine section that was slightly deformed from north to south. Many deep southwest-trending canyons provide good exposures of the section.

La Purísima is an old village along Arroyo la Purísima, 4 km downstream from the newer town of San Isidro. Iray is named for Pozo Iray #1, a Pemex petroleum well at Colonia Santo Domingo, north of Ciudad Constitución and south of La Poza Grande (Text-fig. 56). The area was mapped in 1918 as a potential source of onshore oil reserves by Beal's Marland Oil Company survey (published by Anonymous, 1924, and Beal, 1948) and by Mina-Uhink in 1943 for Petróleos Mexicanos or Pemex (published by Mina-Uhink, 1956, 1957). Data from Pozo Iray #1 and other wells provided subsurface geology for Mina-Uhink's map. Granitoid and metasedimentary basement rocks are not exposed in the western slopes of the Sierra la Giganta.

Zanchi *et al.* (1992) used regional unconformities to separate the main sedimentary units in the La Purísima area. They preferred the terms Lower Sedimentary Sequence, Middle Sedimentary Sequence, and Upper Sedimentary Sequence for the San Gregorio, Isidro, and lower Comondú Formations of earlier mappers.

Stratigraphy

Santo Domingo Formation, Paleocene.—Mina-Uhink (1957) gave the name Santo Domingo Formation to the oldest sediments he recovered from Pemex well Pozo Iray #1, south of La Poza Grande (Text-fig. 56). He reported a maximum thickness of 1,366 m of Paleocene gray shales with interbedded sands and sandstone. Later workers have not recognized the unit.

Bateque Formation, late Middle Eocene.—Flat-lying, yellowish-brown sandstone and siltstone containing marine megafossils and large discocyclinid foraminifers are well exposed near the mouth of Arroyo Mezquital in outcrops studied by Beal (1948), Mina-Uhink (1957), and Squires and Demetrion (1992), among others. Beal (1948) and Mina-Uhink (1957) mapped the sediments as the Tepetate Formation, which was described by Heim (1922) 200 km further south. McLean *et al.* (1985) and Squires and Demetrion (1994a) mapped them as the southernmost outcrops of the Bateque Formation (Text-figs. 13, 18–20).

The Bateque Formation has an overall range of middle Early Eocene to late Middle Eocene (55–42 Ma). Squires and Demetrion (1990a,b, 1992, 1994a,b) refined the age on the basis of megafossils; they documented an older, late Early Eocene "Capay" Stage

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Text-figure 18.—Western embayment, south of Arroyo Patrocinio to San José de Comondú, map showing southernmost outcrops of Eocene diatomite in western North America. Map modified from McLean *et al.* (1987) and McLean and Barron (1988). Middle Miocene K/Ar ages for volcanic flows interbedded with the Comondú Formation are 14.5 ± 1.2 Ma at Purísima Vieja (McLean *et al.*, 1985, sample 15) and 12.9 ± 0.7 Ma in Arroyo San Martín (McLean *et al.*, 1985, sample 10). V, La Ventana, area of lower Arroyo la Purísima where Hausback (1984b) dated Late Oligocene rhyolite tuffs in the San Gregorio Formation as 25.5 ± 0.4 Ma and 23.4 ± 0.3 Ma (K/Ar samples 28-3-8 and 28-3-16, respectively).

Text-figure 19.—Bateque Formation, Eocene foraminiferal facies in Arroyo Mezquital. The beds are composed mainly of the discocyclinid *Pseudophragmina advena* (Cushman) but they also contain abundant *Cubitostrea mezquitalensis* Squires and Demetrion and *Lepidocyclina* sp. (specimens on hammer); above them are fragments of the Eocene pectinid *Batequeus mezquitalensis* Squires and Demetrion and a Holocene land snail. Photo, J. T. Smith, 1984.

Text-figure 20.—Contact between the Miocene Isidro Formation and underlying Eocene Bateque Formation marked by bulbous burrows, Arroyo Mezquital. Photo, J. T. Smith, 1984.

Text-figure 21.—Phosphatic and diatomaceous beds of the Oligocene San Gregorio Formation exposed in Arroyo la Purísima near the dam (*la presa*) at San Isidro. Photo, T. M. Cronin, 1984.

Text-figure 22.—El Pilón, view northwest across Arroyo la Purísima from San Isidro. Oldest to youngest, the units are: San Gregorio Formation in the bottom of the arroyo (Tsg), white Isidro Formation (Tsi, at right of photograph), Comondú Formation forming most of El Pilón (Tc), and younger basalt capping the butte (Tb). Cinder cones to the right are 0.86 Ma (McLean *et al.*, 1987). Photo, J. T. Smith, 1984.

Text-figure 23.—San José de Comondú, type area of Middle Miocene Comondú Formation. Lavas of several ages postdate the Comondú Formation, the youngest flows filling the canyons and the oldest flows capping the mesa. Photo, J. G. Smith, 1982.

sequence in the northern area and a younger, late Middle Eocene, lower "Tejon" Stage in the Purísima-Iray basin. Microfossils at Arroyo Mezquital also indicate this age (Carreño and Cronin, 1993).

At Arroyo Mezquital the Bateque Formation is unconformably overlain by yellowish-gray sediments of Isidro Formation, the contact marked by a striking horizon of bulbous sediment-filled burrows (Text-fig. 20).

San Gregorio Formation, Late Oligocene.—Beal (1948) named the San Gregorio Formation for a folded section of white diatomaceous shale, phosphatic sandstone, tuff, and porcellanite exposed along the bottom and walls of Arroyo la Purísima, from 4 km downstream from the village of La Purísima to tidewater. McLean *et al.* (1987) measured a thickness of 72 m near the base of the butte El Pilón (Text-figs. 21, 22). Early reconnaissance studies referred the unit to the "Monterey-Beds" (Darton, 1921), the "Monterey Formation," or "Monterrey Formation" (Heim, 1922; Mina-Uhink, 1957) because of lithologic similarities to the younger oil-bearing Monterey Shale of California.

Topical paleontological studies by Kim (1986) and Kim and Barron (1986) indicate a Late Oligocene age for the diatomite in the San Gregorio Formation at La Purísima. Kim (1987) listed species from planktonic foraminiferal zones P21 and P22, diatom zones *Rocella vigilans, Bogorovia veniamini,* and *Rocella gelida,* and equivalent calcareous nannofossil zones NP 24 to CP 19b (33 Ma–22.5 Ma, *fide* Barron *et al.*, 1985). Kim (1987) and Kim and Barron (1986) correlated the upper San Gregorio Formation with the latest Oligocene–earliest Miocene *Rocella gelida* diatom zone (23.5–22.5 Ma) at La Ventana. Microfossil ages are corroborated by radiometric ages of 27.2 ± 0.6 Ma near the base of the exposed section in Arroyo San Gregorio, 23.4 ± 0.3 Ma and 23.9 ± 0.4 Ma on an interbedded tuff in the upper part of the formation at La Ventana (Text-fig. 18, herein; Hausback, 1984b).

The San Gregorio Formation is exposed in discontinuous outcrops between Arroyo San Raymundo and Arroyo la Purísima, as mapped by McLean *et al.* (1985). The name was also used for penecontemporaneous sediments in the Magdalena Plain, until a paper by Applegate (1986) introduced the name El Cien Formation for those sections. Further mapping and analyses are needed to refine the correlation between the two areas. The base of the San Gregorio Formation is not exposed; its upper contact is an unconformity with the Isidro Formation.

Isidro Formation, Early Miocene to early Middle Miocene.—Shallow neritic yellowish-gray to white sandstone, siltstone, and coquina were described by Heim (1922) from the type locality "at Canal Head" in Arroyo la Purísima, before the dam was built at what is now the town of San Isidro. Referred informally to the "Yellow beds" by Darton (1921), the Ysidro Formation by Beal (1948), and the San Raymundo Formation by Mina-Uhink (1957), the unit crops out from the area of Arroyo Patrocinio to south of Arroyo la Purísima (Mina-Uhink, 1957; McLean *et al.*, 1985), and several kilometers east of the village of San Isidro.

The type section contains numerous biofacies and abundant well-preserved invertebrate fossils, many with Tertiary-Caribbean faunal affinities (J. T. Smith, 1984). These include the gastropods *Turritella gatunensis rhytodes* Woodring, *Turritella bifastigata* Nelson, *Melongena (Melongena) consors* (Sowerby), *Cymia* sp. cf. *C. cheloma* Woodring, *Strombus* sp. cf. *S. costatus* Gmelin, *Rapana imperialis* Hertlein and Jordan, and the bivalves *Lyropecten pretiosus* (Hertlein), *Spondylus scotti* Brown and Pilsbry, "*Aequipecten*" canalis (Brown and Pilsbry), *Clementia dariena* (Conrad), and *Hyotissa haitensis* (Sowerby). The Isidro Formation is younger than 23 Ma, the age of a tuff near the top of the underlying San Gregorio Formation, and older than 14.5 Ma, the age of a basalt flow in the overlying Comondú Formation near Purísima Vieja (Hausback, 1984a,b; McLean *et al.*, 1987).

The Isidro Formation is regarded as Early Miocene to early Middle Miocene, 15–21.5 Ma, in the type area, based on megafossils, microfossils, and constraining radiometric data. McLean *et al.* (1985) mapped the contact between the Isidro Formation and the Comondú Formation as a time-transgressive unconformity, older to the southeast and younger to the northwest. McLean *et al.* (1987) reported that the Isidro Formation interfingers with the Comondú Formation to the east. At Arroyo Patrocinio the Isidro Formation is disconformable on the Early Eocene Bateque Formation and capped by Late Miocene basalt flows that have radiometric ages of 8 Ma and 10 Ma (McLean *et al.*, 1987).

Beal (1948) referred the rocks above the Eocene sediments at the mouth of Arroyo Mezquital to the Salada Formation, because of the yellow color, lithology, and abundant molluscan fossils. McLean *et al.* (1985) mapped the units as Bateque Formation and Isidro Formation. Recent paleontological work suggests that the upper Isidro Formation could indeed be correlative with parts of the Salada Formation; detailed mapping, well core data, and facies analyses would help verify this correlation.

Beal (1948) mapped the Isidro Formation south of the Magdalena Plain to San José del Cabo, but later workers restricted it to the western embayment between Arroyo Patrocinio and the La Purísima area.

Some authors suggested that it extended east to the present Gulf of California; Helenes and Carreño (1999) reported microfossil assemblages characterized by mixed cool and tropical temperatures that could support such a connection.

Purísima Nueva Formation, obsolete name, Early Miocene to early Middle Miocene.—Heim (1922: 536–537) assigned folded beds 4–5 km downstream from La Purísima to his "Purísima Nueva Formation," but later workers included them in the Isidro Formation. Fossil assemblages are the same as elsewhere in the unit; flat-lying and deformed beds within the formation indicate synchronous deformation and deposition (McLean *et al.*, 1987). Heim used an older name for Arroyo la Purísima: Arroyo Cadegomo. The stream was also known as the San Ramón River. Beal's unpublished map sheets, in Stanford University's Branner Earth Sciences Library and Map Collections, include the local names for streams and old ranchos.

Correlation of Oligocene and Miocene units in the Purísima-Iray basin

The San Gregorio and Isidro Formations are penecontemporaneous with parts of the El Cien Formation of the Magdalena embayment, although exact correlations have yet to be determined. Although the marine parts of all these units are fossiliferous (Kim, 1987; J. T. Smith, 1984, 1986; Gidde *in* Fischer *et al.*, 1995), most of the molluscan species are not the same. Radiometric ages of volcanic rocks associated with the San Ignacio Formation to the north suggest that the Miocene unit is slightly younger than the Isidro Formation at its type area.

Comondú Formation, time-transgressive, late Middle Miocene to early Late Miocene.—Noted by Gabb (1869a) as one of the mesa-forming units of the western Baja California peninsula, the Comondú Formation was formally described in the western Sierra la Giganta by Heim (1922). He listed a number of sedimentary facies—nearly horizontal fluvial sandstone, mudstone, volcaniclastic breccia, and cobble to boulder conglomerate—exposed in canyons around the village of San José de Comondú (Comondú quadrangle), approximately 50 km west of Loreto and 40 km southeast of La Purísima. He emphasized that this is not a volcanic unit. Deposited by braided streams, it is a matrix-supported clastic unit whose volcanic clasts are well-rounded rocks eroded from a volcanic arc that was active from 24–12 Ma in the area of the present Gulf of California (Sawlan, 1991).

The Comondú Formation is at least 1,800 m thick along the crest of the Sierra la Giganta; it thins to the north and west and and is younger at Arroyo Patrocinio, 175 km to the north (McLean *et al.*, 1985; Mina-Uhink, 1957). Constrained to 14.5–12 Ma in the La Purísima area, the Comondú Formation at Mesa las Gallinas is 10 Ma, capped by a basalt with a $^{40}Ar/^{39}Ar$ age of 10.5 ± 0.4 Ma (McLean *et al.*, 1985) (Text-fig. 13, p. 37). Its southernmost extent is regarded by some workers as the eastern Magdalena embayment, as shown in regional maps of Tembabiche (or Tembabichi) and San Juan de la Costa (p. 92).

Mina-Uhink (1957) and Hausback (1984) mapped it as far south as the La Paz Peninsula; Martínez-Gutiérrez and Sethi (1997) showed the unit in the Cabo Trough. The Comondú Formation is well exposed along roads between Mexico 1 at Rosarito, north of Loreto, and the town of San Isidro, and between Loreto and Misión San Javier. It underlies La Giganta, at 1,765 m the highest point on the crest of the Sierra la Giganta. McLean *et al.* (1987) discussed variations in sedimentology, composition and age; McLean (1989) chose to refer sediments in the onshore Loreto embayment to proximal or distal facies, terms related to the volcanic arc source of the clasts, rather than to the Comondú Formation.

Age of the Comondú Formation, late Middle Miocene.—The age of the Comondú Formation is time-transgressive, no younger than capping flows of alkali basalt dated at 8–14 Ma, according to McLean *et al.* (1987). In the type area and to the northwest, most of the unit was deposited in the late Middle Miocene, between 14 and 12 Ma. This is documented by rare interbedded ash-flow tuffs and alkalic basalt flows in Arroyo San Martín, 20 km north of its junction with Arroyo Cadajé, and at Purísima Vieja, 4 km south of Paso Hondo in Arroyo San Gregorio (Text-fig. 18). Hausback (1984b) and McLean *et al.* (1987, figs. 10 and 12, and their Table 1) reported K/Ar ages of 12.9 ± 0.7 Ma and 14.5 ± 1.2 Ma, respectively, for these interbedded flows.

Near La Purísima the Comondú Formation is overlain by 12–6 Ma Late Miocene plateau basalts such as the thick flow capping El Pilón in Arroyo la Purísima (Text-fig. 22), and by unnamed canyon-fill lavas showing reverse topography in the type area, youngest lavas in the canyon floors and oldest basalts toward the top (Text-fig. 23). These are in turn overlain by young cinder cones of 0.4–0.9 Ma (McLean and Hausback, 1984).

West of Loreto, near Cerro de las Parras, McLean (1988) mapped "volcaniclastic rock" along the road to San Javier. Regarded informally by many as the Comondú Formation, these rocks are intruded by a hornblende andesite porphyry with a K/Ar age of 19.4 ± 0.9 Ma (McLean *et al.*, 1987). This and other ages of underlying and intrusive rocks constrain the sediments in this area to approximately 18–22 Ma, considerably older than the type section of the Comondú Formation (McLean, 1988).

Differing concepts of the Comondú Formation.—No other lithologic unit in the Baja California peninsula has been so broadly interpreted. The name "Comondú" has been used for Oligocene to Pliocene volcanic tuffs, flows, and volcaniclastic rocks from Santa Rosalía to San Juan de la Costa, the La Paz peninsula, and the Cabo Trough. Many workers, beginning with Beal (1948), included volcanic rocks in the Comondú Formation or the Comondú Group without regard for the sedimentary nature of the type section. I. F. Wilson (1948), I. F. Wilson and V. S. Rocha (1955), and Mina-Uhink (1957) used Comondú Formation for volcanic rocks as far north as Santa Rosalía. Sawlan and J. G. Smith (1984) and Sawlan (1991) discussed differences between true volcanic arc rocks from the Sierra Santa Lucía (between Santa Rosalía and Mulegé) and the arc-derived sediments at the type locality at San José de Comondú.

Using the definition of a formation in the North American Stratigraphic Code (1983), the Comondú Formation would be restricted to the largely coarse clastic sedimentary unit in its type area in the Sierra la Giganta and finer-grained facies in parts of the western embayment. Derived from older arc volcanic rocks in the area of the present Gulf of California, it is not itself an arc volcanic rock (Sawlan and J. G. Smith, 1984). Its only volcanic components are several minor tuffs and flows in sections north of Arroyo la Purísima (McLean *et al.*, 1987). Younger plateau and canyon-filling basalts in the type area are related to later episodes of volcanism, not arc volcanism; they are not part of the Comondú Formation.

Our concept of the unit contrasts with those of Hausback (1984a,b) and later workers, who include in the Comondú Formation wide bands of volcanic and volcaniclastic rocks from the Concepción Peninsula and the Loreto basin as well as multiple ash-flow tuffs near San Juan de la Costa and La Paz. Those tuffs range in age from 22–12.5 Ma, most between 17 and 22 Ma. By this definition, the Comondú Formation would include both arc and non-arc lithologies of different provenances and an age spanning at least 10 million years.

McFall (1968) regarded his older units on the Concepción Peninsula as the Comondú Group (p. 81). His section includes basalts, tuffs, conglomerates, sandstones, and agglomerates that range in age from 30–17 Ma, Late Oligocene to Early Miocene, significantly older than the Comondú Formation in its type area.

We prefer the descriptive terms "unnamed volcaniclastic rocks, near-vent facies or distal vent facies," following McLean (1987), for sediments derived from the Miocene volcanic arc that lay east of the present Loreto basin between 24 and 11 Ma (Sawlan, 1991). J. G. Smith (1993) provided a concise discussion of the nature and nomenclature of volcanic and volcaniclastic rocks that are formed, deposited, and reworked in a subaerial arc environment. He favors a more interpretive terminology based on composition, age, and facies, as used by McLean (1988) and McLean *et al.* (1987), rather than conventional stratigraphic units such as formations or Groups.

Proximal volcanic arc facies mapped as "Comondú Formation."—"Comondú" has been used in unpublished reports and primarily paleontological papers on the sections at Loreto, Arroyo San Carlos, Punta San Telmo, and Tembabiche, and for the upper, nonmarine volcanic and sedimentary units at San Juan de la Costa. Measured sections from Tembabiche show volcaniclastic sandstone and breccia overlying the El Cien Formation as subunits of the Comondú Formation (Plata-Hernández, 2002; Plata-Hernández and Schwennicke, 2000). Our columns refer to these as unnamed volcaniclastic sediments, pending the further mapping and analysis underway in the Tembabiche area.

Cuesta Formation, obsolete name.—Heim (1922) introduced the name Cuesta Formation for unfossiliferous gray sandstones overlying the Comondú Formation and forming the rim of the mesa near La Purísima. Later mappers included them in the Isidro Formation.

Plateau basalts, capping volcanic rocks, canyon-fill lavas and cinder cones.—Younger volcanic rocks that overlie the Comondú Formation in the western Sierra la Giganta are locally-derived, separate, unnamed andesite and basalt flows 14–11 Ma and 7 or 8 Ma in age (McLean *et al.*, 1987). Quaternary cinder cones and canyon-filling flows are as young as 0.40 to 0.9 Ma. El Pilón, a well known example of an erosional remnant in Arroyo la Purísima, is capped by a younger basalt flow (Text-fig. 22).

Magdalena embayment, southern part of the Western embayment
Plate 1, Columns 17, 18, 19
(Text-figs. 2, 24–34, Table 5, Appendices 1, 2)

Overview

The Magdalena embayment contains Late Cretaceous to Late Miocene or Early Pliocene marine sediments that extend 400 km (250 mi) from north of

Table 5.—Western Magdalena embayment, lithostratigraphic units (Text-figs. 28, 33). Lowercase names indicate informal units that were not established according to the North American Stratigraphic Code (1983).

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
Cerro Colorado Member	Applegate (1986) named as upper member of El Cien Formation.	Member includes sandstone, siltstone, tuffaceous sandstone, conglomerate, and porcellanite. It is nonmarine at its type section on the west side of Cerro Colorado, approximately 5 km east of Las Pocitas in the quadrangle of the same name. In other locations the member varies from marine to lagoonal or nonmarine (Gidde, 1992a). Early Miocene, older than 21.0 ± 0.4 Ma, the date of an ash-flow tuff in the overlying volcaniclastic sediments south of San Juan de la Costa (Hausback, 1984b).
Cerro Tierra Blanca Member	Applegate (1986) named as lowest member of El Cien Formation. Fischer *et al.* (1995) regarded as lower part of their San Juan Member.	Member has a basal marine conglomerate with abundant shark teeth and reworked turritellid fragments overlain by microfossiliferous sandstone and tuffaceous siltstone with calcareous concretions. Type section is on the west side of Cerro Tierra Blanca, which adjoins the southwestern side of Cerro Colorado, Las Pocitas quadrangle. Locally its upper boundary is marked by resistant flag stones, the Llajas Palo Verde of Ojeda-Rivera (1979). Late Oligocene–Early Miocene (Carreño, 1992b).
El Cien Formation	Applegate (1986) named the formation and three members: Cerro Tierra Blanca, San Hilario, and Cerro Colorado. Fischer *et al.* (1995) proposed the San Juan Member as an alternative for Applegate's two lower members.	Formation includes marine and nonmarine clastic sediments with minor tuff beds that overlie the Tepetate Formation with angular unconformity. Type section is approximately 125 m thick, the most complete sequence of the outcrop areas (Fischer *et al.*, 1995); it is a predominantly marine sequence that is exposed on the west flank of Cerro Colorado, northeast of Pénjamo, and in the walls of Arroyo San Hilario east of El Cien (km 100), Las Pocitas and San Juan de la Costa quadrangles, respectively. Late Oligocene–Early Miocene, based on fossils and interbedded and overlying radiometrically dated volcanic rocks (Hausback, 1984b).
Salada Formation	Heim (1922). Schwennicke (1998) relocated and remeasured the type section.	Unit has fossiliferous, shallow-water, marine and nonmarine facies that include sandstone, agglomerate, and coquina described from the southeast side of Arroyo la Salada below the site of Rancho la Salada (GPS coordinates for site are 24°29.797′ N, 111°32.137′ W). Type section extends 600 m along the arroyo at the southern edge of the Santa Rita quadrangle. Originally considered Pliocene, but more recent studies suggest a Late Middle to early Late Miocene age (Smith, 1992; L. G. Barnes, 1995).
San Hilario Member	Applegate (1986) named as the middle member of the El Cien Formation. Fischer *et al.* (1995) included in their San Juan Member. Hausback (1984b) mapped as San Gregorio Formation.	Member consists of fossiliferous marine sandstone and tuffaceous, phosphatic and diatomaceous facies exposed in cliffs along Arroyo San Hilario. Applegate's type section was described from the area of Rancho San Hilario, east of El Cien, San Juan de la Costa quadrangle. Late Oligocene–Early Miocene?, based on a rhyolite tuff with a K-Ar age of 25.5 ± 0.4 Ma near the top of the section in Arroyo San Hilario (Hausback, 1984b).
San Juan Member	Fischer *et al.* (1995) named as lower part of El Cien Formation, after Schwennicke (1992, 1994). These authors regarded the Cerro Tierra Blanca and San Hilario Members of Applegate (1986) as the San Juan Member.	Member includes fossiliferous marine sandstone, conglomerate, fanglomerate, tuffaceous, and phosphatic facies, and the phosphorite layers ("*capas*") that were mined at San Juan de la Costa. Composite type section is exposed east of El Cien along parallel limbs of a syncline. The western outcrops are near Rancho el Agujito de Castro, El Conejo quadrangle; the eastern beds crop out in Arroyo Amarga, 4 km northwest of San Juan de la Costa, San Juan de la Costa quadrangle. Oligocene.
Tepetate Formation	Heim (1922). Fulwider (1976, 1984) distinguished three subunits in Arroyo Colorado, oldest to youngest: Cannonball member, interbedded claystone and siltstone member, and a crossbedded member.	Formation is a marine unit that includes soft greenish sandstone, well-stratified gray sandstone, and claystone with abundant discocyclinid foraminifers. Type section in the bottom of Arroyo Colorado is west of Mexico 1 and 1–2 km southwest of Rancho Tepetate, Las Pocitas quadrangle. Formation originally regarded as Late Cretaceous to Eocene, but later workers suggest Late Paleocene to early Middle Eocene (Carreño *et al.*, 2000).

Ciudad Constitución to south of Arroyo el Conejo; isolated Miocene outcrops are present as far south as Arroyo la Muela, near Todos Santos.

In the Late Oligocene, the Magdalena embayment extended from the east coast of the present Baja California peninsula to the Pacific Ocean, as seen from near-shore deposits from Arroyo San Carlos and Punta San Telmo to San Juan de la Costa (p. 92). Facies and depth changes during the Oligocene complicate correlation between those units and the type section of the El Cien Formation at Cerro Colorado and Arroyo San Hilario, north and east of El Cien (Text-fig. 33).

The Magdalena embayment is the southern part of a series of western embayments that existed as far north as Laguna San Ignacio and included the western slopes of the Sierra la Giganta between Arroyo Mezquital and Arroyo la Purísima (Text-fig. 2). Paleogene and early Neogene marine deposition occurred while the Baja California peninsula lay against mainland Mexico, when the western Magdalena area was the next embayment north of the La Mira basin of Nayarit and Michoacán (Text-fig. 35d,e herein; Durham *et al.*, 1981; Perrilliat, 1987, 1992; J. T. Smith, 1991c).

Reconnaissance maps of the area assign a number of different names to the stratigraphic units (see summaries by Applegate, 1986; Carreño, 1992b; Fischer *et al.*, 1995). Further mapping and detailed analyses are needed to refine interpretations of formations, members, facies, contacts, and correlation. The revised age of the type Salada Formation, from the Pliocene of early workers to Middle to early Late Miocene, has important implications for the geologic history of the region (J. T. Smith, 1992). Marine fossils from hard gray sandstone clasts in the lower part of the Salada Formation are key to correlating sediments in the Purísima-Iray basin and the Magdalena embayment.

Granitic and metamorphic basement rocks are not exposed in the onshore western Magdalena embayment, although Mesozoic (?) rocks of oceanic origin crop out on Isla Margarita and Isla Magdalena (Forman *et al.*, 1971; Rangin and Carrillo-Martínez, 1978; M. C. Blake *et al.*, 1984). Sedlock (1993) interpreted these rocks as parts of volcanic arcs and ophiolitic terranes that were accreted to the Baja California peninsula in Late Jurassic or earliest Cretaceous time.

Arroyo Salada—Santa Rita—El Rifle
Plate 1, Column 17
(Text-figs. 1, 24–30, Table 5, Appendices 1, 2)

Column modified from Heim (1922), Fulwider (1976), and Schwennicke (1998). Area is shown on the Santa Rita quadrangle, G12C68, Puerto Chale quadrangle, G12C78, and Las Pocitas quadrangle, G12C79, 1:50,000. Beal (1948) and Mina-Uhink (1956, 1957) published geologic maps that included the area.

Stratigraphy

Tepetate Formation, latest Cretaceous to Early Eocene.—The Tepetate Formation crops out from Arroyo Salada to Arroyo el Conejo, approximately 75 km north of La Paz on Mexico 1, and as far east as Cerro Colorado (Fulwider, 1976; Galli-Olivier *et al.*, 1986; Squires and Demetrion, 1991) (Text-figs. 28, 30).

Fulwider (1976, 1984, 1991) discussed sections in Arroyo Salada, where he recognized only the two older informal subunits of the type area, the massive, unfossiliferous Cannonball Sandstone and an interbedded claystone and siltstone. They crop out near Rancho el Médano and Rancho el Sauce, where the unit dips 20° to the northeast. He regarded the lowest beds as Late Cretaceous to Eocene in age, based on microfossils. The base is not exposed; the upper contact with the Salada Formation is unconformable.

Salada Formation, late Middle to early Late Miocene.—Heim (1922) described the Salada Formation while staying at Rancho la Salada in 1915. Then a thriving cattle ranch, it is now difficult to find the few green mezquite trees and scattered bricks that represent the original site 30 m from the edge of the plateau (Text-figs. 24, 25, 26). The access ramp has crumbled away; a sketch from Gabb's early traverse showed it 800–1,000 m north of a ranch building (Browne, 1868, p. 12). Schwennicke (1998) relocated the site 10–15 km southwest of Santa Rita, and the type section in the arroyo below. He provided GPS coordinates for the ruins: 24°29.889′ N, 111°31.907′ W (Schwennicke, personal communication, 2003).

Field notes in the Smithsonian Institution's National Museum of Natural History and fossils collected by Heim and later Darton confirm Schwennicke's (1998) report of the type section downstream from Rancho Agua Verde and 1–1.5 km upstream from the section near the ruins of a World War II adobe fort (Text-fig. 28).

Heim (1922: 544–546) published a detailed description of the type section; A, its upstream end, has GPS coordinates 24°30.153′ N, 111°31.573′ W (Schwennicke, oral communication, 2003). He described fine- and coarse-grained sandstone and coquina beds exposed for 600 m along the southeastern wall of the arroyo and dipping a few degrees to the west (Text-figs. 24, 25, 28). He designated the lowest facies as Bed 1, the uppermost unit as Bed 10. Bed 9, his "Great Pecten bed," contains a Tertiary-Caribbean pectinid identified by J. T. Smith (1992) as *Chlamys* sp. cf. *C. tamiamiensis* (Mansfield) subsp. Unconformable Pleistocene marine terrace deposits (Heim's Bed 11) cap the section.

Schwennicke (1998) and Schwennicke *et al.* (2000) measured 14 m of section along A–B at the base of the cliff. They refined descriptions of Heim's ten beds, including a basal lagoonal, phosphatic facies at water level overlain by a key fossiliferous marine conglomerate (Bed 2) and fossiliferous sandstone (Bed 3). They verified differences between the section at A and the facies at B, which include a 2- to 3-m-thick lens of reworked coquina, Schwennicke's Bed 3a (Text-fig. 25). They noted large, unfossiliferous, well-indurated clasts at low-water level, at the boundary between the Bed 2 conglomerate and the sandstones of Bed 3. Schwennicke (1998) also identified a number of fluvial facies within the marine sediments and related the type section to measured sections at El Médano.

A number of workers in the 1980s and 1990 made reconnaissance visits to the area of the old adobe fort, believing it was the type section. A deteriorating stony ramp north of the fort provided access to the arroyo and the section of the Salada Formation. On several visits they observed well-indurated gray sandstone clasts bearing molds of large pectinids and other fossils, the "basal concretionary layer" of Smith (1992). The clasts weather from beds that are exposed intermittently at low water level between the ramp and 50 m upstream; at times they are buried by river mud (Text-fig. 27). The locality is shown on Text-figure 28 as 03JS4 (= 89JS3 = 83JS22). Its GPS coordinates are 24°29.797′ N, 111°32.137′ W.

Regarded as the lowermost bed of the Salada Formation by Smith (1992), the unit was reassessed by Schwennicke and Smith in 2003 as a marine facies of the well-indurated sandstone whose clasts mark the contact between Beds 2 and 3 at the type section. The clasts contain molds of the giant pectinids *Euvola* sp., *Amussiopecten* sp., *Amusium* sp., *Flabellipecten* sp., and external molds of *Chlamys* sp. cf. *C. tamiamiensis* (Mansfield) subsp. (Text-figs. 27, 29). Preliminary taxonomic studies suggest *Amussiopecten* sp. and *Amusium* sp. are the same as Isidro Formation species; the chlamyd occurs in concretions between Beds 2 and 3, in Heim's Bed 9 of the type section, and in Miocene marine rocks of the Paraguaná Peninsula, Venezuela.

The Salada Formation was deposited on an irregular surface in the Magdalena embayment. It overlies the Tepetate Formation with angular unconformity near Rancho el Médano, where the contact is marked by prominent, bulbous burrows in the Tepetate Formation filled with Salada Formation sandstone and fossils. Schwennicke and González-Barba (1995) regarded the Salada Formation there as equivalent to Heim's type section Bed 2. Schwennicke *et al.* (2000) reported that its easternmost outcrops near Microondas El Rifle (km 135) are also penecontemporaneous with the type section. The unit is exposed from Arroyo la Salada to Rancho el Conejo, and intermittently as far south as Arroyo la Muela north of Todos Santos (Text-figs. 30, 73).

To the north the Salada Formation was reported from wells such as Pozo Iray #2 near Puerto Adolfo López Mateos (Text-figs. 30, 56 herein; Mina-Uhink, 1957) and at the mouths of ". . . every river bed near the Pacific coast" from La Poza Grande to Arroyo San Gregorio (Heim, 1922). Heim's figure 6 shows outcrops near the mouth of Arroyo Cadegomo [=Arroyo la Purísima], where he reported the same fossils, including bryozoan-encrusted gastropods, that occur in Arroyo la Salada. He questioned whether fossiliferous marine agglomerates at La Ventana were also a facies of the Salada Formation.

Although Mina-Uhink (1957) mapped the Salada Formation in the valle central of Isla Margarita, offshore from Bahía Almejas, the geologic map of Rangin and Carrillo-Martínez (1978) and reconnaissance field work in 1985 by J. T. Smith, J. R. Ashby, Jr., G. Padilla-Arredondo and S. Pedrín-Avilés found only Quaternary sands. The unit is not present on Isla Magdalena, but marine fossils were observed north of the lighthouse at Cabo San Lázaro in outcrops on the north side of a circular cove (J. A. Minch, written communication, 2002).

Age of the Salada Formation, Late Middle to early Late Miocene.—Although the Salada Formation was regarded as Pliocene by Heim (1922), Beal (1948), and Mina-Uhink (1957), radiometric data and marine fossils indicate it is Late Middle to early Late Miocene (J. T. Smith, 1992, and ongoing research).

A Middle Miocene (14 Ma) to Late Miocene (6 Ma) age, depending on which seawater strontium ratio curves are used to interpret the data, was determined by R. E. Denison, then of Mobil Oil Company. He reported a Miocene age for a pectinid collected from Heim's Bed 9, several meters below the Pleistocene terrace deposits that cap the type section (Text-fig. 28, fossil locality 83JS23, herein; R. E. Denison, written communication, 1991). The dated pectinid was Mobil Oil Corporation sample 8517 with a $^{87}Sr/^{86}Sr$ value of $0.708870 \pm .000026$, $\Delta_{sw} = -20.3$.

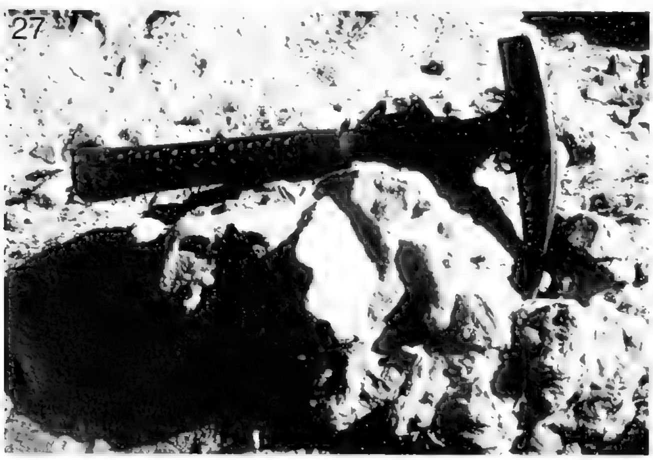
Vertebrates reported from the Salada Formation include Miocene sea lions, walruses, pinnipeds (Barnes, 1995, and oral communication), and Pliocene and Miocene sharks (Ashby, 1987; Schwennicke and González-Barba, 1995). Miocene age-diagnostic marine bivalves such as *Clementia dariena* (Conrad), *Raeta gibbosa* (Gabb), *Cyathodonta gatunensis* (Toula), and *Le-*

24


Rancho site


25

26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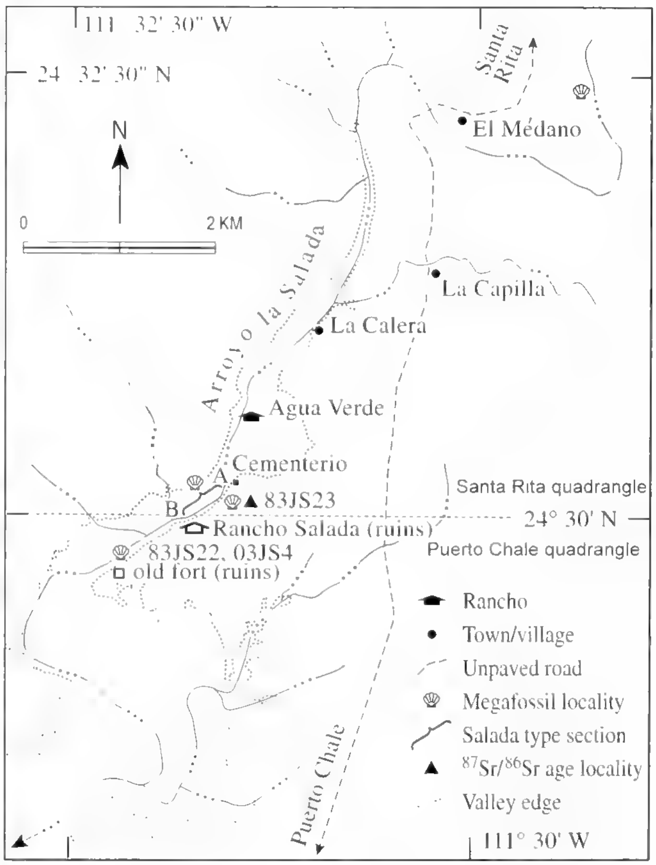

111° 32' 30" W
24° 32' 30" N
N
0
2 KM
Santa Rita
El Médano
Arroyo la Salada
La Capilla
La Calera
Agua Verde
Cementerio
A
B
83JS23
Santa Rita quadrangle
24° 30' N
Rancho Salada (ruins)
Puerto Chale quadrangle
83JS22, 03JS4
old fort (ruins)
Rancho
Town/village
Unpaved road
Megafossil locality
Salada type section
$^{87}Sr/^{86}Sr$ age locality
Valley edge
Puerto Chale
111° 30' W

porimetis trinitaria (Dall) are Tertiary-Caribbean taxa. Gastropods, shells encrusted by the bryozoan *Antopora tincta* (Hastings), and elongate balanid barnacles are also present in the fauna (J. T. Smith, 1992; P. A. Morris and J. T. Smith, 1995).

Correlation

The Salada Formation has been used broadly for rocks of varying lithology, provenance, and age over much of the Baja California peninsula. The name has been applied to areas as distant as the Sierra San Felipe in the northern Gulf of California and the southern San José del Cabo Trough, for any yellow sandstone with "Pliocene marine fossils," based on the age given by Heim (1922). Mollusks, vertebrates, and strontium isotope data from the type area indicate a significantly older unit that is not correlative with Pliocene sections in the ancient Gulf of California (J. T. Smith, 1992; Schwennicke and González-Barba, 1995; Barnes, 1995, and oral communication, 2000).

Mapping is needed to determine overlap between the Salada Formation and the upper Isidro Formation. The Salada Formation at Arroyo la Muela could be older than the type section (Schwennicke *et al.*, 2000). Molluscan taxa from the Salada Formation also occur in the Gatún Formation of Panama, the Tuberá Formation of Colombia, the Cantaure and Paraguaná Formations of Venezuela, the Gurabo Formation of the Dominican Republic, and the Springvale Formation of Trinidad (J. T. Smith, 1992).

Salada Formation at El Rifle, Late Miocene to Early Pliocene.—The Salada Formation near Microondas El Rifle (km 135) is 4–5 m thick and could be penecontemporaneous with the type section Schwennicke *et al.* (2000). Shark teeth suggest an Early Pliocene age (Espinosa-Arrubarrena and Applegate, 1981). The Salada Formation is overlain unconformably by latest Pleistocene lake deposits containing Rancholabrean Stage freshwater turtles and algal stromatolites (E. C. Wilson, oral communication, 1989; Ferrusquía-Villafranca and Torres-Roldán, 1980).

Quaternary terrace deposits.—Highly fossiliferous marine terrace deposits on Isla Margarita at Puerto Alcatraz, east of Puerto Cortés, were dated at 120,000 years (Wehmiller and Emerson, 1980). Fossiliferous Pleistocene terrace deposits also occur at Punta Belcher, Isla Magdalena (Jordan, 1936).

El Cien
Plate 1, Column 18
(Text-figs. 30–35, Table 5, Appendices 1, 2)

Columns modified from Carreño (1992b), Schwennicke *et al.* (1996), Schwennicke and Plata-Hernández (1997), and Fischer *et al.* (1995). Area is shown on Las Pocitas quadrangle, G12C79, La Fortuna del Bajío quadrangle, G12C69, and El Conejo quadrangle, G12D81, scale 1:50,000; the locality maps of Fischer *et al.* (1995); and the geologic maps of Mina-Uhink (1957), Hausback (1984a,b), and Carreño (1992b).

Overview

Oligocene to Miocene marine units crop out in the Magdalena Plain between Rancho San Luis Gonzaga, southeast of Ciudad Constitución (km 212), and Rancho el Aguajito de Castro, near km 70–74 on Mexico 1 (Text-figs. 30, 56). These sediments overlie the marine Tepetate Formation, which was deposited during multiple transgressive-regressive cycles.

Visited by Heim in 1915, Darton in 1920 and Mina-Uhink in 1943, the northern Magdalena Plain from Rancho la Fortuna to Rancho San Luis Gonzaga has not been remapped in recent times. Detailed studies of those outcrops are needed to assess and relate the members of the El Cien Formation of Applegate (1986) and the more recently introduced San Juan Member of Schwennicke (1994, 1995) and Fischer *et*

←

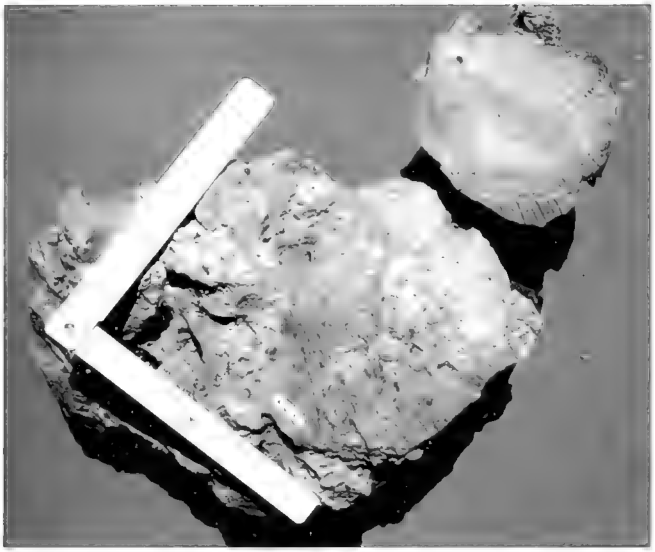
Text-figure 24.—Arroyo La Salada and the Magdalena Plain, view southwest at Heim's type section (A–B) and mezquite trees that mark the site of Rancho La Salada on the Pleistocene terrace. Photo, Tobias Schwennicke, 1996.

Text-figure 25.—Salada Formation at B, southwestern end of type section. Well-indurated, unfossiliferous concretions in the stream bed weathered out of Heim's Bed 2. The highly fossiliferous, prominent 2–3-m-thick resistant coquina is Heim's Bed 3 = Bed 3A of Schwennicke (1998). Photo, Tobias Schwennicke, 1995.

Text-figure 26.—Tobias Schwennicke surveys scattered bricks that remain from Rancho La Salada. Gabb camped here in 1867, Heim stayed in 1915, and Darton visited in 1921. Photo, J. T. Smith, 2003.

Text-figure 27.—Fossiliferous clast of well-indurated gray sandstone in Arroyo La Salada, upstream from the site of an old fort. The adobe walls of the World War II fort were reduced to less than 20 cm by 2003. In the arroyo, 1–1.5 km downstream from the type section, concretions marking the contact between Heim's Bed 2 conglomerate and Bed 3 sandstone contain giant pectinids (J. T. Smith megafossil localities 83JS22 = 89JS3 = 03JS04). Photo, J. T. Smith, 1985.

Text-figure 28. Salada Formation, map of type area south of Santa Rita and El Médano. A–B, type section, Beds 1–9 of Heim (1922); $^{87}Sr/^{86}Sr$ date at 83JS23 determined on a pectinid from Heim's Bed 9 is in the range of Middle to Late Miocene.



Text-figure 29.—Giant pectinid molds from the contact between Heim's beds 2 and 3 at the old fort section. The right valve at lower left could be the largest individual recorded for the genus *Amussiopecten* (Los Angeles County Museum of Invertebrate Paleontology hypotype 7632); the other right valve is *Euvola* sp. (Los Angeles County Museum of Invertebrate Paleontology hypotype 7633). J. T. Smith locality 89JS3 = 03JS04 of Text-figure 28. Photo, J. T. Smith, 1985.

al. (1995). Biofacies studies of the Cerro Colorado Member, the upper subunit of the El Cien Formation, by Gidde (1992a,b and *in* Fischer *et al.*, 1995) indicate it contains both marine and nonmarine facies, regressing upsection to a continental deposit. Earlier literature refers the Oligocene–Miocene marine sequences in this area to older names, including the San Gregorio and Isidro Formations, which were described from the Purísima-Iray basin to the north. Table 5 summarizes the stratigraphic nomenclature, which is still under discussion.

Granitic and metamorphic basement rocks do not crop out in the western Magdalena embayment.

Stratigraphy

Tepetate Formation, late Early Eocene to early Middle Eocene.—The type area in Arroyo Colorado was revisited by Carreño *et al.* (2000), who reviewed its stratigraphy, age, and depositional history. Strata in Arroyo Colorado were not designated by Heim (1922) but were regarded as the stratotype by Mina-Uhink (1957); the section has GPS coordinates 24°23′17.7″ N, 111°07′53.2″ W (Instituto de Geología Museo de Paleontología locality IGM-2984).

Carreño *et al.* (2000) divided the northeast-dipping 55-m-thick section into seven lithological units separated by erosional contacts; they recommended using a composite stratotype to represent the lithologic variation and longer chronostratigraphic range of the unit as a whole. The base is not exposed and the lowest part has no diagnostic planktonic foraminifers. Microfossils from the unit as a whole suggest outer shelf to upper bathyal depths (Carreño *et al.*, 2000). In the El Cien area the upper contact with the Late Oligocene Cerro Tierra Blanca Member is an angular unconformity; in Arroyo Salada the overlying unconformable unit is the Miocene Salada Formation.

Fulwider (1976, 1984, 1991) recognized three informal subunits of the Tepetate Formation in Arroyo Colorado and characterized them as follows. The oldest is the massive, unfossiliferous, Cannonball sandstone with 0.5-m-diameter concretions. The middle interbedded claystone has chocolate-colored upper sediments and purplish lower ones, sandy siltstone lenses, and calcarenite beds; its most recognizable facies is the foraminiferal siltstone in the upper part that consists largely of the discocyclinid identified as *Pseudophragmina (P.) advena* Cushman by Carreño *et al.* (2000) and as *Pseudophragmina (P.) cloptoni* (Vaughan) by earlier workers, including Knappe (1974) and Fulwider (1976). The cross-bedded member, youngest in the sequence, has alternating siltstones, sandstones, and silty-claystone layers that are exposed only in the Arroyo Colorado area. Fulwider's range of Cretaceous to Paleocene for the lower part of the section was based on microfossils.

Perrilliat (1996), sampling a different facies approximately 2 km southwest of El Cien, reported shallow-water tropical mollusks, including the Old World Tethyan gastropod genera *Campanile* and *Gisortia*, and associated late Early Eocene foraminifers (Carreño *in* Perrilliat, 1996).

The Tepetate Formation is mapped from Arroyo la Salada to Arroyo el Conejo, which is 75 km north of La Paz on Mexico 1 (Galli-Olivier *et al.*, 1986; Squires and Demetrion, 1991). Although it was reported in papers on the geology of San Juan de la Costa, we agree with Mina-Uhink (1957) that outcrops are restricted to the western Magdalena embayment.

Age and Correlation, Early Eocene to early Middle Eocene.—The type section contains planktonic foraminifers ranging from the latest Lower Eocene *Acarinina pentacamerata* Zone to the earliest Middle Eocene *Hantkenina nuttalli* Zone, equivalent to the Penutian to Narizian benthic foraminiferal stages of California (Almgren *et al.*, 1988). Its latest Early Eocene to early Middle Eocene age (51.2–48.4 Ma) is based on 54 species of benthic and planktonic foraminifers; Carreño *et al.* (2000) regarded poorly preserved Cretaceous or Paleogene taxa as reworked.

Fulwider (1976, 1984, 1991) reported a latest Cretaceous to Early Eocene age for the formation as a whole, with the section near Rancho el Sauce in Arroyo la Salada older than the type section. Vázquez-García (1996) identified middle Late Paleocene to Early Eocene planktonic foraminifers from the Tepetate Formation in Arroyo el Conejo (Carreño *et al.*, 2000).

Parts of the Tepetate Formation are coeval with parts of the Bateque Formation to the north. The lower part of the Tepetate Formation at Arroyo Colorado correlates with the middle Early Eocene age, "Capay" Provincial Molluscan Stage facies of the lower Bateque Formation at its type area (Squires and Demetrion, 1991). Both formations contain distinctive discocyclinid facies and abundant megafossils, including mollusks, corals, calcareous sponges, and echinoids.

El Cien Formation, Late Oligocene to Early Miocene.—The El Cien Formation was named by Applegate (1986) for marine to continental clastic deposits near El Cien (km 100) and east of the Mexico 1 at Cerro Colorado and Arroyo San Hilario (Text-figs. 31–33). Darton (1921) referred to these units as the "Yellow beds" and the Monterey Formation. Mina-Uhink (1957) mapped them as the Monterrey and Isidro Formations. Hausback (1984a,b) and Kim (1987) regarded the rocks between El Cien and San Juan de la Costa as the San Gregorio and Isidro Formations, names that are used in the Purísima-Iray basin. Early stratigraphic terminology was reviewed by Applegate (1986), Carreño (1992b), and Fischer *et al.* (1995), among others.

Paleontological, stratigraphic, and radiometric data indicate a Late Oligocene to Early Miocene age, 27 Ma to 17 Ma (Carreño *et al.*, 1997), for lithofacies that include sandstone, siliceous shale, limestone, porcellanite, tuff, and conglomerate. The formation crops out over much of the eastern and central Magdalena embayment, from Rancho San Luis Gonzaga, Rancho el Plátano and La Presa, north of Rancho la Fortuna, to north of the Aguajito Fault in the El Conejo quadrangle. It is mapped along the Gulf of California between Arroyo San Carlos and San Juan de la Costa (Carreño, 1992b). Text-figures 35d,e show the paleogeography of the Magdalena embayment at the time the El Cien Formation was deposited.

Applegate (1986) also named three members in the El Cien Formation, from oldest to youngest: Cerro Tierra Blanca, San Hilario and Cerro Colorado. Fischer *et al.* (1995) proposed an alternate interpretation based on sections near San Juan de la Costa and Rancho el Aguajito de Castro. They recognized only two subdivisions, the older San Juan and younger Cerro Colorado Members.

Cerro Tierra Blanca Member of Applegate (1986), Late Oligocene to Early Miocene.—The unconformity between the basal pebble conglomerate of the Cerro Tierra Blanca Member and the underlying Tepetate Formation can be seen along Mexico 1 at km 111 and on the western flanks of Cerro Tierra Blanca. The unit contains diatoms, planktonic foraminifera, and a large number of shark species, including *Carcharodon sokolowi* (Jaeckel) (Applegate, written communication, 1991), that indicate a Late Oligocene to Early Miocene age (Carreño *et al.*, 1997). Pectinids and turritellid fragments from this horizon are under investigation.

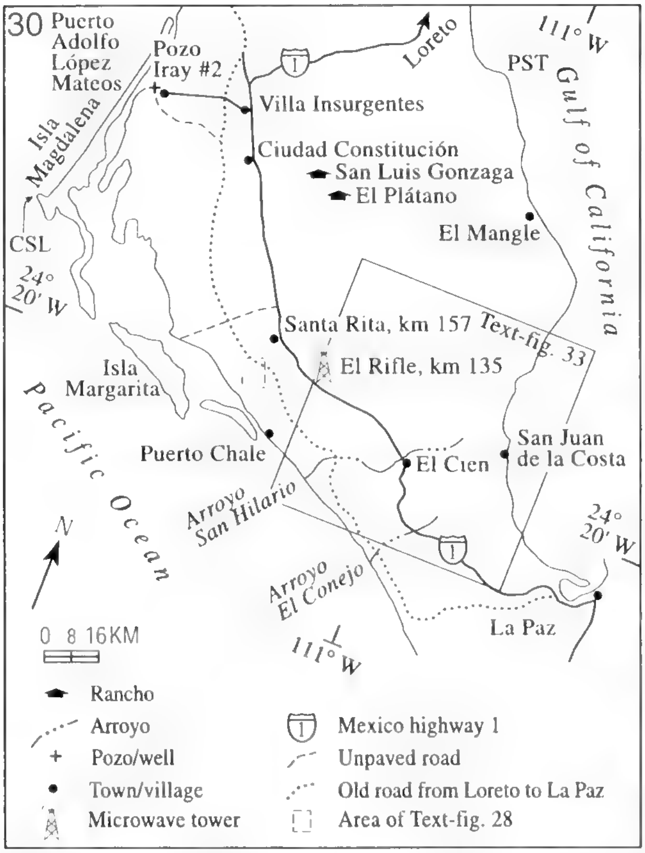
Schwennicke (1992) measured another section of mudstone, tuff, and phosphorite beds at Cerro Colorado; he reported that the local horizon known as Lajas Palo Verde of Ojeda-Rivera (1979) does not extend to Arroyo Aguajito and other drainages. He interpreted this and the following unit as the San Juan Member. Text-figure 33 shows the type and study areas of the El Cien Formation and its members.

San Hilario Member of Applegate (1986), latest Oligocene to Early Miocene.—The San Hilario Member has many facies, including phosphatic and diatomaceous marine sandstones, a widespread horizon of the bivalve *Anadara vanderhoofi* Durham, and an upper massive sandstone. Hausback (1984b) dated a Late Oligocene rhyolite tuff near the top of the section at Arroyo San Hilario (Text-fig. 32); a green porcellanite marks the upper contact with the overlying Cerro Colorado Member.

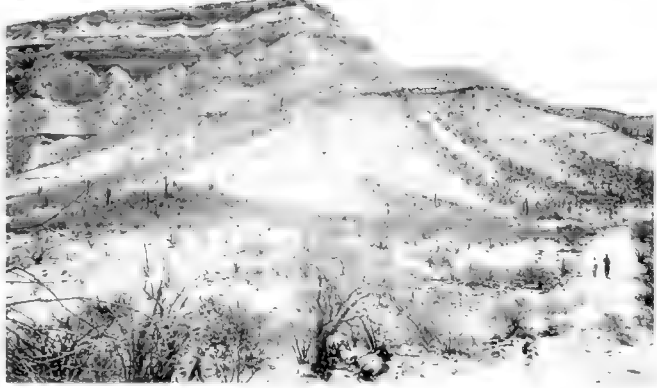
Kim (1987) studied well-preserved planktonic foraminifers from Arroyo San Hilario and assigned the beds to Planktonic Foraminiferal Zones P21 and P22 (31.6–24.4 Ma) of Berggren *et al.* (1985). Kim (1987) and Kim and Barron (1986) referred sections in this area to the San Gregorio and Isidro Formations, most of which fall within Applegate's San Hilario Member. They identified Early to Late Oligocene tropical diatom zones in the two lower members of Applegate, and recognized a mixture of tropical and cool water species that indicate a high rate of upwelling. Their data also suggest that the cool water California Current was already influencing the Magdalena embayment in Oligocene time.

Correlation

Beds at the mouth of Arroyo San Carlos and to the south contain abundant specimens of *Anadara vanderhoofi* Durham that also mark the top of the type section east of El Cien (Applegate and Wilson, 1976; Carreño, 1992b). Diatom zones are the same in several formations in the Magdalena embayment and the Purísima-Iray basin, but correlation is complicated by facies changes and stratigraphic terminology (Kim, 1987; Kim and Barron, 1986).


30
Puerto Adolfo López Mateos
Pozo Iray #2
Loreto
111° W
PST
Villa Insurgentes
Isla Magdalena
Ciudad Constitución
San Luis Gonzaga
El Plátano
El Mangle
Gulf of California
CSL
24° 20' W
Santa Rita, km 157
Text-fig. 33
El Rifle, km 135
Isla Margarita
Pacific Ocean
Puerto Chale
San Juan de la Costa
El Cien
Arroyo San Hilario
24° 20' W
N
Arroyo El Conejo
La Paz
0 8 16KM
111° W
Rancho
Arroyo
Pozo/well
Town/village
Microwave tower
Mexico highway 1
Unpaved road
Old road from Loreto to La Paz
Area of Text-fig. 28

31



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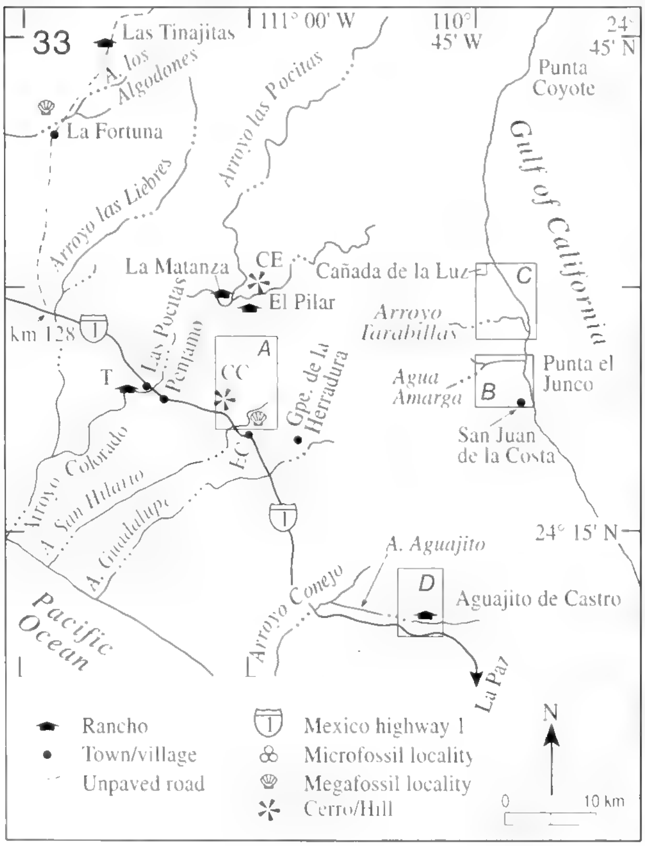

33
Las Tinajitas
111° 00' W
110° 45' W
24° 45' N
A. los Algodones
Arroyo las Pocitas
Punta Coyote
La Fortuna
Gulf of California
Arroyo las Liebres
La Matanza
CE
Cañada de la Luz
C
El Pilar
Arroyo Tarabillas
km 128
Las Pocitas Pentamo
A
CC
Gpe. de la Herradura
Punta el Junco
T
Agua Amarga
B
San Juan de la Costa
Arroyo Colorado
A. San Hilario
A. Guadalupe
EC
24° 15' N
A. Aguajito
Pacific Ocean
Arroyo Conejo
D
Aguajito de Castro
La Paz
Rancho
Town/village
Unpaved road
Mexico highway 1
Microfossil locality
Megafossil locality
Cerro/Hill
N
0 10 km

34

Cerro Colorado Member, late Early Miocene to Middle Miocene.—The Cerro Colorado Member is a regressive sequence of sandstones, tuffaceous sandstones, and conglomerates. It is nonmarine at its type section and some areas east of Rancho la Fortuna, where it contains root casts. Elsewhere it consists of fossiliferous shallow-water marine facies (Gidde, 1992; Gidde *in* Fischer *et al.*, 1995). Reworked silicified wood fragments from mainland Mexico occur in extensive beds at Rancho Matanzas, 22 km north of Cerro Colorado (Applegate, 1986; Cevallos-Ferriz and Barajas-Morales, 1991; Cevallos-Ferriz, 1995) and as float near Rancho la Fortuna (Text-fig. 34).

Fischer *et al.* (1995) presented columnar sections of this member from Cerro Colorado, Cerro el Pleito, and other western localities, where the unit is 50–52 m thick; sections to the east at Agua Amarga, Tarabillas, and Cañada de la Luz are thinner, 39–44 m. The upper boundary varies from a disconformity overlain by tuffs and volcaniclastic rocks at Cerro Colorado and Cerro el Pleito to a gradational contact in the San Juan de la Costa area. There are no datable volcanic layers in the Cerro Colorado Member, but Hausback (1984b) reported an overlying rhyolite tuff of 21.0 ± 0.4 Ma near San Juan de la Costa.

Unnamed volcanic and volcaniclastic rocks, late Early Miocene to early Late Miocene.—We prefer to call the rocks that unconformably overlie the El Cien Formation unnamed volcaniclastic and volcanic rocks, except for the named tuffs of Hausback (1984a,b). Many workers refer these rocks above the phosphatic beds to the Comondú Formation of Heim (1922), but lithologies and ages differ between the Magdalena embayment and Sierra la Giganta areas. The type section of the Comondú Formation is a distinctive volcaniclastic boulder to cobble conglomerate unlike any facies in the Magdalena embayment. Ages vary from 12–14 Ma in the type area to 16–18 Ma for the San Juan Tuff at Rancho Aguajito-San Juan de la Costa, and 21–23 Ma for the La Paz rhyolite tuffs near San Juan de la Costa (Hausback, 1984a,b).

Rancho el Aguajito de Castro
Plate 1, Column 19
(Text-fig. 33, Table 5, Appendices 1, 2)

Column modified from Carreño (1992b), Schwennicke *et al.* (1996), Schwennicke and Plata-Hernández (1997), and Fischer *et al.* (1995). Area is shown on the El Conejo quadrangle, G12D81, scale 1:50,000; the locality maps of Fischer *et al.* (1995); and the geologic maps of Hausback (1984b) and Carreño (1992b).

Tepetate Formation, Early Eocene.—The Tepetate Formation was discussed in the previous section and in Table 5. R. W. Fulwider sampled the unit in 1991 at km 82 west of Rancho Aguajito de Castro and found Early Eocene planktonic foraminifers; J. C. Ingle, Jr. (written communication, 1991) identified benthic microfossils that suggest bathyal to shelf-edge depths.

←

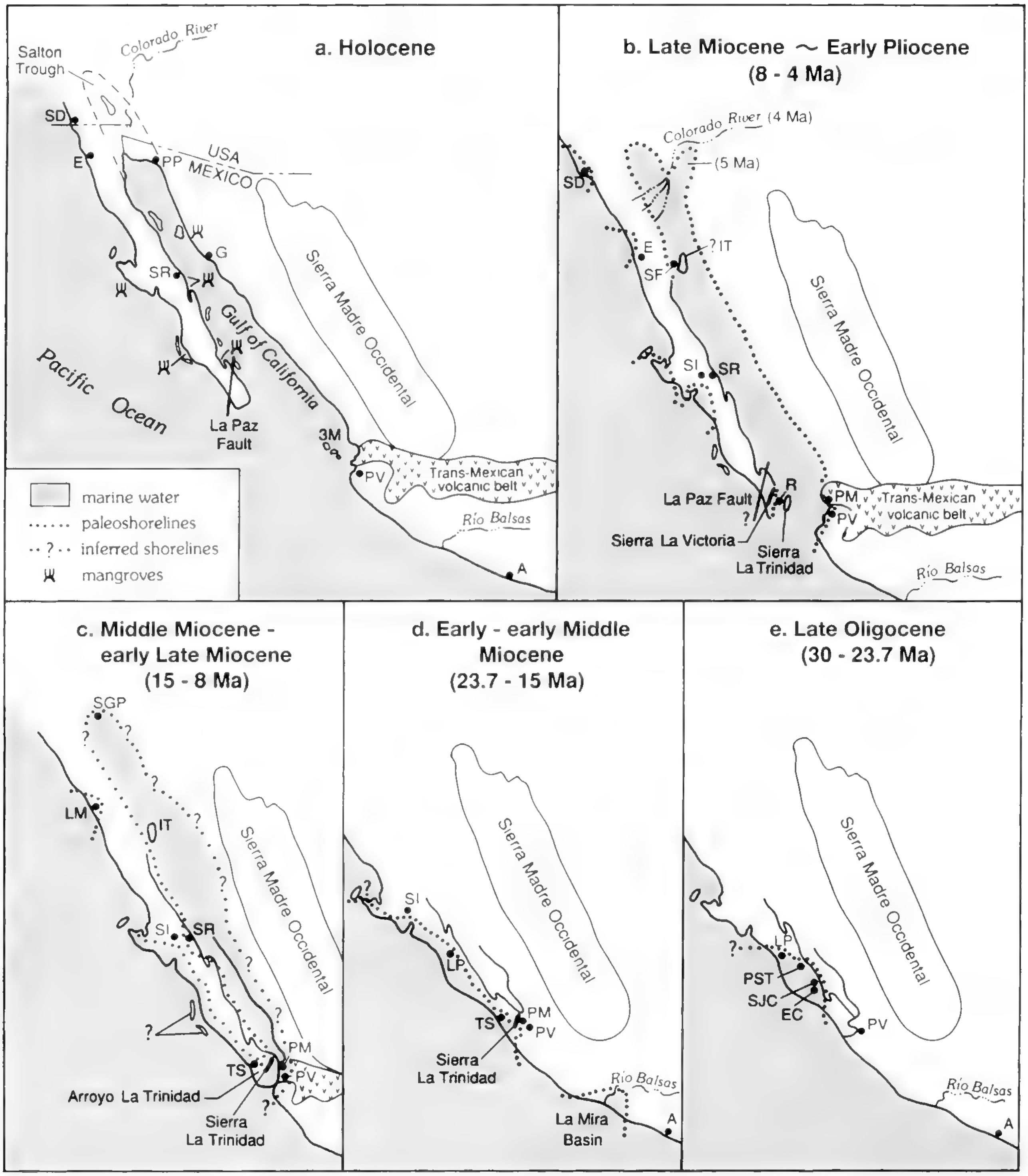
Text-figure 30.—Magdalena Plain, map showing old ranchos and other landmarks. Map modified from J. T. Smith (1992) shows an old trail used by early mappers: Nelson and the Biological Survey Expedition of 1905–1906; Heim in 1915; Beal in 1918; and Darton in 1920. Many of their fossil localities bear the names of ranchos. Mina-Uhink (1957) reported Salada Formation in cores from Pozo Iray #2. The El Cien Formation near El Mangle contains abundant mytilid molds. CSL, Cabo San Lázaro, PST, Punta San Telmo.

Text-figure 31.—Cerro Colorado (highest ridge) and Cerro Tierra Blanca (below and to the right), type sections of the El Cien Formation, Cerro Tierra Blanca and Cerro Colorado Members. The lowest beds are the marine Cerro Tierra Blanca Member; the Cerro Colorado Member, here a nonmarine facies, forms much of Cerro Colorado and is capped by unnamed Miocene volcaniclastic sediments. Photo, J. T. Smith, 1995.

Text-figure 32.—Arroyo San Hilario, type area of the San Hilario Member, El Cien Formation. View east at the "Ten-minute locality" of Applegate (1986) (= Instituto de Geología Micropalentology locality 130 = Natural History Museum of Los Angeles County locality LACMIP 4830), approximately 3 km northeast of El Cien (km 100). The beds contain the Late Oligocene to Early Miocene index species *Anadara vanderhoofi* Durham. Photo, T. M. Cronin, 1984.

Text-figure 33.—El Cien Formation, map showing type sections and study areas from Applegate (1986) and Fischer *et al.* (1995). Map modified from Carreño (1992b); regional index map is shown in Text-figure 30, lithostratigraphic information in Table 5. A–D, study areas of Fischer *et al.* (1995): A, El Cien Formation, all members of Applegate (1986); B, Arroyo Agua Amarga, part of composite type section of San Juan Member and sections of Cerro Colorado Member; C, Cañada de la Luz and Arroyo Tarabillas, outcrops of San Juan and Cerro Colorado Members; D, Aguajito de Castro, part of composite type section of the San Juan Member. Reworked silicified wood (Text-fig. 34) is found in the Cerro Colorado Member at Rancho la Matanza and near La Fortuna. Megafossil symbol in area A represents the "Ten-minute locality" of Applegate (1986) in the San Hilario Member. Megafossil locality near Rancho la Fortuna is in a marine facies of the Cerro Colorado Member. CC, Cerro Colorado and Cerro Tierra Blanca; CE, Cerro de la Estaca, Cerro Colorado Member, Instituto de Geología Micropalentology locality 1580; EC, El Cien, km 100; T, Rancho Tepetate.

Text-figure 34.—Silicified wood, float specimens from the El Cien Formation, Cerro Colorado Member, near La Fortuna. Photo, J. T. Smith, 1989.



Text-figure 35.—Paleogeography of the Baja California Peninsula and ancient Gulf of California, map based on distributions of Late Oligocene to Holocene marine mollusks and associated microfossil and radiometric data. Map after J. T. Smith (1991c: fig. 5), ©AAPG 1991, reprinted by permission of the American Association of Petroleum Geologists, whose permission is required for further use. Present outline of Baja California and the eastern gulf shoreline shown in part, for reference. 35c includes the protogulf of Fenby and Gastil (1991), whose subsurface marine sediments extend an unknown distance to the east. A, Acapulco; E, Ensenada; EC, El Cien; G, Guaymas; IT, Isla Tiburón; LM, La Misión; LP, La Purísima; PM, Punta Mita; PP, Puerto Peñasco; PST, Punta San Telmo; PV, Puerto Vallarta; R, Rancho El Refugio; SD, San Diego; SF, San Felipe; SGP, San Gorgonio Pass; SI, San Ignacio; SJC, San Juan de la Costa; SR, Santa Rosalía; TS, Todos Santos; 3M, Islas Tres Marías.

San Juan Member, Late Oligocene.—Only the middle and upper parts of San Juan Member of the El Cien Formation crop out in the El Cien-Aguajito area, where the 75-m-thick section is unconformable on bioturbated silt and sandstones of the Tepetate Formation. Fischer *et al.* (1995) described a prominent 0.2- to 4-meter-thick fossiliferous basal conglomerate in Arroyo Aguajito that is overlain by 20 m of siltstone and sandstone. The unit is conformably overlain by the Cerro Colorado Member.

The San Juan Member is exposed along parallel outcrop belts of a syncline that trends north-northwest to south-southeast. One limb lies northwest of San Juan de la Costa, the other extends from north of Cerro Colorado to Rancho el Aguajito de Castro near km 68 on Mexico 1. Lithologies vary between western and eastern areas, as shown in detailed sedimentological studies by Schwennicke (1992, 1994). The Late Oligocene age is based mainly on dated tuffs, diatom, and planktonic foraminiferal zones at Arroyo San Hilario; calcareous nannofossils from the middle part of the San Juan Member at Arroyo Aguajito represent nannofossil zones NP 24/NP 25 (Schwennicke, 1992).

Cerro Colorado Member, Early to Middle Miocene.—Detailed studies by Schwennicke (1992, 1994) and Gidde (1991) at a number of localities identified the regressive nature of the Cerro Colorado Member from shallow marine to nonmarine conditions. At Rancho el Aguajito de Castro the member is Early Miocene or older, constrained by the La Paz tuff, 24 Ma, in the overlying volcaniclastic sediments (Hausback, 1984a,b).

Todos Santos, Arroyo la Muela, southern Baja California Sur

Overview

Southwest of La Paz and approximately 10 km north of the town of Todos Santos, highway Mexico 19 crosses a wide arroyo that drains the western side of the Sierra la Laguna and exposes Miocene marine deposits along its northwestern wall. The large stream bed has many names, including Arroyo la Muela on the published El Rosario quadrangle, Arroyo San Juan of Beal (1948), Arroyo Playita of Mina-Uhink (1957), and Arroyo Grande of J. T. Smith (1992). The highway has changed many times due to flooding; access to fossil oucrops in Arroyo la Muela became more difficult after the summer of 1972.

Aranda-Gómez and Pérez-Venzor (1989) studied the igneous and metamorphic rocks of the La Paz Crystalline Complex near Todos Santos and included approximately 10 km^2 of Salada Formation outcrops on their map (1989: text-fig. 3). The southwestern part of the Baja California peninsula is underlain by prebatholithic metamorphic basement rocks and the Cretaceous granitoid plutons that intruded them, but the Cenozoic rocks have not been studied in detail. They lie to the west of the La Paz Fault and the Los Cabos Block. Beal (1948) named the La Paz Fault and mapped three separate areas west of the road between Arroyo Grande and Todos Santos as "Ts," Salada Formation. Reconnaissance field work by J. T. Smith, S. Pedrín-Avilés, G. Padilla-Arredondo, and E. Díaz-Rivera encountered only Quaternary gravels in the southern two areas.

Arroyo la Muela
Plate 1, Column 20
(Text-figs. 36, 37, 73 Appendices 1, 2)

Column modified from Aranda-Gómez and Pérez-Venzor (1989) and Schwennicke *et al.* (2000). The area is shown on El Rosario Quadrangle, F12B23, 1: 50,000; and the geologic maps of Beal (1948, and unpublished field sheets in Stanford University's Branner Earth Sciences Library and Map Collections), Mina-Uhink (1957), and Aranda-Gómez and Pérez-Venzor (1989: figs. 3, 21).

Marine fossils were discovered in Arroyo la Muela by James C. Ingle, Jr., and students during a spring break in 1972. The unit was sampled by J. T. Smith, T. E. Fumal, and J. J. Aranda-Gómez in 1983 and by J. T. Smith and T. M. Cronin in 1984. Schwennicke (written communication, 1999) reported additional outcrops to the north, and Martínez-Gutiérrez and Jorajuría-Lara (2002) found land vertebrates of probable Late Miocene age at La Matanza near Rancho Carrizal during a survey of the El Carrizal Fault.

Stratigraphy

La Paz Crystalline Complex, Cretaceous.—Prebatholithic basement and crystalline rocks of the southwestern Cape region belong to the La Paz Crystalline Complex (El Complejo Cristalino de La Paz) named by Ortega-Gutiérrez (1982) and discussed by Aranda-Gómez and Pérez-Venzor (1989). These authors described several informal units of metamorphosed Mesozoic rocks east and north of Todos Santos and Punta Lobos. Oldest to youngest they include the Punta Lobos gneiss, Todos Santos marble, and El Cardonozo phyllite. The La Buena Mujer tonalite, which has an K/Ar age of 98 Ma, intruded the older metamorphic rocks (Aranda-Gómez and Pérez-Venzor, 1989).

Salada Formation, late Middle Miocene to Late Miocene.—Described by Heim (1922) from a section 170 km to the north, the Salada Formation is represented along the northwestern side of Arroyo la Muela

Text-figure 36.—Arroyo la Muela, north of Todos Santos, B.C.S., where the weathered Salada Formation forms pink, green, and brown badlands topography. Arrow indicates level of the bench where marine fossils are found (Text-fig. 37). Photo, T. M. Cronin, 1984

Text-figure 37.—Salada Formation, coquina and sandstone facies in one-meter-high bench at the base of la Loma el Bayo Flojo. Photo, T. M. Cronin, 1984

by loosely consolidated marine and nonmarine arkosic sediments. Several facies of the unit, whose base is not exposed, extend perhaps 1.5 km along the arroyo at the base of a ridge known as la loma El Bayo Flojo (Text-fig. 36). A northwest-trending normal fault of the Vinatería-La Matanza Fault System forms the northeastern contact between the Salada Formation and Holocene gravels (Aranda-Gómez and Pérez-Venzor, 1989: figs. 3, 21).

Schwennicke (written communication, 1999) estimated a thickness of 36 m for the sequence of greenish, pink, and brown mottled siltstone, well-indurated limy sandstone and conglomerate, and fine-grained, loosely consolidated, granitic sandstone with angular pebbles and weathered phenocrysts. The rocks dip 5° west-southwest and weather to pink and green badlands topography. Megafossils are mainly internal molds of bivalves and gastropod shells replaced by calcite; they commonly weather out on the surface of a meter-high bench (Text-fig. 37). Shallow-water gastropods include *Architectonica nobilis* Röding, *Turritella abrupta fredeai* Hodson, *Cancellaria* (*Pyruclia*) *diadela* Woodring, *Cymia* sp. cf. *C. michoacanensis* Perrilliat, *Phos* sp. cf. *P. crassus* Hinds, and *Vasum haitense* (Sowerby); vertebrates are represented by shark teeth, myliobatid ray plates, whale teeth, and a camelid humerus (J. T. Smith, 1992).

Age and correlation of the Salada Formation in Arroyo la Muela.—The beds were regarded as Pliocene by Beal (1948) and Plio–Pleistocene by Aranda-Gómez and Pérez-Venzor (1989), but reconnaissance paleontological collections indicate a Miocene age for the lower marine facies (J. T. Smith, 1992). Ongoing studies by Schwennicke *et al.* (2000) identified Middle Miocene shark teeth in Arroyo la Muela, and they suggested that the unit there could be older than the type section at Arroyo la Salada.

It is not known how these outcrops relate to oyster-bearing marine rocks 20 km to the north or to unnamed lower Miocene whale-bearing sediments 50 km to the north near Rancho la Palma, northwest of San Pedro (Text-fig. 73, p. 95). The vertebrates that Schwennicke *et al.* (1996) excavated from dark green laminated, tuffaceous mudstone above a basal conglomerate represent a cetotheriid baleen whale of an early evolutionary stage.

Many of the mollusks in the Salada Formation in Arroyo la Muela are Tertiary-Caribbean species that correlate the section with the upper part of the Trinidad Formation, Subunit A of McCloy (1984) in the San José del Cabo Trough and with Miocene marine units in Panamá, Colombia, Trinidad (formerly B.W.I.), and the Dominican Republic. Some of the same species were also reported from the Ferrotepec Formation of the La Mira Basin of Michoacán, mainland west Mexico (Perrilliat, 1981, 1987; J. T. Smith, 1992).

Gravels of Cerro la Bandera, informal name, Pleistocene to Holocene.—Coarse sediments are informally referred to the gravels of Cerro la Bandera (la grava del Cerro Bandera) by Aranda-Gómez and Pérez-Venzor (1989). The unit is discordant on the Salada Formation west of Mexico 19 and on the crystalline complex east of the highway, from which the flat-lying gravels and unconsolidated arkosic sands were eroded. They are named for a small hill in Arroyo Grande northwest of Microondas San Pedro (km 41 on Mexico 19). Quaternary alluvium and beach deposits overlie the gravels.

PART II: ANCIENT AND MODERN GULF OF CALIFORNIA

SALTON TROUGH, CALIFORNIA, TO ISLAS TRES MARÍAS, SOUTHERN GULF OF CALIFORNIA

Salton Trough
Plate 2, Columns 21, 22, 23, 24
(Text-figs. 1, 2, 38, Appendices 1, 2)

Geographic Overview

The Salton Trough covers an area approximately 200 km long by 150 km wide. It extends from south of the San Bernardino Mountains in the San Gorgonio Pass and Whitewater River area, California, to the Gulf of California, Mexico. It lies east of the Peninsular Ranges and the Elsinore Fault, west of the Orocopia and Chocolate Mountains and other desert ranges. The western Salton Trough includes the Imperial Valley and the Fish Creek and Vallecito Mountains; the eastern part includes the Bouse embayment (Text-fig. 38). Stratigraphy is complicated by many facies that change rapidly; they are folded, faulted, overturned, and they wedge out in some places. At the deepest part of the trough, Neogene (primarily Plio–Pleistocene) sediments are estimated to exceed 6 km (20,000 ft) in thickness (Dibblee, 1996). Woodring (1931, 1932), Allen (1957), and Winker (1987) summarized earlier papers on the stratigraphy of the area and showed formation assignments according to numerous workers.

The area has a complex geologic history that includes multiple seawater incursions from the south, the Early Pliocene arrival of Colorado River deltaic sediments from the east, and Late Miocene to present structural offsets along the major fault zones, which include the Elsinore, San Jacinto, and San Andreas Fault Systems. There are two onshore spreading centers, one at Brawley, south of the Salton Sea, the other south of Mexicali between the Imperial and Cerro Prieto Faults (Mueller and Rockwell, 1991). The structural setting of the area is discussed in papers edited by Powell *et al.* (1993).

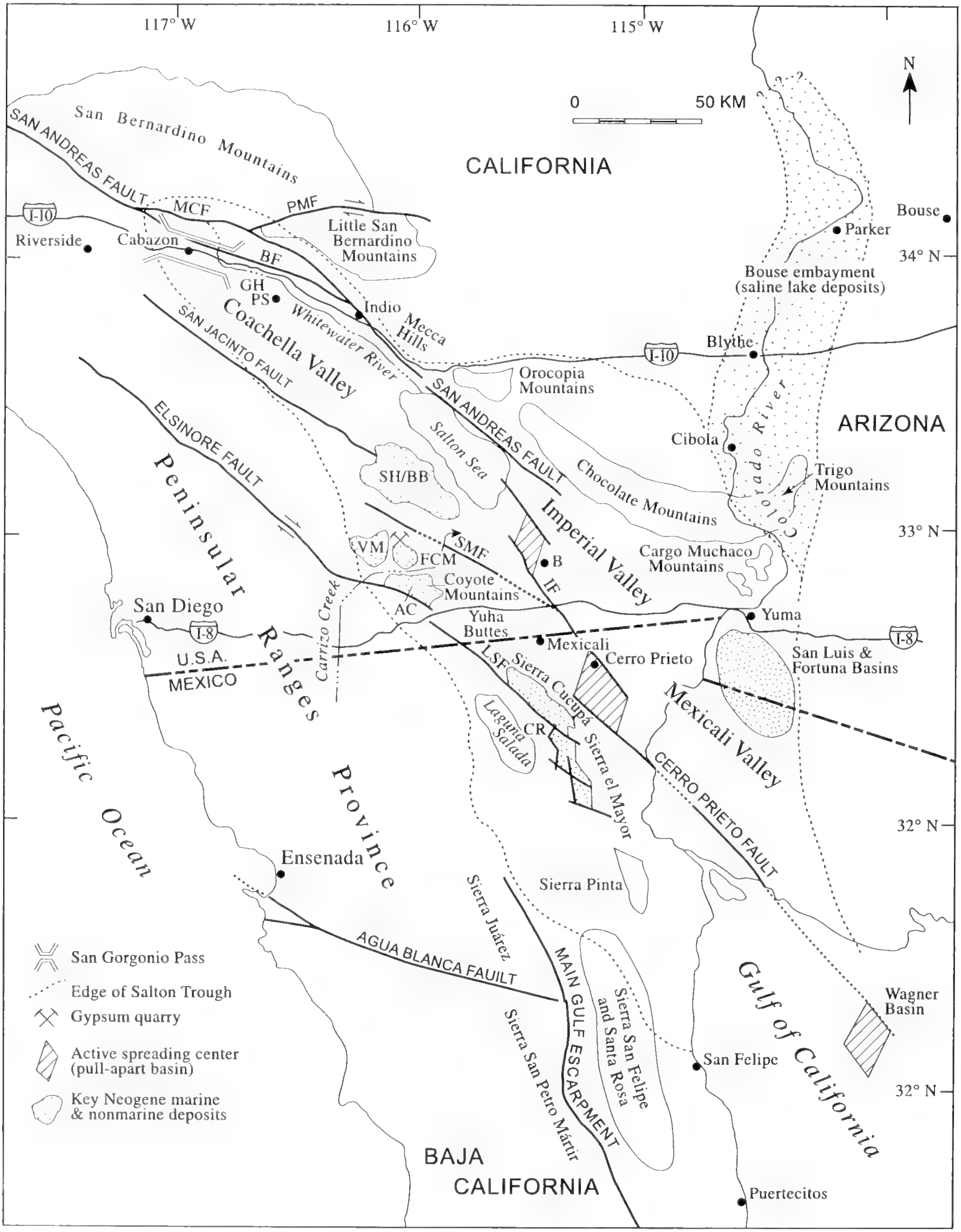
The Salton Trough is the northernmost extension of the ancient Gulf of California; geologists recognize that the northern sections mapped as the Imperial Formation were deposited as much as 180 km to the southeast and displaced to their present locations by Late Miocene to Early Pliocene faulting (Matti and Morton, 1993). These authors included detailed maps showing the relation of key outcrops to the main and subsidiary strands of the San Andreas Fault. Other papers, including those by McDougall *et al.* (1999) and Dibblee (1996a,b), updated the extensive literature on the stratigraphy of the area.

Multiple Cenozoic marine incursions in the Salton Trough

Paleontological and radiometric data suggest that there have been as many as three Neogene seawater incursions in the northern gulf (McDougall, 1996; McDougall *et al.*, 1999), which explains the long-standing disagreements between authors arguing for a Miocene versus a Pliocene age of the Imperial Formation.

First incursion of the ancient gulf, late Middle Miocene.—The presence of a late Middle to Late Miocene gulf is inferred from rare Middle Miocene marine microfossils in isolated occurrences from the northern Salton Trough to wells in the Yuma area and coastal Sonora. Gastil *et al.* (1999) interpreted an unnamed megafossiliferous marine conglomerate at Isla Tiburón, Sonora, as evidence of this incursion. The section contains a 12.9 Ma volcanic breccia and abundant fossil mollusks, including species of *Atrina, Lyropecten, Spondylus, Cardita,* and *Pycnodonta* (*Crenostrea*), which are also present in the northernmost Salton Trough in reworked sediments east of the Whitewater River. The unit at Isla Tiburón is overlain with angular unconformity by an ash-flow tuff of 11.2 Ma and cut by younger dikes of 4.16 ± 1.8 Ma and 5.67 ± 0.17 Ma.

McDougall *et al.* (1999) noted the presence of reworked rare Middle Miocene nannofossils in the Whitewater section in the lower Imperial Formation "worm tube" bed between unnamed lower and upper parts of the unit. The calcareous nannoplankton species *Cyclicargolithus floridanus* (Roth and Hay) became extinct in Middle Miocene Zone CN5a, *Sphenolithus heteromorphus* Deflandre in Zone CN4 (a combined range of 16–13 Ma); their presence in the "worm tube" bed indicates that ". . . marine deposits older than Late Miocene were once present in this area" (McDougall *et al.*, 1999). These authors also reported Middle Miocene taxa from higher in the section, where ". . . they are rare and more poorly preserved than the associated [Late Miocene–Early Pliocene] microflora, and they occur in samples interpreted as having a significant greater amount of transported sediment." Those sediments were referred to the unnamed upper member of the Imperial Formation and to shale lenses and reworked channel deposits in the


117° W
116° W
115° W
0
50 KM
N
San Bernardino Mountains
SAN ANDREAS FAULT
CALIFORNIA
MCF
PMF
I-10
Little San Bernardino Mountains
Riverside
Cabazon
BF
GH
PS
Indio
Mecca Hills
Coachella Valley
Whitewater River
SAN JACINTO FAULT
Bouse
Parker
34° N
Bouse embayment (saline lake deposits)
Blythe
Orocopia Mountains
SAN ANDREAS FAULT
Salton Sea
ELSINORE FAULT
Peninsular
SH/BB
Chocolate Mountains
Cibola
Colorado River
ARIZONA
Trigo Mountains
Imperial Valley
SMF
VM
FCM
B
Coyote Mountains
IF
Cargo Muchaco Mountains
33° N
Carrizo Creek
AC
San Diego
I-8
Yuha Buttes
Yuma
Mexicali
Cerro Prieto
San Luis & Fortuna Basins
U.S.A.
MEXICO
Ranges
LSF
Sierra Cucupá
Laguna Salada
CR
Sierra el Mayor
Mexicali Valley
CERRO PRIETO FAULT
Pacific Ocean
Province
32° N
Ensenada
Sierra Juárez
Sierra Pinta
AGUA BLANCA FAULT
MAIN GULF ESCARPMENT
Sierra San Felipe and Santa Rosa
Gulf of California
Wagner Basin
Sierra San Petro Mártir
San Felipe
32° N
BAJA CALIFORNIA
Puertecitos
San Gorgonio Pass
Edge of Salton Trough
Gypsum quarry
Active spreading center (pull-apart basin)
Key Neogene marine & nonmarine deposits

unconformable overlying Painted Hill Formation (McDougall *et al.*, 1999; Murphy, 1986). They are stratigraphically below a basalt flow in the Painted Hill Formation that has K/Ar ages of 6.04 ± 0.18 Ma and 5.94 ± 0.18 Ma (J. L. Morton *in* Matti *et al.*, 1985).

Hydrothermally altered, poorly preserved, Middle Miocene foraminifers identified as *Cassigerinella chipolensis* (Cushman and Ponton) were listed from two wells in the Cerro Prieto geothermal field (Cotton and Vonder Haar, 1979). P. B. Smith *in* Lucchita (1972) noted "... a puzzling abundance of *Bolivina guadalupae* Parker characteristic of the Middle and Late Miocene of California" from the Yuma, Arizona area. Marine Miocene rocks were reported from wells in the basin south of Yuma, Arizona (Mattick *et al.*, 1973), and in the subsurface of coastal Sonora (Lozano-Romen, 1975; Gómez-Ponce, 1971; King, 1939).

Second incursion of the ancient gulf, late Miocene to earliest Pliocene.—A Late Miocene incursion between 9 Ma and 6 Ma is represented in the San Gorgonio Pass area of the northern Salton Trough by the upper member of the Imperial Formation, which is interpreted as 6.0–7.4 Ma in the Cabazon and Whitewater River sections (McDougall *et al.*, 1999). These authors reported a Late Miocene to earliest Pliocene faunule that includes the benthic foraminifers *Amphistegina gibbosa* d'Orbigny, *Cassidulina delicata* Cushman, and *Uvigerina peregrina* Cushman, planktonic foraminifers from zones N17–N19, and calcareous nannoplankton from Calcareous Nannoplankton Zones CN9–NN11. Dean (1988, 1996) listed four of the same Late Miocene calcareous nannoplankton index species from claystones intercalated with the Fish Creek Gypsum in the Fish Creek Mountains: *Braarudosphaera bigelowii* (Gran and Braarud) Deflandre, *Coccolithus pelagicus* (Wallich) Schiller, *Reticulofenestra pseudoumbilica* (Gartner), and *Sphenolithus abies* Deflandre. Quinn and Cronin (1984) and Ingle (1974) reported similar Late Miocene Planktonic Foraminiferal Zone N17 microfossils, including *Amphistegina gibbosa* d'Orbigny, from the lower part of the Imperial Formation in Fish Creek Wash in the Vallecito Mountains.

Miocene to Pliocene marine microfossils were also collected from a section in the Sierra Cucupá east of Laguna Salada (Vázquez-Hernández *et al.*, 1996; Martín-Barajas *et al.*, 2001).

As discussed by Ingle *in* Gastil *et al.* (1999), inner to outer neritic foraminiferal assemblages from southwestern Isla Tiburón indicate an age of latest Miocene to Early Pliocene Planktonic Foraminiferal Zones N17B–N19 for the white sandstone facies mapped as Unit M8c. The planktonic and benthonic foraminifers include a number of taxa that range from Miocene to Holocene, some currently living in the Gulf of California. Species lists for the upper part of the Imperial Formation in the San Gorgonio Pass area and Unit M8c of southwestern Isla Tiburón have some taxa, including *Amphistegina gibbosa* d'Orbigny, in common (McDougall *et al.*, 1999; Ingle *in* Gastil *et al.*, 1999). Gastil *et al.* (1999) acknowledged but could not explain the discrepancy between dates based on latest Miocene–earliest Pliocene microfossils from Unit M8c that correspond to 6.4–4 Ma and the late Middle to early Late Miocene age based on megafossils from Unit M8d associated with radiometric dates of 12.9 Ma and 11.2 Ma from underlying and overlying volcanic rocks.

Third incursion of the ancient gulf, Early Pliocene.—The youngest incursion, at 5–3 Ma, is represented by foraminifers of Early Pliocene Planktonic Foraminiferal Zone N19/20 in sediments surrounding the Fish Creek and Vallecito Mountains that precede and post date the Early Pliocene arrival of Colorado River deltaic sediments in the Fish Creek and Vallecitos area "... no later than 4.3 Ma" (Winker and Kidwell, 1986, 1996), based on magnetostratigraphic ages from Johnson *et al.* (1983). Sediments record the marine–nonmarine transition at 4.0 Ma and the presence of the Colorado River in the western Salton

←

Text-figure 38. Salton Trough, map of the ancient Gulf of California, northern part from San Gorgonio Pass to San Felipe, B.C. Map compiled from McDougall *et al.* (1999), Vázquez-Hernández *et al.* (1996), Mueller and Rockwell (1991), Kidwell (1988), Winker and Kidwell (1986), and Dillon *et al.* (1993). Active spreading centers, north to south, are Brawley, Cerro Prieto, Wagner Basin. Abbreviated fault names: MCF, Mission Creek and BF, Banning strands of the San Andreas San Fault; CR, Cañón Rojo Fault; IF, Imperial Fault; LSF, Laguna Salada Fault; PMF, Pinto Mountain Fault; SMF, Superstition Mountain Fault. Place names: AC, Alverson (Fossil) Canyon; B, Brawley; FCM, Fish Creek Mountains, including Split Mountain Gorge, Fish Creek Gypsum quarry, and Barrett Canyon, which flows south to Carrizo Creek. GH, Garnet Hill; PS, Palm Springs; SS/BB, Superstition Hills and Borrego Badlands; VM, Vallecito Mountains. The northern side of the Coyote Mountains includes Vallecito Badlands, Carrizo Badlands, and Garnet Canyon; the southern and southeastern sides include Alverson Canyon, the Flat Iron, and Painted Gorge. Earlier workers interpreted the Bouse embayment as an extension of the northern gulf, but based on fieldwork, Ehlig *in* Dillon and Ehlig (1993) and Spencer and Patchett (1997) regarded the travertine and fossiliferous sediments north of Cibola, Arizona, as saline lake deposits, not marine in origin. The San Luis and Fortuna Basins south of Yuma contain subsurface Neogene marine sediments (McDougall *et al.*, 1999).

Trough until 2.8 Ma (date interpolated by Johnson *et al.*, 1983).

The eastern Salton Trough, which includes the area called the Bouse embayment, is underlain by the Late Miocene to Pliocene Bouse Formation, a unit that is correlative with parts of the Imperial Formation. A tuffaceous horizon at the base of the Bouse Formation is 5.47 ± 0.20 Ma, slightly older than the arrival of the first Colorado River sediments in the eastern Salton Trough (P. B. Smith, 1970; Damon *et al.*, 1978; Shafiquallah *et al.*, 1980). Buising (1990) reported widely varying radiometric ages for a tuffaceous horizon from Milpitas Wash, 30 km south of Cibola, Arizona: 8.1 ± 0.5 Ma (Metzger *et al.*, 1973), 5.47 ± 0.20 and 3.02 ± 1.15 Ma (Damon *in* Metzger *et al.*, 1973). She regarded the Bouse Formation as marine to brackish water; Spencer and Patchett (1997) interpreted it as lacustrine.

Correlating the Imperial Formation, a time-transgressive unit

Before marine units from south of the border can be related to the northern outcrops of the ancient gulf, it is important to know ages and lithologies of particular sections. Rocks mapped as the Imperial Formation range from approximately 9–3 Ma, latest Middle or Late Miocene to Middle Pliocene. Multiple seawater incursions, rapid facies changes, reworked sediments, and deformation within active fault zones and developing basins contribute to complex stratigraphic relationships that are best understood from a multidisciplinary perspective. In one such study, Kidwell (1988) used sedimentation and the taphonomy of shell beds and skeletal concentrations within the Imperial Formation to assess the fossil record of a recently rifted continental margin.

Paleontology at the species level can measure packages of time, rates of change, depositional environment, and provincial affinities. With more information about key sections of the Imperial Formation, the location and age of its oldest sediments and significant marker beds, and improved resolution based on fossil species, a unit that transgressed as much as six million years can be used to relate the ancient Gulf of California to a more specific tectonostratigraphic context. Marine deposits containing isolated, reworked microfossils can be better understood, and meaningless correlations in the literature with "the Imperial" can be avoided once outcrop areas and stratigraphic intervals are specified. Maps showing specific localities are beyond the scope of this paper; cited references and topographic maps should be consulted for details.

Representative columns of the Salton Trough

We include four columns, from north to south: east of the Whitewater River, Riverside County, California; the Fish Creek and Vallecitos Basin, Riverside County, 110 km to the south; the southern Coyote Mountains, Imperial County, California, 25 km further south; the Sierra Cucupá, Cerro Prieto and Laguna Salada area, Baja California, 50 km further southeast.

Basement rocks in all the columns are late Cretaceous plutonic rocks of the Peninsular Ranges batholith or the Paleozoic metasedimentary rocks they intruded (see summary by Dibblee, 1996a). At times the metamorphic rocks of the Coyote Mountains and tonalites in the Fish Creek and Vallecito Mountains stood as islands in the ancient gulf and provided substrata for shallow water attached and boring organisms.

Table 6 summarizes lithostratigraphic units in the ancient Gulf of California from the San Gorgonio Pass to the Sierra Cucupá.

Whitewater River—San Gorgonio Pass area
Plate 2, Column 21
(Text-figs. 1, 2, 38, 39, Table 6, Appendices 1, 2)

Column modified from Allen (1957) and McDougall *et al.* (1999); area is shown on the Whitewater, Desert Hot Springs, and Cabazon 7½-minute and Palm Springs 15-minute quadrangles, California. Outcrops are shown on the maps of Allen (1957) and Matti *et al.* (1985).

Overview

Our column includes the northernmost outcrops of the Imperial Formation in the Salton Trough. The unit is exposed in an unnamed south-flowing tributary to Super Creek over a relatively small area in the NW ¼ Section 1, T 3 S, R 3 E and SW ¼ Section 36, T 2 S, R 3 E, Whitewater River 7½-minute quadrangle. The section is southwest of Painted Hill, in an area used for many years to orient students from the University of California, Riverside, to field geology (Murphy, 1986). Bramkamp (1935a,b), Allen (1957), and McDougall *et al.* (1999) discussed contemporaneous outcrops near Cabazon, 12 km to the west.

Stratigraphy

Coachella Fanglomerate, Late Miocene.—In the Whitewater area, the Coachella Fanglomerate forms cliffs along the eastern side of the Whitewater River, approximately 6.4 km north-northwest of Painted Hill, the prominent orange-colored peak seen from the unnamed canyon where the Imperial Formation is exposed. The locally-derived sediments contain Late Miocene olivine basalt flows and volcanic breccias that constrain the age of the unconformable overlying Imperial Formation to younger than 10.1 ± 1.2 Ma (D. Krummenacher *in* Peterson, 1975). Peterson (1975) interpreted the unit as an alluvial fan that originated to the north and was deposited in a deep basin.

Imperial Formation, Late Miocene–Early Pliocene.—The Imperial Formation was named for a section in the southern Coyote Mountains; it has been applied to marine deposits from many sediment sources in widely separated areas. East of the Whitewater River the unit is limited to discontinuous narrow outcrops over a distance of 1.6 km between two strands of the San Andreas Fault (Text-fig. 39). It consists of 30 m of locally-derived, steeply dipping to overturned sediments that pinch out upcanyon and rest nonconfomably on crystalline basement at the lower end of the arroyo (Allen, 1957; McDougall *et al.*, 1999). Farther north the beds are unconformable on the Coachella Fanglomerate, whose interbedded basalt flow constrains the Imperial Formation in this area to younger than early Late Miocene.

The lower part of the section includes channel deposits in the underlying rocks, coarse- to medium-grained sandstone, and conglomerate. Mollusks, including articulated pectinids, *Spondylus*, and oysters, are found in the basal breccias (Murphy, 1986).

A distinctive yellowish-gray, one-meter-thick "worm tube bed" of siltstone and sandstone separates the two members of the Imperial Formation. It contains detached, fragmented, and randomly oriented calcareous tubes (whether they include only worms or also vermetid gastropods has not been determined) and microfossils that indicate transported sediments deposited at outer neritic depths up to 152 m (McDougall *et al.*, 1999). The upper member is a medium- to fine-grained sandstone and siltstone that interfingers and can also be in unconformable contact with the Painted Hill Formation, although the boundary is commonly obscured by alluvium. McDougall *et al.* (1999) detailed the micropaleontology of this section and correlative beds near Cabazon, which they interpreted as deeper water, "possibly upper bathyal (152–244 m)." Upsection from the "worm tube bed" they also noted shallowing and warming trends that correspond to global sea-level and paleotemperature trends at 6.5–6.3 Ma.

Murphy (1986) and his students studied the "worm tube bed" and a yellowish-gray micaceous silt facies before the unit was over-collected; they observed ". . . abundant specimens of *Atrina* in living position . . . with the most diverse fauna in the formation." Bramkamp (1935b) and Powell (1986, 1988) illustrated some of the articulated marine mollusks, barnacles, and corals that are no longer easy to find. These mollusks and those that are reworked in the channel breccias, many with Caribbean affinities, are also known from the late Middle or early Late Miocene marine conglomerate on Isla Tiburón (J. T. Smith, 1991c, and *in* Gastil *et al.*, 1999).

Bryozoans, brachyuran crabs, corals, and baleen whales have also been reported from the Whitewater area (Text-fig. 39 and Appendix 1). The megafossil collections can be seen at the University of California, Riverside, the University of California, Berkeley Museum of Paleontology, and the Natural History Museum of Los Angeles County.

Age and correlation of the Imperial Formation, northernmost Salton Trough, Late Miocene–Early Pliocene, with reworked Middle Miocene fossils.—Age-diagnostic foraminifers and nannoplankton indicate a Late Miocene to Early Pliocene age of 7.4 Ma to older than 6.04 Ma for the Imperial Formation in the Whitewater and Cabazon (also known as Lion Canyon) sections; McDougall *et al.* (1999) favored an age of 7.4–6.0 Ma based on sea-level fluctuations, paleotemperature, and radiometric data from adjacent units. They referred the microfossils to Planktic Foraminiferal Zones N17–N19 and Calcareous Nannoplankton Zones CN9–CN11 of Okada and Bukry (1980). Species lists include such Late Miocene–Early Pliocene index species as the benthic foraminifers *Cassidulina delicata* Cushman, *Uvigerina peregrina* Cushman, and *Amphistegina gibbosa* d'Orbigny; planktic foraminifers *Globogerinoides obliquus* Bolli, *G. extremus* Bolli and Bermúdez, and *Globigerina nepenthes* Todd; calcareous nannoplankton *Sphenolithus abies* Deflandre and *Reticulofenestra pseudoumbilicata* (Gartner). They also listed *Discoaster brouweri* Tan Sin Hok emend. Bamlette and Riedel, *D.* sp. aff. *D. surculus* Martini and Bramlette, and *Sphenolithus neoabies* Deflandre of Calcareous Nannoplankton Zones CN9a–CN11. The assemblage corresponds to the microfossils reported by Dean (1996) from siltstone layers in the Fish Creek Gypsum.

McDougall *et al.* (1999) also found rare, poorly preserved Middle Miocene microfossils in the "worm tube bed" and in channels and siltstone deposits of the lower Painted Hill Formation. They identified the calcareous nannofossils *Cyclicargolithus floridanus* (Roth and Hay) and *Sphenolithus heteromorphus* Deflandre, which became extinct in zones CN5a and CN4 (16–13 Ma), respectively. Reworked taxa were sparse and less well preserved than younger microfossils; the samples with a mixed fauna had a greater amount of transported sediment.

Other northern outcrops of the Imperial Formation

Table 6.—Salton Trough, California and Baja California, lithostratigraphic units (Text-fig. 38). Lowercase names indicate informal units that were not established according to the North American Stratigraphic Code (1983).

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
Alverson Formation	Tarbet *in* Tarbet and Holman (1944) and Tarbet (1951). Woodward (1974) called Alverson Andesite volcanic facies of the Anza Formation. Winker and Kidwell (1996) renamed the Elephant Trees formation, informal name, of the Split Mountain Group.	Formation was originally proposed for a sequence of nonmarine sandstones and volcanic flows. Type section is in Fossil Canyon (formerly Alverson Canyon), in the southern Coyote Mountains, Carrizo Mountain 7½-minute quadrangle. Dibblee (1996a,b) referred to the volcanic part as the Alverson Volcanics, 130 m (400 ft) of dark-colored vesicular olivine basalt and minor basaltic andesite and tuff-breccia. Early to early Middle Miocene, based on a 16 ± 1.0 Ma basalt (Eberly and Stanley, 1978) and other radiometric dates ranging from 22 to 14 Ma (Kerr and Abbott, 1996).
Anza Formation	Woodward (1974) renamed the sediments below the Alverson Andesite. Kerr (1984) referred Fish Creek Mountains outcrops to the Red Rock formation, informal name.	Unit is a reddish brown, coarse-grained sandstone and arkosic conglomerate described from the eastern Fish Creek Mountains, southern part of the Borrego Mountain SE 7½-minute quadrangle [sections 25 and 36, T 13 S, R 8 E]. Kerr (1984) described a section 8 km southeast of Split Mountain Gorge in Red Rock Canyon, Carrizo Mountain NE 7½-minute quadrangle. Early Miocene.
Canebrake Conglomerate	Dibblee (1954).	Unit is a coarse conglomerate and sandstone with a maximum thickness of 2,100 m (7,000 ft); it is a western marginal facies of parts of the Palm Spring and Imperial Formations (Dibblee, 1996). Named for Canebrake Wash, but type section is to the north in the Vallecitos Badlands, Agua Caliente Springs and Arroyo Tapiado 7½-minute quadrangles. Plio–Pleistocene.
Cañón Rojo conglomerate, informal name	Vázquez-Hernández *et al.* (1996).	Unit consists of locally-derived fanglomerate that was described from the southwestern Sierra Cucupá and northern Sierra Mayor where the Laguna Salada and Cañón Rojo faults form a pull-apart basin, Sierra Cucupá quadrangle (Mueller and Rockwell, 1991). Dorsey and Martín-Barajas (1999) referred the unit to the Cañón Rojo redbed sequence. Plio–Pleistocene.
Coachella Fanglomerate	F. E. Vaughan (1922). Allen (1957) and Peterson (1975) elaborated on the description.	Unit consists of 1,500 m of east-dipping nonmarine, well-indurated, sandstone, gray-green claystone, siltstone, and fanglomerate with minor basalt. Sediments are deeper orange upsection as volcanic components increased. Type section is at the Whitewater Trout Farm, eastern side of Whitewater Canyon and 6.4 km (4 mi) upstream from Bonnie Bell, Whitewater 7½-minute quadrangle. Originally regarded as Quaternary (F. E. Vaughan, 1922), it contains a series of olivine basalt flows and volcanic breccias 250 m above the base; one flow has a K-Ar age of 10.1 ± 1.2 Ma (D. Krummenacher *in* Peterson, 1975).
Colonia Progreso volcanics, informal name	Barnard (1968).	Andesitic and dacitic volcanic breccias overlie granodiorite basement in the northeastern Sierra Cucupá near the Colonia Progreso section of western Mexicali, in the quadrangle of the same name. Middle Miocene, based on a K-Ar age of 15.3 ± 0.8 Ma (Barnard, 1968).
Fish Creek Gypsum	Dibblee (1954). Dean (1996) reported interbedded marine claystone layers.	Unit consists of a 30 m (100 ft) thick section of white and tan-colored gypsum and anhydrite with intercalated marine claystones in the northwestern Fish Creek Mountains. Type area is northeast of Split Mountain Gorge in a U.S. Gypsum Co. quarry, Borrego Mountain SE 7½-minute quadrangle. Late Miocene, based on calcareous nannoplankton in the claystone partings (Dean, 1988; K. McDougall, oral communication, 1998).
Imperial Formation	G. D. Hanna (1926) renamed the basal part of the preoccupied Carrizo Formation of Kew (1914). Later workers subdivided the formation into the: "Latrania sands," "Coyote Mountain Clays," and "Yuha reefs," uppermost clays with oyster biostromes. Woodring (1931, 1932) amplified the lithologic descriptions. Dibblee (1996a,b) refined the stratigraphic nomenclature and suggested a more representative type section.	Formation includes beds of coral fragments, shallow marine and deltaic sandstones and siltstones, and claystones with oyster shells. Hanna (1926) used Imperial Formation for only the basal 200 m (650 ft) reworked beds. Neither he nor Woodring specified a type section, although it was always regarded as Fossil Canyon in the southern Coyote (formerly Carrizo) Mountains. Dibblee (1996a,b) designated a 1,000 m (3,300 ft) thick type section in the Vallecito Badlands between the Fish Creek and Coyote Mountains, near the area where Kew (1914) mapped the "Carrizo Formation" (Arroyo Tapiado and Carrizo Mountain NE 7½-minute quadrangles). The formation is Late Miocene and Early Pliocene, deposited during successive seawater incursions; ages are based mainly on microfossils, dated rocks in adjacent units, and stratigraphic position. Late Miocene in the northern Salton Trough; Late Miocene–Early Pliocene in the Fish Creek Mountains and Vallecito Badlands (McDougall *et al.*, 1999). Miocene/Pliocene boundary, 5 Ma, and older in the Coyote Mountains, based on a dated pectinid from the Painted Gorge 7½-minute quadrangle (J. T. Smith *in* Gastil *et al.*, 1999). Rare reworked Middle Miocene fossils in some sections.

Table 6.—Continued.

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
Latrania Sand Member	G. D. Hanna (1926); Woodring (1931, 1932) elaborated on the description; Keen and Bentson (1944) first listed as a member of the Imperial Formation in a table.	Member is a 60 m (200 ft) thick, locally-derived fossiliferous marine sandstone in the lower part of the Imperial Formation. It overlies a layer of coral rubble (the "reef" of early workers, or the oyster-coral deposit near the head of lower Alverson Canyon of Kidwell, 1988: figs. 3, 4). Type section is in Fossil Canyon, southern Coyote Mountains, Carrizo Mountain 7½-minute quadrangle [Sec. 10, T 16 S, R 9 E]. Late Miocene to earliest Pliocene
Painted Hill Formation	Allen (1957).	Formation consists of more than 1,020 m (3,400 ft) of continental pale-brown to light-gray, coarse-grained conglomerate and conglomeratic sandstone with clasts as large as 0.6 m (2 ft) in diameter. The unit includes light-gray, coarse-grained cobble and pebble lenses, discontinuous, distinctive, yellowish-brown, intercalated siltstones, and a basalt flow in the lower 300 m. Reworked marine fossils from the underlying Imperial Formation are found in a siltstone bed and in channels in the conglomerates (Murphy, 1986). Type area is east of Painted Hill in the Whitewater and Desert Hot Springs 7½-minute quadrangles. Originally regarded as Pliocene, it is Late Miocene based on a dated olivine basalt with ages of 6.04 ± 0.18 and 5.94 ± 0.18 Ma (J. L. Morton *in* Matti *et al.*, 1985; Matti and Morton, 1993). Microfossils from the shale lenses included foraminifers from zones N17–N19 and calcareous nannoplankton from zones CN9–CN11 of Bukry (McDougall *et al.*, 1999: fig. 3, section WWX).
Palm Spring Formation	Woodring (1931, 1932).	Formation is a 1,450 m (4,800 ft) thick, poorly-consolidated, brackish to fluviatile, brown and red sandstone and claystone with abundant lacustrine ostracodes (Quinn and Cronin, 1984). Type locality is at Mountain Palm Spring (SW ¼ Sec. 25, T 14 S, R 9 E), near the Old Carrizo Overland Stage site where Vallecito Creek joins Carrizo Wash, southern Vallecito Badlands, Arroyo Tapiado 7½-minute quadrangle. Originally considered Late Pliocene, but probably Early Pleistocene based on vertebrates reported by Downs and White (1967) and Downs and Woodard (1961) (Dibblee, 1996a,b).
Split Mountain Formation	Tarbet *in* Tarbet and Holman (1944) and Tarbet (1951) Winker and Kidwell (1996) reinterpreted some facies as the Elephant Trees formation, informal name, and included it with other units (Garnet formation, Red Rock [= Anza] formation, and the Alverson Volcanics) in the Split Mountain Group.	Basal sedimentary unit of the southwestern Imperial basin includes a 400 m (1,300 ft) thick, nonmarine conglomerate and conglomeratic sandstone with mostly tonalite boulders from the basement underlying the Fish Creek Mountains. Kerr and Abbott (1996) regarded the tonalite megabreccia exposed in Split Mountain Gorge as part of the Split Mountain Formation and interpreted it as multiple *sturzstroms* or rock avalanche deposits. Type section is along Fish Creek Wash where it cuts through Split Mountain Gorge [Sec. 36, T 13 S, R 8 E], Borrego Mountain, SE 7½-minute quadrangle. Miocene, older than the overlying microfossiliferous Late Miocene Fish Creek Gypsum.

at Indio Hills, the south slopes of Garnet Hill, and Willis Palm include Late Miocene and Pliocene facies, based on megafossils and radiometric data (Rymer *et al.*, 1994; Powell, 1988). None of the Imperial Formation fossils from the Salton Trough document a Tertiary marine connection to the Pacific through southern California marine basins, where penecontemporaneous rocks mapped as the Castaic, Pico, and Monterey Formations contain temperate California margin faunules (McDougall *et al.*, 1999).

Painted Hill Formation, latest Miocene to Pliocene.—Allen (1957) gave this name to olivine basalts and interbedded sediments northeast of Cabazon and to all the continental beds that are conformable above the Imperial Formation east of Painted Hill. The unit constrains the youngest age of the Imperial Formation in the Whitewater River section to 6.04 ± 0.18 to 5.94 ± 0.18 Ma, the radiometric ages for a basalt flow in the lower 300 m (J. L. Morton *in* Matti *et al.*, 1985; Matti and Morton, 1993) [see Table 6, herein, for the sample location, which was published in a footnote to a map]. Allen (1957) reported camel remains from the Painted Hill Formation north of Cabazon and east of Deep Canyon, but they were not age-diagnostic.

Text-figure 39.—Imperial Formation in unnamed, south-flowing tributary to Super Creek, east of the Whitewater River, northernmost Salton Trough. Steeply dipping to overturned sediments of the Imperial Formation, including the basal "worm tube-bed," overlie granitic basement. Patches of finer-grained sands (arrow) yielded vertebrae and a mysticete (baleen whale) skull fragment (Thomas and Barnes, 1993). The Banning strand of the San Andreas Fault Zone is to the south (left). Two collectors (circled) for scale. Photo, E. C. Wilson, 2002

Fish Creek/Vallecito basin
Plate 2, Column 22
(Text-figs. 38, 40, Table 6, Appendices 1, 2)

Column modified from Dibblee (1996b); area is shown on the following 7½-minute quadrangles: Harper Flat, Borrego Mountain, Arroyo Tapiado, and Carrizo Mountain, California. See also the geologic maps of Winker (1987) and Winker and Kidwell (1996).

Tertiary Stratigraphy

The Fish Creek/Vallecito Mountains area is underlain by late Cenozoic units as thick as 4,000 m (13,900 ft), including 1,000 m (3,300 ft) of exposed Imperial Formation facies and a number of other units not present at the Whitewater River area. The area south of the Fish Creek Mountains and north of the Coyote Mountains includes the Vallecito Badlands, the broad valley of the Carrizo Creek, and the thickest accumulation of sediments referred to the Imperial Formation. Kew (1914) described the Carrizo Creek formation here, but his preoccupied name was replaced by the Imperial Formation. Dibblee (1996b) again designated the area as ". . . the most appropriate type section" for the Late Miocene–Pliocene Imperial Formation.

Alverson Formation, Early to early Middle Miocene.—The oldest Cenozoic unit here is the Alverson Formation, which interfingers with the Split Mountain Formation and is exposed along Fish Creek Wash. Associated red beds underlie the volcanic unit in several areas, including the southern Fish Creek Mountains between Red Rock and Barrett Canyons and the southeastern Coyote Mountains between Fossil Canyon and Painted Gorge. In its type area the Alverson Formation contains an Early to Middle Miocene basalt and is considerably older than the oldest known Imperial Formation. Winker and Kidwell (1996, and work in progress) preferred to rename the units below the Imperial Formation in the Fish Creek-Split Mountain Gorge area and place them in the Split Mountain Group.

Other names that have been used for the associated redbeds are the Anza Formation, Red Rock formation, and Miocene braided stream and alluvial fan deposits of Kerr and Kidwell (1991). The beds are well-indurated conglomerates and pebbly sandstones, coeval with the basalts of the Alverson Formation (Text-fig. 40).

Split Mountain Formation in Split Mountain Gorge, Miocene.—Dibblee (1996b) described the lithology of up to 400 m (1,300 ft) of conglomerate that is cut by Fish Creek Wash to form Split Mountain Gorge. Reddish alluvial conglomerates are overlain by rock slide megabreccias of tonalite basement clasts, then by a thin, brown, conglomeratic sandstone with claystones that could also be included in the overlying Fish Creek Gypsum.

Boulder beds with car-sized clasts are seen in spectacular outcrop in Split Mountain Gorge. They have been called the lower megabreccia, a member of the Split Mountain Formation, landslide, and rock avalanche deposits, but were identified by Kerr and Abbott (1996) as two *sturzstroms*, voluminous mass transport deposits of shattered basement rocks that resulted from successive events such as large magnitude earthquakes. The lower sturzstrom is an older, red and gray breccia; the upper megabreccia is the Split Mountain sturzstom, a larger, tonalite deposit. Younger marine fan-delta mudstones and sandstones separate the younger megabreccia from the overlying Fish Creek

Text-figure 40.—Split Mountain Gorge, Miocene reddish-brown alluvial fan deposits exposed in Fish Creek Wash. View west at rocks that Woodward (1974) referred to the Anza Formation (Borrego Mountain SE 7½-minute quadrangle SE ¼, NW ¼ Sec. 25, T 13 S, R 8 E). The alluvial sediments underlie the "lower boulder beds," which are now regarded as a sturzstrom in the Split Mountain Formation (D. R. Kerr, written communication, 2004). Photo, J. C Ingle, Jr., 1984

Gypsum, as seen on the geologic map by Kerr and Abbott (1996).

Rapid movement of such massive deposits (hundreds of millons of cubic meters) from adjacent mountains to emplacement would have taken minutes, but the time-frame for this catastrophic event can be estimated from adjacent units. Kerr and Abbott (1996) reviewed microfossil data from overlying marine sediments and estimated that the rock fall and rapid flow occurred at 5.4 ± 0.3 Ma.

Fish Creek Gypsum, Late Miocene.—The Fish Creek Gypsum, long regarded as a nonmarine evaporite, has claystone intercalations that contain Late Miocene, 9.5–7.5 Ma microfossils typical of a normal salinity environment (Dean, 1996; McDougall, oral communication, 1998). Peterson and Jefferson (1997) suggested the gypsum could have been deposited near a high-temperature hydrothermal vent. The deposits represent the second of three seawater incursions in the northern ancient gulf, and the earliest seawater in the Fish Creek Mountains area; they correlate with the lower Imperial Formation section east of the Whitewater River. Dean (1996) regarded the Fish Creek Gypsum as a facies of the Imperial Formation because both units are marine and have similar fossil assemblages.

A rock slide megabreccia of basement rock above the Fish Creek Gypsum was called the upper fanglomerate by Woodward (1974), upper boulder bed by Winker (1987), and upper breccia by Dean (1988). Rightmer and Abbott (1996) named it the Fish Creek sturzstrom and described its distinctive jig-saw puzzle fabric and catastrophic Early Pliocene or latest Miocene origin. It is the youngest of three such mass-transport deposits exposed in Split Mountain Gorge.

Imperial Formation in the Fish Creek/Vallecito Mountains, Late Miocene–Pliocene.—Dibblee (1996b) discussed the reasons why he proposed the Fish Creek Mountains/Vallecito Badlands area as a new type section for the Imperial Formation: it has the most complete section, the maximum exposed thickness, and both lower and upper contacts (conformable with the underlying Split Mountain Formation and gradational with the overlying fluviatile Palm Spring Formation). Also, the earlier workers who first used the formation name assumed but never clearly stated that Fossil Canyon was the type section.

The Imperial Formation in this area was most recently mapped by Winker (1987) and Winker and Kidwell (1986, 1996), who recognized a number of facies as informal members based upon lithology and origin. They termed locally derived marine units as "L"-suite sediments, and those transported by the ancient Colorado River as "C"-suite sediments. The oldest Colorado River deposits are earliest Pliocene, found in the upper part of their Wind Caves member, which was dated by magnetostratigraphy as 4.3 Ma (Johnson *et al.*, 1983). Here as elsewhere in the Salton Trough, Colorado River sediments are distinguished by magnetite-bearing sands and the presence of reworked Cretaceous microfossils from the Mancos Shale of the Colorado Plateau (Gastil *et al.*, 1996).

Winker and Kidwell (1996) regarded the Imperial Group as including the Latrania Formation, which they further divided into six informal members, and the Deguynos formation (informal name), which has four members. Pending their publication of formal descriptions, we use the earlier stratigraphic nomenclature of Dibblee (1996b).

The Barrett Canyon-Carrizo Impact Area in the Carrizo Mountain NE 7½-minute quadrangle is not readily accessible now, but it was mapped in 1904 by Mendenhall (1910), who recorded the detrital coral layer (termed a "reef") of the Imperial Formation above a 60 m (200 ft) thick lava flow at the head of Barrett Canyon. He noted a stratigraphically lower sandstone 6–15 m (20–50 ft) thick on top of more lava flows. Mendenhall (1910) wrote that the Fossil Canyon section has only the upper part of this lowermost unit, and that the Barrett Canyon section is more complete.

Quinn and Cronin (1984) sampled the lowest outcrop of the middle Imperial Formation in Fish Creek Wash and reported a diverse assemblage of foraminifers that McDougall *et al.* (1999) noted were ". . . similar to faunas found in the Late Miocene Imperial Formation near San Gorgonio Pass and very different from faunas higher in the Fish Creek Wash section which are clearly Pliocene." The upper section microfaunule in Fish Creek Wash consists mainly of the intertidal to brackish foraminifer *Elphidium gunteri* Cole (Quinn and Cronin, 1984).

Palm Spring Formation and Canebrake Conglomerate, Pliocene and Pleistocene.—Palm Spring Formation unconformably overlies the deltaic and shallow tidal flat deposits of the upper Imperial Formation and intertongues with the Canebrake Conglomerate to the west.

Southern Coyote Mountains
Plate 2, Column 23
(Text-figs. 38, Table 6, Appendices 1, 2)

Column after Dibblee (1996b); the area is shown on the Carrizo Mountain and Painted Gorge 7½-minute quadrangles, Imperial County, California.

Basement and pre-Imperial Formation rocks, Paleozoic to Miocene.—Paleozoic metasediments form the core of the Coyote Mountains; they are overlain unconformably by the Anza Formation, described from the northern Coyote Mountains, and the Alverson Formation, described from the southern Coyote Mountains. The Miocene Alverson Formation is overlain by the Miocene Split Mountain Formation, here a 100-m-thick, unfossiliferous conglomerate (Dibblee, 1996b) that is in turn unconformably overlain by the Imperial Formation.

Imperial Formation, Miocene and Pliocene.—The Imperial Formation crops out around the northern, eastern, and southern flanks of the Coyote Mountains, but the best known section is on the southern side where Hanna (1926) identified the lowest facies as a basal "coral reef," a well-indurated layer consisting of broken coral fragments and other invertebrates. Pieces of coral in this canyon caught the attention of the earliest geologists, including Fairbanks (1893) and Mendenhall (1910), who collected specimens that T. W. Vaughan (1917) monographed; Vaughan recognized their Caribbean affinities at once and termed them "reef-corals," although they were collected from a detrital deposit, not a true reef.

The basal coral layer in Fossil Canyon is overlain by a 650 m (200 ft) sandstone, the "Latrania Sands," which Dibblee (1996b) interpreted as a thin marine transgressive unit with abundant large echinoids. Kidwell (1988) discussed details of the sands, which came from a source to the south-southwest. She identified shell beds in both upper and lower Alverson (also known as Fossil or Shell) Canyon, and differentiated fossil assemblages that correspond to changes in sedimentology. The Latrania Sand Member is covered by very thick "Coyote Mountain Clays"; where they contain oyster shell bioherms, as in the Yuha Basin, Hanna (1926) called the facies "Yuha Reefs." The claystone member with sandstone and concentrations of oyster shells is the equivalent of the middle muddy sandstone member "Tim2" of Vázquez-Hernández *et al.* (1996) from the Sierra Cucupá and Laguna Salada basin.

Because the Imperial Formation in Fossil Canyon was not given the name, complete description, and locality details that formalize a lithographic unit, Dibblee (1996b) designated a different type section in the Vallecito Badlands southwest of the Fish Creek Mountains.

Age and correlation of the Latrania Sand Member, Imperial Formation, southern Coyote Mountains.—Abundant megafossils were described from the Latrania Sand Member (see Appendix 1), but its age requires refinement. The Fossil Canyon outcrops are possibly as young as the Early Pliocene predeltaic Wind Caves member of Winker and Kidwell (1996) in the Fish Creek/Vallecito Mountains (McDougall, oral communication, 1999), but some of the megafossils are Miocene.

Lyropecten tiburonensis Smith is found in Fossil Canyon; a specimen from the Painted Gorge quadrangle [Section 5, T 16 S, R 10 E] had a $^{87}Sr/^{86}Sr$ age of 5 Ma. It also occurs in the 12.9 Ma conglomerate of Isla Tiburón with other Fossil Canyon mollusks such as *Turritella imperialis* Hanna, *Strombus obliteratus* Hanna, "*Aequipecten*" *plurinominis* (Pilsbry and Johnson), and *Spondylus bostrychites* Guppy of Hanna (1926) [not of Guppy] (Gastil *et al.*, 1999). Most of these are also found in Miocene units in the Boleo basin and the southern Cabo Trough east of Santa Anita (J. T. Smith, 1991c).

The Latrania Sand Member has abundant large echinoids referred to the genera *Clypeaster* and *Encope*. Kew (1914) illustrated *Clypeaster bowersi* Weaver from Fossil Canyon, and J. T. Smith collected it from Late Pliocene beds at Isla Cerralvo. The associated mollusks are older than the echinoids, and the Late Pliocene pectinids from Isla Cerralvo are missing in the northern gulf. This suggests that the type section of the Latrania Sand contains a mixed assemblage of Miocene to Late Pliocene megafossils whose individual ages are not accurate for determining the age of the formation in the southern Coyote Mountains.

Coral genera reported from the Imperial Formation include *Dichocoenia*, *Solenastrea*, *Meandrina*, *Siderastrea*, and *Porites* (Vaughan, 1917; Kidwell, 1988). All of the megafossil species from the southern Coyote Mountains require a thorough taxonomic review that reflects Tertiary-Caribbean nomenclature and a biostratigraphic assessment, because many of the early collections came from float and some seem to have been reworked. For these reasons the Fossil Canyon section might not be the best place for determining the biostratigraphy of Imperial Formation species; many of the same taxa are not reworked in Baja California, where they are associated with dated volcanic units.

Palm Spring Formation and Canebrake Conglomerate, Pliocene.—The upper Imperial Formation is overlain by the Palm Spring Formation and the Canebrake Conglomerate, nonmarine clastic units that were named for sections in the Coyote Mountains. They intertongue in Carrizo Wash, north and west of the Coyote Mountains, Palm Spring Formation to the east and Canebrake Conglomerate to the west.

Cerro Prieto to Sierra Cucupá, Baja California
Plate 2, Column 24
(Text-figs. 38, 41, Table 6, Appendices 1, 2)

Column modified from Vázquez-Hernández *et al.* (1996); shown on the Sierra Cucapá quadrangle, I11D75, scale 1:50,000; and the geologic maps of Barnard (1968), scale 1 inch represents 1 mile; and Mueller and Rockwell (1991).

Geographic Setting

The Salton Trough south of the international border includes the Mexicali Valley, Laguna Salada basin, Sierra Cucupá [also spelled "Cucapá"], and the Sierra Mayor. The northwest-trending Imperial and Cerro Prieto Fault zones outline a spreading center in the area of the Cerro Prieto geothermal field, which is underlain by more than 5 km of deltaic and marine Neogene sediments (Mueller and Rockwell, 1991). An early incursion of the ancient Gulf of California is represented by rare, hydrothermally altered, poorly preserved, Middle Miocene, marine microfossils, including *Cassigerinella chipolensis* (Cushman and Ponton), in three samples from two deep wells in the Cerro Prieto area (Cotton and Vonder Haar, 1979, 1980, 1981). Pliocene to Quaternary advances of the gulf, the shifting Colorado River delta, and erosion of the uplifted surrounding sierra contributed to the thick basin sediments. Ostracods were the most common microfossils in cores from 185–1,952 m depths examined by Ingle (1982); he interpreted a "significant mid-Pleistocene marine incursion" from associated foraminifers and correlated the sediments with the Palm Spring Formation.

The Laguna Salada basin is elongate, relatively wide (10–20 km), and bounded by faults. Ongoing investigations of the basin by Mueller and Rockwell (1991, 1995), Vázquez-Hernández *et al.* (1996), Stock *et al.* (1996), and Martín-Barajas *et al.* (2001) include data from unpublished theses and geologic maps. Late Quaternary uplift and the formation of stepped, en echelon basins disrupted the sedimentary sequence and complicate the interpretation of facies that have been faulted, pulled apart, and deformed during subsidence.

Stratigraphic nomenclature and correlation of marine deposits

Colonia Progreso volcanics, informal name, Middle Miocene.—Isolated outcrops of the Colonia Progreso volcanics of Barnard (1968) near the international border in western Mexicali are andesitic and dacitic breccias of 15.3 ± 0.8 Ma, but they are not in contact with the younger Imperial Formation and do not constrain its age.

Imperial Formation, Pliocene.—The Imperial Formation exposed in the Cerro Colorado Basin in southwestern Sierra Cucupá and northern Sierra Mayor has three marine members—"Tim1," "Tim2," and "Tim3" described by Vázquez-Hernández *et al.* (1996)—that correlate with the upper claystone member of the Imperial Formation in the southern Coyote Mountains. In the Sierra Cucupá, basal member "Tim1" is a thin conglomerate and breccia layer in low-angle fault contact with underlying Paleozoic metamorphic and granitic basement rocks. It is overlain by "Tim2," a mudstone, and "Tim3," a yellow-beige, muddy sandstone.

The middle and upper members of the Imperial Formation in this area contain abundant, Pliocene, shallow-water, benthic microfossils (Vázquez-Hernández *et al.*, 1996). Some are the same as those reported by Cotton and Vonder Haar (1980) from Cerro Prieto. Many occur with reworked Cretaceous foraminifers, calcareous nannofossils, and palynomorphs transported by the ancient Colorado River from the Colorado Plateau to the prograding river delta.

Siem (1992) reported corals from the basal conglomerate-breccia facies,"Tim1" at "Coral Hill," on the eastern side of the Sierra Mayor (location shown by Vázquez-Hernández *et al.*, 1996); E. C. Wilson (written communication, 1991) identified specimens as *Dichocoenia* sp. aff. *D. merriami* (Vaughan), a coral that lived in a shallow-water, high-energy environment.

Coquinas of the fossil scallop *Argopecten deserti* (Conrad), small oysters, mounds of *Ostrea vespertina* of authors, and *Anomia subcostata* Conrad are common in the middle and upper members of the Imperial Formation in the Sierra Cucupá and northern Sierra Mayor. They could represent the impoverished faunule of the last seawater incursion or an intermittent estuarine environment; Woodward (1974) regarded the unit as Palm Spring rather than Imperial Formation. The mollusks suggest correlation with younger Imperial Formation facies in the Fish Creek/Vallecito Badlands and similar coquinas in the upper beds of the northern Loreto basin.

Nonmarine sediments, Quaternary.—The Imperial Formation is separated by an unconformity from the overlying Palm Spring Formation. It grades upward to the Cañón Rojo conglomerate, an informal name for alluvial sediments in the western Sierra Cucupá and northern Sierra el Mayor (Vázquez-Hernández *et al.*, 1996: fig. 1). This area along the Laguna Salada offers a unique opportunity to see Recent fault scarps in Holocene sediments and a developing pull-apart basin (Text-figs. 38, 41). One of a series of dilational right steps is taking place where the northwest-southeast-trending Laguna Salada Fault meets the northeast-trending late Quaternary Cañón Rojo Fault (Mueller and Rockwell, 1991).

San Felipe embayment, Baja California
Plate 2, Column 25
(Text-figs. 1, 38, 42, Appendices 1, 2)

Column after R. L. Andersen (1973) and Boehm (1982, 1984); area is shown on the Santa Clara quadrangle, H11B46, 1:50,000; and the geologic map of R. L. Andersen (1973), scale 1:62,500.

Overview

The San Felipe embayment extends from northwest of the port of San Felipe east and south of the southern Sierra San Felipe (Text-fig. 2). The area includes 340 m of exposed Miocene and Pliocene marine sediments representing bathyal to littoral depths (Boehm, 1984).

Text-figure 41. Cañón Rojo area, western Sierra Cucupá, where scarps of the northwest-striking Laguna Salada Fault and the northeast-striking Cañón Rojo Fault meet to form a corner of a pull-apart basin (Mueller and Rockwell, 1991). Fault scarps are 3–4 m high; Imperial Formation sediments to the south are Late Pliocene and younger marine to estuarine facies with abundant *Argopecten deserti* (Conrad), anomiids and oysters. Photo, J. T. Smith, 1990.

The units have undergone uplift, folding, and faulting related to rifting in the Gulf Extensional Province (Stock *et al.*, 1996).

P. V. Anderson (1993) named the prebatholithic basement rocks the Playa San Felipe Group, which includes eight informal formations described from north of San Felipe. Those units were correlated provisionally with Late Proterozoic and Early Cambrian age rocks east of the Gulf of California in northwestern Sonora, Mexico. In an earlier thesis, R. L. Andersen (1973) reported andesite, basalt, and volcaniclastic rocks of probable Miocene age and aeolian sandstone of unknown age overlying the basement rocks. He also mapped the Late Miocene and Pliocene marine sequence and illustrated a large assemblage of Neogene megafossils.

Stratigraphy of Neogene marine units west of San Felipe

Llano el Moreno Formation. Late Miocene.—The formation and its two members were formally named by Boehm (1984), who designated a composite type section for the Llano el Moreno Formation. The sediments crop out approximately 25 km west-northwest of the town of San Felipe along the eastern side of the southern Sierra San Felipe, and 3–7 km north of the unpaved road between Mexico 5 and Valle de San Felipe. Detailed geology and sample locations for this part of the San Felipe quadrangle were presented by Boehm (1982). The thickness of the marine section is estimated as 100 m.

San Felipe Diatomite Member, Late Miocene–Early Pliocene.—Boehm's lower member was described from exposures along the eastern side of the southern Sierra San Felipe. The unit is more than 30 m thick and contains Late Miocene, middle bathyal diatoms, silicoflagellates, radiolarians, and deep-water foraminifers that suggest marine deposition in the embayment began at 6.0–5.5 Ma. Most of the microfossils support a Late Miocene age, but there are exceptions. The radiolarian *Didymocyrtis hughesi* (Campbell and Clark) has a last appearance datum of 8.6 Ma; it might have been reworked from an earlier seawater incursion in the northern gulf. *Thalassiosira oestrupii* (Ostenfeld), an Early Pliocene diatom zonal marker, and the radiolarians *Didymocyrtis penultimus* (Riedel) and *Spongaster pentas* Riedel and Sanfilippo in the upper part of the member suggest it is 3.6 Ma. The diatomite member grades upward to the Cañón las Cuevitas Mudstone Member.

Cañón las Cuevitas Mudstone Member, Late Miocene.—The type section is exposed along an unpaved road just east of Buenavista Pass (Nelson, 1921), approximately 12–15 km west of Pete's Camp on Mexico 5. The pumiceous mudstone is almost 65 m thick and contains middle bathyal microfossils such as the Late Miocene to Early Pliocene *Uvigerina peregrina* Cushman (Boehm, 1984, and revised ages for Zones N17–N19). Stock (1997) reported a pumice and lapilli layer just above the base that had a $^{40}Ar/^{39}Ar$ age of 6.65 ± 0.14 Ma.

Unnamed marine conglomerate, Pliocene.—The overlying unnamed marine conglomerate of R. L. Andersen (1973) was referred to the Salada Formation by Boehm (1984) and later authors, but that name is not appropriate because of differences in lithology, provenance, and age (see discussion of Arroyo Salada, southern Magdalena Plain, p. 46). R. L. Andersen (1973) estimated the composite thickness of the conglomerate as more than 250 m. The coarsely grained, poorly sorted, shallow-water sandstone, distinguished by cavernous weathering, crops out at "las Cuevitas" (3.1 mi by odometer east of Buenavista Pass) and in the southwestern Valle de San Felipe (Text-fig. 42). It is a locally derived, granitic, beach deposit that overlies the mudstone with angular unconformity and contains abundant internal molds of Pliocene mollusks.

Correlation

Megafossils in the unnamed marine conglomerate are also found in the younger parts of the Imperial

Text-figure 42.—Unnamed granitic beach deposits northwest of San Felipe contain internal molds of Pliocene mollusks. Outcrop is 12–15 km from Mexico 5 and approximately 750 m south of a local landmark known as "Las Cuevitas." Photo, J. T. Smith, 1986.

Formation in the Fish Creek/Vallecito area of California, and in Early to Middle Pliocene sediments in the southern Coyote Mountains. Exceptionally well preserved gigantic specimens of the Late Miocene–Early Pliocene pectinid *Euvola keepi* (Arnold) are common in the southernmost 15-m high ridge west of the road after it turns south from the Buenavista Pass road.

Sierra de Santa Rosa
Plate 2 Column 26
(Text-fig. 38)

Column from Stock *et al.* (1996, 1999), after Bryant (1986); area is shown on the Punta Estrella and Bahía Santa Maria quadrangles, H11B57 and H11B67, respectively, scale 1:50,000; and the geologic map of Bryant (1986).

Stratigraphic Overview

The Sierra de Santa Rosa lie 20 km southwest of San Felipe, betweeen the San Felipe and Puertecitos marine embayments. The sierra represent a nonmarine basin that contains an important marker bed, the Tuff of San Felipe, which was described by Stock *et al.* (1999) from farther south.

Metamorphic and Cretaceous granitic to dioritic basement rocks are unconformably overlain by a sequence of pre-Middle Miocene to Pliocene fluvial deposits and Miocene tuffs and basalts. Bryant (1986) recognized three divisions of the Neogene clastic rocks—Sequences 1, 2, and 3—which were further subdivided by Stock *et al.* (1996). They distinguish a lower arkosic sandstone overlain by conglomerate in Sequence 1; Bryant's Sequence 2 is a series of basalts and pyroclastic flows ranging in age from 15 Ma to 8.9 Ma. Of these, the Tuff of San Felipe is the most extensive and significant for the history of the northern Gulf of California. Sequence 3 consists of alluvial fan deposits and fanglomerates.

Tuff of San Felipe, Middle Miocene.—Called "Tmr_1" by Bryant (1986), the Tuff of San Felipe was named and described by Stock *et al.* (1999) for a widespread, rhyolitic tuff that is well-exposed near Cañón el Parral between the Sierra de Santa Rosa and the Sierra San Fermín (Text-fig. 43). It is characterized by densely welded lithic lapilli and a thickness of 180 m near its presumed vent area close to the present coastline. It has a radiometric age of 12.6 Ma and a low-inclination reversed magnetization that was interpreted by Stock *et al.* (1999) as within reversed polarity subchron C5Ar.2r (12.401–12.678 Ma). The Tuff of San Felipe extends over an 18,000 km² area, from the eastern side of the Sierra San Pedro Mártir to the coast of the Gulf of California and 40 km to the southwest. Ongoing studies suggest the unit is present in Sonora, providing a link between the eastern and western sides of the ancient Gulf of California (Oskin *et al.*, 2000).

The Tuff of San Felipe is overlain by alluvial fan deposits, younger tuffs, basalts dated at 8.9 ± 1.2 Ma, and Plio–Pleistocene continental deposits (Stock *et al.*, 1999).

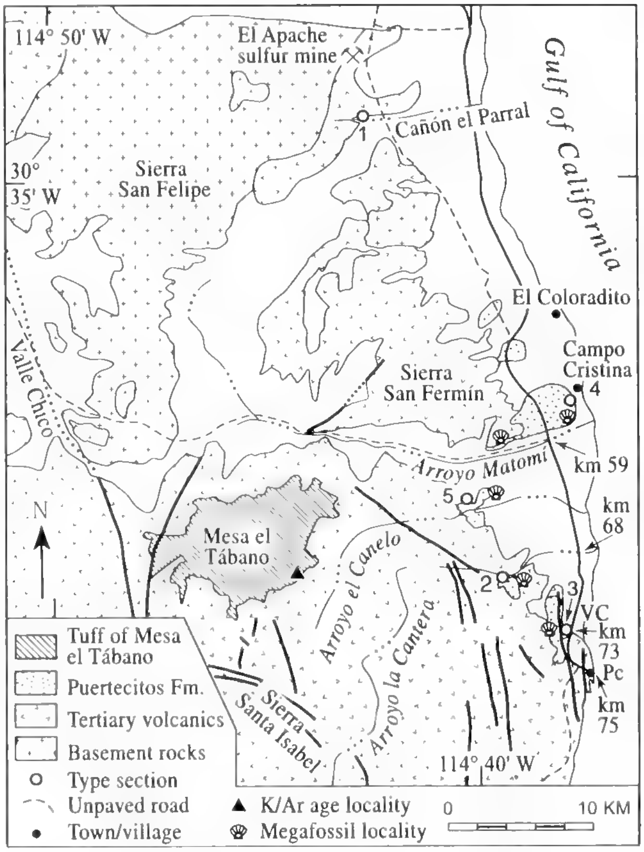
Puertecitos embayment
Plate 2, Column 27
(Text-figs. 2, 43–45, Appendices 1, 2)

Column after Martín-Barajas *et al.* (1997); the area is shown on the Puertecitos quadrangle, H11B77, 1: 50,000; and geologic maps of Martín-Barajas *et al.* (1995, 1997), Lewis (1994), and Stock *et al.* (1991).

Geographic Setting

The Puertecitos embayment extends over approximately 300 km² from the southern Sierra San Fermín to the fishing port of Puertecitos; it lies east of the Sierra San Pedro Mártir and the main Gulf escarpment. Late Miocene to Early Pliocene shallow-water sediments dominate the section in the northern part of the basin; volcanic units are more voluminous in the south. The basin lies north of most of the Puertecitos Volcanic Province, which has a history of volcanism from 21 Ma to 3 Ma, major pulses of activity at 6 Ma and 3 Ma. The principal pyroclastic units are, oldest to youngest: the Tuff of San Felipe, 12.6 Ma; the informally named tuff of el Canelo, 6 Ma; two informal units within the Puertecitos Formation, the tuff of Mesa el Tábano, 5.9–3 Ma, and the tuff of Valle Curbina, 3.27 Ma.

The region is the subject of a number of ongoing investigations (Martín-Barajas *et al.*, 1995; Lewis, 1996; Nagy *et al.*, 1999, among others) because it is key to the tectonic history of the Gulf Extensional Province. The rocks record the transition from arc-volcanism to rift-volcanism and the Pliocene opening of the Gulf of California (Martín-Barajas *et al.*, 1995). Text-figures 43 and 44 show principal locations.



Text-figure 43 Puertecitos embayment, map showing Neogene marine type sections. Regional map of northeastern Baja California and the Puertecitos Volcanic Province (Tertiary volcanics symbol) modified from Martín-Barajas *et al.* (1997) and Lewis (1996). Type sections of units described from the area: 1, Tuff of San Felipe, late Middle Miocene pyroclastic flows, 12.6 Ma, Cañón el Parral; 2, 3, Puertecitos Formation, Matomí Member, Late Miocene, composite sections: 2, Arroyo la Cantera [also known as "Arroyo los Heme Norte"], 3, Valle Curbina; 4, 5, Puertecitos Formation, Delicias Member, Early Pliocene, composite sections: 4, Campo Cristina (CC), 5, Arroyo el Canelo, constrained by the Pliocene age of the Tuff of Mesa el Tábano. SPMF Sierra San Pedro Mártir Fault, western boundary of the Gulf Extensional Province. Only a few faults are shown to indicate three major structural trends in strike in this area: north-northwest, northeast, and northwest (Stock, 2000).

Stratigraphy

Unnamed volcaniclastic rocks, pre-Middle Miocene.—Pre-Cretaceous metamorphic and Cretaceous granitic basement rocks are overlain unconformably by volcaniclastic breccia and sedimentary rocks that were intruded by young andesitic (?) dikes that have an Ar⁴⁰/

Text-figure 44.—Puertecitos Formation, view from south of Arroyo El Canelo toward Mesa el Tábano (dark rocks in left background). A welded tuff, 5.9 ± 0.2 Ma at its base and 3.1 ± 0.5 at its top, caps the mesa (Sommer and García, 1970). Photo, J. T Smith, 1987.

Ar^{39} age of 8.6 ± 0.5 Ma (Nagy, 1997). Another volcaniclastic breccia overlies the basement sequence and has an Ar^{40}/Ar^{39} age of 15.5 ± 0.5 to 16.1 ± 0.5 Ma (Stock *et al.*, 1999).

Tuff of San Felipe, Middle Miocene.—The Tuff of San Felipe is a west-dipping, mesa-forming unit that crops out over much of the western range front of the southern Sierra San Felipe. It is a widespread, densely welded, Middle Miocene, lithic-lapilli ash-flow deposit that was identified and analyzed by Stock *et al.* (1999) in several areas in northeastern Baja California. It probably erupted from a vent north of the Sierra San Fermín and east of the southern Sierra San Felipe. It measures more than 100 m thick at its type section near Cañón el Parral, 2–3 km south of El Apache Sulphur Mine in the Bahía Santa María quadrangle (Lewis, 1994, 1996).

The tuff is an important marker bed that has distinctive petrographic and paleomagnetic characteristics. It was labelled "Tmr_1" on thesis maps of the Santa Rosa Basin (Bryant, 1986) and in southern Valle Chico (Stock, 1993). Detailed mapping of the intervening Sierra San Fermín (Lewis, 1994, 1996) and Sierra Santa Isabel (Nagy *et al.*, 1999), and other geochronology and paleomagnetic studies by these authors demonstrated that the same flow extends through all the areas.

Stock *et al.* (1999) interpreted its age as approximately 12.6 Ma, based on Ar^{40}/Ar^{39} determinations and the ages of associated units. The tuff was also reported east of the gulf in mainland Mexico; it is key to the reconstruction of the Gulf Extensional Province, which straddles the Pacific-North American Plate boundary (Oskin *et al.*, 2000).

Tuff of El Canelo, informal name, Late Miocene.—The Late Miocene ignimbrites known informally as the tuff of El Canelo of Martín-Barajas *et al.* (1995) and another rhyolite flow rest unconformably on a volcaniclastic breccia in the area of Arroyo el Canelo, which drains to the northeast from Mesa el Tábano (Text-fig. 44). The age of the tuff of El Canelo is 6.4 ± 0.02 Ma (Martín-Barajas *et al.*, 1997). It includes three lithologic units: an unwelded lithic lapilli tuff, a densely welded lithic, crystal-, and lapilli-rich tuff, and a non- to partly-welded lithic and pumice tuff containing large landslide blocks (Lewis, 1996). This unit is unconformably overlain by a marine sedimentary sequence.

Puertecitos Formation, Late Miocene–Late Pliocene.—Martín-Barajas *et al.* (1997) named the Puertecitos Formation for a type section 5 km northwest of Puertecitos in the quadrangle of the same name (see also Martín-Barajas *et al.*, 1993). The formation consists of two westward-thinning, wedge-shaped, transgressive-regressive, shallow-water, marine sequences: the Matomí Mudstone Member, which interfingers with pyroclastic deposits mapped as "Ptb" by Stock *et al.* (1996), and the younger Delicias Sandstone Member ("Ptg" of Stock *et al.*, 1991). The two members are separated by an angular unconformity in the north; in the south they are divided by a pyroclastic unit, the tuff of Valle Curbina, dated at 3.27 ± 0.04 Ma (Martin-Barajas *et al.*, 1997). Other volcaniclastic units are included in the upper part of the Puertecitos Formation.

Matomí Mudstone Member, Late Miocene–Early Pliocene.—The type locality of the Matomí Mudstone Member is a composite section exposed along the range front bordering an alluvial plain 5 km northwest of Puertecitos. It crops out in two adjacent valleys, Valle Curbina and Arroyo la Cantera (= Arroyo los Heme Norte of Stock *et al.* (1991), who mapped the unit as "Pmy"). Martín-Barajas *et al.* (1997) named the mustard-colored shallow marine unit, which contains oyster biostromes, abundant bivalve molds, and a turritellid that to date is unique in west Mexico (Text-fig. 45). The Matomí Mudstone is probably Late Miocene in age; it overlies and pinches out against a 5.8 ± 0.5 Ma rhyolite dome on the western side of Valle Curbina (Martín-Barajas *et al.*, 1995, 1997). At El Coloradito, east of the Sierra San Fermín, the basal conglomerate overlies a 6.5 Ma rhyolite tuff (Lewis, 1996). In Valle Curbina the sediments are 35 m thick and grade upsection to a coarse-grained fossiliferous sandstone and pebble conglomerate. Megafossils from this member in Arroyo el Canelo were dated by R. E. Denison, then of Mobil Oil Company, using $^{87}Sr/^{86}Sr$ analyses; the ages were interpreted as Late Miocene

Text-figure 45.—Matomí Mudstone Member, west of the road from San Felipe to Puertecitos. Between Arroyo Matomí and Arroyo El Canelo, the mustard-colored beds contain large, double-valved oysters with distinctive radial furrows; the sediments are overlain by a 2-m ash bed and terrace deposits. Photo, J. T. Smith, 1987

and latest Middle Miocene (Gastil *et al.*, 1999: table 7).

Delicias Sandstone Member, Pliocene.—The stratotype for the Delicias Sandstone Member is a composite of sections exposed along the southern and eastern front of the Sierra San Fermín in the Puertecitos quadrangle. It is Pliocene in age, the lower part cropping out in a hill north of Arroyo el Canelo and the upper part forming marine terraces at Campo Cristina, 500 m south of the San Felipe–Puertecitos road between km 57 and the gulf. Fossiliferous muddy sandstones alternate with sandstone-siltstone beds, reworked ash-lapilli, and bentonitic layers; coarser marine deposits cap the section in Valle Curbina, where it is unconformably overlain by alluvial conglomerate. The member is not correlative with the earlier named Early to Middle Eocene Delicias Formation of the Tijuana basin (Flynn, 1970).

Martín-Barajas *et al.* (1997) regard the lower section of the Delicias Sandstone Member as time-transgressive; the upper part of the unit interfingers with several distinct pyroclastic deposits.

Tuffs associated with the upper Puertecitos Formation, informal names of Stock et al. (1996), Early to Late Pliocene.—Extrusive volcanic units, including the tuff of Valle Curbina, informal name, are interbedded with or overlie the Puertecitos Formation. They include pyroclastic deposits shown on the maps by Stock *et al.* (1996) and in our column for the Puertecitos embayment as "Ptb" (dark gray lithic tuff), "Ptg" (white, crystal-rich pumiceous tuff) and "Ptf" (reworked air-fall deposits). "Pte" is a reworked green tuff in the upper part of the Delicias Sandstone Member. The flat-lying welded tuff of Mesa el Tábano, informal name, caps the mesa west of Arroyo El Canelo (Text-fig. 44). Sommer and García (1970) reported K/Ar dates of 5.9 ± 0.2 Ma and 3.1 ± 0.5 Ma for the base and top, respectively, of this unit; Martín-Barajas *et al.* (1995) obtained an Ar^{40}/Ar^{39} age of 3.08 ± 0.04 Ma for the same tuff.

Correlation

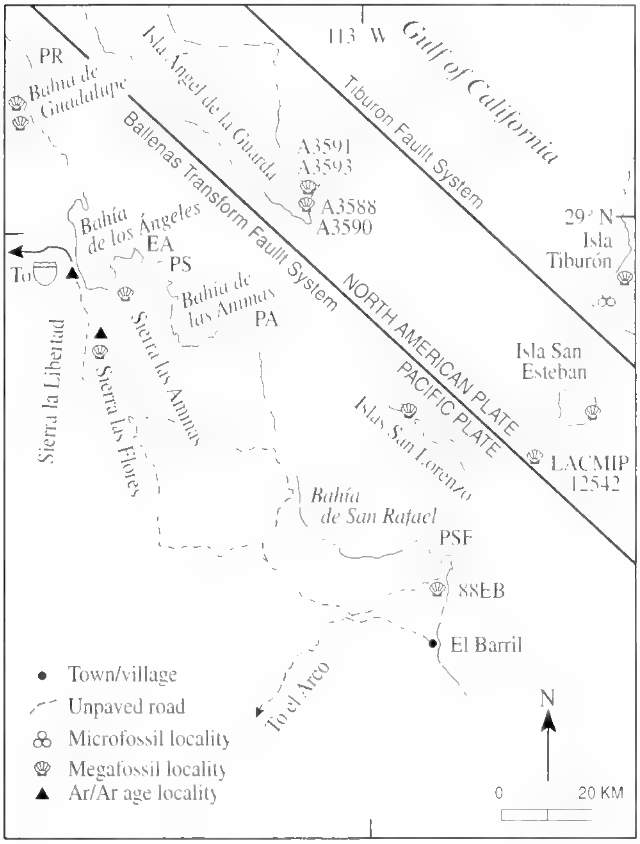
The Puertecitos Formation has not been recognized outside of the Puertecitos area except for a dredged sample from east-northeast of Isla San Lorenzo, one of the Midriff Islands 240 km to the south (28°37.0′ N, 112°43.2′ W, Natural History Museum of Los Angeles County Invertebrate Paleontology locality 12542) (Text-fig. 46). Correlation of the Puertecitos Formation is complicated by a great variety of marine facies that include intertidal mudstone, fine-grained sandstone, conglomeratic sandstone, and colluvium. Molluscan fossils from the lower Matomí Mudstone Member, including the Miocene Panamic pectinid *Amusium toulae* (Brown and Pilsbry) and the epitoniid gastropod *Amaea* (*Scalina*) *edwilsoni* DuShane, are also found in the Late Miocene to Middle Pliocene Tirabuzón Formation of the Boleo basin.

Bahía de Guadalupe to Bahía las Ánimas
Plate 2, Columns 28, 29, 30
(Text-figs. 2, 46, Appendices 1, 2)

Column 28 modified from Parkin (1998). The Guadalupe Basin is shown on the Campo Juárez quadrangle, H12C42, 1:50,000; and the geologic maps of Gastil *et al.* (1975), scale 1:250,000, and Parkin (1998), scale 1:10,000; Bahía de los Ángeles and Bahía las Ánimas are shown on the Bahía de los Ángeles quadrangle, H12C52, scale 1:50,000.

Geographic Setting

The area from Bahía de Guadalupe to Bahía de las Ánimas lies west and south of Isla Ángel de la Guarda and the Canal de Ballenas, west of the boundary between the Pacific and North American Plates marked by the Ballenas, Partida, and San Lorenzo Fault Zones. Although many lithologic units are not yet formally described, ongoing and recently completed studies indicate that the region contains marine sediments as-



Text-figure 46.—Bahía de Guadalupe to El Barril, map including Isla Ángel de la Guarda. $^{40}Ar/^{39}Ar$ ages (Delgado-Argote *et al.* 2000a): ash-flow tuff west of Bahía de los Ángeles, 14.2 ± 0.1 Ma; basalt, northern Sierra las Flores, 12.1 ± 0.1 Ma). Megafossils: A-numbers and Islas San Lorenzo localities are from University of California, Berkeley, Museum of Paleontology collections (Durham, 1950). Rocks dredged from 200 m at 28°37.0′ N, 112°43.2′ W [Natural History Museum of Los Angeles County, Paleobiology Department locality LACMIP 12542] have the same lithology and megafossils as the Puertecitos Formation, Matomí Member. 88EB: Ensenada Blanca area fossil locality of D. and J. Cox, 1988. Sources of data for other fossil localities: southwestern Isla Tiburón, Gastil *et al.* (1999); Isla San Esteban, Desonie (1992); Bahía de Guadalupe to Ensenada Alcatraz, Parkin (1998), G. Axen and M. Téllez-Duarte field collections; Sierra las Flores and Sierra las Animas, Delgado-Argote *et al.* (2000a). EA, Ensenada Alcatraz; PA, Punta de las Ánimas; PR, Punta Remedios; PS, Punta Soledad; PSF, Punta San Francisquito.

sociated with datable volcanic rocks that can provide further important details on the geologic history of this part of the Gulf Extensional Province. Prior to Pliocene time, Isla Ángel de la Guarda and the San Lorenzo Islands were part of the Baja California peninsula (Delgado-Argote *et al.*, 2000b). These islands moved southeast as a rigid block along the San Lorenzo and Partida Faults (Escalona-Alcázar *et al.*, 2001).

The Guadalupe Basin extends over 50 km², from approximately 29°15′ N, 113°40′ W to west of Ensenada Alcatraz. Its rocks are younger than those in the embayments to the south, where the record of Early to late Middle Miocene volcanic rocks and Late Pliocene fossiliferous marine sediments is more extensive (Parkin, 1998; Delgado-Argote *et al.*, 2000a,b).

Stratigraphy

Pre-Cenozoic basement rocks.—Cretaceous granitoid rocks that intruded Paleozoic metasediments and Mesozoic sandstones and shales have K/Ar ages of 99 Ma and 91.5 Ma (Delgado-Argote *et al.*, 1997; Romero-Espejel and Delgado-Argote, 1997). They are overlain unconformably by a sequence of volcanic units, sandstones, conglomerates, and alluvial and lacustrine deposits.

Unnamed Miocene sediments and volcanic debris-flow deposits.—The oldest Tertiary unit in the Guadalupe Basin is a pink biotite-rich, poorly welded tuff that has an Ar^{40}/Ar^{39} age of 22.6 ± 0.4 Ma (Parkin, 1998). It is discontinuous and separated by unconformities from both overlying and underlying rocks. In the western part of the basin volcanic debris-flow deposits contain isolated packages of 8–15 m thick limestone coquina and siltstone interbeds; they are overlain by younger green debris-flow deposits (Parkin, 1998).

Andesitic lava flows of 17 and 18 Ma were reported by Delgado-Argote *et al.* (1997, 2000a) from Isla Ángel de la Guarda and Bahía de los Ángeles. To the west Middle Miocene pyroclastic flows and basaltic andesites comprise three parallel ranges, thickening east to west: the Sierra las Ánimas, Sierra las Flores, and Sierra la Libertad. Dacitic to rhyolitic rocks have Ar^{40}/Ar^{39} ages of 14 ± 0.1 and 12.1 ± 0.1 Ma, respectively (Delgado-Argote *et al.*, 2000a). Associated fossiliferous marine sediments in the Sierra las Ánimas are interpreted by Delgado-Argote *et al.* (2000a,b) as Middle Miocene marine deposits of the ancestral Gulf of California; they illustrate internal molds of *Dosinia* and *Glycymeris* from Cañada la Tinaja, western side of Cerro Las Tinajas in the Sierra Las Ánimas.

West of Bahía las Ánimas the marine sequence is overlain by volcanic debris-flow and pyroclastic deposits of 5 ± 1.0 Ma and 3.8 ± 0.3 Ma (Delgado-Argote *et al.*, 2000a) and by Quaternary beach and fluvial sediments (Parkin, 1998).

Unnamed marine sediments near El Barril, Pliocene.—Unnamed fine- to medium-grained, mustard brown, friable sandstones and limy gray concretions with fossil molds are associated with volcaniclastic breccias approximately 2 km south of Punta San Francisquito and north of El Barril in the El Barril quadrangle. Dennis and June Cox made reconnaissance collections of Late Pliocene marine megafossils in 1988 from an unnamed coquina in Arroyo Ensenada Blanca. The fossils included abundant oysters, coralline algae, and internal molds of gastropods, as well as the pectinid index species *Argopecten abietis* (Jordan and Hertlein), *Argopecten revellei* (Durham), "*Aequipecten*" *corteziana* (Durham), and the sand dollar *Encope shepherdi* Durham.

The unit corresponds to the unnamed marine sediments west of San Felipe, the Carmen-Marquer Formation, undifferentiated, of the Loreto embayment, and marine units in the Islas Tres Marías and Isla Cerralvo. The pectinids and the sand dollar *Encope shepherdi* Durham correlate fossiliferous sandy siltstones in the Guadalupe basin with unnamed marine beds on the southeastern part of Isla Ángel de la Guarda, Isla las Ánimas of the San Lorenzo archipelago (Durham, 1950), and the eastern side of Isla San Esteban (Desonie, 1992) (Text-fig. 46).

San Lorenzo Archipelago
Plate 2, Column 31
(Text-fig. 46)

Column from Escalona-Alcázar *et al.* (2001); the area is shown on the geologic map by Gastil *et al.* (1975), scale 1:250,000; and by Durham (1950: fig. 14).

Geographic Setting

The San Lorenzo Archipelago is 27 km long and includes Isla San Lorenzo and Isla Ánimas, approximately 20 km northeast of Bahía San Rafael. The exposed sequence correlates with a section on the eastern side of the Sierra las Ánimas (Delgado-Argote and García-Abdeslem, 1999).

Stratigraphy

Crystalline basement in the central and southern part of Isla San Lorenzo consists of Paleozoic (?) greenschist facies metamorphic rocks and a tonalite pluton. It is unconformably overlain by a sequence of Neogene marine sandstone, conglomerate, and gypsum overlain by subaerial Pliocene andesitic lavas, lapilli-rich crystalline tuff, brecciated lithic tuff, and pumice. Quaternary alluvium and beach deposits cap the section.

Unnamed marine sediments, Late Pliocene.—Durham (1950) collected Late Pliocene megafossils from a section on the western side of Isla las Ánimas (his "North Island," University of California, Berkeley, Museum of Paleontology locality A-3594). Specimens occurred in well-bedded, northwest-dipping, coarse sandstone deposits overlain by conglomerates and volcanic rocks. Molluscan taxa included *Euvola keepi* (Arnold), *Argopecten deserti* Conrad, *Argopecten revellei* (Durham), and *Ostrea vespertina* Conrad.

Correlation

Contemporaneous sedimentary and volcanic activity has continued since the Miocene in the northern Gulf of California, as seen from similar volcano-sedimentary sequences at San Felipe, Puertecitos, Isla Ángel de la Guarda, Bahía de los Ángeles, Isla Tiburón, and Isla San Esteban (Escalona-Alcázar *et al.*, 2001). The Isla las Ánimas taxa include common index species found from the Islas Tres Marías to Bahía de Guadalupe and the younger sections of the Imperial Formation.

Southwestern Isla Tiburón, Sonora
Plate 2, Column 32
(Text-figs. 1, 2, 46, 47, 48, Appendix 1)

Column from Gastil *et al.* (1999). Geologic map, Gastil *et al.* (1999), scale 1:250,000, and Oskin and Stock (2003), scale 1:50,000.

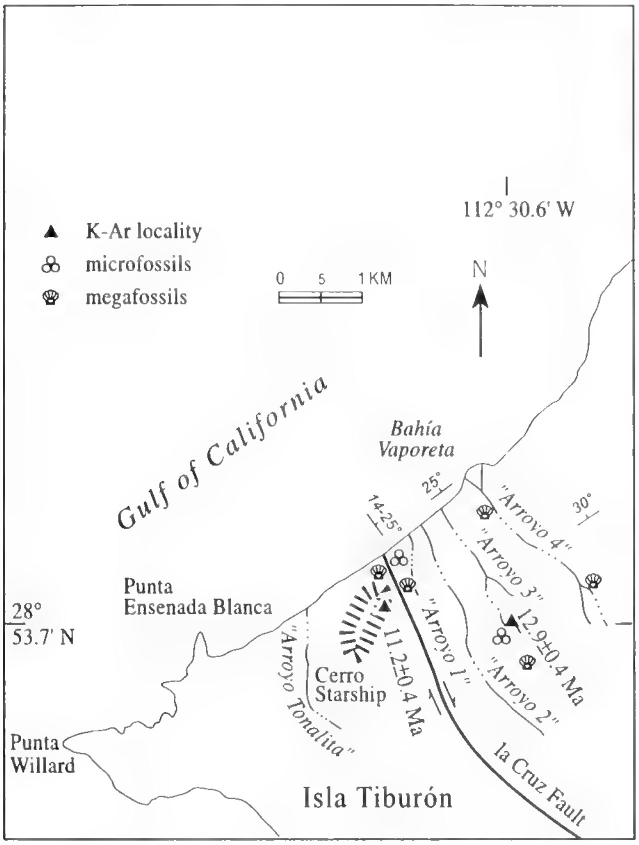
Geographic Setting

Isla Tiburón, the largest island in the Gulf of California, lies at approximately 29° N, 112°30′ W, east of the boundary between the North American and Pacific Plates and within the area of the southern Basin and Range Province. It is 10–20 km offshore from Bahía Kino and Puerto Lobos, Sonora, Mexico. The northwest to southeast-trending la Cruz Fault can be traced on the northern side of the feature informally known as "Cerro Starship" (Text-fig. 47).

Mapped by Gordon Gastil and students from 1983–1987, the southwestern part of Isla Tiburón includes almost 3 km of stratified Early Miocene to Quaternary volcanic and sedimentary rocks that record the geologic history of this part of the ancient gulf (Gastil *et al.*, 1999). Rocks older than 9–11 Ma are tilted; those younger than 9 Ma are generally horizontal. A key unit is a distinctive marine conglomerate, unit M8 of Gastil *et al.* (1999), which has not been identified west of the Pacific/North American Plate boundary. It is older and thicker than the sequences at Islas Tres Marías near the mouth of the Gulf of California (McCloy *et al.*, 1988). Pleistocene marine terrace deposits are found near Punta Willard on the southwestern part of the island.

Stratigraphy

Basement rocks and pre-Miocene sedimentary and volcanic units.—Continental redbeds, chert, and carbonate rocks overlie Cretaceous granodiorite and tonalite basement. They are intercalated with or overlain by Miocene volcanic rocks 22–14 Ma in age and by



Text-figure 47.—Southwestern Isla Tiburón, Sonora, locality map modified from Smith (1991c).

Middle to Late Miocene andesites, dacites, and rhyolites between 13 Ma and 9 Ma that are interbedded with or unconformably overlie the marine conglomerate. All units bear informal lithostratigraphic designations rather than formal formation names (Gastil *et al.*, 1999).

Unnamed volcanic rocks, Units M1–M7 of Gastil et al. (1999), Early and Middle Miocene.—The volcanic units, part of the magmatic arc that existed from 24 to 11 Ma in the area of the present Gulf of California, were studied by Neuhaus (1989a,b) and Neuhaus *et al.* (1988). They include andesitic flows and breccias of 22.7–18.8 Ma, tuffs, flows, and breccias of 14.9–20.5 Ma; they are designated Units M1–M7 as detailed by Gastil *et al.* (1999), who reported radiometric dates for 22 samples. These ages fall within the 24–11 Ma range published for volcanic rocks in the Sierra Santa Ursula east of Guaymas, Sonora (Mora-Álvarez and McDowell, 2000).

Unnamed conglomerate and sandstone, Unit M8 of Gastil et al. (1999), Miocene to Early Pliocene.—The primarily marine sandstone and pebble to cobble and boulder conglomerate is a unique 1,500-m-thick unit

Text-figure 48. Miocene volcanic breccia, southwestern Isla Tiburón. Gastil *et al.* (1999) reported a K/Ar age of 12.9 ± 0.4 Ma for a monomict breccia interbedded with marine conglomerate in "Arroyo 3" (sample 83BSJ260). Photo, J. G. Smith, 1983; area of photograph approximately 0.8 m across.

that crops out over an 8 km^2 area. It is exposed in several northwest-trending arroyos that cut perpendicular to the strike of the beds and empty into Bahía Vaporeta, 3–4 km northeast of Punta Willard. Cassidy (1989) measured sections and investigated the primarily volcanic clasts and silt to coarse sand sediments, which dip 15° to 25° to the northwest. Gastil *et al.* (1999) recognized four facies of sandstone and conglomerate, Units M8a through M8d, of which Unit M8d contains the highest concentration of marine megafossils.

The marine conglomerate was deposited on considerable topographic relief over volcanic rocks dated at 15–17.6 Ma. Its late Middle or earliest Late Miocene age is based on a 5- to 1-m-thick monolithologic volcanic debris-flow deposit exposed in the floor of the south branch of "Arroyo 3" (Text-fig. 48). The deposit has a K/Ar age of 12.9 ± 0.4 Ma (J. G. Smith *in* J. T. Smith *et al.*, 1985). Sampled before a topographic base map and GPS were available, its coordinates were determined as accurately as possible as 28°53.7′ N, 112°30.6′ W; the outcrop was not seen by Oskin and Stock (2003; M. Oskin, oral communication, 2003). The marine conglomerate is overlain with angular unconformity by an ash-flow tuff and dikes that cap Cerro Starship (Unit M9 of Gastil *et al.*, 1999).

Megafossils from Unit M8 represent faunules from several habitats, the most important of which is a shallow neritic assemblage of articulated pectinids that were buried alive and are now well exposed in the section near the mouth of "Arroyo 4," locality 3 of Gastil *et al.* (1999). Many of the taxa have strong Tertiary Caribbean affinities, in contrast to the endemic younger Gulf of California assemblages that evolved in the Pliocene. Representative species include *Argopecten demiurgus* (Dall), "*Aequipecten*" *muscosus* (Wood) or an ancestral subspecies, *Lyropecten tiburonensis* Smith, *Strombus obliteratus* Hanna, *Strombus* (*Tricornis*) sp. cf. *S.* (*T.*) *galeatus* (Swainson), *Turritella* sp. cf. *T. imperialis* Hanna, and species of *Euvola, Flabellipecten, Spondylus,* and *Atrina* under review by J. T. Smith.

A white sandstone facies mapped as Unit M8c crops out upsection from the debris-flow deposit in "Arroyo 3"; it has few megafossils and its inner to outer neritic (50–150 m) microfossils suggest that the facies is Late Miocene to Early Pliocene, no older than 6.5 Ma (Ingle *in* Gastil *et al.*, 1999, who also reported on samples from earlier reconnaissance studies by Weaver, 1979, 1981). Ingle listed planktonic species from Planktonic Foraminiferal Zones N17B to N19 (6.4 Ma–4 Ma). Benthic species range from Miocene to Recent; many currently live in the Gulf of California. The exception is *Amphistegina gibbosa* d'Orbigny, a tropical shallow-water species that ranges from Miocene to Holocene in the Caribbean; it lived only from latest Miocene to Early Pliocene, no later than 4.3 Ma, in the early Gulf of California and Pacific Ocean (McDougall *et al.*, 1999). *Amphistegina gibbosa* d'Orbigny is also reported from a Late Miocene (6.5–6.04 Ma) section of the Imperial Formation in the northernmost Salton Trough (McDougall *et al.*, 1999) and in the Fish Creek and Vallecito Mountains (Ingle, 1974; Quinn and Cronin, 1984), from Isla Carmen (Natland, 1950, as *Amphistegina* sp.), and from Early Pliocene sediments at Isla María Madre (McCloy *et al.*, 1988). Calcareous nannofossils listed from Isla Tiburón suggest ". . . an age close to the Miocene–Pliocene boundary . . ." (Ingle *in* Gastil *et al.*, 1999).

Ingle *in* Gastil *et al.* (1999) also included comparative data for microfossils from Punta Mita, Nayarit, and he listed species common to Isla Tiburón and the "Santiago diatomite" of the Cabo Trough. Tropical-subtropical, latest Miocene to Early Pliocene foraminifers from the white sandstone facies at Isla Tiburón are different from and younger than more temperate, early Late Miocene, outer neritic taxa from Punta Mita, north of Puerto Vallarta; there unnamed microfossiliferous siltstones are intercalated with or immediately underlain by volcanic rocks with K/Ar ages of 10.2 and 11.1 Ma (Jensky, 1975; Gastil *et al.*, 1978).

Gastil *et al.* (1999) acknowledged but were not able to explain the discrepancy between radiometric and megafossil ages and those from micropaleontology. They did not observe relationships between facies, possible faults or other aspects that could resolve these differences.

Oskin and Stock (2003) estimated that the marine conglomerate is considerably thinner than originally described, and that foreset beds were repeated by slumping and landslides. They also favored the younger age of the microfossils for the entire section and a marine origin concurrent with Pliocene spreading and *en echelon* faulting.

Ash-flow tuffs and rhyolite flows, Units M9–M11 of Gastil et al. (1999), Late Miocene to Pliocene.—The tilted marine conglomerate of Unit M8 is separated by an angular unconformity from Units M9–M11, which include flat-lying ash-flow tuffs dated at 11.2 ± 1.3 by Gastil and Krummenacher (1975, 1977), rhyolite flows and Early Pliocene dikes that cap Cerro Starship. The dikes yielded ages of 4.16 ± 1.8 Ma and 5.67 ± 0.17 Ma (Gastil *et al.*, 1999); Oskin and Stock (2003) redetermined the capping unit as feeder dikes of 5.7 ± 0.2 Ma.

Implications of the section at southwestern Isla Tiburón for the history of the ancient gulf.—The Miocene marine conglomerate and interbedded 12.9 Ma debris-flow deposit pre-date by almost 8 Ma the seafloor spreading and oblique rifting that occurred between 3 Ma and 5 Ma at the mouth of the Gulf of California (Larson, 1972). The section at southwestern Isla Tiburón is unique in lithology and thickness, although some of the same megafossils are found in reworked Late Miocene sediments of the lower part of the Imperial Formation near the Whitewater River, and in the southern Coyote Mountains, the Boleo basin at Santa Rosalía, and unnamed sediments east of Santa Anita in the southern San José del Cabo Trough. Reworked late Middle Miocene microfossils were reported from younger units in the northernmost Salton Trough (McDougall *et al.*, 1999), Yuma basin (Mattick *et al.*, 1973; P. B. Smith *in* Lucchita, 1972), Cerro Prieto geothermal field (Cotton and Vonder Haar, 1979, 1980, 1981), and subsurface cores from Sonora (Lozano-Romen, 1975; Gómez-Ponce, 1971; King, 1939). These records suggest an earliest incursion of seawater in the northern gulf area by 12–13 Ma, and provide evidence of the Miocene protogulf of Fenby and Gastil (1991) that was proposed for the area between the Sierra Madre Occidental and the eastern shore of the modern gulf. The megafossils from Isla Tiburón include live-buried assemblages, whereas the other evidence comes from reworked late Middle Miocene taxa associated with Late Miocene or younger marine sediments.

Isla San Esteban
Plate 2, Column 33
(Text-fig. 46, Appendix 1)

Column is from Desonie (1992), who also published a reconnaissance geologic map, scale 1 cm represents 0.4 km.

Isla San Esteban is primarily a calc-alkaline volcanic island in a zone of active rifting approximately 15 km southwest of Isla Tiburón. Desonie (1992) mapped an area of marine fossiliferous sandstone near the mouth of a major west to east drainage known as Arroyo Limantour. She reported a dacitic flow below the marine rocks with a radiometric age of 2.77 ± 0.05 Ma. Megafossils from this sandstone include the common Late Pliocene index species *Argopecten abietis* (Jordan and Hertlein) and other taxa that correlate the rocks with the Carmen-Marquer Formation, undifferentiated, in the Loreto embayment, the Infierno Formation at Santa Rosalía, and unnamed sediments at Bahía de Guadalupe, Isla Cerralvo, and the Islas Tres Marías.

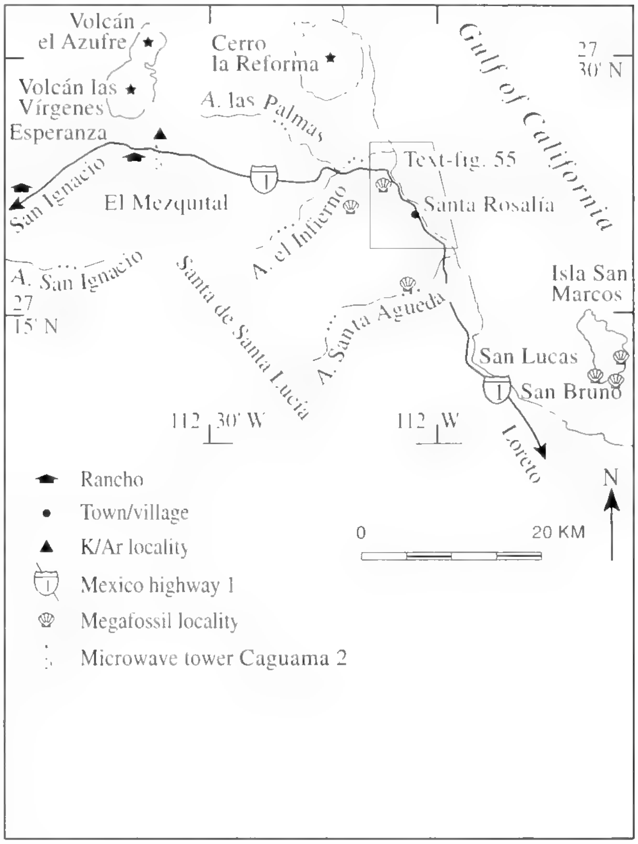
Boleo Basin
Plate 2, Column 34
(Text-figs. 2, 49, 55, Appendices 1, 2)

Column modified from Touwaide (1930), I. F. Wilson (1948), and I. F. Wilson and V. S. Rocha (1955). Area is shown on the Santa Agueda, Santa Rosalía and Punta Santa Ana quadrangles, G12A35, G12A36 and G12A25, respectively, 1:50,000. Geologic maps are included in I. F. Wilson (1948), I. F. Wilson and M. Veytia (1949), I. F. Wilson and V. S. Rocha (1955), and Holt *et al.* (2000).

Overview

The Boleo basin lies along the central Gulf of California, south of Caldera La Reforma and east of the Sierra Santa Lucía. It could extend as far south as the northern tip of the Concepción Peninsula. The basin includes the 33 km² Boleo Copper District, mined from 1885 to 1947 by the Compagnie du Boleo, and the Lucifer Manganese District, 12 km northwest of Santa Rosalía (I. F. Wilson and M. Veytia, 1949). Its western edge is obscured by Tertiary volcanic arc rocks of the Sierra Santa Lucía (Sawlan and J. G. Smith, 1984). A number of east-flowing arroyos with names such as Arroyo Purgatorio and Arroyo Infierno expose the section (Text-figs. 49, 55).

The area is critical for documenting the time-stratigraphic framework of the tectonic history of the central Gulf of California and its volcanic arc. More than 500 m of volcanic rocks, 600 m of marine sediments, and numerous unconformities record the Neogene volcanic and depositional history of the basin from 24 Ma to 1 Ma. Sawlan (1991) discussed the geochemistry of the volcanic rocks through time. The earliest seawater entered the Boleo basin in the late Middle Miocene to early Late Miocene, as seen from shallow-water assemblages of Tertiary-Caribbean fossils draped over a submerged dome that has a K/Ar age of approximately 12 Ma (J. T. Smith, 1991b,c) (Text-fig. 50).



Text-figure 49.—Tres Vírgenes to Santa Rosalía, B.C.S., index map to the Boleo basin and surrounding area. Sawlan and J. G. Smith (1984) reported a K/Ar age of 10.1 ± 0.4 Ma for a subaerial tholeiitic flow in the basalt of Rancho Esperanza north of Rancho Mezquital (27°25.36′ N, 112°34.05′ W). Late Pliocene fossils from Isla San Marcos discussed by Anderson (1950: fig. 11) and Durham (1950) are deposited in the University of California, Berkeley, Museum of Paleontology collections.

The origin of secondary copper and manganese ores associated with the Boleo Formation is under ongoing investigation. Conly and Scott (2000) believe the formation of copper sulfide involved hydrothermal alteration of clayey tuffs within the Boleo Formation. The manganese oxide deposits formed separately, perhaps in cold water (Freiberg, 1983).

Stratigraphy

Cretaceous basement rocks.—Cretaceous quartz monzonite basement is overlain unconformably by

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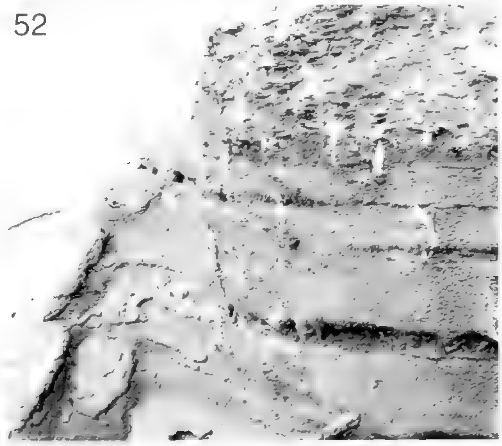

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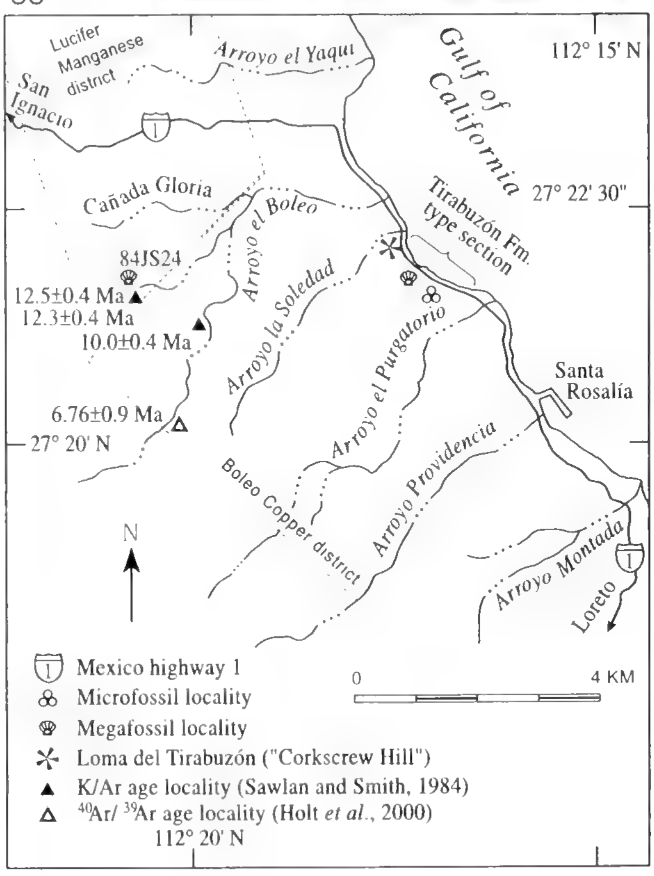

Miocene volcanic rocks and Miocene to Pleistocene marine and nonmarine sediments that crop out in arroyos north and south of the town of Santa Rosalía.

Volcanic arc rocks, including the andesites of Sierra Santa Lucía, Early to Middle Miocene.—Andesites, basalt flows, tuffs, and volcanic breccias underlie the Sierra Santa Lucía from west of the Boleo basin to north of Mulegé. Referred to the Comondú Formation by I. F. Wilson (1948), Beal (1948), Demant (1975), and others, these rocks differ in lithology, origin, and age from the type section of that unit. Sawlan and J. G. Smith (1984) and Sawlan (1991) discussed the differences between the 24–11 Ma Early to Middle Miocene calcalkaline arc rocks near Santa Rosalía and the non-arc, primarily volcaniclastic, Middle-Late Miocene Comondú Formation described from the Sierra la Giganta. Sawlan's informal descriptive name, andesites of Sierra Santa Lucía, is more appropriate for the volcanic rocks near Santa Rosalía.

In places 10 Ma tholeiitic lavas covered the volcanic sequence before it was faulted, tilted, and deeply eroded, and before seawater covered the area. A late Middle Miocene submarine rhyolite dome extruded near the head of the present Arroyo del Boleo is a late volcanic arc feature, especially significant for determining the age of the earliest marine deposits in this part of the ancient gulf (J. T. Smith, 1991b).

Tertiary marine units of the Boleo basin: the Boleo, Tirabuzón and Infierno Formations. Boleo Formation, Middle–Late Miocene.—I. F. Wilson (1948) named the oldest marine unit the Boleo Formation. He did not specify a type section but probably based his description on the sequence exposed in Arroyo Purgatorio, north of the town of Santa Rosalía in the quadrangle of the same name. He described beds of conglomerate that crop out at four separate stratigraphic levels, a lowermost nonmarine facies overlain by alternating beds of conglomerate, fossiliferous limestone, and clayey tuff beds associated with later copper sulfide and manganese oxide deposits, sandstone, and gypsum.

Eight *mantos* or mineralized ore beds of copper deposits have been studied by many authors, including Conly and Scott (2000), who investigated potential metal sources for the copper-cobalt-zinc deposits. The manganese deposits are thickest in the northwestern part of the area; Freiberg (1983) discussed their origin and geological setting. I. F. Wilson and V. S. Rocha (1955) mapped as much as 80 m of gypsum overlying the marine limestone, and illustrated an enormous twinned crystal exposed in Arroyo del Boleo (I. F. Wilson and V. S. Rocha, 1955: fig. 15). Careful study of the gypsum deposits might locate intercalated marine microfossiliferous layers as in the Fish Creek Gypsum of the Salton Trough (Dean, 1996).

A basal coquina draped over a calcalkaline vent in an unnamed northeast-flowing tributary to Arroyo del Boleo probably formed as soon as the dome cooled. K/Ar dates of 12.3 ± 0.4 Ma and 12.5 ± 0.4 Ma constrain the age of the oldest marine fossils, which are Tertiary-Caribbean species (Sawlan and J. G. Smith, 1984; J. T. Smith, 1991b,c). Representative late Middle or early Late Miocene mollusks include *Flabellipecten gatunensis* (Toula), *Nodipecten nodosus* (Linnaeus), *Spondylus bostrychites* (Guppy of Maury,

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Text-figure 50.—Boleo basin, ridge between the headwaters of Cañada Gloria (drainage in the background) and Arroyo del Boleo. A coquina in the basal Boleo Formation drapes over mudflows and pelagonitic tuffs that dip off the flanks of a submarine dacite dome with a K/Ar age of 12.3 ± 0.4–12.5 ± 0.4 (Sawlan and Smith, 1984). Arrow indicates the coquina facies that contains late Middle Miocene Tertiary-Caribbean mollusks (J. T. Smith, 1991b, megafossil locality 84JS24). Photo, J. G. Smith, 1981.

Text-figure 51.—Tirabuzón Formation, type section along Mexico 1 north of Santa Rosalía. Photo, T. M. Cronin, 1984.

Text-figure 52.—Loma del Tirabuzón, northwestern end of the type section of the Tirabuzón Formation, which dips to the southeast. The lowest cliff-forming sandstone contains mollusks, echinoids, barnacles, and the largest recorded specimens of corkscrew trace fossils referred to *Gyrolithes*. Spiral burrows were probably made by decapod crustaceans (E. C. Wilson, 1985).

Text-figure 53.—*Gyrolithes* fragment with surface ridges interpreted as scratch marks made by the organism that dug the burrow (E. C. Wilson, 1985). Height 0.25 m (10⅞ in), diameter 3 cm (1¼ in), Natural History Museum of Los Angeles County general collection, locality LACMIP 4828. Photo, E. C. Wilson, 1979.

Text-figure 54.—*Gyrolithes*, the corkscrew part of a burrow, with an "associated *Thalassinoides* 'turnaround'" at the lower end (E. C. Wilson, 1985). Height 0.8 m (2 ft 8 in), Natural History Museum of Los Angeles County general collection, locality LACMIP 4828. Photo, E. C. Wilson, 1979.

Text-figure 55.—Boleo basin arroyos mapped by I. F. Wilson (1948) and I. F. Wilson and V. S. Rocha (1955), including the type section of the Tirabuzón Formation of Carreño (1981). The type section, 4 km along Mexico 1 north of Santa Rosalía, is Instituto de Geología Microfossil locality 81 [= Natural History Museum of Los Angeles County locality LACMIP 4828]. Late Miocene $^{40}Ar/^{39}Ar$ sample is from the *cinta colorada* horizon of the Boleo Formation, 40 m above its base (Holt *et al.*, 2000, sample location E). Basal Boleo Formation megafossil locality 84JS24 is shown in Text-figure 50.

1917), the Tertiary-Caribbean oyster *Hyotissa hyotis* (Linnaeus), and the muricid gastropod *Murexiella* (*Subpterynotus*) *textilis* (Gabb) (J. T. Smith, 1991b,c).

The *cinta colorada* is a thin (0.5–2 m), coarse-grained, reddish-purple, lithic tuff. The marker bed was named by I. F. Wilson (1948) for a widespread horizon of mainly andesitic volcanic cinders, ash, and lapilli. He reported it ". . . everywhere above ore bed no. 3" and a useful horizon for measuring offsets on faults. The *cinta colorada* lies approximately 140 m (the average was 80 m) upsection from the basal coquina. Holt *et al.* (1997, 2000) reported its Ar^{40}/Ar^{39} age as 6.76 ± 0.90 Ma (Text-fig. 55, location E). They regarded the base of their section as 6.93–7.09 Ma and the top of the Boleo Formation as 6.14–6.27 Ma; the megafossils in the basal coquina are late Middle Miocene, younger than the age of the underlying 12.3-Ma dome and older than the 6.76 ± 0.90 Ma marker horizon. The upper part of the Boleo Formation could be as young as Late Miocene, but it is older than the overlying Tirabuzón Formation, which contains Late Miocene to middle Pliocene microfossils, sharks, and mollusks.

Tirabuzón Formation, Late Miocene to Pliocene.—The marine Tirabuzón Formation of Carreño (1981) was originally named the Gloria Formation (I. F. Wilson, 1948) from a type section in Cañada Gloria near the boundary of the Santa Águeda and Santa Rosalía quadrangles. The unit has a basal conglomerate that is overlain by yellow to light brown fossiliferous sandstone, shale, and siltstone. Marine facies near the coast grade laterally to nonmarine facies in the western Boleo basin.

Because Wilson's name was in prior use in eastern Mexico, Carreño (1981) renamed it, in accordance with the North American Stratigraphic Code (1983, articles 7b and 7c). She designated a 185-m-thick section exposed along Mexico 1 north of the turnoff to Santa Rosalía as the hypostratotype (Text-figs. 51, 52, 55). Known as "Loma del Tirabuzón" or "Corkscrew Hill," the area is abundantly fossiliferous, best known for 1–2-meter-long spiral, sand-filled burrows in the yellowish to gray sandstone. These trace fossils are referred to *Gyrolithes*, burrows most likely dug by decapod crustaceans (E. C. Wilson, 1985). Early gulf pectinids are common; they include *Euvola keepi* (Arnold), *Flabellipecten bösei* (Hanna and Hertlein), "*Aequipecten*" *corteziana* (Durham), "*Aequipecten*" *dallasi* (Jordan and Hertlein), *Nodipecten subnodosus* (Sowerby), *Leopecten bakeri* (Hanna and Hertlein), and *Pseudamussium* (*Peplum*) *fasciculatum* n. subsp. Representative taxa were illustrated or listed by Quiroz-Barroso and Perrilliat (1989) and J. T. Smith (1991c). The unit is loosely consolidated, and many fossils are not in stratigraphic position; careful sampling of *in situ* fossils could yield a more precise chronostratigraphy.

Based on microfossils, Carreño (1982) assigned the unit an Early–Middle Pliocene age. Later McDougall (oral communication, 1996) identified Late Miocene benthic foraminifers from the basal Tirabuzón Formation. We now estimate the age of this formation as Late Miocene to Middle Pliocene. Neritic sediments in the lower part of the Tirabuzón Formation change abruptly upsection to deeper water deposits of 200–500 m, based on planktonic foraminifers (Carreño, 1982) and 34 species of sharks that suggest deposition 2–3 km offshore (Applegate and Espinosa-Arrubarena, 1981).

Infierno Formation, Late Pliocene.—The Boleo basin shallowed in the Late Pliocene during deposition of the Infierno Formation, a basal sandstone and conglomeratic sand that I. F. Wilson (1948) probably described from the south side of Arroyo el Infierno, west of Santa Rosalía and mostly south of the present Mexico 1, in the Santa Águeda and Punta Santa Ana quadrangles (Text-fig. 49). The unit lies with angular unconformity above the Tirabuzón Formation and grades upward to nonmarine facies of the Santa Rosalía Formation. Well-exposed and accessible in Arroyo Santa Agueda, the marine facies contains many of the same Late Pliocene mollusks as the Carmen-Marquer Formation, undifferentiated, in the Loreto embayment.

Santa Rosalía Formation, Pleistocene.—I. F. Wilson (1948) did not designate a type section for the unit that caps the mesas around Santa Rosalía. It unconformably overlies the Infierno Formation and grades from marine sandstone and conglomerate to loosely consolidated nonmarine clastic sediments. Ortlieb (1991) regarded the formation as late Early Pleistocene, approximately 1 Ma in age.

Pleistocene marine terraces.—Ortlieb (1991: fig. 7) presented a map and detailed analyses of 11 transects across 300 m of terraces in the Santa Rosalía and Caldera La Reforma area. He used deep-sea cores and paleoclimatic curves to interprete their ages as late Early Pleistocene to Late Pleistocene.

Tres Vírgenes volcanic rocks, Quaternary.—I. F. Wilson and V. S. Rocha (1955), Sawlan and J. G. Smith (1984), and Sawlan (1991) described Quaternary calcalkaline flows, pumice, welded tuff, breccia, and cinder cones from the area of the Tres Vírgenes volcanoes west of Santa Rosalía. Volcanic rocks from Caldera la Reforma on the coast north of Santa Rosalía were dated as >0.7–<1.5 Ma (Sawlan, 1991). Hausback *et al.* (2002) reported a radiometric age of 1.09 Ma from Schmidt (1975) for pyroclastic and lava sheets surrounding the caldera.

Correlation of Boleo basin marine units.—Species level redeterminations of the older Boleo Formation mollusks are in progress. Preliminary results show some taxa in common between the basal coquina of the Boleo Formation and the unnamed conglomerates of southwestern Isla Tiburón. Most are Tertiary Caribbean index species described from Trinidad to Panamá. The Tirabuzón Formation correlates with the lower Matomí Member of the Puertecitos Formation on the basis of the epitoniid gastropod *Amaea (Scalina) edwilsoni* DuShane and the pectinid *Amusium toulae* (Brown and Pilsbry). The Infierno Formation is equivalent to the Carmen-Marquer Formation, undifferentiated of the Loreto embayment and unnamed marine sediments of the Guadalupe basin to the north.

Isla San Marcos

Isla San Marcos lies 25 km to the southeast of Santa Rosalía (Text-figs. 49, 56). Anderson (1950) visited the island during the 1940 *E.W. Scripps* Cruise and made a sketch map of the geology of the southern part of the island, describing the oldest exposed rocks as lava flows, volcanic breccia, and tuffs. An angular unconformity separates these units from sediments that include a nonmarine basal sandstone containing wood and leaf fragments, marine sandstone, gypsum with thin interbeds of sandstone and shale, and overlying conformable marine sandstone, conglomerate, and limestone.

Anderson (1950) named the clastic sediments and gypsum deposits the San Marcos Formation and interpreted its age as Early Pliocene. Redeterminations of the megafossils, which include the Late Pliocene Gulf of California index species *Argopecten abietis* (Jordan and Hertlein), for this paper indicate a Late Pliocene age, correlative with the upper part of the Tirabuzón Formation and the Infierno Formation of I. F. Wilson (1948). Wilson's formation names take precedence because they were published earlier than the San Marcos Formation of Anderson (1950).

Concepción Peninsula
Plate 2, Column 35
(Text-figs. 1, 2, 56, 60, Table 7, Appendices 1, 2)

Column is modified from McFall (1968) and Meldahl *et al.* (1997). Area is shown on the Mulegé, El Coyote, and San Nicolás quadrangles, G12A57, G12A67 and G12A68, respectively, scale 1:50,000; and on the geologic map of Ledesma-Vázquez *et al.*, 2004, scale 3 cm represents 2 km.

Overview

The Concepción Peninsula is primarily composed of volcanic and volcaniclastic rocks, with several local areas underlain by marine sediments whose correlation is under investigation. The area is important to the tectonostratigraphic history of the gulf because the volcanic units on the eastern side of the Peninsula represent vent or near-vent facies of a volcanic arc that was active from 24 to 12 Ma (Sawlan, 1991). Marine sediments in the northern and south-central parts of the Peninsula are neither extensive nor continuous; they could range in age from Late Miocene or Early Pliocene in the north to Late Pliocene in the south, based on microfossils (Carreño *in* Ledesma-Vázquez and Johnson, 2001) and preliminary megafossil determinations for this paper.

The Concepción peninsula is 10–15 km wide, separated from the Baja California peninsula by Bahía Concepción, a 40 km long, 5–10 km wide embayment (Text-fig. 60). Mehldahl *et al.* (1997) and Foster *et al.* (1997) studied the modern fauna, flora, sediments, and subsidence rates in Bahía Concepción.

Stratigraphy

Basement rocks and the Salto Formation, Cretaceous–Late Oligocene.—Bedrock in this area consists of metamorphic rocks and Cretaceous granite for which McFall (1968) reported an age of 78.4 ± 2.9 Ma. These rocks are overlain on the eastern coast of the peninsula by unnamed quartzose sandstone redbeds that McLean (1988) considered Eocene(?) in age, possibly equivalent to cross bedded aeolian red sandstones at San Carlos and Tembabiche to the south. McFall (1968) named these beds the Salto Formation and regarded them as Late Oligocene, based on a tuff in the upper part; it is the oldest unit in the Comondú Group (Table 7).

Volcanic and volcaniclastic units, the "Comondú Group" of McFall (1968), Late Oligocene–Early Miocene.—McFall (1968) used the name Comondú Group for six new formations representing more than 4,000 m of Oligocene to Miocene volcanic and volcaniclastic rocks (Mehldahl *et al.*, 1997). From oldest to youngest, they are: the Salto Formation, Pelones Formation, Ricasón Formation, Minitas Formation, Pilares Formation, and the Hornillos Formation. Their lithologies, Early to early Middle Miocene radiometric ages, and type localities are summarized in Table 7, p. 82. Gabbro and tonalite intrusions penetrate these units as well as the basement rocks, the tonalite having a K/Ar age of 20.0 ± 2.0 Ma (McFall, 1968).

A comparison of McFall's Comondú Group with the type section of the Comondú Formation of Heim

Table 7.—Concepción Peninsula, lithostratigraphic units (Text-fig. 60). Lowercase names indicate informal units that were not established according to the North American Stratigraphic Code (1983).

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
Bahía Concepción Member	Johnson *et al.* (1997) named as member of Infierno Formation.	Member consists of fossiliferous and unfossiliferous limestones and alluvial siltstones, one of which is a red layer containing localized rhizoliths. Type section is in the south-central peninsula (shaded rectangle, Text-fig. 60), along the western side of Arroyo Cayuquitos on the road to San Sebastián (26°35′82″ N, 111°38′34″ W), San Nicolás quadrangle. Late Pliocene.
Calabaza Member	Johnson *et al.* (1997) named as member of Infierno Formation.	Lowest member of the Infierno Formation in this area includes alluvial conglomerate, sandstone, siltstone, and mudstone with *in situ* oyster beds in the area of Arroyo la Calabaza (26°33′52″ N, 111°37′38″ W) between Cerro Prieto and Rancho Santa Rosalíta, west-central Concepción Peninsula, San Nicolás quadrangle. Late Pliocene.
Cayuquitos Chert Member	Johnson *et al.* (1997) named as member of Infierno Formation.	Unit is a poorly consolidated chert breccia and red mudstone with andesitic pebbles; it was named for a 2-m-thick section on the western flank of Cerro Prieto (approximately 26°37′04″ N, 111°38′54″ W), San Nicolás quadrangle. Late Pliocene.
Comondú Group of McFall (1968)	Heim (1922) named as Formation; McFall (1968) raised to Group.	Formation originally described as a nonmarine conglomerate near San José de Comondú in the Sierra la Giganta, but the name has been used for a wide variety of lithologies in many parts of the Baja California peninsula. Rocks from the Concepción Peninsula have both volcanic and volcaniclastic compositions and formed at or near the vents of a volcanic arc that occupied the present Gulf area until the early Neogene. Late Oligocene (?)–Early Miocene.
El Mono Chert Member	Johnson *et al.* (1997) named as member of Infierno Formation.	Member is a dark brown to beige bedded chert and chert breccia with limestone lenses and fossil mangrove roots. Type section is in the south-central peninsula near a bend in Arroyo El Mono (26°35′8″ N, 111°40′10″ W), El Coyote quadrangle. Late Pliocene.
Hornillas Formation	McFall (1968) named as part of Comondú Group.	Unit is a 150-m-thick coarse tuffaceous conglomerate that contains volcanic clasts and a thin basal basalt flow. Type section in the southeastern Concepción Peninsula, San Nicolás quadrangle, is an almost 90 m vertical cliff along the left bank of Arroyo San Sebastián, 0.5 km southwest of its mouth. Early Miocene, 22–23 Ma.
Infierno Formation	Wilson (1948). Johnson *et al.* (1997) divided into four members in the Concepción Peninsula.	Formation is a fossiliferous marine to nonmarine sandstone and conglomerate at type locality in Arroyo Infierno near Santa Rosalía, 70 km north of Concepción Peninsula. McFall (1968) mapped isolated outcrops in the northern and southwestern part of the peninsula. Lithologies of members in south-central Concepción Peninsula include sandstone, siltstone, alluvial conglomerate, chert, chert breccia, limestone, and mudstone. Late Pliocene.
Minitas Formation	McFall (1968) named as part of Comondú Group.	Unit is a coarse tuffaceous conglomerate and sandstone with local basal tuffs, 30–150 m thick. Type section is in the northeastern Concepción Peninsula in Arroyo de las Minitas, approximately 400 m south and west of the lower part of the arroyo, Mulegé quadrangle. McFall (1968) mapped it as part of the Comondú Group. Earliest Miocene.
Pelones Formation	McFall (1968) named as part of Comondú Group.	Formation includes interbedded reddish volcanic agglomerate, basalt flows, minor tuffs, rare tuffaceous sandstone, and conglomerate. The more than 1,800-m-thick type section crops out in the west-central peninsula, eastern side of coxcomb-like Los Pelones Ridge, 2.5 km north of Rancho Salto, El Coyote quadrangle. It is also exposed on the western shore of Bahía Concepción north of Cerro San Pedro. Early Miocene, 20.0 ± 2.0 Ma, based on an intruded tonalite near Cerro Blanco, the highest peak on Concepción Peninsula.
Pilares Formation	McFall (1968) named as part of Comondú Group.	Unit is an aphanitic and porphyritic basalt, more than 90 m thick. Type section is south of Punta Pilares and just north of the Gavilán manganese mine, at the northeastern tip of Concepción Peninsula, Mulegé quadrangle. Late Oligocene to Early Miocene.
Ricasón Formation	McFall (1968) named as part of Comondú Group.	Formation consists of 1,700 m of basalt, breccia, tuff flows, and interbedded agglomerates, tuffs, and andesites. Type section was not fully worked out (*fide* McFall, 1968) but was regarded as south of Punta Arena along the southwestern shore of Bahía Concepción, El Coyote quadrangle. Unit also crops out in the core of the Los Llanos syncline at the southern end of the peninsula. Early Miocene, 17–22 Ma, youngest unit of McFall's Comondú Group.

Table 7.—Continued.

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
Salto Formation	McFall (1968) named as part of Comondú Group.	Formation is a distinctive volcaniclastic and tuffaceous 300-m-thick red sandstone with large-scale cross beds and interbedded tuffs. Type section in the west-central peninsula is along the mountain front just north of the mouth of Arroyo Amolares and 3.2 km north of Rancho Salto, El Coyote quadrangle. Late Oligocene, based on a dated tuff of 28.1 ± 0.9 Ma in the upper part (McFall, 1968) or Eocene (?) (McLean, 1988).
Tirabuzón Formation	Carreño (1981) renamed Gloria Formation of I. F. Wilson (1948), preoccupied.	Formation includes 185 m of fossiliferous marine sandstone, siltstone, and conglomerate. Type section is at Loma del Tirabuzón (Corkscrew Hill), 4 km north of the turn-off to Santa Rosalía, in the Boleo basin. Yellow marine sandstone at Punta Paredón Amarillo at the northern tip of the Concepción Peninsula is probably this unit. Late Miocene–middle Pliocene, based on microfossils and stratigraphic position above dated volcanic rocks in the underlying Boleo Formation at Santa Rosalía.

(1922) shows important differences in lithology and age. Described from the Sierra la Giganta 50–60 km to the southwest, the Comondú Formation at its type area is primarily a fluvial, clast-supported, boulder to cobble conglomerate, a distal facies derived from the volcanic arc in the area of the present gulf but not itself an arc rock. It is 12–14 Ma in age at San José de Comondú.

McFall's sequence occupies the medial line of an arc or a near-vent position along a volcanic arc. His Ricasón Formation, the youngest volcanic unit of the Concepción Peninsula, ranges in age from 17–22 Ma. In view of these differences and the long-standing confusion surrounding the Comondú Formation we use McFall's formational names rather than his overarching Comondú Group.

Tertiary marine sediments, northern Concepción Peninsula, Tirabuzón Formation and Infierno Formation, Late Miocene–Early Pliocene.—Flat-lying marine sediments referred by MacFall (1968) to the Late (?) Pliocene Infierno (?) Formation of I. F. Wilson (1948) unconformably overlie volcanic units in the northern part of the peninsula. Outcrops include a grayish white sandstone mapped by McFall near Arroyo del Agua Amargo, inland from Ensenada Santo Domingo. An unnamed yellow marine fossiliferous sandstone from Punta Paredón Amarillo, west of Punta Concepción, contains Late Miocene megafossils and Late Miocene to Pliocene microfossils (Text-figs. 58, 59, 61). Carreño *in* Ledesma-Vázquez and Johnson (2001) and Carreño *in* Ledesma-Vázquez *et al.* (1999) reported the same microfossil species from these units as in the Tirabuzón Formation near Santa Rosalía.

Infierno Formation, central Concepción Peninsula, Pliocene.—Ledesma-Vázquez *et al.* (1997) and Johnson *et al.* (1997) mapped the sediments in the south-central part of the peninsula in a 7 by 9 km area between Cerro Prieto and Rancho Santa Rosaliíta (Text-fig. 60). They recognize four small upper Pliocene basins underlain by the Late Pliocene Infierno Formation, which they divide into four members that crop out approximately 5 km east of the fishing camp of San Sebastián (Johnson *et al.*, 1997, fig. 1*b*). The units are exposed in arroyos shown on the El Coyote and San Nicolás quadrangles. Oldest to youngest, they are the mainly alluvial Calabaza Member, El Mono Chert (which includes fossil mangrove roots), Bahía Concepción Member and the Cayuquitos Chert Member.

Mollusks and echinoids reported from the Bahía Concepción Member correlate this unit with the Late Pliocene Carmen-Marquer Formation, undifferentiated, in the onshore Loreto embayment, unnamed units at Punta Chivato reported by Simian and Johnson (1997), and the Infierno Formation in the Boleo basin.

San Nicolás basin
Plate 2, Column 36
(Text-figs. 60, Appendices 1, 2)

Area is shown on the San Nicolás quadrangle, G12A68, scale 1:50,000; and the geologic maps of Ledesma-Vázquez (2000) and Ledesma-Vázquez *et al.* (2004), scale 3 cm represents 2 km.

Overview

The San Nicolás basin lies between Concepción Peninsula and the northern Loreto embayment. It is delimited by three fault zones: La Ramadita on the northwest, Los Volcanes (trends west-northwest or west to east), and San Antonio on the southeast. It contains outcrops of an informally-named Late Pliocene marine unit, the San Nicolás formation, which includes several members that are exposed in arroyos that drain into the Gulf of California west of Punta

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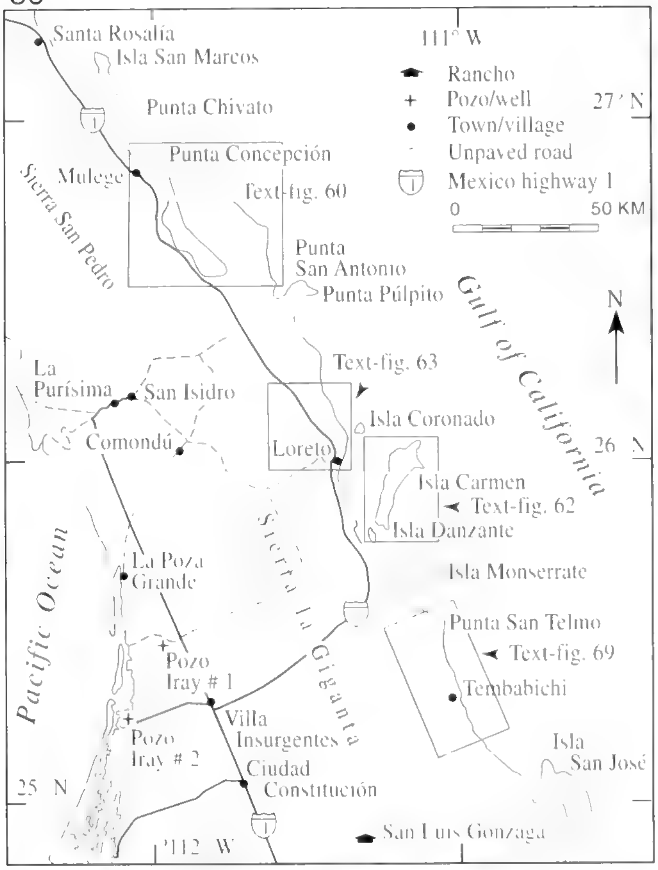

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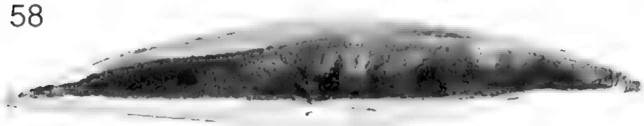

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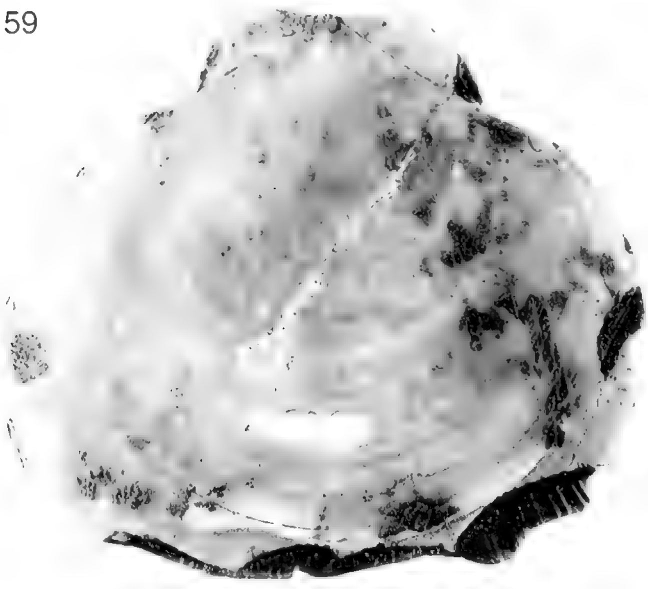

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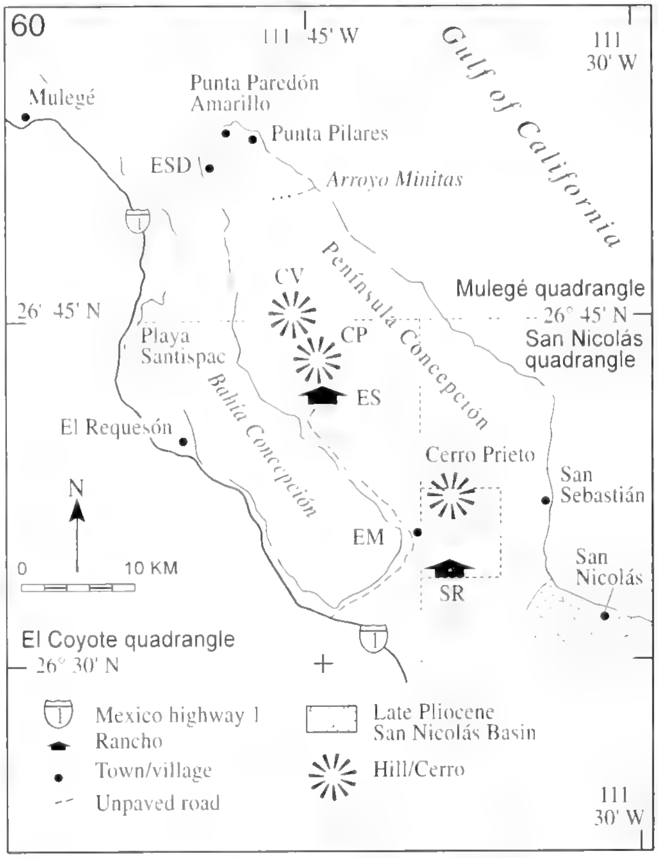

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San Antonio, the prominent point northwest of Punta Púlpito. The area is 18 km east of Mexico 1 by unpaved road from Rancho El Rosarito.

Stratigraphy

Granodiorite basement rocks, Cretaceous.—Bedrock in this area consists of Cretaceous granodiorite. A sample from Punta San Antonio was dated at 98.2–99.0 Ma (D. Kimbrough *in* Ledesma-Vázquez, 2000).

Volcanic and volcaniclastic units, part of the "Comondú Group" of McFall (1968), Late Miocene.—Ledesma-Vázquez (2000) mapped volcanic and volcaniclastic rocks in fault contact with the Tertiary marine sediments as andesite of Sierra Santa Lucía and regarded them as the "Comondú Group" of McFall (1968). He also mapped the lowest unit as the Salto Formation, which was described from the western Concepción Peninsula. As discussed above, we prefer lithologic terms for these units, which differ in age and composition from the late Middle Miocene boulder conglomerates of the Comondú Formation at its type section.

San Nicolás formation, informal name, Pliocene.—The San Nicolás formation was proposed informally by Ledesma-Vázquez (2000) for composite sections of the Late Pliocene marine sequence that unconformably overlies volcanic and volcaniclastic rocks in the San Nicolás basin. The rocks are well exposed from Arroyo el Saucito on the northwest to Arroyo San Antonio, southwest of Punta San Antonio. The four new members discussed by Ledesma-Vázquez (2000) are formally named in Ledesma-Vázquez *et al.* (2006). From oldest to youngest they are: toba San Antonio (lithic tuff reported as "red beds" by the California Academy of Sciences expedition collectors of 1921), conglomerado Los Volcanes (conglomerate), lodolita Arroyo Amarillo (mudstone), and El Saucito member (a limy sandstone called the La Ballena member in an earlier paper by Ledesma-Vázquez and Johnson, 2001).

The San Antonio tuff crops out only at Punta San Antonio. Ledesma-Vázquez (2000) correlated it with the Mencenares complex of the northern Loreto embayment, which Bigioggero *et al.* (1995) dated as 3.3 ± 0.5 Ma. The Los Volcanes conglomerate and the marine Arroyo Amarillo mudstone overlie the tuff.

El Saucito is the youngest member, a highly fossiliferous biocalcarenite, coarse sand, and conglomerate exposed in Arroyo el Saucito and to the east. Abundant well-preserved *Flabellipecten bösei* (Hanna and Hertlein) were described from this unit; the commonest fossils in the arroyos are internal molds of marine mollusks and echinoids that correlate the beds with the Carmen-Marquer Formation, undifferentiated, of the Loreto embayment. The San Nicolás basin sediments are mostly flat-lying and show no reworking, in contrast to many of the deltaic facies and braided gravel deposits near Loreto.

El Púlpito Rhyolite, Quaternary.—Flat-lying, light to dark gray rhyolite was dated as 0.5 Ma by Cassarubias-Unzueta and Gómez-López (1994), who named the unit Basalto el Púlpito. Ledesma-Vázquez (2000) redescribed and renamed it Riolita el Púlpito for a series of lava flows that outcrop at Punta Púlpito.

Pleistocene marine terrace deposits and alluvium cap the section (Ledesma-Vázquez, 2000). Ortlieb (1991: fig. 10) published a detailed map of Pleistocene shoreline deposits in the area.

Mulegé area

Ortlieb (1991) also studied Pleistocene terrace deposits near the town of Mulegé. Uranium series ages

←

Text-figure 56.—Gulf islands and index map of important localities in southern Baja California Sur. Mina-Uhink (1957) named the southern end of the Purísima-Iray basin for Pozo Iray #1, near Colonia Santo Domingo; he reported the Salada Formation in the subsurface at Pozo Iray #2, at Puerto Adolfo López Mateos.

Text-figure 57.—La Giganta (right, 5,794 m) and the Sierra la Giganta crest, view west from Arroyo el León, Loreto embayment. Photo, J. T. Smith, 1986.

Text-figures 58, 59.—*Amusium toulae* (Brown and Pilsbry), U. S. National Museum hypotype no. 418203, from Punta Paredón Amarillo. 58, ventral view (right valve on top); 59, right valve of specimen from unnamed yellow conglomeratic sandstone outcrops in the northern Concepción Peninsula. Unusually large and complete specimen measures 10.5 cm in height, 12.2 cm in length; the species was originally described from the Gatún Formation, Panama. Photos, Bradford Ito, U. S. Geological Survey.

Text-figure 60.—Concepción Peninsula, location map. Map modified from Johnson *et al.* (1997) shows type sections of units described by McFall (1968), Johnson *et al.* (1997), and Ledesma-Vázquez *et al.* (2004). Rectangle includes type sections of the Calabaza, Bahía Concepción and Cayuquitos Members of the Infierno Formation. CP, Cerro los Pelones; CV, Cerro Vinorama, elevation 720 m; EM, El Mono; ES, Rancho el Salto; ESD, Ensenada Santo Domingo; SR, Rancho Santa Rosaliita. Regional index map is shown on Text-figure 56.

Text-figure 61.—Punta Paredón Amarillo and the unnamed Miocene yellow conglomeratic sandstones west of Punta Concepción. J. R. Ashby, Jr., collector. Photo, J. T. Smith, 1985.

of the coral *Porites californica* Verrill from the Upper Pleistocene +12-m terrace deposit were reported by Ashby *et al.* (1987, 1988) as 124,000 ± 5,000 and 144,000 ± 7,000 years. Ashby (1984) and Ashby and Minch (1987) presented detailed stratigraphic and paleoecologic data from the area of the Mulegé estuary.

Loreto embayment
(Text-figs. 2, 56, 62, 63)

Overview

The Loreto embayment extends from approximately 30 km to 5 km north of Loreto, and from the base of the Sierra la Giganta on the west to Isla del Carmen, 14 km (9 mi) offshore. The area is highly significant in the history of the modern Gulf of California because of its sequence of Miocene arc volcanic and volcaniclastic sediments overlain by a thick wedge of Pliocene marine, nonmarine, and deltaic facies that was deposited during the transition from extensional to transtensional regimes. The onshore Loreto embayment was mapped by McLean (1988) at a scale of 1:50,000, and as part of detailed sedimentary and tectonic studies by Dorsey *et al.* (1997), Zanchi (1994), and Bigioggero *et al.* (1995).

Long recognized as an important key to the geologic history of the central Gulf of California, the offshore Loreto embayment represented by the sediments on Isla del Carmen needs further detailed mapping.

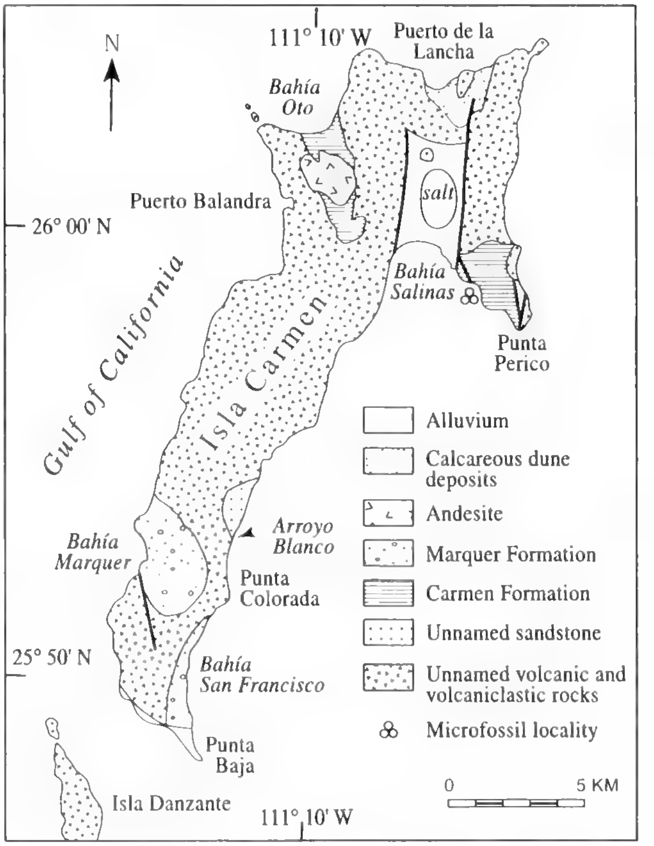
Isla del Carmen
Plate 2, Column 37
(Text-figs. 56, 62, Appendix 1)

Column modified from the geologic sketch map of Anderson (1950: fig. 4).

Isla del Carmen is 28 km long by 3–8 km wide, composed of unnamed volcanic and volcaniclastic rocks overlain unconformably by a number of facies of marine clastic deposits that were described by Anderson (1950). We are unable to separate two of these in the onshore basin, shown in Plate 2, Column 38 as the Carmen-Marquer Formation, undifferentiated.

Stratigraphy

Basement rocks, Oligocene or Miocene.—The oldest rocks that crop out on northeastern Isla Carmen are the reddish tuff breccias and lava flows that Anderson (1950) referred to the Comondú Formation. Near Perico Point he reported well-stratified reddish siltstone and shale overlain by volcanic breccia that grades upward to well-bedded tuffaceous sandstone; it was, he noted, "... the only place on the island where sediments were observed interbedded with lavas and breccias." Given the great confusion surrounding the use



Text-figure 62.—Isla Carmen, map of the eastern or offshore Loreto embayment. Modified from Anderson (1950), the map shows the stratigraphic units of Durham (1950) and Anderson (1950). Microfossil symbol is University of California, Berkeley, Museum of Paleontology locality A-3502 of Natland (1950), now regarded as Late Miocene–earliest Pliocene. Megafossils from the facies exposed north of Arroyo Blanco correspond to those from western Arroyo el Salto, Loreto onshore embayment. Regional index map is shown on Text-figure 56.

of the Comondú Formation outside its type area in the Sierra la Giganta, we label these units on Plate 2 as unnamed volcanic and volcaniclastic rocks, pending further field mapping.

Tertiary marine units: the Carmen and Marquer Formations of Anderson (1950). Carmen Formation, Pliocene.—Anderson (1950) named the Carmen Formation, a poorly bedded volcanic pebble and cobble conglomerate, marine sandstone, and limestone, from a section on northeastern Isla Carmen, along the eastern shore of Bahía Salinas to Punta Perico. In some places it is in fault contact, in others gradational contact with the underlying volcaniclastic rocks. As in the onshore Loreto embayment, "islands" of volcanic rocks are surrounded by conglomerate, indicating a depositional surface of considerable relief.

Anderson (1950) and other early workers included these rocks in the Salada Group because they believed the Salada Formation consisted of "all Pliocene deposits," but this is not appropriate. The Salada Formation was described from the Magdalena Plain of western Baja California and differs from the Loreto embayment formations in age, lithology, provenance and fossils (p. 46).

Dorsey *et al.* (2000) studied a 1,100-m-thick section of the Carmen Formation at Punta Perico. From base to top the lithologies include a lower conglomerate that they interpreted as a submarine debris flow, conglomerate, sandstone, marlstone, and a 3.5–3.1 Ma mudstone containing benthic foraminifers that indicate depths of 400–500 m. These are overlain by dacite breccia and boulder beds, stratified conglomerate, and shallow shelf bioclastic limestone.

Pliocene ages assigned to marine sediments in the Loreto embayment were originally based on molluscan data from the 1940 *E.W. Scripps* cruise (Durham, 1950). More recent radiometric data refined the age to middle to Late Pliocene (McLean, 1989; Dorsey *et al.*, 1997). Planktonic foraminifers from samples of the Carmen Formation on Isla del Carmen were reported by Natland (1950), reexamined by Ingle (1974) and reinterpreted by McDougall (oral communication, 1996). Time scale revisions and new information on the ranges of planktonic foraminifers suggest that Natland's sample A3502 (Text-fig. 62) is Late Miocene to earliest Pliocene in age, Planktic Foraminiferal Zone N17–N20, based on the co-occurrence of *Globigerinoides obliquus* Bolli and *Globoquadrina humerosa* (Takayanagi and Saito). McDougall (oral communication, 1996) found age-diagnostic benthic foraminifers, including *Bulimina uvigeriniformis* and *Lenticulina cushmani* = *Robulus cushmani* of Natland (1950), in most samples from the Carmen Formation on Isla del Carmen. The species is restricted to the Late Miocene, Mohnian Stage of California and suggests that the age of the Carmen Formation on Isla del Carmen could be Late Miocene, probably Planktic Foraminiferal Zone N17a, upper Mohnian Stage, 8–6 Ma, based on benthic foraminifers.

Marquer Formation, Pliocene.—The Marquer Formation was described by Anderson (1950) from seacliffs and arroyos east of Marquer Bay in the southwestern part of Isla del Carmen. It is a white to grayish white calcareous conglomerate containing volcanic pebbles, sandstones, marls, coquina, algal limestone, coral fragments, and abundant megafossils regarded by Durham (1950) as Late Pliocene in age. Except for the pectinids and echinoids, most of the fossils are leached. In places the unit is unconformable or in fault contact with underlying volcanic and volcaniclastic rocks. Anderson (1950) also reported outcrops at Puerto Balandra. The unit is overlain by lavas, dunes, alluvium, beach deposits and, at Bahía Salinas, evaporite deposits (Kirkland *et al.*, 1966).

A third unit described by Anderson (1950), the San Marcos Formation, is discussed above under the Boleo basin (p. 81). Its age is reinterpreted from megafossils from its type section on Isla San Marcos, southeast of Santa Rosalía, as a Late Pliocene equivalent of the earlier named Infierno Formation of I. F. Wilson (1948). Beds near Arroyo Blanco on Isla del Carmen yielded *Argopecten abietis* (Jordan and Hertlein), a common pectinid index species in the Carmen, Marquer, and Infierno Formations.

Andesite flows.—Andesite flows cap the section on the northwestern part of the island, east of Puerto Balandra and south of Oto Bay (Anderson, 1950).

Isla Monserrate
(Text-figs. 1, 56)

Reconnaissance collections of marine mollusks by J. A. Minch in 1987 from unnamed rocks on northwestern Isla Monserrate, 30 km southwest of Isla del Carmen, yielded a deeper water facies containing an assemblage of the marine epitoniid gastropod *Sthenorhytis toroense* (Dall) and abundant disarticulated specimens of *Flabellipecten bösei* (Hanna and Hertlein) of probable Pliocene age. Megafossils collected by the 1940 *E.W. Scripps* cruise suggest the unit on the southeastern side of the island is the Carmen Formation (University of California, Berkeley, Museum of Paleontology localities A-3568, A-3566) (Anderson, 1950).

Loreto basin
Plate 2, Column 38
(Text-figs. 1, 2, 56, 63–67, Appendices 1, 2)

Column modified from McLean (1988). Area is shown on the Loreto quadrangle, G12A88, 1:50,000; and the geologic maps of McLean (1988, 1989), Anderson (1950), Zanchi (1994), Bigioggero *et al.* (1995), and Dorsey *et al.* (1997).

Overview

The onshore Loreto embayment was recognized by workers from Gabb (1869a) to the present as a highly significant area of good access and exposures for mapping and topical studies of all kinds. The marine sediments that Anderson (1950) and Durham (1950) referred to the Carmen Formation and the Marquer Formation were classified as lithofacies associated with different depositional environments by Dorsey *et al.* (1997). Zanchi *in* Piazza and Robba (1994, 1998) gave the units informal names. In this paper we regard the onshore marine sequence as Carmen-Marquer Formation, undifferentiated. Recent workers have focused on the half-graben setting of the basin, the zone of normal faults, and the irregular topography of underlying volcanic and volcaniclastic rocks on which later sediments were deposited. Arroyos exposing many different facies are shown in a sketch map from McLean (1989) (Text-fig. 63).

Stratigraphy

Cretaceous granitic and prebatholithic metamorphic basement rocks.—Cretaceous granitic batholithic rocks and prebatholithic metasedimentary basement rocks are exposed in the southwestern Loreto basin between the Sierrra la Giganta and the area west of Mexico 1. They were mapped and discussed by McLean (1988), who also reported an Eocene (?) quartzose red cross-bedded sandstone in the upper part of Arroyo de Gua and an aeolian red sandstone in Arroyo el Salto (Text-fig. 67). Tunesi *et al.* (2000) analyzed the chemistry of gabbro and pyroxenite xenoliths in the granite, interpreting them as fragments of lower crust brought to the surface by lavas that are less than 1 Ma in age.

Unnamed volcanic and volcaniclastic rocks, Late Oligocene–Middle Miocene.—Late Oligocene, Early Miocene, and Middle Miocene volcaniclastic and near-vent volcanic facies, welded tuffs, breccias, and lavas overlie the Loreto basin basement rocks (Text-fig. 66). Referred to the Comondú Formation by many workers, these vent and near-vent facies of the Miocene volcanic arc differ from that unit in age and lithology. In part they represent source rocks for the younger fluvial deposits of the type Comondú Formation that constitutes much of the Sierra la Giganta to the west (Text-fig. 57). McLean (1988, 1989) discussed their lithologies and distribution; he reported K/Ar and fission track ages on zircons that range between 20.4 and 29.5 Ma for a welded tuff interbedded with the volcanic and volcaniclastic complex. Chávez (1978) referred these rocks to the Huertitas formation, informal name, and the Comondú Formation.

Carmen-Marquer Formation, undifferentiated, Late Pliocene.—The Carmen and Marquer Formations, originally described from Isla del Carmen, have been sampled extensively in sections exposed in Arroyo de Arce and Arroyo de Gua, 4–6 km north of the town of Loreto. The sandstones, conglomerates, and coquinas in these outcrops represent many facies that are mappable only at very large scales. Abundant Pliocene mollusks are found throughout the section. McLean documented the Late Pliocene deposition with three K/Ar ages on water-lain tuffs within the sediments: 3.3 ± 0.5, 2.1 ± 0.4, and 1.9 ± 0.5 Ma (Text-fig. 65).

Umhoefer *et al.* (1994, 1996) divided the Pliocene Loreto basin sediments into four informal stratigraphic units that overlie the Miocene volcanic rocks with angular unconformity. Oldest to youngest, they are: sequence 1, nonmarine alluvial fan, conglomerate, and sandstone; sequence 2, shallow marine fossiliferous sandstone; sequence 3, shell-rich bioclastic limestone with minor sandstone and conglomerate; sequence 4, rocky shoreline facies overlain by carbonate shelf deposits. Tuffs from sequences 2, 3, and 4 of Umhoefer *et al.* (1994) have Late Pliocene Ar^{40}/Ar^{39} ages of 2.61 ± 0.01 Ma, 2.46 ± 0.06 Ma, 2.36 ± 0.02 Ma, and 1.97 ± 0.02 Ma, respectively.

A few data suggest isolated, older marine facies west of Mexico 1 in Arroyo Amarillo, a north-flowing tributary to Arroyo León (McLean, 1988; fossil locality h = J. T. Smith locality 86JS8). Most of the radiometric dates from the Loreto area indicate that the marine deposits range from middle Pliocene to Late Pliocene (McLean, 1989; Dorsey *et al.*, 1997), but diatomaceous beds in Arroyo Amarillo contain earliest Pliocene foraminifers (H. Olson, oral communication, 1986) and Late Miocene–earliest Pliocene open-ocean diatoms of the *Thalassiosira oestrupii* Zone Ma (Barron, oral communication, 1986, *in* J. T. Smith, 1991c: 638).

Zanchi *in* Piazza and Robba (1994, 1998) proposed new names for the Carmen-Marquer Formation, undifferentiated, but they remain informal until published with designated type sections. From oldest to youngest, the lower sequence is: La Vinorama conglomerate, Cerro Microondas conglomerate, Uña de Gato sandstone, Piedras Rodadas sandstone, and Arroyo de Arce Norte sandstone. The unconformable upper sequence includes the San Antonio formation, Cañada de Arce Sur limestone, El Troquero volcaniclastics, San Juan limestone, and El Atacado pyroclastic rocks. The lower sequence of debris-flow and fan-delta deposits rests unconformably on Miocene volcaniclastic rocks.

Mencenares volcanic complex, Late Pliocene–Quaternary.—The Cerro Mencenares volcanic complex occupies the northern area of the basin, 30 km north of Loreto near the coast between San Juanico and Boca San Bruno. Bigioggero *et al.* (1995) studied the Late Pliocene to Quaternary alkalai-rich andesites and basaltic andesites and the magmatic change they record; they also dated a tuff at 3.3 Ma. Tephra and lava flows from Cerro Mencenares interfinger with the Pliocene marine sediments of the Carmen-Marquer Formation, undifferentiated. Bigioggero *et al.* (1995) referred the marine rocks to a lower sequence of fan delta and marine deposits and an upper sequence of yellow siltstones containing Late Pliocene foraminifers.

Correlation

Megafossils correlate coarse marine deposits exposed in arroyos of the Loreto basin west of Mexico 1 with younger Pliocene units elsewhere in the gulf: the Delicias Member of the Puertecitos Formation in the Puertecitos embayment, the Infierno Formation of the Boleo basin, and unnamed sediments at Isla Cerralvo and Isla María Madre. Common fossils from the Loreto embayment were listed and illustrated by Durham (1950), J. T. Smith (1991c), and Piazza and Robba (1994, 1998).

Eastern Magdalena embayment
Plate 2, Columns 39, 40
(Text-figs. 2, 69, Appendices 1, 2)

Overview

The eastern side of the Baja California peninsula from approximately 120 km south of Loreto to San Juan de la Costa represents the eastern shoreline of the Paleogene Magdalena embayment (Text-fig. 35, p. 54). Eight to ten million years before seawater occupied the ancient Gulf of California, when the Baja California peninsula lay against mainland Mexico, this area of eastern Baja California was the next large embayment north of the La Mira basin of Michoacán (Durham *et al.*, 1981; Perrilliat, 1981, 1992). A forearc basin, it received sediments from the Sierra Madre Occidental and from a volcanic arc that was active between 32 Ma and 23 Ma (McDowell and Henry, 1983).

There are few geologic maps of the area (Beal, 1948; Mina-Uhink, 1957; Hausback, 1984b), except for the region that includes the Roca Fosfórica Mexicana (RoFoMex) phosphorite mines at San Juan de la Costa and the area from San Carlos to Tembabiche (Escandón-Valle, 1977a,b), and the thesis map of Plata-Hernández (2002). This section of the Gulf of California and major islands are shown in Text-figure 56.

San Carlos, Punta San Telmo,
Tembabiche (or Timbabichi)
Plate 2, Column 39
(Text-figs. 2, 68–71, Appendices 1, 2)

Column modified from Durham (1950) and Grimm (1992). Area shown on the following 1:50,000 quadrangles: Timbabichi, G12D31; Los Burros, G12D41; San Pedro de la Presa, G12D51, scale 1:50,000; and on the geologic maps of Escandón-Valle, 1977b, scale 1:10,000; and Plata-Hernández, 2002, scale 1:10,000.

Stratigraphy

Los Pargos formation, Jurassic–Cretaceous, and Cretaceous granite.—Basement rocks that crop out between Arroyo San Carlos and Tembabiche were mapped and studied by Plata-Hernández and Schwennicke (2000) and Plata-Hernández (2002), who recognized a new Late Jurassic–earliest Cretaceous sedimentary unit, the Los Pargos formation. Escandón-Valle (1977b) mapped these rocks as Mesozoic schists at Punta del Estero, Punta Botella, and Punta San Telmo (= Punta Prieta of some maps), and on Islas Roca Negra, Santa Cruz, and Santa Catalina. He referred them to the San Telmo formation, an informal name preoccupied by a unit in western Baja California (p. 23).

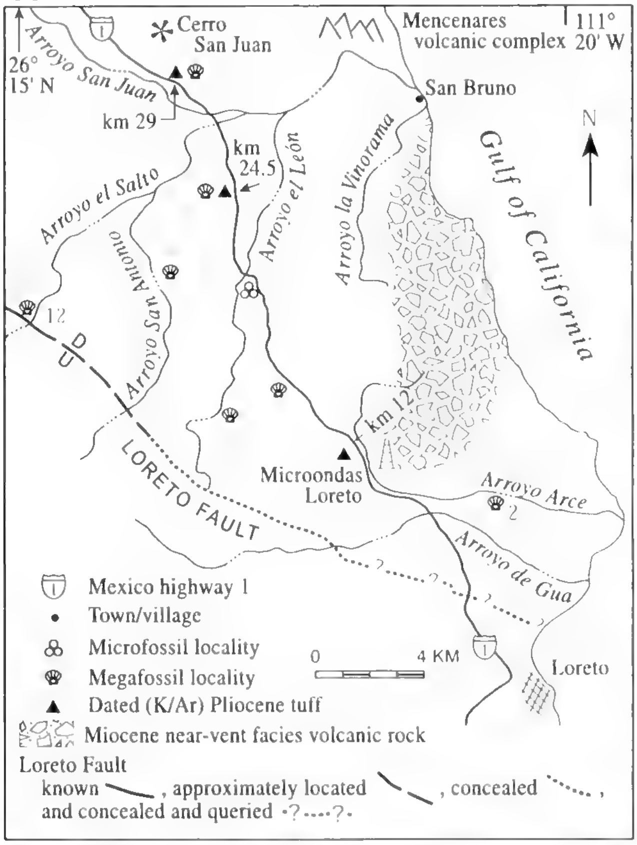
The Los Pargos formation is exposed north of Arroyo Tembabiche in a gentle anticline that strikes east-west (Text-figs. 69, 71). It is the first Jurassic sedimentary unit described from the eastern side of the Baja California peninsula (Plata-Hernández, 2002; Plata-Hernández *et al.*, 2003). The type section on the southern side of Ensenada los Pargos, Timbabichi quadrangle, includes 153 m of mudstone, sandstone, and limestone (Plata-Hernández *et al.*, 2003). Its Late Jurassic to earliest Cretaceous age is based on microfossils and the similarity of associated dikes to an early Late Cretaceous trachybasalt 7 km south of Timbabichi and west of Punta Montalva. The granitic rocks at Cerro Montalva have a K/Ar age of 97.4 ± 2.5 Ma (Plata-Hernández, 2002: 27, fig. 13). Los Pargos formation microfossils include the foraminifer *Globuligerina oxfordiana* (Grigelis), *Nannoconus* sp., and *Saccocoma arachnoidea* (Bronniman).

Granite exposed at the core of the anticline at Punta Botella, 1–2 km north of Ensenada los Pargos, is considered part of the Peninsular Ranges batholith. The Los Pargos formation is overlain unconformably by the Salto Formation.

Red sandstones, probably the Salto Formation, early Late Oligocene.—Large-scale red cross-bedded eolian sandstones and debris-flow deposits of sandy fanglomerates unconformably overlie basement rocks from Arroyo San Carlos, north of Punta San Telmo, to south of Punta Montalva, where the unit is 60–100 m thick (Escandón-Valle, 1977b; Text-fig. 70 herein).The basal contact is marked by a conglomerate containing clasts of limestone and silicified porphyry (Plata-Hernández, 2002). Mina-Uhink (1957) and other early workers referred these rocks to the marine Tepetate Formation, which does not crop out on the eastern side of the Baja California peninsula.

At Punta San Telmo the upper part of the section contains two ash-flow tuffs, the upper of which has an

63


Cerro San Juan
Mencenares volcanic complex
111° 20' W
26° 15' N
Arroyo San Juan
San Bruno
km 29
km 24.5
Arroyo el Salto
Arroyo el León
Arroyo la Vinorama
Gulf of California
N
Arroyo San Antonio
12
D
U
km 12
LORETO FAULT
Microondas Loreto
Arroyo Arce
2
Arroyo de Gua
Loreto
Mexico highway 1
Town/village
Microfossil locality
Megafossil locality
Dated (K/Ar) Pliocene tuff
Miocene near-vent facies volcanic rock
0
4 KM
Loreto Fault
known , approximately located , concealed ,
and concealed and queried ·?····?·

64

65

66

67

early Late Oligocene age of 28.1 ± 0.9 Ma (Hausback, 1984b). The sandstones and fanglomerates probably correlate with the Salto Formation at its type area in the Concepción Peninsula.

El Cien Formation, Timbabichi member, Late Oligocene.—Some authors, including Plata-Hernández (2002), preferred the spelling "Timbabichi" following the usage of the 1:50,000 topographic map, while others such as Mina-Uhink (1957) and Escandón-Valle (1977b) used "Tembabiche." Grimm (1992) called sedimentary rocks conformably overlying the Salto Formation the "Timbabichi formation" but did not publish a formal description or a type section. Earlier workers regarded the Timbabichi member as the San Gregorio Formation (Beal, 1948; Mina-Uhink, 1957; Hausback, 1984b), the Monterrey Formation (Escandón-Valle, 1977b), the undescribed San Carlos member or the San Hilario Member of the El Cien Formation, formally named from 120 km south (Applegate, 1986).

The new unit is the lowest member of the El Cien Formation in this area, correlative with the San Juan Member to the south and west and with volcaniclastic rocks eroded from the volcanic arc. It is 130 m thick at the type section 500–800 m northeast of the village of Timbabichi and dips 3°–5° west (Plata-Hernández, 2002, fig. 33); the member has many lithologies, including characteristic dolomite beds in the lower and middle parts, siltstone, mudstone, phosphatic sandstone, phosphorite, and coquina. It crops out from north of San Carlos to south of Punta Montalva, but does not extend as far as San Juan de la Costa (Plata-Hernández, 2002, and oral communication, 2003). Except for the distinctive dolomite facies, the new member is lithologically very similar to the San Juan Member of Fischer *et al.* (1995). All of these units were deposited, along with the younger Cerro Colorado Member, in the extensive eastern Magdalena embayment, but the Timbabichi member is restricted to the northeastern part.

The dolomites form concretions, bioturbated beds and resistant ledges, some with burrows of *Gyrolithes* (but the corkscrews are smaller than those in the Tirabuzón Formation). Formerly exposed upper surfaces are bored by lithophagid and gastrochaenid clams (Plata-Hernández, 2002: fig. 43B); a measured section showing facies and details of fossiliferous horizons is presented in appendix 1 of her thesis.

Other fossils in the Timbabichi member, beginning with the oldest records, include the shallow water desmostylid *Cornwallius sookensis* Vanderhoof collected by Durham (1950) from a massive, well-cemented sandstone and bone bed exposed at low tide at Bahía San Carlos (Text-fig. 68). Its type locality is 35 m stratigraphically below a coarse-grained conglomerate and sandstone that contains the widespread *Anadara vanderhoofi* Durham marker bed; the desmostylid's age is constrained by a K/Ar date of 28.1 ± 0.9 Ma (Hausback, 1984b) from the underlying formation. The sea cow-like marine mammal foraged in shallow water along the Late Oligocene shoreline. Plata-Hernández (2002) also reported a patch of coral from the lower part of the section near Cerro Montalva, southeast of Punta Montalva.

Many fossils are scattered throughout the unit, but there are no age-diagnostic microfossils, only ostracods and diatom fragments. Ophiuroids, barnacles, and the sclerosponge *Diplochaetetes mexicanus* Wilson are present. High-spired, turritellid-like gastropods from the middle of the section (Plata-Hernández, 2002, fig. 44F) resemble taxa figured by Gidde (1992 and *in* Fischer *et al.*, 1995) from the Cerro Colorado Member

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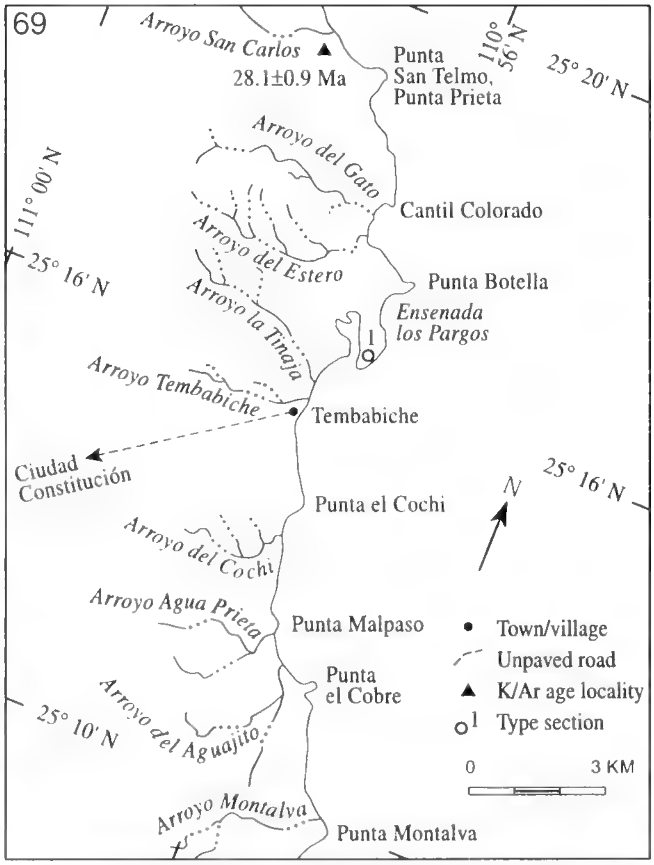
Text-figure 63.—Loreto onshore embayment, sketch map of major arroyos modified from McLean (1989). McLean localities 2 and 12 are shown in Text-figures 64 and 65; ages for the Pliocene tuffs range from 1.9 ± 0.5 Ma-3.3 ± 0.5 Ma. Microfossil locality in Arroyo el León (0.6 km or 0.4 mi from km 20.6 on Mexico 1) is from "amarillo beds" that contain earliest Pliocene shelf-edge foraminifers (H. C. Olson, oral communication, 1986). Yellow mudstones in a tributary one kilometer to the northwest yielded earliest Pliocene open-ocean diatoms of the *Thalassiosira oestrupii* Zone (U. S. Geological Survey Microfossil locality Mf7247, J. A. Barron, oral communication, 1986). Regional index map shown on Text-figure 56.

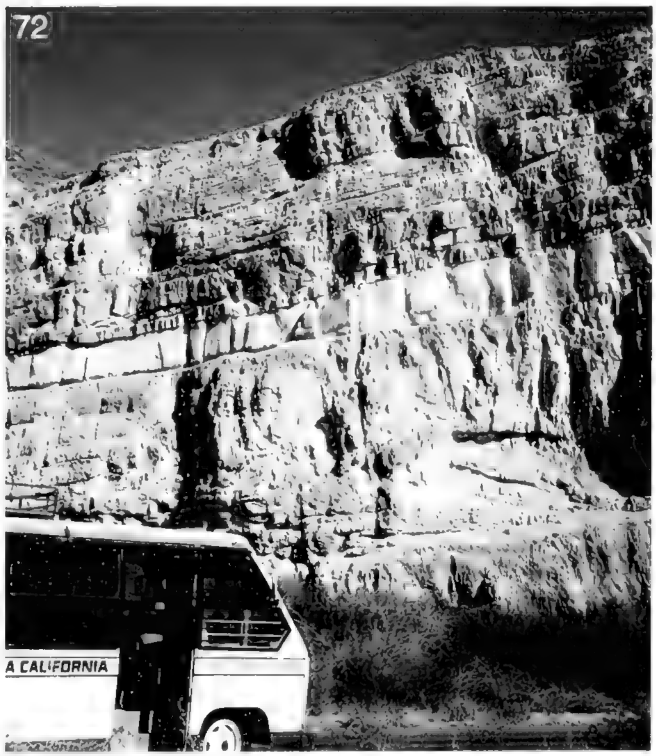
Text-figure 64.—Arroyo de Arce, prominent cliff with cavernous weathering in calcareous sandstone and coquina of the east-dipping Carmen-Marquer Formation, undifferentiated (locality 2 of McLean, 1989). Photo, J. T. Smith, 1986.

Text-figure 65.—Loreto embayment, view west from Mexico 1 at km 12 of the Carmen-Marquer Formation, undifferentiated, and interbedded Late Pliocene tuffs (McLean, 1989). Photo, J. T. Smith, 1986.

Text-figure 66.—Arc-volcanic and volcaniclastic rocks, Oligo-Miocene vent and near-vent facies north of Loreto and south of San Bruno. Photo, J. T. Smith, 1986.

Text-figure 67.—Unnamed Oligocene (?) red cross-bedded aeolian sandstone in Arroyo El Salto, 500 m downstream from Rancho el Salto (locality 12 of McLean, 1989 and Text-fig. 63 herein). Hill behind and to the right is composed of overlying unconformable Pliocene marine sediments. Photo, J. T. Smith, 1986.


69
Arroyo San Carlos
28.1±0.9 Ma
Punta San Telmo, Punta Prieta
110° 56' N
25° 20' N
Arroyo del Gato
111° 00' N
Cantil Colorado
Arroyo del Estero
25° 16' N
Punta Botella
Arroyo la Tinaja
Ensenada los Pargos
1
Arroyo Tembabiche
Tembabiche
Ciudad Constitución
25° 16' N
N
Punta el Cochi
Arroyo del Cochi
Arroyo Agua Prieta
Punta Malpaso
Town/village
Unpaved road
K/Ar age locality
Type section
Punta el Cobre
25° 10' N
Arroyo del Aguajito
0
3 KM
Arroyo Montalva
Punta Montalva


A CALIFORNIA

farther west. Coquinas are more abundant in the upper part, and bivalves are more common than gastropods, many of which are recrystallized. Small gastropods (0.5–1 cm height) are found in the upper dolomite and phosphatic conglomerate beds.

Dense blocks of silty sandstones with internal molds of two-valved mytilids occur in the proposed new member (Plata-Hernández, 2002: fig. 44D) in the same lithology and distinctive concentrations that were reported by Grimm (1992) from outcrops at El Mangle (Text-fig. 30 herein). Mytilids and *Anadara vanderhoofi* Durham are common in lenses and beds in the upper 10 m of the type section. Marine vertebrate fossils include an aetiocetid whale skull, marine mammal bones, desmostylid teeth, and Oligocene shark teeth identified as *Carcharodon angustidens* (Agassiz) by Applegate and Espinosa-Arrubarena (1996). The *Anadara vanderhoofi* Durham bed correlates this sequence with the the type section of Applegate's (1986) San Hilario Member near El Cien.

There are no datable volcanic facies in the Timbabichi member, but an overlying tuff from Arroyo Timbabichi (25°14.780′ N, 110°58.939′ W) constrains its age to Late Oligocene. The dated sample came from a volcaniclastic unit 10 m above the contact; it has a ^{87}Rb/^{86}Sr age of 25.9 ± 1.0 Ma (analysis for Plata-Hernández by the Laboratorio Universitario de Geoquimica Isotópica, UNAM). Plata-Hernández (2002: 90, fig. 50C) suggested that the Timbibichi member ranges from approximately 28 to 26 Ma.

Escandón-Valle (1977b) discussed several zones of gypsum and phosphorite beds between Arroyo San José and Tembabiche. He identified two important phosphorite deposits, the Capa Aguilera and Capa del Castillo, 2–5 m below porcellanite beds in Arroyo Montalva.

Unnamed nonmarine volcaniclastic rocks, the Comondú Formation or Group of authors, Late Oligocene–Miocene.—Plata-Hernández (2002) and Schwennicke and Plata-Hernández (2003) referred a 700–750 m section of Late Oligocene to Miocene terrestrial sediments overlying the marine rocks south of Tembabiche to the Comondú Formation. They recognized three packages of volcanic and volcaniclastic facies, subunits A, B, and C, at Cerro Las Chivas, west of Punta El Cochi (Plata-Hernández, 2002: fig. 47). The lowest part, subunit A, consists of tuffaceous sand, conglomeratic lenses, and tuff beds, one with a ^{87}Rb/^{86}Sr age of 25.9 ± 1.0 Ma. These are overlain by subunit B, a fluvial sand and conglomerate debris-flow deposit with interbedded tuffs, and subunit C, which consists of sandy breccias and lahars. Plata-Hernández (2002) estimated the overall age of subunits A–C as Late Oligocene–Middle Miocene, representing, respectively, proximal, medial, and distal facies of a prograding volcanic arc. The unit is correlative with similar facies in the Loreto embayment.

Marine terrace deposits and alluvium, Pleistocene–Holocene.—Terrace deposits containing bivalves and corals and alluvium cap the section.

San Juan de la Costa
Plate 2, Column 40
(Text-figs. 30, 33, 69, Appendices 1, 2)

Column modified from Hausback (1984a,b), Grimm (1992), and Schwennicke (1994). Areas shown on the following 1:50,000 quadrangles: Los Burros, G12D41; San Pedro de la Presa, G12D51; Punta Coyote, G12D61; San Juan de la Costa, G12D71; the locality maps of Fischer *et al.* (1995); and the geologic maps of Anonymous (1924), Hausback (1984a,b), Escandón-Valle (1977a), and Carreño (1992b).

Stratigraphy

The Paleogene Tepetate Formation, an extensive marine unit that underlies the El Cien Formation to the

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Text-figure 68.—*Cornwallius* bed in the El Cien Formation exposed at low tide, northern side of Arroyo San Carlos, eastern edge of the Late Oligocene–Early Miocene eastern Magdalena embayment. S. P. Applegate, collector. (See Text-figs. 35d,e, p. 54). Photo E. C. Wilson, 1983.

Text-figure 69.—Punta San Telmo, Tembabiche, and Punta Montalva, map of the eastern Magdalena embayment. Map modified from E. C. Wilson (1986) and Escandón-Valle (1977b). "Tembabiche" is also spelled "Timbabichi"; Arroyo Montalva is also known as Arroyo Monte Albán. 1, Late Jurassic–earliest Cretaceous Los Pargos formation of Plata-Hernándaz (2002), type section (Text-fig. 71)

Text-figure 70.—Red cross-bedded sandstone referred to the early Late Oligocene Salto Formation, south of Arroyo Montalva. Photo, E. C. Wilson, 1983.

Text-figure 71.—Los Pargos formation, Late Jurassic–earliest Cretaceous unit exposed at the core of an anticline 1.5 km northeast of Arroyo Tembabiche (Plata-Hernández, 2002). Earlier authors regarded these rocks as schists of the "San Telmo Formation," an informal and preoccupied name. Photo, Tobias Schwennicke, 2002.

Text-figure 72.—La Paz tuff, northern side of Arroyo el Sauzoso, south of San Juan de la Costa and Punta Los Tules. An andesitic clast from this section has a K/Ar age of 22.7 ± 1.7–23.9 ± 0.7 Ma (Hausback, 1984a,b). Photo, J. T. Smith, 1995.

west, is not exposed on the eastern side of the Baja California peninsula. Although basement rocks do not crop out in this area, subsurface units are believed to be the same as for San Carlos and Tembabiche.

El Cien Formation, San Juan Member, Oligocene.—The oldest outcrops in this area belong to the San Juan Member of the El Cien Formation. Regarded as the Monterrey Formation by Mina-Uhink (1957) and Escandón-Valle (1977a,b), the member was named by Fischer *et al.* (1995), based on the work of Schwennicke (1992, 1994). The composite type locality includes sections at Mesa del Tesoro, Agua Amarga, and Mesa del Junco, in the eastern San Juan de la Costa quadrangle, 1–10 km north of the phosphate mines at San Juan de la Costa (Text-fig. 33, p. 52). The unit is exposed in two limbs of a shallow syncline; the eastern outcrops are between San Juan de la Costa and Cañada de la Luz, north of 24°28′ N, the western ones between Cerro Colorado and Arroyo Aguajito. A Late Oligocene biotite-bearing ash in the latter area was dated at 25.4 ± 0.2 Ma. (Hausback, 1984a,b).

The member consists of phosphatic sandstone, siltstone, mudstone, conglomerate, and coquina; it includes the phosphorite-bearing beds or *mantos Capas Humboldt, Capas Humboldt superior, Capa Cuatro,* and *manto principal* of Escandón-Valle (1977a), which was the most important source of the phosphorite mined at San Juan de la Costa. The San Juan Member is approximately 130 m thick in its type area; it thins to 70 m to the west near El Cien and Rancho Aguajito de Castro (Schwennicke, 1994). Galli-Olivier (1993) summarized 17 years of reports on the phosphorites.

The San Juan Member is characterized by nine facies, including tuffaceous mudstones, silt and sandstone containing phosphatic conglomerates, and pelletal phosphorite. Late Oligocene cetaceans are abundant in the middle mudstone and siltstone of the *Capas Humboldt* (González-Barba, 1997; González-Barba *et al.*, 2000). The horizon known as *Capa Inferior* contains *Anadara vanderhoofi* Durham, the bivalve index species that marks the upper part of the San Hilario Member of Applegate (1986) at its type locality. Kim (1987: 59) reported foraminiferal assemblages that include *Globigerinita glutinata* (Egger) and *Globigerinita uvula* (Ehrenberg) that correlate the section at San Juan de la Costa with Planktonic Foraminiferal Zone P22 (approximately 28 Ma to 24 Ma) and the section at Arroyo San Hilario. The contact between the San Juan Member and the overlying Cerro Colorado Member is conformable.

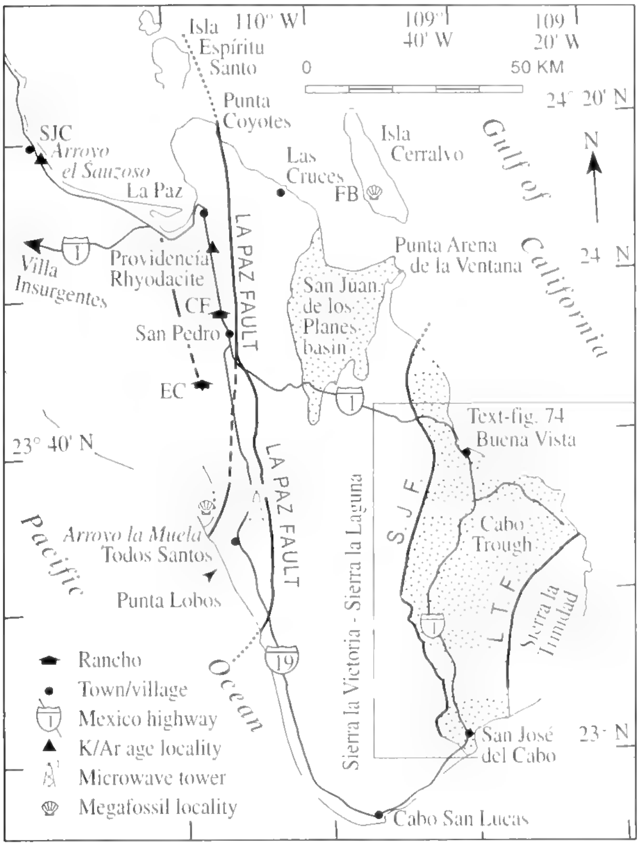
Cerro Colorado Member, Miocene.—The Cerro Colorado Member of Applegate (1986) is not well known in the San Juan de la Costa area. It contains andesitic breccia, multiple welded and unwelded, interbedded ash-flow tuffs, and finer-grained clastic sediments than in the underlying San Juan Member. Fischer *et al.* (1995) recognized this member at Agua Amarga, Tarabillas, and Cañada de la Luz (Text-fig. 33, p. 52), where the unit consists of 39–44 m of clastic rock grading from offshore to nearshore marine depositional environments (Gidde, 1992).

Andesitic breccia, ignimbrites, the La Paz Tuff and San Juan Tuff of Hausback (1984), Early Miocene.—Hausback (1984a) mapped andesitic breccia in discontinuous outcrops in the San Juan de la Costa area between Arroyo las Ánimas and Arroyo el Sauzoso, south of Punta Los Tules, Baja California Sur. Massive pink bands of rock can be seen to the west from the malecón in La Paz; they belong to a series of rhyolitic ignimbrites and tuffs that overlie the El Cien Formation. Hausback (1984b) named these voluminous unwelded ash-flows the San Juan Tuff for exposures near the mine at San Juan de la Costa. He performed chemical analyses and determined a radiometric age of 16–18 Ma for the late Early Miocene San Juan Tuff, younger than the early Early Miocene 21.0–24 Ma La Paz Tuff, which in this area crops out only at Arroyo el Sauzoso (Text-figs. 72, 73 herein and Hausback, 1984b: fig. 14). The La Paz Tuff is strongly welded on the La Paz peninsula, closer to its volcanic arc source; it is not welded at Arroyo el Sauzoso (Hausback, 1984b).

Unnamed volcaniclastic rocks, Miocene.—Sediments overlying the tuffs were referred to the Comondú Formation by many authors, but the facies here do not include the thick, rounded boulder, clast-supported conglomerates of the type section in the Sierra la Giganta 100–150 km to the north. They are more like the near-vent facies of the onshore Loreto basin. Hausback (1984a,b) reported that interbedded rhyolite ash-flow tuffs comprise 20% of the stratigraphic sequence at San Juan de la Costa, and that clasts are angular and matrix-supported.

Correlation

Before the El Cien Formation was proposed, many studies referred the rocks of the Magdalena embayment to the San Gregorio and Isidro Formations, units described from the Purísima-Iray basin of western Baja California Sur. Lithologies, megafossils, and datable volcanic units differ between the two areas, both of which have the potential for more precise correlations based on further mapping, associated volcanic rocks, and fossils.



Text-figure 73.—San Juan de la Costa and the La Paz peninsula to Cabo San Lucas, index map of key localities. Map was modified from Aranda-Gómez and Pérez-Venzor (1989), Schwennicke *et al.* (1996), and Fletcher *et al.* (2000). Arroyo la Muela exposes the southernmost outcrops of the Miocene Salada Formation; Miocene whales were excavated near La Palma, the unnamed rancho shown north of San Pedro. K/Ar ages are 21–24 Ma for the La Paz tuff at Arroyo el Sauzoso (Hausback, 1984a,b) and 18–20 Ma for the Providencia Rhyodacite (Hausback, 1987). EC, Rancho El Carrizal; FB, Farallones Blancos; SJC, San Juan de la Costa; faults include CF, El Carrizal Fault; SJF, San José del Cabo Fault; LTF, La Trinidad Fault.

Isla Espíritu Santo and Isla la Partida
Plate 2, Column 41
(Text-fig. 73)

Columns after Hausback (1984b, 1987) and Aranda-Gómez and Pérez-Venzor (1988); the area is shown on the geologic maps of Hausback (1984a,b), Aranda-Gómez and Pérez-Venzor (1986, 1988), and the El Coyote quadrangle, G 12 D73, scale 1:50,000.

Overview

The La Paz peninsula and islands to the north-northwest are composed primarily of Miocene volcanic rocks overlying Cretaceous tonalite, granodiorite, granite, and calcareous metsediments, the La Paz Crystalline Complex of Ortega-Gutiérrez (1982). The volcanic arc that contributed these flows, tuffs, and breccia was northeast of the present La Paz peninsula when the area lay against mainland Mexico. An important structural feature is the La Paz Fault, which traverses the peninsula from southern Baja California Sur near Todos Santos to a kilometer west of Punta Coyote and along the eastern part of the islands (Text-fig. 73).

Isla Espíritu Santo and Isla Partida

Cretaceous (?) basement rocks crop out in the southeastern part of Isla Espiritu Santo. Aranda-Gómez and Pérez-Venzor (1986) described them informally as the Pailebot augen gneiss of granitic composition that contains deformed mafic dikes. They also described and gave informal names to a number of Miocene volcanic and volcaniclastic units that are similar to those at Punta Coyotes and La Paz. Outcrop areas were shown by Aranda-Gómez and Pérez-Venzor (1986: text-fig. 2). From oldest to youngest, they are the La Bonanza rhyolitic ignimbrite (21.2 ± 0.2 Ma), Punta Lupona volcanic complex, Espíritu Santo volcaniclastic conglomerate, El Gallo rhyodacitic ignimbrite, Isla Partida volcanic complex, and the Pinta Tintorera, an olivine basalt dated at 16.5 ± 0.3 Ma. Young alluvium overlies the section.

The islands lie mainly to the west of the La Paz Fault; sediments were uplifted and tilted to the west, creating deep marine embayments along the western side of Isla Espíritu Santo. These shallow water subtropical bays support abundant marine life and provide a natural laboratory for modern carbonate sedimentation studies (Halfar, 1997; Halfar *et al.*, 1996, 2001; Goodfriend *et al.*, 2000).

La Paz Peninsula
Plate 2, Column 42
(Text-fig. 73)

Stratigraphy

Basement rocks of Aranda-Gómez and Pérez-Venzor (1986), Cretaceous.—Aranda-Gómez and Pérez-Venzor (1986) recognized and named several informal Cretaceous components within the La Paz Crystalline Complex of Ortega-Gutiérrez (1982). The oldest rocks are the La Buena tonalite and granodiorite, which is intercalated with calcareous metasediments in the Sierra de las Cruces southeast of La Paz. The La Palmilla gabbro and the pink, medium-grained Sierra de las Cruces granite crop out in the same area. Younger aplite and pegmatite dikes differentiated from the Sierra de las Cruces granite cut through the La Paz Crystalline Complex.

Aranda-Gómez and Pérez-Venzor (1986: fig. 6) identified three younger sequences of rocks that they termed prevolcanic, volcanosedimentary and postvolcanic units. They regarded the names as informal and used lower case lithologic terms (tuff, sandstone) to denote units without formal published descriptions, specified type sections, and contact information.

Prevolcanic rocks of Aranda-Gómez and Pérez-Venzor (1988), Late Oligocene–Miocene.—Two sedimentary units of unknown age overlie the basement rocks: a continental, possibly aeolian, red sandstone and a medium- to fine-grained, beige to white sandstone known as the Cerro del Chichonal sandstone, informal name, that crops out southeast of La Paz. Hausback (1984b) grouped the sandstone, pebble breccia, and interbedded welded ash-flow tuff in his informal "Salinas member"; he reported a K/Ar age of 25.0 ± 0.6 Ma for the ash-flow tuff. Altimirano (1970a,b) referred the rocks to the Comondú Formation; we use the lithologic terms of Aranda-Gómez and Pérez-Venzor (1986).

Tertiary volcanic and volcaniclastic rocks, informal names of Aranda-Gómez and Pérez-Venzor (1988), late Early Miocene.—Basement and sedimentary rocks are unconformably overlain by Miocene volcanic rocks that include a basal heterogeneous volcanic and volcaniclastic complex, the Balandra breccia and conglomerate, El Caimancito pink tuff, Las Calaveras tuff, and El Engaño conglomerate. The basal complex is overlain by the La Paz tuff, informal name of Hausback (1984a,b), which is thick and welded in the La Paz peninsula, and thin but not welded near San Juan de la Costa. In the area between La Paz and Punta Coyotes its K/Ar age ranges from 18.7 ± 1.1 to 20.6 ± 0.2 Ma. Monolithologic basaltic breccia is common in the northern peninsula; reworked volcaniclastic conglomerates and breccia dominate to the southeast. Hausback (1984b) recognized a series of ash-flow tuffs and breccias in the area, including the La Paz tuff and the Corumuel tuff, with ages ranging from 19.2 ± 0.5 to 22.0 ± 0.4 Ma.

Providencia Rhyodacite of Hausback (1987), late Early Miocene.—Hausback (1987) formally described a widespread rhyodacite flow from a type section at Rancho la Divina Providencia 15 km south-southeast of the city of La Paz (Text-fig. 73). The Providencia Rhyodacite, which is quarried for building stone, is unusually extensive for a single silicic lava flow. Emplaced when very hot, it caps flat-topped hills more than 27 km north and south of La Paz. The youngest volcanic unit in the area, it has a K/Ar age of 19.1 ± 1.2 to 19.7 ± 0.2 Ma (Hausback, 1987).

The Providencia Rhyodacite was called the uppermost member of the Comondú Formation by Hausback (1984a,b); we include it with the Miocene volcanic rocks of the La Paz peninsula.

Postvolcanic rocks of Aranda-Gómez and Pérez-Venzor (1988), Pliocene to Quaternary. El Coyote conglomerate, Palmira conglomerate, Punta Coyotes gravels, informal names.—The post-volcanic deposits of the La Paz peninsula are semi-consolidated Pliocene to Quaternary sediments referred informally to the Ei Coyote conglomerate and the unconformably overlying Palmira conglomerate. Aranda-Gómez and Pérez-Venzor (1988) described the El Coyote conglomerate as more than 50 m thick and composed of 90–95% volcanic clasts. They mapped the unit in the northeastern part of the La Paz peninsula and discussed uncertainties about its age, Miocene to Pliocene and Pleistocene–Holocene (?). The Palmira conglomerate is a semi-consolidated unit that crops out along the La Paz–Pichilingue road and seems to consist largely of Providencia Rhyodacite clasts.

Punta Coyotes gravels include slope deposits, alluvium, fluvial terrace deposits, and associated marine conglomerates that were mapped by Aranda-Gómez and Pérez-Venzor (1984). Coral species of *Pocillopora* from these deposits 2 km south of Punta Coyotes have uranium-series ages of 140,000 ± 6,000 (Szabo *et al.*, 1990) and 123,000–138,000 (Sirkin *et al.*, 1990). These dates are significant because they constrain the most recent movement on the La Paz Fault in this area to more than 140,000 years before the present (Szabo *et al.*, 1990).

Other Late Pleistocene to Holocene stratigraphy was reported by Pedrín-Avilés *et al.* (1992) for terrace deposits in the Balandra coastal lagoon area in the northwestern La Paz peninsula. Their C^{14} and uranium-series ages indicate the formation of peat deposits from 4,120 ± 100 years before present.

Isla Cerralvo
(Text-figs. 1, 73, 75)

Isla Cerralvo lies off the eastern La Paz peninsula, 9 km north of Punta Arena de La Ventana and approximately 15 km east of Las Cruces. It is 240 km^2 in area and consists mainly of granitic and metamorphic rocks (Aranda-Gómez and Pérez-Venzor, 1989). Sawlan (1991: fig. 2) showed 25–17 Ma rhyolite ignimbrites on Isla Cerralvo as age equivalents of the Late Oligocene–Early Miocene ignimbrites in the La Paz region.

An inlier of shallow neritic Late Pliocene marine sediments is exposed on the western side of Isla Cerralvo at "Farallones blancos" (Text-figs. 73, 75). Marine outcrops extend for perhaps 1.5 km along the beach north of an arroyo that meets the gulf at the site of the old Ruffo Ranch. The sediments crop out from the strand line to cliffs more than 40 m above the beach. Early authors such as Hertlein (1966) incorrectly located the fossiliferous section at El Mostrador, 10 km to the north in an area of metamorphic rocks.

Megafossils, including *Argopecten abietis* (Jordan and Hertlein), *Argopecten revellei* (Durham), and *Leopecten bakeri* (Hanna and Hertlein), correlate this unnamed southeast-dipping white marine sandstone, conglomerate and algal limestone with sections at Caleras Beach, Isla María Madre, and the Carmen-Marquer Formation, undifferentiated, of the onshore Loreto embayment. These Late Pliocene taxa are not found with the earlier Pliocene species in the Refugio Formation at Rancho el Refugio, in the Cabo Trough south of La Paz.

Fossiliferous Pleistocene terrace deposits were reported from the southern coast of the island (Emerson, 1960).

San José del Cabo Trough
Plate 2, Columns 43, 44
(Text-fig. 1, 2, 73, 74, Table 8)

Overview

The San José del Cabo Trough lies at the southeastern end of the Baja California peninsula between the coastal towns of Buena Vista and La Ribera and the granitic hills near the Los Cabos International Airport. Approximately 2,000 km^2 in area, the elongate basin lies in a graben between two crystalline masses. It is bounded by the east-dipping San José del Cabo normal fault along the Sierra la Victoria-Sierra de la Laguna to the west and the La Trinidad Fault along the Sierra la Trinidad to the east. The basin is underlain by Miocene to Quaternary marine and nonmarine sediments; it lacks the associated late Neogene volcanic rocks of the La Paz peninsula. In terms of terranes, it lies in the Southern Gulf Extensional Province and east of the Los Cabos Block (Fletcher *et al.*, 2000, 2003).

Fossiliferous marine and terrestrial sediments record late Middle or Late Miocene to Pliocene deposition in the ancient gulf, the transition to nonmarine conditions, and a period of Neogene uplift. Significant lithologic differences exist between *in situ* deposits in the northern trough east of Santiago and reworked sediments west of Mexico 1 at the Tropic of Cancer, 25–30 km to the south at Rancho Algodones, and east of Santa Anita. Narrow outcrops of 10° south- and southeast-dipping unnamed marine rocks along the coastline between San José del Cabo and Punta Gorda are probably a different, older unit. Faunules and formations described from the Cabo Trough in early topical studies (Appendix 1) can now be analyzed in a broader context related to the Tertiary-Caribbean faunal province and the ancient Gulf of California. The rocks record complex interactions between sediment sources, sea level changes, uplift of the Los Cabos Block, basin subsidence, and Neogene extensional faulting. Interdisciplinary studies involving structural geology, sedimentology, and paleontology constrain timing and provide new insights on the regional history of the basin within its larger, complex tectonostratigraphic setting.

Arroyo la Trinidad, Rancho El Refugio
Plate 2, Column 43
(Text-figs. 74, 77–80, Table 8, Appendices 1, 2)

Column modified from McCloy (1984), Carreño (1992a) and Martínez-Gutiérrez and Sethi (1997). Area is shown on the Cabo Pulmo quadrangle, F12 B35, 1:50,000; and the generalized geologic maps of López-Ramos (1973) and Martínez-Gutiérrez and Sethi (1997).

Stratigraphy

Crystalline basement rocks, Late Cretaceous.—Aranda-Gómez and Pérez-Venzor (1986) included the Mesozoic granitic basement rocks in the La Paz Crystalline Complex of Ortega-Gutiérrez (1982). The San José del Cabo Trough separates two plutonic masses in the southern peninsula: the Sierra la Victoria and Sierra la Laguna igneous-metamorphic complex of the Los Cabos Block to the west and the less extensive La Trinidad igneous complex to the east. The former is earliest Late Cretaceous, 98.4–93.4 Ma; the La Trinidad complex is early Late Cretaceous, 88.2 ± 5.4 Ma, (Gastil *et al.*, 1976). Fletcher *et al.* (2000, 2003) and Kohn *et al.* (2003) used low-temperature thermochronology to study cooling rates related to exhumation along the San José del Cabo Fault (Text-figs. 73, 74). They determined that rapid uplift of crystalline rocks during the Late Miocene–Early Pliocene and lower rates since the Late Pliocene exposed the granitoids of the Los Cabos Block.

Unnamed volcanic rocks of Martínez-Gutiérrez and Sethi (1997), probably Late Oligocene–Miocene.—Martínez-Gutiérrez (1994) reported felsic ash, lapilli, and rhyolitic and dacitic lava flows that crop out over a 30 km^2 area north of the Sierra la Trinidad. Steeply dipping to vertical, the volcanic rocks strike northeast and overlie granitoid basement. They crop out near Cabo Pulmo and La Ribera, but have not been radiometrically dated. They might be related to the 25–17.6

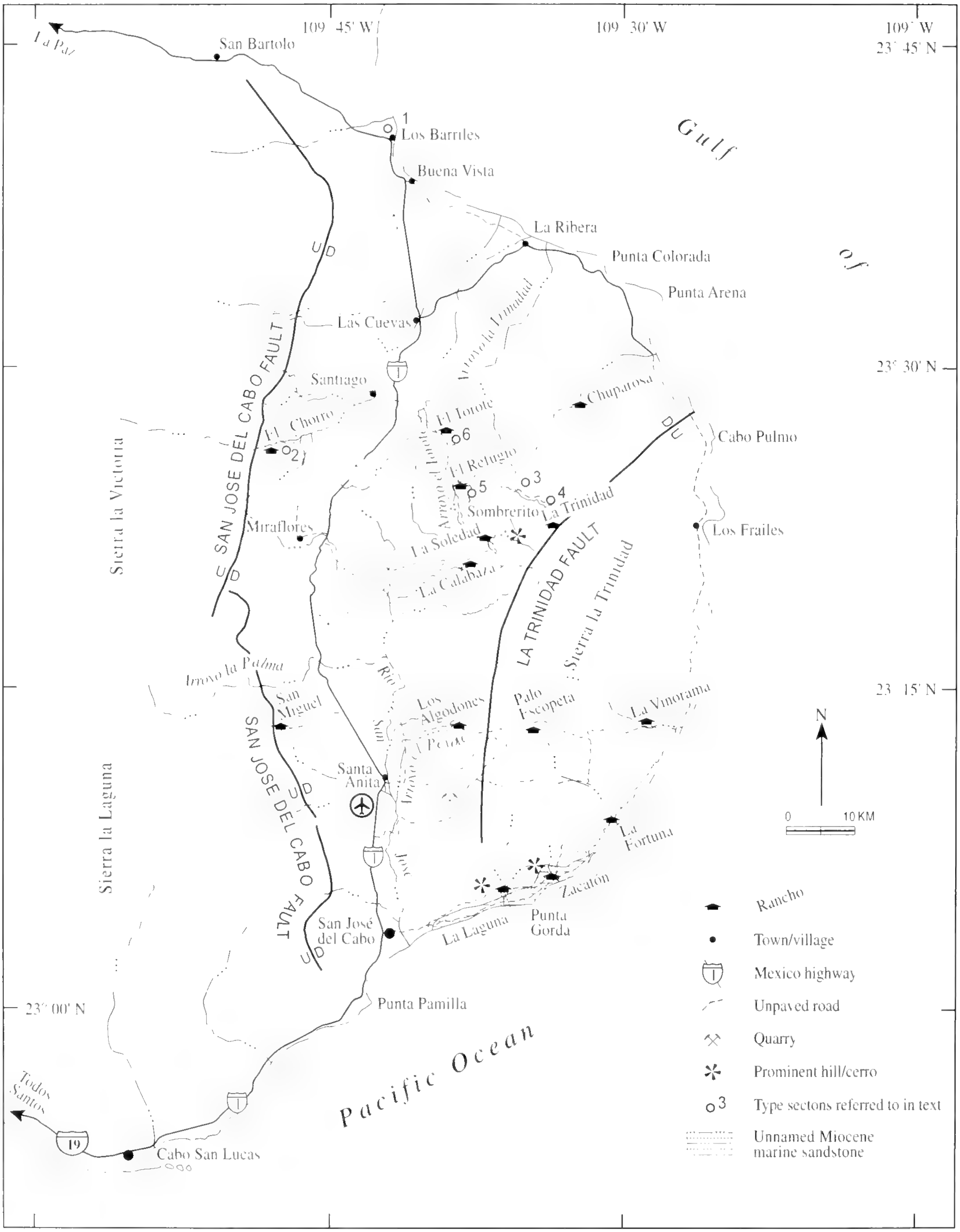

109° 45' W
109° 30' W
109° W
23° 45' N
23° 30' N
23° 15' N
23° 00' N
La Paz
San Bartolo
Los Barriles
Buena Vista
La Ribera
Punta Colorada
Punta Arena
Las Cuevas
Santiago
El Chorro
Miraflores
Sierra la Victoria
SAN JOSE DEL CABO FAULT
El Torote
El Refugio
Sombrerito
La Trinidad
La Soledad
La Calabaza
Chuparosa
Cabo Pulmo
Los Frailes
LA TRINIDAD FAULT
Sierra la Trinidad
Gulf of
Arroyo la Palma
San Miguel
Los Algodones
Palo Escopeta
La Vinorama
Santa Anita
Sierra la Laguna
La Fortuna
Zacatón
Punta Gorda
La Laguna
San José del Cabo
Punta Pamilla
Pacific Ocean
Todos Santos
Cabo San Lucas
N
0 10 KM
Rancho
Town/village
Mexico highway
Unpaved road
Quarry
Prominent hill/cerro
Type sectons referred to in text
Unnamed Miocene marine sandstone

Table 8.—San José del Cabo Trough, lithostratigraphic units (Text-fig. 74). Lowercase names indicate informal units that were not established according to the North American Stratigraphic Code (1983).

Lithostratigraphic unit	*Author, reference*	*Lithologic description, type locality, age*
El Chorro Formation	Martínez-Gutiérrez and Sethi (1997).	Formation consists of flat-lying, coarse-grained sandstone, conglomerate, and alluvium that form young terrace deposits. Type section is near Rancho Chorro, 10 km southwest of Santiago, Santiago quadrangle. Thickest and best preserved along the western side of the Cabo Trough. Pleistocene to Holocene.
La Calera Formation	Martínez-Gutiérrez and Sethi (1997) = Coyote Red Beds of McCloy (1984), informal name.	Unit consists of 300 m of cross-bedded terrestrial red sandstone and conglomerate eroded from the Sierra la Trinidad igneous complex and now exposed in the northern (lower) part of Arroyo la Trinidad. Type section is in Cañada La Calera, an eastern tributary to Arroyo la Trinidad, 2 km downstream from where the road from Santiago enters the arroyo, Cabo Pulmo quadrangle. Older than the late Middle or early Late Miocene marine megafossils in the overlying Trinidad Formation
Los Barriles Formation	Martínez-Gutiérrez and Sethi (1997).	Formation is a nonmarine sandstone and coarse pebble to boulder conglomerate limited to its type area near the small coastal town of Los Barriles, 25 km north of Buena Vista, Las Cuevas quadrangle. Late Pliocene to Early Pleistocene.
Refugio Formation	Pantoja-Alor and Carrillo-Bravo (1966) mentioned name; Martínez-Gutiérrez and Sethi (1997) formally described and measured.	Unit is a 380-m-thick, gray-white, coarse- to medium-grained, fossiliferous, marine sandstone with limestone, shale, and anomiid-rich conglomeratic facies. Type section is southeast of Santiago near Rancho el Refugio (23°24.1′ N, 109°38.5′ W), Cabo Pulmo quadrangle. Early Pliocene.
"Santiago diatomite," informal name	Carreño (1992a) named as informal member of Trinidad Formation; also = Subunit C of McCloy (1984).	Unit consists of 248 m of diatomaceous sediments that crop out over a limited area near Rancho el Torote, Cabo Pulmo quadrangle. Upper bathyal, Latest Miocene to middle Pliocene (Carreño, 1992a; Pérez-Guzmán, 1985).
Trinidad Formation	Pantoja-Alor and Carrillo-Bravo (1966) named. McCloy (1984) recognized four informal members, Subunits A–D; Martínez-Gutiérrez and Sethi (1997) identified three.	Formation includes estuarine to marine, gray to greenish shale, mudstone, sandstone, and diatomaceous mudstone. Type section includes the lower, estuarine member; it is 26 km east of Santiago in Arroyo la Trinidad, downstream from Rancho la Trinidad, Cabo Pulmo quadrangle. Martínez-Gutiérrez and Sethi (1997) subdivided the units into lower, middle, and upper members; the upper member is exposed west of Cerro Sombrerito near Rancho la Soledad, Cabo Pulmo quadrangle. Late Middle or Late Miocene at its base to Early or middle Pliocene.

Ma ignimbrites of the La Paz region or those in the Sierra Madre Occidental (Sawlan, 1991).

La Calera Formation, older than late Middle or Late Miocene.—Red terrestrial sandstone and conglomerate that overlie basement rocks northeast of the La Trinidad Fault were referred to the Comondú Formation by Pantoja-Alor and Carrillo-Bravo (1966). Martínez-Gutiérrez and Sethi (1997) renamed the unit La Calera Formation and mapped exposures in and near a small box canyon in Arroyo la Trinidad (Text-fig. 79). They inferred an age older than the Miocene marine fossils of the overlying Trinidad Formation. Field parties have suggested the rocks may correlate with the Salto Formation of the Concepción Peninsula.

Trinidad Formation, late Middle or early Late Miocene–Pliocene.—Pantoja-Alor and Carrillo-Bravo (1966) described the Trinidad Formation, which they regarded as Pliocene, from a type area near Rancho la Trinidad in Arroyo la Trinidad. Martínez-Gutiérrez (1994) measured a thickness of 400 m; the unit dips 10°–30° to the southwest and crops out over the north-

←

Text-figure 74. San José del Cabo Trough, map showing important features, ranchos and type sections. Open circles indicate type sections of formally described lithologic units, many named for nearby ranchos: 1, Los Barrilles Formation; 2, El Chorro Formation; 3, La Calera Formation; 4, Trinidad Formation; 5, Refugio Formation. Unnamed marine sediments along the coast west of Punta Gorda dip 10° S or SE (C. H. Beal, unpublished field sheet in Stanford University's Branner Earth Sciences Library and Map Collections). Regional index map shown in Text-figure 73.

ern two thirds of the Cabo Trough. It represents the earliest seawater incursion in the basin.

The basal member, Subunit A of McCloy (1984), is equivalent to the lower facies of Martínez-Gutiérrez and Sethi (1997); it is restricted to the eastern part of the Cabo Trough. The lower part is an *in situ* estuarine siltstone with sandstone and shale that contains Miocene molluscan index species such as *Anadara patricia* (Sowerby), *Melongena* (*M.*) sp. cf. *M. patula* (Broderip and Sowerby), *Turritella mimetes colinensis* Hodson, and *Neritina luteofasciata* (Miller) that indicate near-mangrove conditions (Text-figs. 74, 80). Martínez-Gutiérrez and Sethi (1997) also reported impressions of plant debris. Upsection near the head of Arroyo la Trinidad, Subunit A grades to a coarser-grained sandstone deposited at inner neritic depths (Smith, 1991c), and the Tertiary-Caribbean turritellid species changes to *Turritella abrupta fredeai* Hodson. The neritic facies contains the teeth of several kinds of sharks, including *Carcharadon megalodon* (Agassiz) and the genera *Hemipristis, Carcharinus,* and *Isurus* (identifications by J. R. Ashby, Jr., in 1985, of a collection belonging to the Enrique Fiol family of Rancho la Trinidad).

Martínez-Gutiérrez and Sethi (1997) mapped their middle facies near Rancho la Soledad. Its lithology matched McCloy's Subunit B, described as alternating sandstones and siltstones containing the planktonic foraminifers *Globorotalia lenguaensis* Bolli, *G. mayeri* Cushman and Ellisor, and *Globigerina angustiumbilicata* (Bolli).

McCloy's Subunit B is conformably overlain by Subunit C, the "Santiago diatomite" of Carreño (1992a) that crops out in Arroyo el Torote. The diatomite is an upper bathyal, latest Miocene to middle Pliocene deposit (Carreño, 1992a; Pérez-Guzmán, 1985) that bears a transitional microflora indicating the convergence of the California Current and the North Equatorial System. Representative microfossils include the planktonic foraminifers *Globigerina pachyderma pachyderma* (Ehrenberg), *G. pachyderma incompta* Cifelli, *G. quinqueloba* Natland, *Globigerinita uvula uvula* (Ehrenberg), and *Neogloboquadrina dutertrei blowi* Rögl and Bolli, and calcareous nannoplankton *Discoaster brouweri* Tan Sin Hok. Lithologic and faunal differences between Subunits A and C suggest an abrupt change in depth in the Late Miocene. McCloy's Subunit D consists of coarser, shallower water clastic deposits that grade laterally and vertically to the Refugio Formation.

Martínez-Gutiérrez and Sethi (1997) reported good exposures of their upper facies near Rancho la Soledad, Rancho la Calabaza, and Cerro Sombrerito. Greenish and reddish quartzose sandstones and siltstones contain the Miocene gastropod genera *Cancellaria, Pyruclia, Cymia, Solenosteira, Strombus,* and *Melongena* (Rodríguez-Quintana and Segura-Vernis, 1992). Some of these taxa are also found in reworked coarse-grained sediments near the Tropic of Cancer west of Mexico 1 (Text-figs. 76, 77). The facies grades laterally and vertically to the overlying Refugio Formation.

Correlation

The Trinidad Formation correlates on the basis of Miocene megafossils with parts of the Imperial Formation in California, the Salada Formation north of Todos Santos, Baja California Sur, the Ferrotepec Formation of the La Mira Basin, Michoacán, and Tertiary-Caribbean units such as the Gatún Formation of Panama and the Cercado Formation of the Dominican Republic (Smith, 1991c).

Ingle *in* Gastil *et al.* (1999) tabulated planktonic foraminiferal species from the "Santiago diatomite" that he identified from southwestern Isla Tiburón in Unit M8c. They include *Globigerina quinqueloba* Natland, *Globigerinoides extremus* Bolli and Bermúdez, *G. obliquus* Bolli, and *G. ruber* s.l. (d'Orbigny). McDougall *et al.* (1999) listed the same species from the northern Salton Trough; they assigned them to Planktonic Foraminiferal Zones N17 and N18, Late Miocene–Early Pliocene. Carreño (1992a) and Pérez-Guzmán (1985) regarded the "Santiago diatomite" microfossils as latest Miocene to middle Pliocene.

Refugio Formation, Early Pliocene.—Diverse, poorly preserved marine fossils were collected from Rancho el Refugio more than 50 years before Martínez-Gutiérrez and Sethi (1997) formally named this unit (see Appendix 1). The 360–380-m-thick type section near Rancho el Refugio (23°24.1′ N, 109°38.5′ W) includes sandstone, limestone, and shale facies that dip 10°–20° to the southwest and contain abundant mollusks (Text-figs. 74, 78). Diagnostic species, including *Euvola keepi* (Arnold) [= *E. refugioensis* (Hertlein)] and *Pecten aletes* Hertlein, are interpreted as Early Pliocene in age. The Refugio Formation species are different from the radiometrically constrained Late Pliocene taxa found in the Loreto embayment and at the Islas Tres Marías, Isla Cerralvo, and Bahía Guadalupe in the northern Gulf of California.

Regarded as "Salada Formation" by many workers (Beal, 1948; Mina-Uhink, 1957; Pantoja-Alor and Carrillo-Bravo, 1966; McCloy, 1984), the Refugio Formation differs in provenance, lithology, depositional history, and a younger age. Its megafossils are latest Miocene or Early Pliocene ancient gulf species that are also found in the Tirabuzón Formation of the Boleo basin. They are not present in the western Baja California embayments.

Los Barriles Formation, Late Pliocene–Early Pleistocene.—The Los Barriles Formation is an alluvial sandstone and coarse-grained conglomerate that overlies the Refugio Formation in the northern part of the Cabo Trough, and conformably overlies or interfingers with it to the south. Martínez-Gutiérrez and Sethi (1997) reported a thickness of 1,650 m.

El Chorro Formation, Late Pleistocene–Holocene.—Martínez-Gutiérrez and Sethi (1997) interpreted the youngest continental deposit in the Cabo Trough as Pleistocene in age, possibly mixed with Holocene alluvium. They measured 150 m of coarse-grained sandstone and conglomerate along the western side of the Cabo Trough, 3–8 m in the eastern basin. The unit is locally faulted against the Sierra la Victoria complex and it is unconformable above the Los Barriles Formation.

Rancho Algodones, Santa Anita

Southern Cabo Trough
Plate 2, Column 44
(Text-fig. 74, Appendices 1, 2)

Column data from Espinosa-Arrubarrena (1979) and reconnaissance visits by the authors. Area shown on San José del Cabo and Palo Escopeta quadrangles, F12B44 and F12B45, 1:50,000.

Geographic setting and lithologic units in the southern Cabo Trough

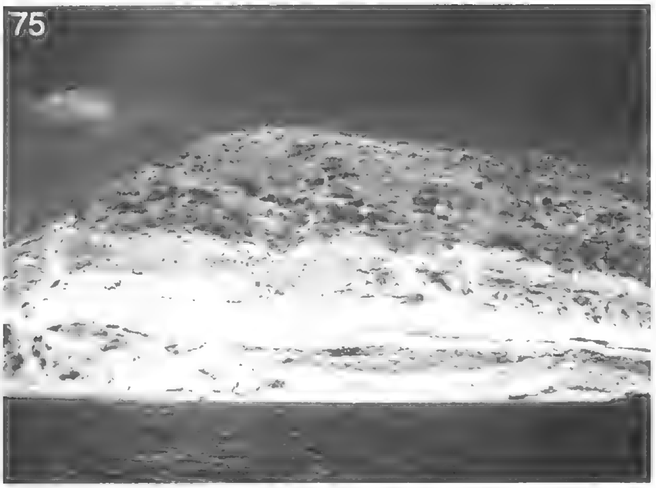
Although there is overlap in units between the northern and southern parts of the Cabo Trough, sediment compositions differ between the rocks in three areas: Arroyo Trinidad and Rancho el Refugio to Cerro Sombrerito; Rancho Algodones, 25 km to the south, and surrounding arroyos; and the hills near Santa Anita east of the Los Cabos International Airport. The Neogene sediments are generally more reworked in the south.

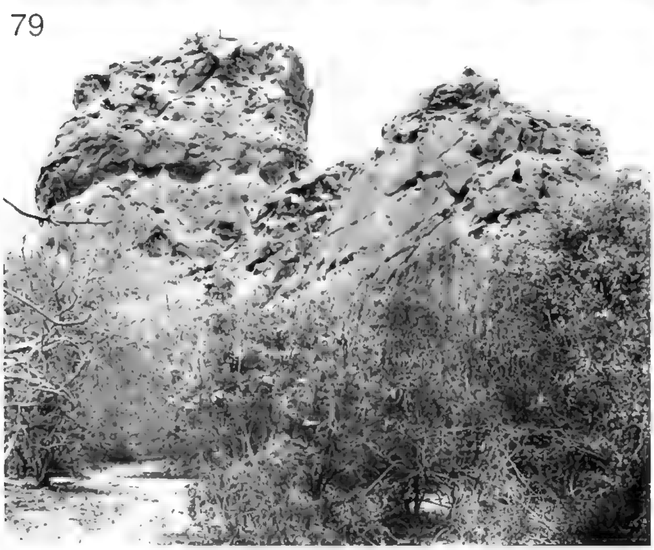
Stratigraphy

Unnamed marine sandstones near Punta Gorda, Miocene.—Beal and others (unpublished field sheets in the Stanford University Branner Earth Sciences Library and Map Collections) mapped a well-indurated, sparsely fossiliferous, thin, gray, marine sandstone that dips 10° to the south and southeast along the coast between San José del Cabo and Punta Gorda (Text-fig. 74). They assigned this unit to the "Ysidro Formation"; it might be a deposit of the protogulf subprovince of Fenby and Gastil (1991), correlative with the oldest marine rocks at Isla Tiburón. A large *Lyropecten* sp. collected by the Beal expedition from Zacatón, approximately 5 km northeast of Punta Gorda, confirms a Miocene age, but most of the other megafossils could not be extricated from the hard matrix. A large *Flabellipecten* sp. collected by the Beal expedition from Zacatón, approximately 5 km northeast of Punta Gorda, confirms a Miocene age, but most of the other megafossils could not be extracted from the hard matrix.

Reworked marine sediments near Rancho Algodones and Santa Anita, Miocene and Pliocene.—A 30-m-thick section of unnamed coarse-grained, fossiliferous marine and non marine sandstones in the hills near Rancho Algodones and along Arroyo el Peyote was measured by Martínez-Gutiérrez and Sethi (1997); they assigned the massive, coarse-grained sandstone to the Refugio Formation. Floods have eroded the roads and arroyos in this area, which is approximately 9 km northeast of Santa Anita. The sandstones and mudstones contain vertebrates and invertebrates, both reworked and live-buried, from a variety of habitats (Espinosa-Arrubarrena, 1979; Espinosa-Arrubarrena and Applegate, 1981; authors' field observations, 1995).

Miller (1980) identified Late Pliocene terrestrial and nonmarine vertebrates from outcrops north of Rancho Algodones and southeast of Miraflores. In Arroyo las Tunas he reported marine beds that grade into and interfinger with brown micaceous quartz sandstones, siltstones, and shale with an apparent dip of 6°–7° to the east. Fossils, of which the horse was the most abundant, were mostly disarticulated lower Blancan Stage vertebrates with western North American faunal affiliations. Miller (1980) listed, among others: skulls, jaws, teeth, and bones of rabbits referred to *Hypolagus* sp. cf. *H. vetus* (Kellogg); ground squirrel skull, jaw, and teeth described as new species *Ammospermophilus jeffriesi* Miller; minimally diagnostic fragments identified as the camelid genera cf. *Camelops* and cf. *Hemiauchenia*; teeth and leg bones of a cougar-like cat, *Felis*? *lacustris* Gazin; jaws, teeth, and other bones from a "moderately large" species of horse, *Equus* (*Dolichohippus*) sp. cf. *E.* (*D.*) *simplicidens* (Cope); crocodile jaw fragments and teeth of *Crocodylus* sp. cf. *C. moreleti* (Dumeril and Bocourt); rattlesnake vertebra, genus cf. *Crotalus* sp.; a few bones referred to the hawk genus ? *Buteo*; tortoise fragments of *Geochelone* (*Hesperotestudo*) sp.; and lower jaw, teeth, tusks, and other bones of the proboscid *Rhynchotherium* sp. cf. *R. falconeri* Osborn. The faunule suggests a subtropical savanna environment (Miller, 1980; Torres-Roldán, 1980; ongoing investigations by Wade E. Miller and Oscar Carranza-Castañeda). Uplift and erosion of the Sierra la Victoria to the west could account





Text-figure 75. —Isla Cerralvo, "Farallones blancos," near the site of Ruffo's rancho. Unnamed Late Pliocene sandstones, conglomerates, and coquina contain abundant marine megafossils that correlate the rocks with the Carmen-Marquer Formation, undifferentiated, of the Loreto embayment. Photo, J. T. Smith, 1983.

Text-figure 76. —Junction of Tropic of Cancer (approximately 23 25′ N) and Mexico 1, view west at the Sierra la Laguna. Outcrops between the highway and the sierra consist of very coarse, reworked sediments that contain fragments of robust fossils from the Refugio and upper Trinidad Formations. Photo, J. T. Smith, 2003.

for differences in sediment composition between the vertebrate-bearing rocks and those farther north, but detailed mapping and sedimentological studies are needed.

Correlation

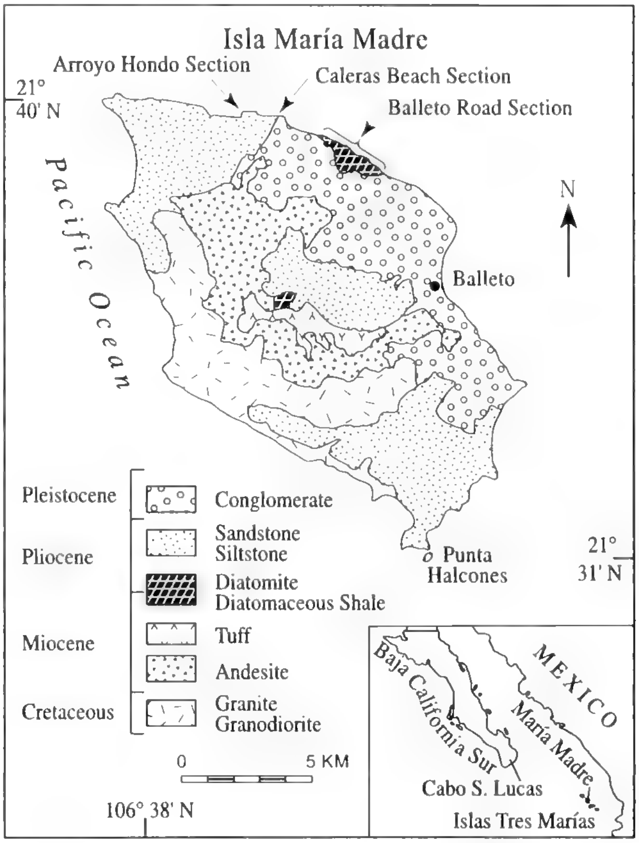
Espinosa-Arrubarrena (1979) correlated the beds at Rancho Algodones with the Tirabuzón Formation of the Boleo basin on the basis of shark teeth. Molluscan fossils from unnamed, reworked, marine sediments of the southern Cabo Trough also include a number of taxa in common with the late Middle to Late Miocene section at southwestern Isla Tiburón and parts of the Imperial Formation in the Salton Trough (Gastil *et al.*, 1999). They include "*Aequipecten*" *muscosus* (Wood), *Chlamys mediacostata* (Hanna), *Anadara thauma* (Maury) [= *A. carrizoensis* (Reinhart) described from the Imperial Formation], *Codakia* sp. cf. *C. orbicularis* (Linnaeus), *Conus spurius* Gmelin, *Strombus obliteratus* Hanna, and *Turritella imperialis* Hanna.

Islas Tres Marías, Nayarit
Plate 2, Column 45
(Text-figs. 1, 81, Appendices 1, 2)

Column modified from Carreño (1985), McCloy *et al.* (1988) and Chiñas-Laló (1963).

Overview

The Tres Marías Islands are important to Gulf of California history because of their position 100 km offshore from Punta Mita, Nayarit, Mexico. The rocks record part of the Late Miocene to Pleistocene history at the mouth of the Gulf, although the 1.5-km-thick section is considerably thinner than correlative 5- to 6-km-thick Neogene sequences in the northern Gulf (J. T. Smith, 1989). Early interpretations of a middle Pliocene ancient gulf must be modified to accomodate evidence of seawater in the northern gulf as much as eight million years earlier than the onset of spreading at its mouth at 4–6 Ma (Larson, 1972; Hagstrum *et al.*, 1987). Of the Islas Tres Marías, Isla María Madre is the largest and has the most extensive stratigraphic record. Late Miocene diatoms are also reported from Isla María Cleofas (Pérez-Guzmán, 1985).



Text-figure 81.—Isla María Madre, index map and geology modified from Carreño (1985) and McCloy *et al.* (1988).

Stratigraphy

Basement rocks consist of Cretaceous granite and granodiorite overlain by Tertiary (?) andesites and rhyolites (McCloy *et al.*, 1988).

Units on Isla María Madre were designated by informal location names in discussions by Carreño (1985) and McCloy *et al.* (1988), whose geologic sketch map is included here (Text-fig. 81). A section approximately 1,145 m thick, including unconformi-

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Text-figure 77.—Coarse-grained conglomerates with fragments of oysters, the gastropods *Oliva*, *Melongena*, and *Cancellaria* (*Pyruclia*), west of Mexico 1 at the Tropic of Cancer marker. Photo, J. T. Smith, 2003.

Text-figure 78.—Refugio Formation, type section at Rancho el Refugio with poorly preserved Early Pliocene fossils, including the abundant pectinid *Euvola refugioensis* (Hertlein) [= *E. keepi* (Arnold)]. Photo, J. T. Smith, 1983.

Text-figure 79. La Calera Formation, red cross-bedded sandstones at the entrance to a box canyon in the type area near junction of Cañada la Calera with Arroyo la Trinidad. Photo, J. T. Smith, 1985.

Text-figure 80.—Trinidad Formation, basal Member A, type locality in Arroyo la Trinidad. The Miocene mudstone and siltstone lower facies contains abundant double- and single-valved *Anadara patricia* (Sowerby) and the tiny estero-dwelling snail *Neritina luteofasciata* (Miller). Photo, J. T. Smith, 1983.

ties, represents Late Miocene to Late Pliocene time, 8.2 Ma–2.5 Ma. Deposition occurred during an early Late Miocene to Early Pliocene subsidence event followed by the Late Pliocene uplift of a seamount that provided shallow water habitats for organisms found as fossils in the section at Caleras Beach.

The section includes Middle Miocene (?) nonmarine and shallow marine sandstone overlain unconformably by younger Miocene upper to middle bathyal diatomite, mudstones, and limestones that are exposed at Arroyo Hondo (McCloy *et al.*, 1988). An unconformity separates these sediments from Early Pliocene middle to lower bathyal sandstones and siltstones that crop out in Balleto Road. Another unconformity divides these units from Late Pliocene to Pleistocene limestones and siltstones that occur at Caleras Beach. Unnamed conglomerate of Chiñas-Laló (1963), Pleistocene marine terrace deposits, and alluvium cap the section.

Carreño (1985), and McCloy *et al.* (1988) listed microfossils, including *Globorotalia tumida flexuosa* (Koch) and *G. scitula scitula* (Brady), that indicate upper to middle bathyal depths for the early Late Miocene diatomite, mudstone, and limestone exposed in Arroyo Hondo. Late Pliocene shallow neritic mollusks are abundant in the sandstones and limestones that crop out at Caleras Beach. They were illustrated or cited by Smith (1991c) and E. J. Moore (1984) and include "*Aequipecten*" *dallasi* (Jordan and Hertlein), *Argopecten abietis* (Jordan and Hertlein), *A. revellei* (Durham), *Leopecten bakeri* (Hanna and Hertlein), and *Ostrea vespertina* of authors. Pliocene to Holocene species that live in the modern gulf are *Oppenheimopecten vogdesi* (Arnold), *Undulostrea megadon* (Hanley), and *Placunanomia cumingii* (Broderip).

Correlation

The rocks on Isla María Madre are contemporaneous with Late Miocene to Quaternary sediments, mainly unfossiliferous, from DSDP site 473 and Pliocene cores from DSDP 475 and 476 (Curray *et al.*, 1982). Abundant fossil mollusks at Caleras Beach represent a faunal assemblage that lived as far north as Bahía Guadalupe during the mid-Pliocene spreading event at the mouth of the modern gulf (Larson, 1972; Curray and Moore, 1984; Hagstrum *et al.*, 1987). The megafossils provide good correlation between the southern Gulf islands, the Loreto embayment, and basins underlain by the Infierno Formation from Santa Rosalía to Concepción Peninsula.

Punta Mita, Nayarit
(Text-fig. 1)

Unnamed marine siltstones, Late Miocene.—Ingle *in* Gastil *et al.* (1999) recorded early and middle Late Miocene temperate microfossils from unnamed marine siltstones at Punta Mita, Nayarit, north of Puerto Vallarta, Jalisco, mainland Mexico (Text-fig. 1). The foraminifers indicate outer neritic depths for sediments that overlie volcanic rocks with K/Ar ages of 10.2 Ma and 11.1 Ma (Jensky, 1975; Gastil *et al.*, 1978).

Ingle listed the planktonic species *Globigerina angustiumbilicata* (Bolli), *Neogloboquadrina continuosa* (Blow), and *Orbulina suturalis* (Bronniman). Benthic foraminifers include *Bolivina californica* Cushman, *B. foraminata* R. E. and K. C. Stewart, *B. granti* Rankin, *B. hughesi* Cushman, *B. mulleri* Kleinpell and Tipton, *Buliminella brevior* Cushman, *B. curta* Cushman, *B. elegantissima* (d'Orbigny), *Cassidulina panzana* Kleinpell, *Epistominella reliziana* (Kleinpell), *Gallicherina uvigerinaformis* (Cushman and Kleinpell), and *Hansensica multicamerata* (Kleinpell).

Many of these species are common in central and southern California in temperate faunas referred to the provincial Mohnian benthic foraminiferal stage of Kleinpell (1938, 1980). Ingle *in* Gastil *et al.* (1999) noted the absence of these temperate taxa at southwestern Isla Tiburón and the tropical-subtropical environment indicated by the latest Miocene–earliest Pliocene faunule he reported from Unit M8c.

CONCLUSIONS

As microfossil and megafossil paleontologists, respectively, we are aware that meticulous stratigraphy can be time-consuming, but correlations that are based on better-defined, time-stratigraphic units provide the best resolution for dating and synthesizing large scale tectonic events in areas of complex geology. Models and topical studies in the ancient gulf and Baja California require the best possible time constraints and stratigraphic correlations to test and answer the larger questions of plate tectonic history and Tertiary Caribbean faunal dispersal prior to the closure of the Isthmus of Panama. We acknowledge that correlation is an ongoing process, and that the columns we present here reflect current information at the time of writing.

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APPENDIX I:
Selected Paleontological and Radiometric References, by Embayment

Part 1: San Diego, California to Todos Santos, Baja California Sur

San Diego, Rosarito, and Rosario embayments (San Diego to 28° N.).—

Paleodata

Microfossils

Abbott et al., 1993a,b, 1995
Buch, 1984
Bukry and Kennedy, 1969
Deméré *et al.*, 1984
Doyle & Bandy, 1972
Holden, 1964, 1970
Lothringer, 1984
McGee, 1967
Mickey, 1970
Miller and Abbott, 1989
Pérez-Guzmán, 1985
Sliter, 1968, 1984
White, 1885
Wicander, 1970

Megafossils

Abbott *et al.*, 1995
Allison, 1955, 1974
Almazán-Vázquez and Buitrón, 1984
Aranda-Manteca and Téllez-Duarte, 1989
Arnold, 1903, 1906
Ashby, 1989c
Ashby and Minch, 1984
Cushing-Woods and Saul, 1986
Deméré, 1983, 1988
Deméré *et al.*, 1984
Durham and Allison, 1960
Emerson, 1956
Fife *et al.*, 1967
Filkorn, 2003
Grant and Gale, 1931
Hanna, G. D., 1925, 1927
Hanna, M. A., 1926
Hertlein and Allison, 1959
Hertlein and Grant, 1960, 1972
Jones and Miller, 1982
Jordan, 1926, 1936
Kennedy, G. L., 1973
Kennedy, G. L. *et al.*, 1986, 2000
Kidwell and Gyllenhaal, 1998
Ledesma-Vázquez and Johnson,1994
Lescinsky *et al.*, 1991
Marincovich, 1975
Miller and Abbott, 1989
Minch, 1970
Minch *et al.*, 1984
Moore, E.J., 1968, 1983, 1984, 1987
Perrilliat, 1968
Popenoe, 1954
Popenoe and Saul, 1987
Popenoe *et al.*, 1960
Rowland, 1972
Saul, 1970, *in* Kennedy, M. P. and Moore, G. W., 1971
Saul and Popenoe, 1992, 1993
Saul and Squires, 1997
Squires and Saul, 1997, 2001
Squires *et al.*, 1988, 1989
Téllez-Duarte and Helenes, 2002
Valentine, 1957
Valentine and Rowland, 1969
Walsh and Deméré, 1991
Webster, 1983
Zinsmeister and Paredes-Mejía, 1988
Zullo, 1992

Vertebrates

Aranda-Manteca and Téllez-Duarte, 1989
Ashby and Minch, 1984
Barnes and Aranda-Manteca, 1997

Barradas and Stewart, 1993
Deméré, 1983, 1988
Deméré *et al.*, 1984
Gascón-Romero and Aranda-Manteca, 1997
Kopelman, 1997
Lillegraven 1972, 1976
Minch *et al.*, 1970
Molnar, 1974
Morris, W. J., 1970, 1973, 1974, 1981
Novacek *et al.*, 1991
Stewart and Aranda-Manteca, 1993
Walsh and Deméré, 1991

Radiometric ages

K/Ar, Ar^{40}/Ar^{39}, Sr, Fission Track, Pb-U, $^{230}Th/^{234}U$, $^{231}Pb/^{235}U$

Abbott *et al.*, 1993, 1995
Aranda *et al.*, 1993
Barthelmy, 1974
Bushee *et al.*, 1963
Delgado-Argote *et al.*,1995 (Ar/Ar)
Dorsey, 1991 (Fission tracks)
Fife *et al.*, 1967
Gastil *et al.*, 1975 (K/Ar)
Hawkins, 1970
Krummenacher *et al.*, 1975 (K/Ar)
Luhr *et al.*, 1995
Morris, W. J., 1981
Renne *et al.*, 1991
Rockwell *et al.*, 1989

Vizcaíno embayment.—

Paleodata

Microfossils

Berry and Miller, 1984
Dávila-Alcocer and Pessagno, 1986
Drake, 1995
Helenes, 1984
Helenes and Ingle, 1979
Helenes-Escamilla, 1980, 1984
McGee, 1967
Moreno-Ruiz and Carreño, 1994
Pérez-Guzmán, 1985
Pessagno *et al.*, 1979
Smith, D. P. *et al.*, 1993
Whalen and Carter, 2002
Whalen and Pessagno, 1984

Megafossils

Abbott *et al.*, 1995
Alderson and Saul, 1992
Emerson, 1980
Emerson *et al.*, 1981
Finch *et al.*, 1979
Gabb, 1869a,b
Hertlein, 1925, 1933
Hertlein and Emerson, 1959
Hertlein and Grant, 1960
Hertz and Hertz, 1984
Imlay, 1963
Jordan and Hertlein, 1926a,b
Kilmer, 1963, 1984
Moore, E. J., 1983, 1984, 1988
Robinson, 1979b
Smith, J. T., 1984, 1991a,c
Troughton, 1974
Whalen and Pessagno, 1984

Vertebrates

Applegate *et al.*, 1979
Aranda-Manteca and Barnes, L. G., 1993
Barnes, L. G., 1973, 1984, 1992
Barnes, L. G. *et al.*, 1997
Gascón-Romero and Aranda-Manteca, 1997
Kilmer, 1977, 1984
Stewart, 1997

Radiometric ages

K/Ar, Ar^{40}/Ar^{39}, Sr, Fission Track, Pb-U, $^{230}Th/^{234}U$, $^{231}Pb/^{235}U$

Baldwin, 1989 (Ar/Ar)
Baldwin and Harrison, 1989, 1992
Baldwin *et al.*, 1987 (Ar/Ar)
Barnes, D. A., 1982, 1984 (U/PB)
Busby-Spera. 1988
Gastil, 1979 (K/Ar)
Kimbrough, 1980 (K/Ar), 1982 (U-PB)
Kimbrough *et al.*, 1987 (U-PB)
Moore, T. E., 1976
Robinson, 1975 (K/Ar)
Sedlock *et al.*, 1991
Smith, D. P. *et al.*, 1991 (Ar/Ar)
Suppe and Amstrong, 1972 (K/Ar)
Troughton, 1974 (K/Ar)

Western embayment, San Ignacio to Arroyo San Raymundo.—

Paleodata

Microfossils

McLean and Barron, 1988
Sorensen, 1982

Megafossils

Hertlein, 1925
Hertlein and Jordan, 1927
Smith, J. T., 1984, 1986

Squires and Demetrion, 1989, 1992, 1994a,b

Radiometric ages

K/Ar, Ar^{40}/Ar^{39}, Sr, Fission Track, Pb-U, $^{230}Th/^{234}U$, $^{231}Pb/^{235}U$

Hausback, 1984a,b
McLean *et al.*, 1987
Sawlan and Smith, J. G., 1984

Purísima-Iray basin.—

Paleodata

Microfossils

Carreño and Cronin, 1993
Kim, 1987
Kim and Barron, 1987
Martínez-Hernández and Ramírez-Arriaga, 1997
McLean and Barron, 1988
Mina-Uhink, 1957

Megafossils

Arnold and Clark, 1917
Heim, 1922
Hertlein, 1925, 1968
Hertlein and Jordan, 1927
McLean *et al.*, 1984, 1987
Smith, J. T., 1984, 1986, 1991c
Squires, 1990a,b
Squires and Demetrion, 1990a,b, 1991, 1992, 1993, 1994a,b, 1995
Squires and Saul, 1997

Vertebrates

González-Barba, 1997
González-Barba *et al.*, 2001

Radiometric ages

K/Ar, Ar^{40}/Ar^{39}, Sr, Fission Track, Pb-U, $^{230}Th/^{234}U$, $^{231}Pb/^{235}U$

Hausback, 1984a,b (K/Ar)
McLean and Hausback, 1984
McLean *et al.*, 1985, 1987
Sawlan and Smith, J. G., 1984
Smith, J. T., 1991c

Magdalena embayment.—

Paleodata

Microfossils

Carreño, 1992b
Carreño *et al.*, 1997, 2000
Carreño *in* Perrilliat, 1996
Coleman, 1979
Fulwider, 1976, 1984, 1991
Kim, 1987
Kim and Barron, 1986
Knapp, 1974
Martínez-Hernández, 1992
Martínez-Hernández and Ramírez-Arriaga, 1997

Megafossils

Applegate, 1986
Arnold and Clark, 1917
Fischer *et al.*, 1989, 1995
Galli-Olivier *et al.*, 1986
Gidde *in* Fischer *et al.*, 1995
Hertlein, 1925, 1968
Jordan, 1924, 1936
Morris, P. A. and Smith, J. T., 1995
Perrilliat, 1996
Schweitzer *et al.*, 2002
Schwennicke, 1998
Smith, J. T., 1992
Squires and Demetrion, 1991
Wehmiller and Emerson, 1980
Wilson, E. C., 1979

Vertebrates

Applegate, 1986
Ashby, 1987
Barnes, L. G., 1995
Ferrusquía-Villafranca and Torres-Roldán, 1980
González-Barba, 1995a, 1997
González-Barba *et al.*, 2000, 2001, 2002
Schwennicke, 1998
Schwennicke and González-Barba, 1995

Plants

Cevallos-Ferriz, 1995, 1997
Cevallos-Ferriz and Baraja-Morales, 1991, 1993, 1994

Radiometric ages

K/Ar, Ar^{40}/Ar^{39}, Sr, Fission Track, Pb-U, $^{230}Th/^{234}U$, $^{231}Pb/^{235}U$

Forman *et al.*, 1971 (Th/U, Pb/U)
Hausback, 1984a,b (K/Ar)
Omura *et al.*, 1979 (Sr)
Wehmiller and Emerson, 1980 (Sr)

Todos Santos and San Pedro.—

Paleodata

Megafossils

Schwennicke *et al.*, 2000
Smith, J. T., 1992

Vertebrates

Ferrusquía-Villafranca and Torres-Roldán, 1981

González-Barba, 1995b
González-Barba *et al.*, 2000
Schwennicke *et al.*, 1996

Radiometric ages

K/Ar, Ar^{40}/Ar^{39}, Sr, Fission Track, Pb-U, $^{230}Th/^{234}U$, $^{231}Pb/^{235}U$

Aranda-Gómez and Pérez-Venzor, 1989

Part 2: Salton Trough to Islas Tres Marías

Salton Trough, Whitewater River area to Sierra Cucupá.—

Paleodata

Microfossils

Cotton and Vander Haar, 1979, 1980, 1981
Dean, 1996
Ingle, 1974
McDougall *et al.*, 1999
Miller and Dockum, 1983
Quinn and Cronin, 1984
Smith, P. B., 1960, 1970
Vázquez-Hernández *et al.*, 1996

Megafossils

Arnold, 1906
Bramkamp, 1935*b*
Durham, 1950
Foster, 1979
Hanna, G. D., 1926
Kew, 1914
Kidwell, 1988
Kidwell and Gyllenhaal, 1998
Powell, 1986, 1988
Siem, 1992
Taylor, 1985
Tucker *et al.*, 1994
Vaughan, T. W., 1917
Van Syoc, 1992
Watkins, 1992
Wilson and Cuffey, 1998
Winterer, 1975
Zullo, 1992
Zullo and Buising, 1989

Vertebrates

Downs and White, 1967
Downs and Woodard, 1961
Metzger *et al.*, 1973
Mitchell, 1961
Thomas and Barnes, L. G., 1993

Radiometric ages

K/Ar, Ar^{40}/Ar^{39}, Sr, Fission Track, Pb-U, $^{230}Th/^{234}U$, $^{231}Pb/^{235}U$

Barnard, 1968
Buising, 1990
Damon *et al.*, 1978
Eberly and Stanley, 1978
Johnson *et al.*, 1983
Kerr, 1982, 1984
Mace, 1981 (K/Ar)
Matti *et al.*, 1985 (K/Ar)
Ruissard, 1979 (K/Ar)
Spencer *et al.*, 1998
Winker, 1987

San Felipe—Puertecitos—Bahía de los Angeles—Isla Tiburón.—

Paleodata

Microfossils

Boehm, 1984
Hertlein, 1968
Ingle, 1974; *in* Gastil *et al.*, 1999
Mandra and Mandra, 1972
Martín-Barajas *et al.*, 1993a,b, 1997
Natland, 1950
Pérez-Guzmán, 1985
Vázquez-Hernández *et al.*, 1996

Megafossils

Andersen, 1973
Delgado-Argote and García-Abdeslem, 1999
Delgado-Argote *et al.*, 1999
Durham, 1950
Gastil *et al.*, 1973, 1999
Hertlein, 1968
Martín-Barajas *et al.*, 1997
Smith, J. T., 1991c
Stump, 1981

Radiometric ages

K/Ar, Ar^{40}/Ar^{39}, Sr, Fission Track, Pb-U, $^{230}Th/^{234}U$, $^{231}Pb/^{235}U$

Delgado-Argote *et al.*, 1995, 1997, 1998 (K/Ar, Ar/Ar)
Desonie, 1992
Dorsey, 1991 (Fission Track)
Gastil and Krummenacher, 1977
Gastil *et al.*, 1999
Lewis, 1994, 1996
Martín-Barajas *et al.*, 1995, 1997 (Ar/Ar)
Nagy *et al.*, 1999, 2000
Neuhaus, 1988a,b

Oskin and Stock, 2003
Oskin *et al.*, 2000
Smith, J. T. *et al.*, 1985
Sommer and García-Abdeslem, 1970
Stock and Hodges, 1989
Stock *et al.*, 1999

Boleo basin, Concepción Peninsula, Loreto basin, and the central Gulf islands.—

Paleodata

Microfossils

Carreño, 1981, 1982
Natland, 1950

Megafossils

Cuffey and Johnson, 1997
Durham, 1947, 1950
DuShane, 1977
Emerson, 1960
Foster *et al.*, 1997
Hanna and Hertlein, 1927
Hertlein, 1925
Johnson and Simian, 1996
Johnson *et al.*, 1997
Ledesma-Vázquez, 2000
Ledesma-Vázquez and Johnson, 2001
Ledesma-Vázquez *et al.*, 1997, 2004
McLean, 1987, 1988, 1989
Moore, E. J., 1983, 1984, 1987, 1988, 1992
Piazza and Robba, 1994, 1998
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Vokes, H. E., *in* McFall, 1968
Wilson, E. C., 1985

Vertebrates

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Applegate and Espinosa-Arrubarrena, 1981
Flores-J., and Barnes, L. G., 1991

Radiometric ages

K/Ar, Ar^{40}/Ar^{39}, Sr, Fission Track, Pb-U, $^{230}Th/^{234}U$, $^{231}Pb/^{235}U$

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Casarrubias-Unzueta and Gómez-López, 1994
Dorsey *et al.*, 1995
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McFall, 1968 (K/Ar)
McLean, 1987, 1989
Sawlan, 1991
Sawlan and Smith, J. G., 1984
Smith, J. T., 1991b,c
Stone, 1994

Eastern Magdalena embayment, Punta San Telmo and Tembabiche to San Juan de la Costa and Arroyo el Sauzoso.—

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Microfossils

Gidde *in* Fischer *et al.*, 1995
Kim, 1987
Martínez-Hernández, 1992
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Megafossils

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Vertebrates

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Radiometric ages

K/Ar, Ar^{40}/Ar^{39}, Sr, Fission Track, Pb-U, $^{230}Th/^{234}U$, $^{231}Pb/^{235}U$

Grimm, 1992
Hausback, 1984a,b

La Paz peninsula.—

Radiometric ages

K/Ar, Ar^{40}/Ar^{39}, Sr, Fission Track, Pb-U, $^{230}Th/^{234}U$, $^{231}Pb/^{235}U$

Aranda-Gómez and Pérez-Venzor, 1986, 1988
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Microfossils

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Torres-Roldán, 1980

Radiometric ages

K/Ar, Ar^{40}/Ar^{39}, Sr, Fission Track, Pb-U, $^{230}Th/^{234}U$, $^{231}Pb/^{235}U$

Gastil *et al.*, 1976
Hausback, 1984a,b
Sirkin *et al.*, 1990

Appendix II: Cited Topographic Quadrangle Maps, Southern California, Baja California, and Baja California Sur

California topographic quadrangles mentioned in text

Quadrangle	County
Arroyo Tapiado 7½′	San Diego County
Borrego Mountain 7½′	Imperial County
Cabazon 7½′	Riverside County
Carrizo Mountain 15′; 7.5′	15′, San Diego and Imperial Counties; 7.5′, Imperial County
Carrizo Mountain NE 7½′	Imperial County
Del Mar 7½′	San Diego County
Desert Hot Springs 7½′	Riverside County
Encinitas 7½′	San Diego County
Escondido 7½′	San Diego County
Harper Canyon 7½′	San Diego County
Jamul Mountains 7½′	San Diego County
La Jolla 7½′	San Diego County
La Mesa 7½′	San Diego County
National City	San Diego County
Painted Gorge 7½′	Imperial County
Palm Springs 15′	Riverside County
Point Loma 7½′	San Diego County
Poway 7½′	San Diego County
Rancho Santa Fe 7½′	San Diego County
Whitewater 7½′	Riverside County

Mexican Quadrangles cited, scale 1:50,000

Quadrangle name (some duplicate names in use)	Number
Agua Caliente	H 11 B25
Agua Caliente	H 11 B66
Agua de Higuera	H 12 C51
Algodón	H 11 B56
Año Nuevo	G 12 A56
Arroyo del Sauz	I 11 D84
Arroyo San José	G 12 A21
Bahía Asunción	G 11 B49
Bahía de Los Ángeles	H 12 C52
Bahía Magdalena	G 12 C66
Bahía Santa María	H 11 B67
Bahía Tortugas	G 11 B27
Benito Juárez	G 12 C47
Boca de San Cristobal	F 12 B53
Cabo Pulmo	F 12 B35
Cabo San Lucas	F 12 B54
Camalu	H 11 B53
Campo Juárez	H 12 C42
Cerro El Huerfanito	H 11 B87
Chapala	H 11 D38
Ciudad Constitución	G 12 C48
Ciudad Morelos	I 11 D67
Comondú	G 12 A87
Conquista Agraria	F 12 B11
Delicias	G 12 C57
Desierto El Vizcaíno	G 12 A31
El Arco	H 12 C82
El Agua Escondida	H 11 B75
El Aguajito	H 11 B85
El Barril	H 12 C74
El Cajete	G 12 D72
El Canelo	G 12 C27
El Caracol	G 12 A24
El Centenario	G 12 D82
El Centinela	I 11 D64
El Conejo	G 12 D81
El Coyote	G 12 A67
El Crucero	H 11 D49

Punta Santa Ana	G 12 A25
Punta Santo Domingo	G 12 A74
Real del Castillo Nuevo	H 11 B13
Rosarito	H 11 D69
Rodolfo Sánchez Taboada	H 11 B22
Salinas Ometepec	H 11 B37
San Antonio	F 12 B13
San Borja	H 12 C61
San Esteban	G 12 A32
San Felipe	H 11 B47
San Francisco	G 12 A23
San Ignacio	G 12 A34
San Isidro	G 12 A86
San Javier	G 12 C18
San Jerónimo	H 12 C71
San Joaquín	G 12 A44
San José de La Noria	G 12 C39
San José de La Piedra	H 11 D37
San José de Gracia	G 12 A64
San José de Magdalena	G 12 A46
San José del Cabo	F 12 B44
San Juan de La Costa	G 12 D71
San Juan de Los Planes	F 12 B14
San Juan de Dios	I 11 D83
San Juanico	G 12 A75
San Luis Gonzaga, B.C.	H 11 D18
San Luis Gonzaga, B.C.S.	G 12 C59
San Martín	H 12 C81
San Nicolás	G 12 A68
San Pedro de La Presa	G 12 D51
San Rafael	H 11 B45
San Raymundo	CGSNEGI 1982
San Roque	G 11 B48
San Simón	H 11 D17
San Venancio	G 12 C17
San Vicente	H 11 B33
Santa Águeda	G 12 A35
Santa Catarina	H 11 D26
Santa Clara	H 11 B46
Santa Cruz	H 11 B55
Santa Rita	G 12 C68
Santa Rosa	G 12 A78
Santa Rosalía	G 12 A36
Santiago	F 12 B34
Santo Domingo	H 11 B54
Sierra Campo Nuevo	G 11 B39
Sierra Cucapá	I 11 D75
Sierra de Colombia	H 11 D48
Sierra Los Indios	G 11 B28
Tecate	I 11 D62
Tepentu	G 12 C49
Tijuana	I 11 C69 and I 11 C79
Timbabichi	G 12 D31
Todos Santos	F 12 B33
Vale Agua Amarga	H 12 C41
Valle Calamajue	H 11 D39
Valle Laguna Seca	H 12 C31
Valle las Palmas	I 11 D72
Valle San Rafael	H 12 C63
Venustiano Carranza	H 11 B74
Villa Insurgentes	G 12 C37
Villa Morelos	G 12 C58

Mexican quadrangles in number order

Number	Quadrangle name
I 11 D61	Murúa
I 11 D62	Tecate
I 11 D63	La Rumorosa
I 11 D64	El Centinela
I 11 D65	Mexicali
I 11 D66	Islas Agrarias
I 11 D67	Ciudad Morelos
I 11 C69	Tijuana
I 11 D71	La Presa
I 11 D72	Valle las Palmas
I 11 D73	Neji
I 11 D74	La Poderosa
I 11 D75	Sierra Cucapá
I 11 D76	Guadalupe Victoria
I 11 C79	Tijuana
I 11 D81	Primo Tapia
I 11 D82	Francisco Zarco
I 11 D83	San Juan de Dios
I 11 D84	Arroyo del Sauz
I 11 D85	Guardianes de la Patria
I 11 D86	Plan de Ayala
H 11 B11	El Sauzal de Rodríguez
H 11 B12	Ensenada
H 11 B13	Real del Castillo Nuevo
H 11 B14	El Rayo
H 11 B15	José Saldana
H 11 B16	El Oasis
H 11 B17	El Doctor
H 11 B22	Rudolfo Sánchez Taboada
H 11 B23	El Zacatón
H 11 B24	Héroes de la Independencía
H 11 B25	Agua Caliente
H 11 B26	La Ventura
H 11 B27	Isla Montague
H 11 B32	Puerto San Isidro
H 11 B33	San Vicente
H 11 B34	Jesús García
H 11 B35	Francisco R. Serrano
H 11 B36	Llano El Chinero
H 11 B37	Salinas Ometepec

H 11 B43	Punta Colonet
H 11 B44	Potreros
H 11 B45	San Rafael
H 11 B46	Santa Clara
H 11 B47	San Felipe
H 11 B53	Camalu
H 11 B54	Santo Domingo
H 11 B55	Santa Cruz
H 11 B56	Algodón
H 11 B57	Punta Estrella
H 11 B64	Lázaro Cárdenas
H 11 B65	El Morro
H 11 B66	Agua Caliente
H 11 B67	Bahía Santa María
H 11 B74	Venustiano Carranza
H 11 B75	El Agua Escondida
H 11 B76	Matomí
H 11 B77	Puertecitos
H 11 B84	El Rosario
H 11 B85	El Aguajito
H 11 B86	El Metate
H 11 B87	Cerro El Huerfanito
H 11 B88	El Huerfanito
H 11 D14	Punta Baja
H 11 D15	Emiliano Zapata
H 11 D16	Guayaquil
H 11 D17	San Simón
H 11 D18	San Luis Gonzaga
H 11 D25	Punta San Carlos
H 11 D26	Santa Catarina
H 11 D27	La Bocana
H 11 D28	Jaraguay
H 11 D29	Punta Final
H 11 D36	Puerto Canoas
H 11 D37	San José De La Piedra
H 11 D38	Chapala
H 11 D39	Valle Calamajue
H 11 D47	Punta Blanco
H 11 D48	Sierra de Colombia
H 11 D49	El Crucero
H 11 D58	Punta El Diablo
H 11 D59	Punta Prieta
H 11 D69	Rosarito
H 11 D79	José María Morelos y Pavón
H 11 D89	La Islita
H 12 C31	Valle Laguna Seca
H 12 C41	Valle Agua Amarga
H 12 C42	Campo Juárez
H 12 C51	Agua De Higuera
H 12 C52	Bahía De Los Ángeles
H 12 C53	Punta Las Ánimas
H 12 C61	San Borja
H 12 C62	Los Paredones
H 12 C63	Valle San Rafael
H 12 C71	San Jerónimo
H 12 C72	Los Tepetates
H 12 C73	El Progreso
H 12 C74	El Barril
H 12 C81	San Martín
H 12 C82	El Arco
H 12 C83	Miraflores
H 12 C84	Los Corrales
G 12 D31	Timbabichi
G 11 B17	Punta Eugenia
G 11 B18	Punta Malarrimo
G 11 B19	Guerrero Negro
G 11 B27	Bahía Tortugas
G 11 B28	Sierra Los Indios
G 11 B29	Laguna Ojo De Liebre
G 11 B38	Puerto Nuevo
G 11 B39	Sierra Campo Nuevo
G 11 B48	San Roque
G 11 B49	Bahía Asunción
G 12 A11	Las Bombas
G 12 A12	Mesa Los Venados
G 12 A13	Prosperidad
G 12 A14	La Trinidad
G 12 A21	Arroyo San José
G 12 A22	Gustavo Díaz Ordaz
G 12 A23	San Francisco
G 12 A24	El Caracol
G 12 A25	Punta Santa Ana
G 12 A31	Desierto El Vizcaíno
G 12 A32	San Esteban
G 12 A33	Los Mártires Uno
G 12 A34	San Ignacio
G 12 A35	Santa Águeda
G 12 A36	Santa Rosalía
G 12 A41	Mesa El Ejidatario
G 12 A42	Mesa Piedra Rodada
G 12 A43	Mesa Las Lagunitas
G 12 A44	San Joaquín
G 12 A46	San José de Magdalena
G 12 A51	Estero La Bocana
G 12 A52	Punta Abreojos
G 12 A53	Laguna San Ignacio
G 12 A54	El Patrocinio
G 12 A56	Año Nuevo
G 12 A57	Mulegé
G 12 A63	Punta Delgadito
G 12 A64	San José de Gracia
G 12 A65	Mesa Los Tepetates
G 12 A66	El Potrero
G 12 A67	El Coyote
G 12 A68	San Nicolás
G 12 A74	Punta Santo Domingo
G 12 A75	San Juanico
G 12 A76	Paso Hondo

G 12 A77	El Duguajal
G 12 A78	Santa Rosa
G 12 A85	Punta Pequeña
G 12 A86	San Isidro
G 12 A87	Comondú
G 12 A88	Loreto
G 12 C16	Poza Grande
G 12 C17	San Venancio
G 12 C18	San Javier
G 12 C19	Juncalito
G 12 C26	Las Ánimas
G 12 C27	El Canelo
G 12 C29	Ligui
G 12 C36	Isla Santo Domingo
G 12 C37	Villa Insurgentes
G 12 C38	Ley Federal De Aguas Número Uno
G 12 C39	San José De La Noria
G 12 C46	Puerto Adolfo López Mateos
G 12 C47	Benito Juárez
G 12 C48	Ciudad Constitución
G 12 C49	Tepentu
G 12 C56	Puerto San Carlos
G 12 C57	Delicias
G 12 C58	Villa Morelos
G 12 C59	San Luis Gonzaga
G 12 C66	Bahía Magdalena
G 12 C67	Puerto Alcatraz
G 12 C68	Santa Rita
G 12 C69	La Fortuna Del Bajío
G 12 C77	Puerto Cortés
G 12 C78	Puerto Chale
G 12 C79	Las Pocitas
G 12 C89	Ignacio Zaragoza
G 12 D31	Timbabichi
G 12 D41	Los Burros
G 12 D51	San Pedro De La Presa
G 12 D61	Punta Coyote
G 12 D62	Isla La Partida
G 12 D71	San Juan De La Costa
G 12 D72	El Cajete
G 12 D73	El Coyote
G 12 D81	El Conejo
G 12 D82	El Centenario
G 12 D83	La Paz
G 12 D84	El Sargento
F 12 B11	Conquista Agraria
F 12 B12	La Victoria
F 12 B13	San Antonio
F 12 B14	San Juan De Los Planes
F 12 B22	Melitón Albánez
F 12 B23	El Rosario
F 12 B24	Las Cuevas
F 12 B25	La Rivera
F 12 B33	Todos Santos
F 12 B34	Santiago
F 12 B35	Cabo Pulmo
F 12 B43	La Candelaria
F 12 B44	San José Del Cabo
F 12 B45	Palo Escopeta
F 12 B53	Boca De San Cristóbal
F 12 B54	Cabo San Lucas

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Informal stratigraphic names are given in lower case with the embayments where they are found; formal stratigraphic units are capitalized.

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Plates 1-2 of:

STRATIGRAPHY AND CORRELATION FOR THE ANCIENT GULF OF CALIFORNIA AND BAJA CALIFORNIA PENINSULA, MEXICO

By Ana Luisa Carreño and Judith Terry Smith

Plate 1. The western Baja California peninsula, San Diego, California to Todos Santos, Baja California Sur

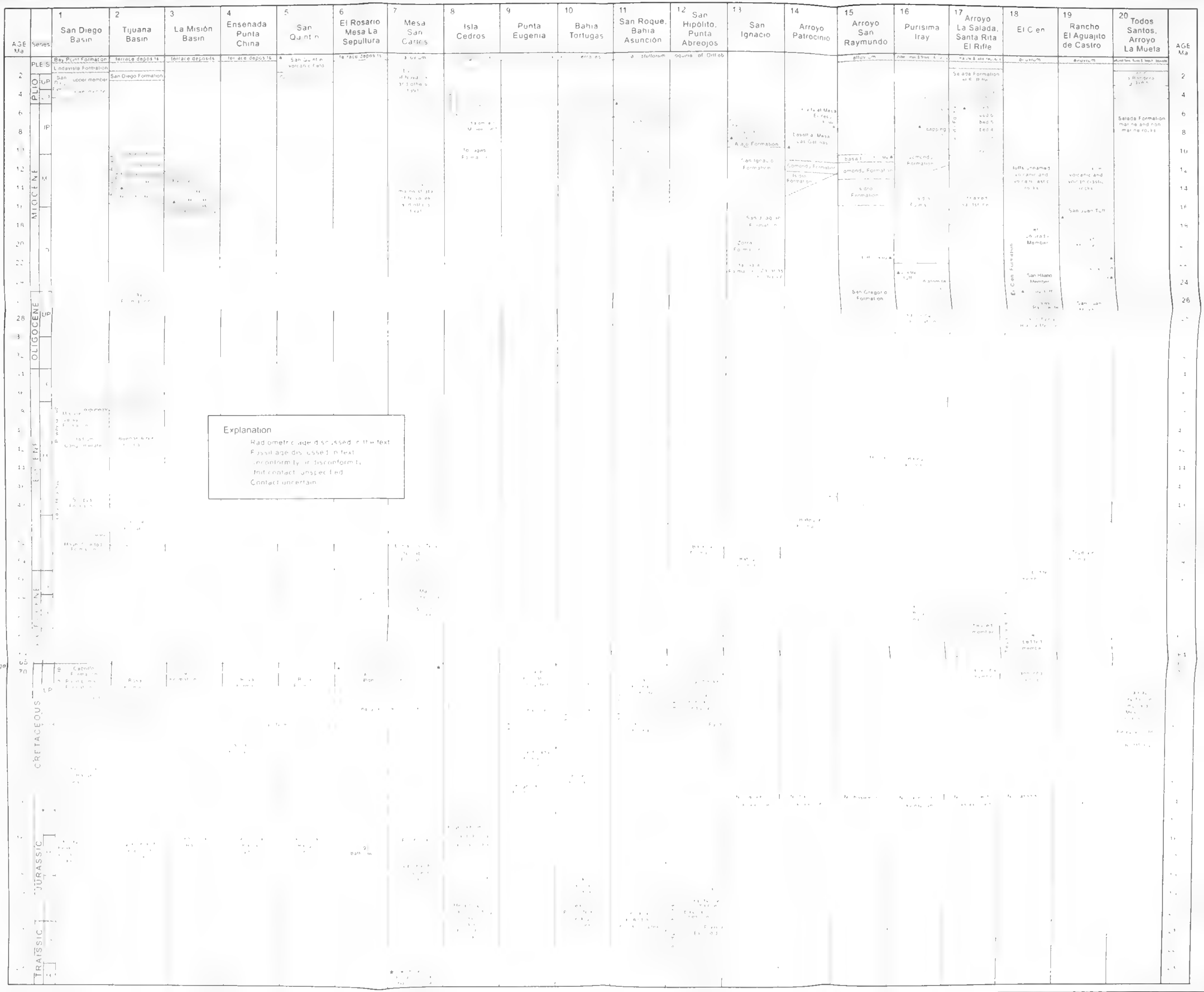
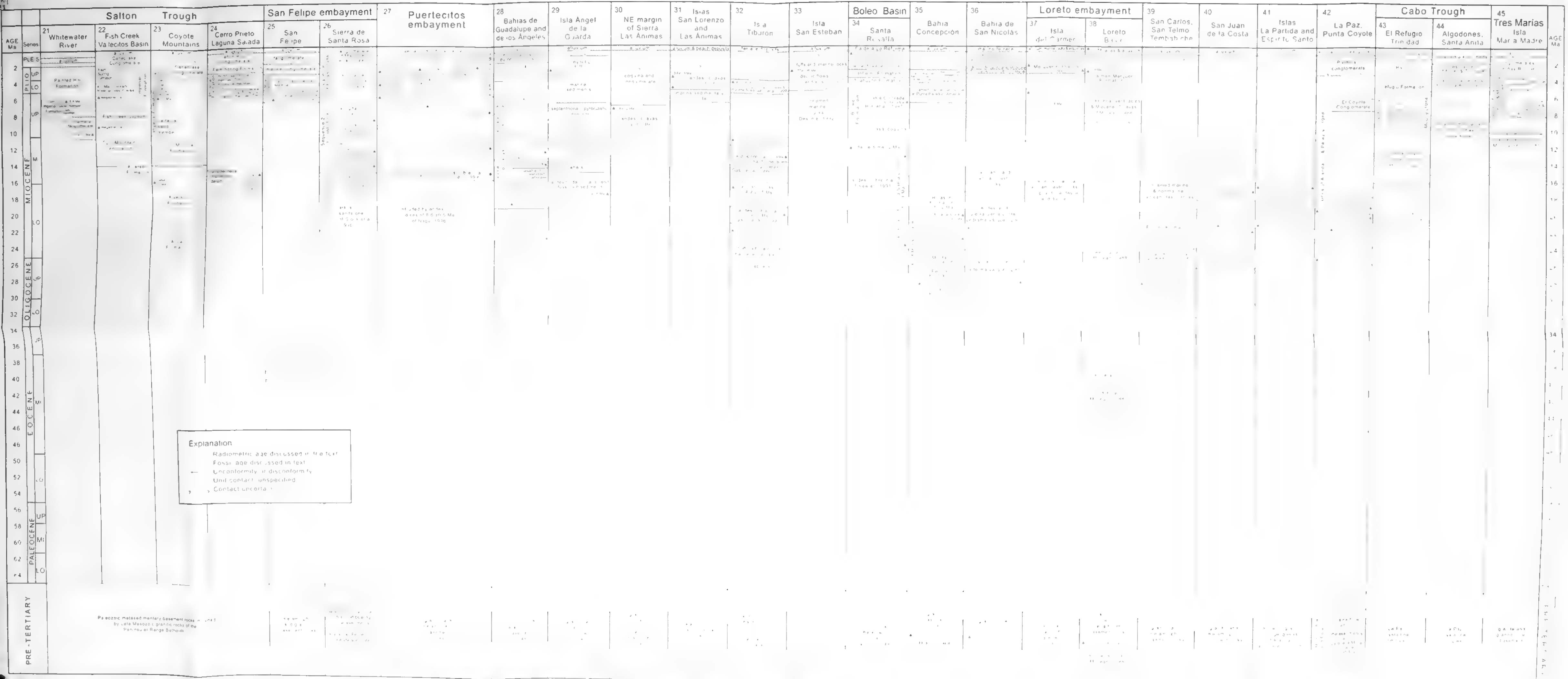


Plate 2. Ancient and modern Gulf of California, Salton Trough, California to Islas Tres Marías, southern Gulf of California



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