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GEOLOGY AND PALEONTOLOGY OF SOUTHWESTERN ISLA TIBURÓN, SONORA, MEXICO

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ABSTRACT

An almost 3-km-thick section of Neogene volcanic, marine and non-marine sedimentary rocks is exposed on Isla Tiburón in the northern Gulf of California, Sonora, Mexico and provides a key record of early Miocene through Quaternary events during the evolution of the Gulf. The Miocene age of the marine sediments is of special significance because these deposits pre-date by almost 8 m.y. the sea-floor spreading, oblique rifting and formation of the modern Gulf of California via invasion of the East Pacific Rise beginning at 6-5 Ma. The K-Ar ages of volcanic rocks overlying fossiliferous marine sediments and strontium isotope dates on calcareous megafossils within these sediments indicate that marine water entered the gulf as early as 13-12 Ma, during the extensional Basin and Range phase of Gulf history. However, microfossils date some marine beds as no older than 6.5 Ma, an age in conflict with an 11.2 Ma radiometric date on an ash flow tuff that unconformably overlies the sediments; this discrepancy likely reflects unresolved structural or depositional configurations in the section. Megafossils and microfossils permit correlation of the Tiburón section with other marine sequences and facies exposed along the eastern margin of Baja California (the Cabo Trough and Boleo Basin), the southeastern mouth of the gulf (Isla María Madre and Punta Mita, Nayarit), and within the Salton Trough to the north. A geologic map (Plate I, scale 1:12,500) shows continental redbeds intercalate with lower Miocene volcanic rocks *ca.* 21 Ma in age, lower Miocene andesite and basalt units between 21 and 16 Ma in age, and an interval of middle to upper Miocene dacites and rhyolites dated between 13 and 9 Ma which are interbedded with or overlie a predominantly fossiliferous marine conglomerate. The latter conglomerate is a unique 1,500-m-thick unit and constitutes the oldest Neogene marine sediments recognized to date within the gulf proper. All strata older than 9 Ma are tilted, separated by an angular unconformity from younger, flat-lying rhyolites and sediments. The composition of volcanic rocks older than 12 Ma points to their origin within an arc. Those rocks dated as 6 Ma and younger display compositions reflecting the transtensional opening of the modern Gulf of California.

Key words: Geology, Paleontology, Isla Tiburón, Sonora, Mexico.

RESUMEN

En la isla Tiburón, al noreste del golfo de California, Sonora, México, se encuentra expuesta una sección de 3 km de espesor, compuesta por rocas sedimentarias marinas y continentales, así como volcánicas, la cual constituye un registro importante de los eventos relacionados con la evolución del Golfo ocurridos desde el Mioceno temprano hasta el Cuaternario. La presencia de sedimentos marinos de edad miocénica es especialmente significativa, ya que documenta una invasión marina y una extensión oblicua 8 m.a. antes de que ocurriera el emplazamiento de la corteza oceánica y la formación del moderno Golfo, vía la cordillera del Pacífico oriental ocurrida entre 6 y 5 Ma. Las edades K-Ar de las rocas volcánicas que yacen sobre la secuencia marina fosilífera y los fechamientos con isótopos de estroncio en megafósiles calcáreos incluidos en estas rocas, indican que las aguas marinas invadieron esta zona hace 13–12 Ma, durante la fase extensional de Cuencas y Sierras. Sin embargo, los microfósiles indican una edad de por lo menos 6.5 Ma, en contraste con la edad isotópica de 11.2 Ma, obtenida de una toba de derrame de ceniza que yace discordantemente sobre estos sedimentos, reflejando una configuración deposicional o estructural no resuelta en la sección. Los micro- y macrofósiles de la sección de la isla Tiburón, permiten relacionar esta secuencia con otras expuestas a lo largo de la margen oriental de Baja California (la región de los Cabos y la cuenca El Boleo), la parte sudoriental de la boca del Golfo (isla María Madre y Punta Mita, Nayarit) y con el Salton Trough hacia el norte. El mapa geológico (Lámina I, escala 1:12,500) muestra capas rojas continentales intercaladas con rocas volcánicas del Mioceno inferior, *ca.* 21 Ma, andesita y basalto del Mioceno inferior con edades de 21 y 16 Ma, y un intervalo del Mioceno medio y superior de dacitas y riolitas fechadas entre 13 y 9 Ma, sobre las cuales yace o se intercalan con un conglomerado marino fosilífero de 1,500 m de espesor, que constituye los sedimentos más antiguos del Neógeno reconocidos dentro del Golfo. Los estratos más antiguos que 9 Ma están inclinados y separados por una discordancia angular de riolitas y sedimentos horizontales más jóvenes. Las rocas volcáni-

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cas más antiguas que 12 Ma, están químicamente clasificadas como rocas de arco. Las rocas fechadas como 6 Ma y más jóvenes tienen una composición que refleja el estilo transtensional de la apertura del moderno Golfo de California.

Palabras clave: Geología, paleontología, Isla Tiburón, Sonora, México.

INTRODUCTION

Isla Tiburón lies within the Basin and Range Province, east of a series of *en échelon* faults marking the boundary between the North American and Pacific Plates. Allied more with the west Mexican mainland than with other Gulf islands, it is composed of rocks that were extruded, intruded or deposited as part of the magmatic arc that existed from 24 to 11 Ma in the area of the present Gulf. The setting of its marine section is unlike the basins of the eastern two thirds of Sonora (McDowell *et al.*, 1997) or eastern Baja California in the Loreto, Santa Rosalía and Puertecitos areas. Those embayments are much larger and well developed, with a variety of facies and recognizable boundaries, whereas Isla Tiburón contains a unique marine conglomerate exposed in a few arroyos over an 8 km^2 area. There are no large regionally significant structures. Rocks older than 11 Ma are tilted, cut by a minor fault system and unconformably overlain by a horizontal ash flow tuff 11.2 Ma in age. The Sonoran sediments to the east are generally capped conformably by volcanic rocks of 12.8–11.5 Ma (McDowell *et al.*, 1997).

The Cretaceous granodiorite and tonalite basement and a sequence of Tertiary to Holocene igneous and sedimentary rocks of Isla Tiburón record the history of the northern Gulf of California between 21 Ma and the present. Rocks spanning the period between late middle Miocene and late Miocene formed during the end of subduction and andesitic arc volcanism, the beginning of strike slip faulting, and the onset of extension brought about by oceanic rifting. A unique 1,500-m-thick tilted, bevelled, and mainly marine cobble to boulder conglomerate extends over one quarter of the 30 km^2 study area; it contains abundant marine fossils of Tertiary Caribbean and Pacific Panamic faunal affinity. Constrained by isotopic ages, the sediments correlate on the basis of megafossils with other key reference sections in the Cabo Trough, the Boleo Basin near Santa Rosalía, and the northern and southern Salton Trough of California. This paper, which is accompanied by a geologic map and cross sections (Plate I), contains descriptions of stratigraphic units, summaries of geochemical and radiometric data, lists of fossils, and discussions of age, environment of deposition and correlation.

Most importantly, the study documents a seawater incursion into the northern Gulf of California by 13 Ma, 8 million years before the onset of rifting at its mouth. The Tiburón section is older, thicker, and more complete than Gulf sequences that have been studied at the Islas Tres Marías near its mouth (McCloy *et al.*, 1988). The larger structural setting of the Gulf of California is discussed in numerous papers in a memoir on the Gulf and Peninsular Provinces of the Californias (Dauphin and Simoneit, 1991).

LOCATION AND ACCESS

The largest island in the Gulf of California, Isla Tiburón lies at 29° N, 112°30'W, off Bahía Kino, Sonora (Figure 1). Regarded as one of the Midriff Islands, its topography looks more like that of coastal Sonora than of Isla Salsipuedes and the other western Gulf islands on the Pacific Plate. Vegetation is sparse, consisting of Sonoran Desert cacti and desert scrub (Case and Cody, 1983). Access to the southwestern area is by charter boat from Bahía Kino and takes 5–6 hours, depending on weather. No drinking water is available, and daily radio contact with the mainland is recommended. Permission to visit the area was obtained through the Secretaría de Desarrollo Urbano y Ecología in Hermosillo.

The terrane consists of hills that rise gradually toward the east and southeast to an elevation of 2,500 feet (760 m). The study area is traversed by a number of north-trending arroyos that drain into Bahía Vaporeta, 3–4 km northeast of Punta Willard (= Punta Yayahmeko) and cut through beds that dip 15° to 25° to the northeast, providing numerous exposures of volcanic rocks and conglomerate. The highest point in the mapped area, 840' (305 m) above sea level, is known informally as Cerro Starship (Plate I and Figure 2). A topographic base map with a 20-foot contour interval was made from photos taken in June, 1975 by CETENAL.

PREVIOUS WORK

Prior to 1975, little had been published on the geology of Isla Tiburón. Work by graduate students at San Diego State University (Gastil and Krummenacher, 1976) discovered tilted marine strata overlain unconformably by volcanic rocks dated at approximately 11 Ma; subsequent papers provided reconnaissance data on the section and megafossils (Weaver, 1979, 1981; Stump, 1981).

In 1983 the area was visited by a multidisciplinary party including Jim Ingle, Judith Smith, and Mark Boehm of Stanford University, Jim Smith of the United States Geological Survey, Richard Casey, then of Rice University, Jaime Roldán-Quintana of the Instituto de Geología, Hermosillo, and Gordon Gastil of San Diego State University. They confirmed the angular relationship between the fossiliferous marine strata and younger 11.2 Ma ash flow cap and located a volcanic debris flow interbedded with the marine conglomerate that was subsequently dated at 12.9 ± 0.4 Ma (K-Ar on feldspar; Smith *et al.*, 1985).

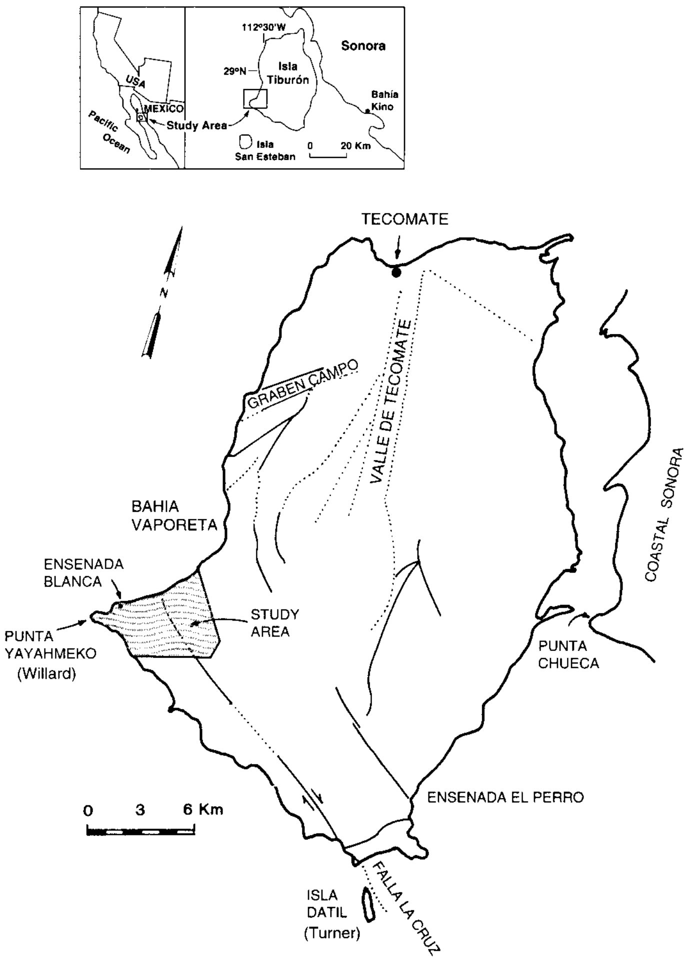


Figure 1. Location map of Isla Tiburón, Mexico (after Gastil and Krummenacher, 1976).

Gordon Gastil and Jim Ingle then obtained a National Science Foundation grant to study this critical area in greater detail, supporting two master's theses at San Diego State University (Neuhaus, 1988; Neuhaus *et al.*, 1988; Neuhaus 1989; Cassidy, 1989). The following report is largely a composite of their work. Additional published reports include Boehm (1987), Fenby and Gastil (1991), Neuhaus and collaborators (1988), and Smith (1989, 1991a, c).

AGE OF THE EARLIEST SEAWATER IN THE NORTHERN GULF OF CALIFORNIA

Controversy has surrounded two aspects of our Miocene age for the marine section at Isla Tiburón: the early age of seawater in the northern Gulf 8 million years prior to the onset of rifting at its mouth and discrepancies between ages given by megafossils and radiometric analyses versus that according to microfossils. Stratigraphic succession, megafaunal occurrences known from other constrained sequences, and radiometric ages support a late middle to late Miocene age for the ancient gulf. Other Miocene marine sediments in the northern gulf may be less well constrained but suggest early marine conditions: the

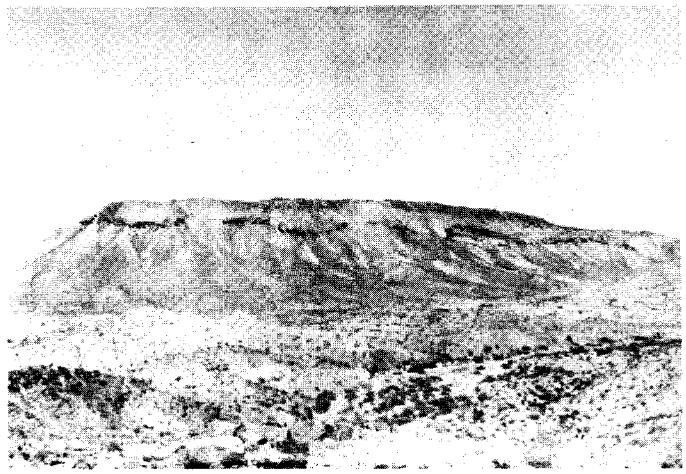


Figure 2. Cerro Starship, southwestern Isla Tiburón (see Figure 1 for location). The black exposures are the basal vitrophere of the capping ignimbrite (Unit M10), which angularity overlies the underlying clastic marine strata.

Fish Creek Gypsum microfossils reported by Dean (1996) from the Salton Trough; poorly preserved microfossils from wells in the Cerro Prieto geothermal field (Cotton and Vonder Haar, 1980); and the marine "Mioceno inferior" sediments in the subsurface near Empalme, Sonora (King, 1939). It is important to distinguish between these deposits associated with an earlier flooded Basin and Range depression, represented at Isla Tiburón, and younger sediments laid down in rifted basins of the modern gulf.

Microfossils at Isla Tiburón suggest an age no older than late Miocene, although they are stratigraphically below the unconformable ash flow tuff dated at 11.2 Ma. Data are discussed under microfossils, below.

Radiometric ages that constrain the marine section are given in Table 1 and are discussed under Stratigraphy and K-Ar Geochronology, below. The most critical ages are those for the volcanic breccia interbedded with the tilted conglomerate in Unit M8 (12.9 Ma) and for the unconformably overlying horizontal ash flow cap, Unit M9 (11.2 Ma). They suggest a short span of a few million years for deposition, tilting, and erosion, consistent with the timetable for processes in a tectonically active area. Although the ages listed for units in Table 1 are not in strict chronologic order, overlapping error bars suggest they are the same within the limits of analytical uncertainty. Younger ages for Unit M9 are for dikes that cut the section. Strontium ages obtained for megafossils (Table 6, below) include older ranges than expected from K-Ar data, but the conditions of preservation suggest alteration could have affected those results.

STRATIGRAPHY

Stratigraphic units are shown on the geologic map (Plate I) and composite column (Figure 3), modified from Cassidy (1989). The strata are exposed by north-trending arroyos that cut through predominantly northwest-striking beds with dips of

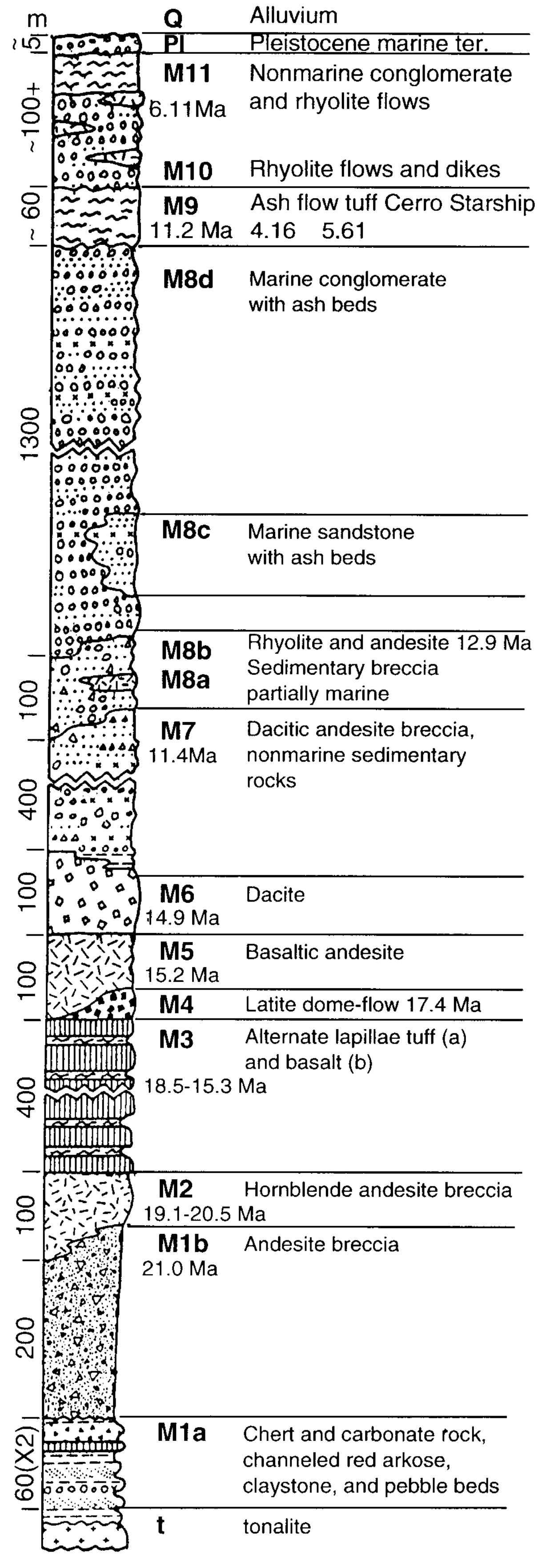


Figure 3. Stratigraphic column, southwestern Isla Tiburón, Sonora, Mexico.

15° to 25° to the northeast. Informal lithostratigraphic units are used in this paper rather than formation names.

CRETACEOUS UNITS

Tonalite and granodiorite basement (K)

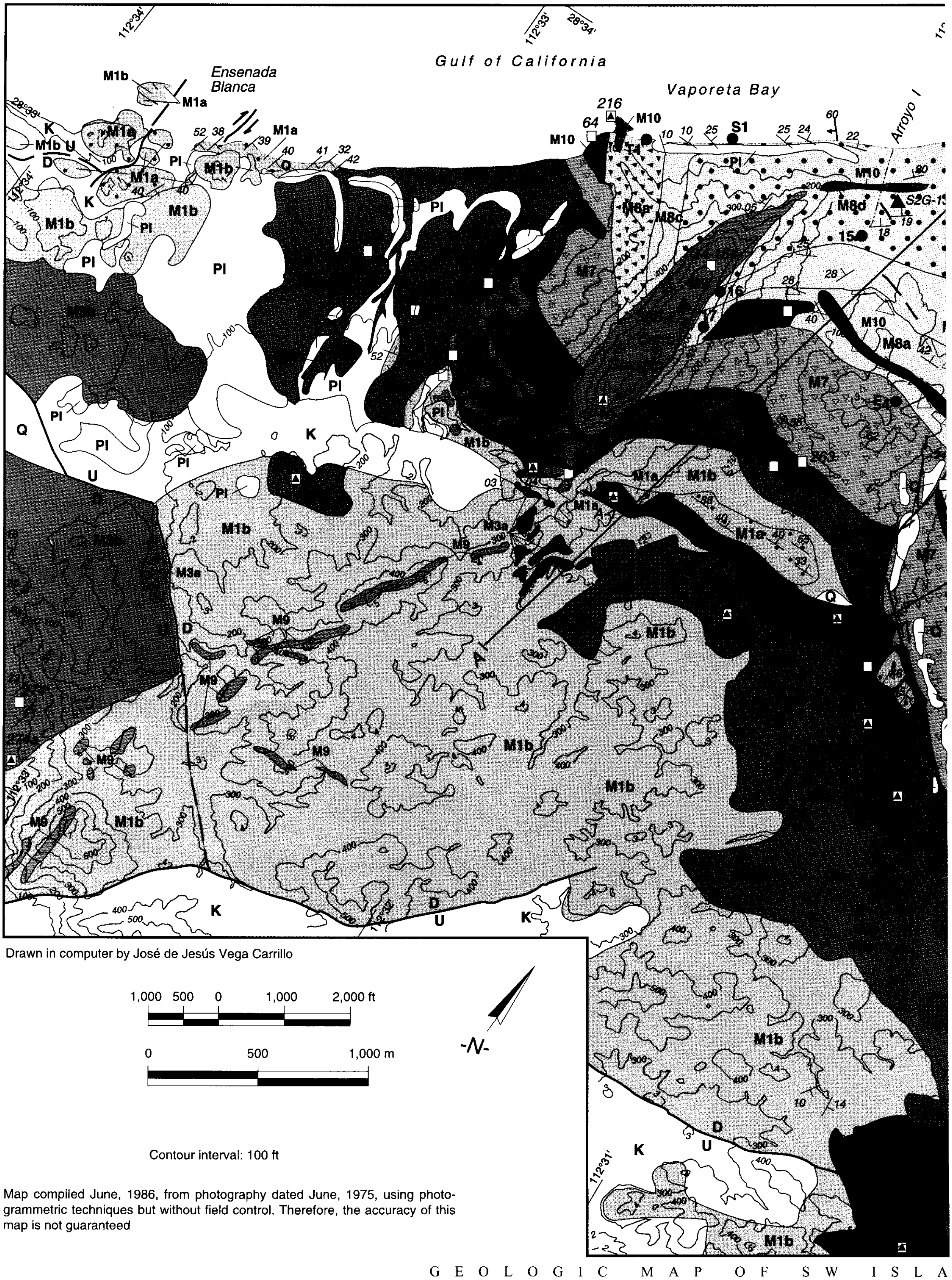
The basement rocks are Cretaceous leucocratic tonalite and granodiorite such as those reported for northeastern and northwestern Isla Tiburón by Gastil and Krummenacher (1977). Basement rocks crop out in the southern part of the study area.

MIOCENE UNITS

Redbeds (Unit M1a)

The Unit M1a fluvial redbeds at Ensenada Blanca are a 250-m-thick sequence of volcanogenic siltstone, sandstone, sedimentary breccia, and carbonate rock deposited in an alluvial fan to fluvio-lacustrine environment. Bed thicknesses average approximately 30 cm. Tilted beds are well exposed along the northwest coast near the fish camp at Ensenada Blanca. Sections south and southeast of Cerro Starship contain a 2-m bed of resistant cherty limestone believed to have formed as a lacustrine evaporite. The Ensenada Blanca redbeds overlie granitic basement and are capped by the basalt flows of Unit M4. In other areas, the redbeds appear to overlie and possibly interbed with the andesite breccia of Unit M1b (Figure 3). In general, the clasts that form Unit 1a redbeds are highly angular, with a clay matrix and a carbonate cement. The redbeds consist of unsorted, massive, silty to sandy debris flows containing lenses of pebble–to cobble–sized clasts of porphyritic andesite and rhyolite and metasedimentary rocks (Figures 1, 2; Neuhaus, 1989). A few well-preserved channels and channel-fill deposits are present between arroyos I and II southeast of Cerro Starship (Plate 1). The average paleo-current direction for these channels is S15°W. No source for these clasts was found in the study area; however, metasedimentary roof pendants were mapped by Gastil and Krummenacher (1976) to the north and east.

In arroyo II, Unit M1a redbeds (Plate I, near sample locality 202) contain hemispherical structures of micrite that resemble algal deposits. These are approximately 30 cm above the prominent cherty limestone stratum. Bioturbation is here apparent in a 15-cm-thick limy mudstone lens. A similar cherty limestone occurs near the Sierra Las Picus in western Sonora, where it is interbedded with redbeds and contains nonmarine gastropods and stromatolitic algal remains (Mattox, 1972). In the section at Ensenada Blanca the uppermost redbeds appear to be hyaloclastites and are overlain by basalt flows.



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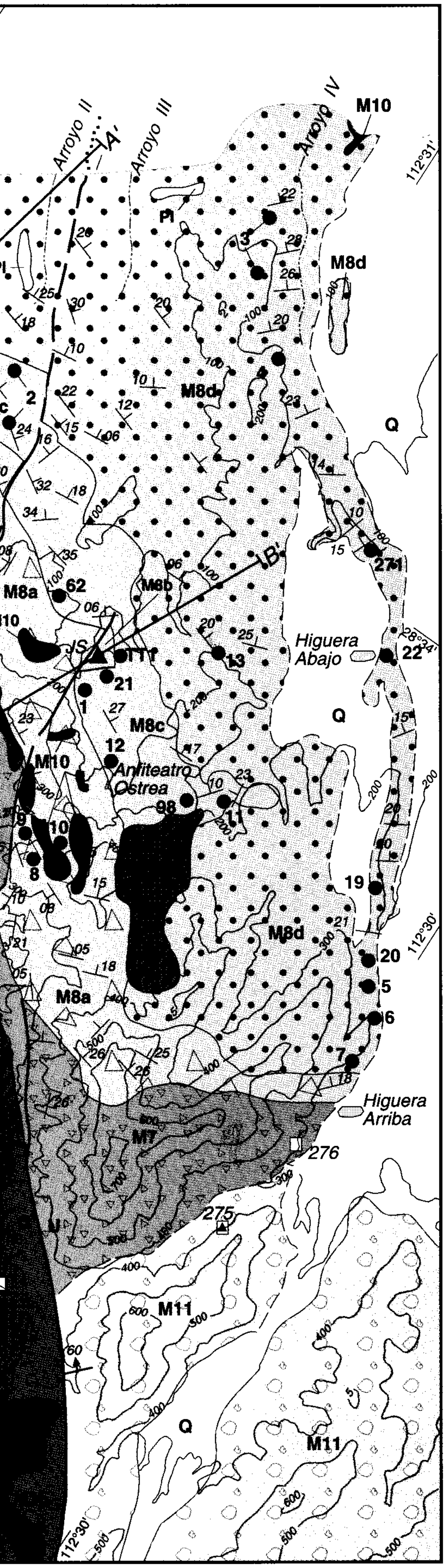


EXPLANATION

QUAT.	Q	Stream terraces and alluvial deposits		
PLEIST.	Pl	Marine terraces		
MIOCENE	M11	Fluvial conglomerate		Dacite
		Rhyolite flows and dikes		Basaltic andesite and related dikes
		Ash flow tuff		Hornblende latite dome flow
	M8d	Marine conglomerate		Basalt
	M8c	Marine sandstone		Lapilli tuff
	M8b	Rhyolite and andesite flows		Hornblende andesite
	M8a	Marine sedimentary breccia	M1b	Andesite breccia
	M7	Dacitic andesite breccia	M1a	Redbeds of Ensenada Blanca
CRETAC.	K	Tonalite and granodiorite		

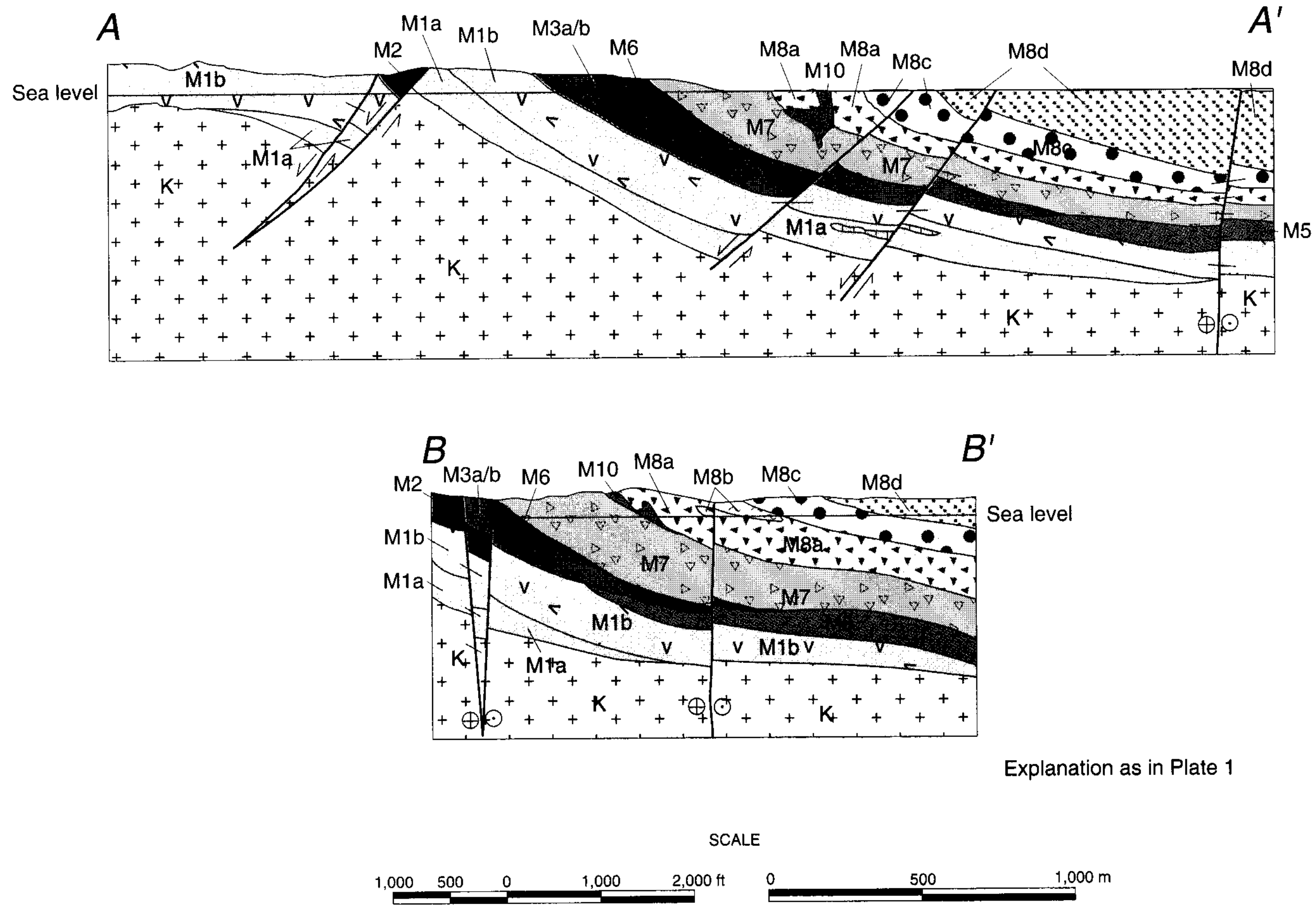
SYMBOLS

- ▲ Radiometric age locality
- ● Rock chemistry locality
- □ Fossil locality
- 60 U D — Fault indicating dip. Dashed where approximately located; dotted where concealed
  - **U:** upthrown side
  - **D:** downthrown side
- Fault showing relative strike-slip separation
- Contact
- 10 — Strike and dip of bedded rock strata

EQUIVALENCY OF FOSSIL LOCALITY NUMBERS

T1	JSmith 83T1 = TT69 (MC)
S1	JSmith 87JS1, marine conglomerate
1	JC Ingle measured section, 1983
2	JC Ingle measured section, 1983
3	83T2 = 87JS3 = USGS M9117
4	87 JS4
5	87JS5
6	87JS6
7	87JS7
8	87JS8, microfossil sample
11	87JS11 = MC285 microfossil sample, white sandstone facies
12	83T6 = 87JS12, *Anfiteatro ostrea*, USGS M9162, Mobil 8977
13	87JS13 = Mobil Sr sample 8478, white sandstone facies in Unit 8D
15	87JS15 = MC271 = USGS M9164, white sandstone facies
16	87JS16
17	87JS17
19	87JS19
20	87JS20
21	87JS21
22	87JS22 = USGS M9163

TIBURÓN, SONORA, MEXICO



Redrawn in computer by José de Jesús Vega-Carrillo

STRUCTURAL SECTIONS OF SW ISLA TIBURÓN, SONORA, MÉXICO

Andesite breccia (Unit M1b)

Unit M1b andesite breccia tuff is the most extensive volcanic unit of southwestern Isla Tiburón. The rock is highly weathered and friable at most outcrops; its color varies from hematite red to dark purplish brown. The rock is composed of fragments of andesite in a matrix of hematite-red ash. Andesite makes up 50 to 70% of the rock fragments. The unsorted cuspate fragments are 1 to 16 cm in diameter. Some fragments are well-preserved hornblende andesite, whereas others are highly fragmented (exploded?), and partially reassimilated into the matrix. Some hornblende prisms have been replaced by chlorite and sericite. Unit M1b seems to have been extruded as part of a sequence of andesitic domes, explosive flows, and lahars, which cross-cut, overlie, and interbed with red-beds.

Using the classification of Cas and Wright (1987), Unit M1b can be described as having a breccia-closed framework produced by gravitational caldera-margin collapse and epiclastic deposition. In some localities this rock is hydrothermally altered and occurs as an andesite ash-flow tuff. In other localities, deposition is as a lahar, where bedding is evident and clasts are highly weathered. In all locations, the unit is unimodal.

The ash matrix forms 20 to 80% of the rock. The lithic phase of the breccia contains 10 to 15% plagioclase phenocrysts (An_{27}) and shreads of chlorite in a trachytic to orthophyric intersertal groundmass. The only dated sample (15) yielded a K-Ar age of 21.0 ± 0.5 Ma (Table 1 and Figure 4).

Hornblende andesite (Unit M2)

Unit M2 is a light-gray to bluish-gray (5B7/1) andesite. In Arroyo II, a hornblende andesite outcrop (plug) forms a ridge approximately 1,500 m long with a relief of 15 m. Petrographic analysis shows 17 to 20%, 5- to 12-mm oxyhornblende phenocrysts and 3 to 5% plagioclase phenocrysts (Neuhaus, 1989, Appendix B). The groundmass consists of seriate orthophyric plagioclase crystals with intergranular hornblende. Approximately 25% of the rock has an intersertal texture with glass intersticies. K-Ar dating of Unit M2 yielded ages of 19.1 to 20.5 Ma (Figure 4). A small section of redbeds overlies Unit M2 southeast of Cerro Starship (Figure 2), suggesting that redbed sections were deposited at different times at different localities (*i.e.*, Arroyo II and Ensenada Blanca sections).

Interbedded lapilli tuff and basalt flows (Unit M3a and M3b)

The basaltic lapilli tuff of Unit M3a is dark yellowish-orange (10YR6/6) to light-red (5R6/6), predominantly a lapilli-fall deposit is locally agglomeratic. It is highly altered to clay and, in some portions, reworked. The air-fall deposit seems to be Strombolian in scale and may fall under Cas and Wright's (1987) classification of breccia-closed framework, subheading scoria fall deposit. The rock is highly susceptible to weathering and alteration. Lapilli tuff beds are basal to, or inter-layered with, basalt flows. Some lapilli tuff exposures grade into agglomerate flows containing shaped bombs and breadcrusted or jointed blocks.

Glass, which is the major component of the rock, has been largely altered to montmorillonite and palagonite. A matrix of plagioclase microlites and iron oxide surrounds pseudomorphed phenocrysts of orthopyroxene, which are now hematite, uralite, sericite, and/or chalcedony. Secondary calcite makes up 25% of the rock. The agglomeratic portions consist of 15% palagonite and 20% calcite. Phenocrysts are orthopyroxene and pseudomorphs of hematite after hornblende. The groundmass is seriate plagioclase crystals, altered glass, and minor cristobalite, forming a pilotaxitic to hyalo-pilitic texture.

Basalt (M3a), the most voluminous volcanic rock in the southwestern corner of Isla Tiburón, occurs in Hawaiian- to Strombolian-scale tabular flows and minor dikes. As seen in plan view on Plate I, basalt flows and dikes encircle two-thirds of the Unit M1b andesite breccia tuff. Dike swarms are found along the northern perimeter of the large central outcrop of Unit M2 andesite tuff breccia (Plate I). The green color of these primarily alkaline-olivine-augite basalts is due to low-temperature alteration.

Along the west shoreline, tabular basalt flows are 5 to 8 m thick and interbedded with 1-to 2-m-thick lapilli tuff deposits. Unit M3b basalt apparently erupted through vents located along the granitic basement exposures south of the northern shore, 0.5 km south of Enseneda Blanca, and flowed northward toward what is now the beach. The basalt flows exposed along the northern and western shore angularly overlie Units M1, M2, and M3a.

Unit M3b contains both olivine-augite-alkaline basalt (hypersthene normative) and olivine-subalkaline basalt (quartz normative) (Neuhaus, 1989). The olivine-augite alkaline basalt is generally intersertal to hyalophitic and contains 16% olivine phenocrysts (Mg_{80} Fe_{20}). Other phenocrysts include, in order of decreasing abundance, diopsidic augite, biotite, and leucite. The groundmass consists of, in decreasing order of abundance, plagioclase (An_{47}), brown glass, opaque oxides, biotite, pigeonite, and aegirine-augite. Gas cavities are filled with calcium carbonate, chalcedony, and clay and are radially surrounded by laths of clinopyroxene. In contrast, the olivine-subalkaline basalt has an intergranular texture, no pyroxene phenocrysts, olivine phenocrysts that suggest xenocrysts, less mica, opaque oxides, and no feldspathoid minerals. Whole rock K-Ar ages range from 19 to 15.5 Ma (Table 1).

Hornblende latite dome flow (Unit M4)

A hornblende latite dome in the southeastern corner of the study area was dated at approximately 17.4 Ma. This unit forms a prominent mountain located on the southeastern portion of the study area (Loc. 237, Plate I), and seems to intrude both Unit M1b breccia and Unit M3b basalt. Another small dome is located on the southeastern flank of Cerro Starship. It contains more phenocrysts of oxyhornblende and less silica than the larger dome and was dated at approximately 15.2 Ma (Sample 219, Table 1; Figure 4).

Acicular oxyhornblende (13%), minor plagioclase, and quartz phenocrysts occur in a hyalopilitic seriate groundmass. The glass-rich groundmass contains magnetite, plagioclase, zeolite and apatite.

Basaltic andesite and related dikes (Unit M5)

Basaltic andesite dome-plug intrusions and dome flows form an arcuate band around Unit M1b (Plate I). Tabular flows of basaltic andesite cap basalt flows along the western coast of southwestern Isla Tiburón (not shown on Plate I). Fresh hand samples exhibit a felty to silky appearance, but sericitization and chloritic mineralization are common. The rock is massive and medium gray (2.5Y N6/).

The texture is trachytic to variolitic with pyroxene glomerocrysts. Orthopyroxene is more common in brown high-silica, varieties. Groundmass crystals are 80 to 90% plagioclase, 7 to 12% orthopyroxene, and 2% opaque oxides and green mica.

The brown silicic rock of this unit (sample location 242) exhibits a more felty, trachytic texture than the gray variety. Plagioclase microphenocrysts of this rock type exhibit sieve textures, and in some examples, plagioclase has replaced pyroxene. Glomerocrysts are composed of twinned augite and orthopyroxene clustered with biotite. This unit yielded dates of 17.40 ± 0.40, 17.07 ± 0.5 and 15.24 ± 0.54 Ma (Table 1 and Figure 4).

Dacite (Unit M6)

This crystal-rich dacite has a glomerophyric hypocrystalline texture with seriate orthophyric groundmass. Hypersthene, biotite, and oxyhornblende are the dominant mafic minerals. Phenocrysts are dominantly glomerocrystic alkali feldspar and plagioclase (An_{43}), biotite, hornblende, and hypersthene. The groundmass contains stubby feldspar prisms (65%) and glass (25–30%), pigeonite, biotite, hematite, and secondary calcium carbonate. In hand sample it displays abundant euhedral phenocrysts of feldspar (2 to 3 mm), biotite, and minor hornblende in a brown glass matrix. A flow is dated at 14.96 ± 2.17 Ma (Table 1; Figure 4).

Dacitic andesite breccia (Unit M7)

Unit M7 breccia tuff consists of three facies: welded, unwelded, and autobrecciated. Unwelded breccia tuff consists largely of dacitic blocks (6 cm to 1 m) in a matrix of ash and lapillae. Outcrops display segregation pods and pipes. The block-to-matrix ratio varies from 1:2 to 1:1. The chemistry of blocks varies from hypocrystalline rhyodacite to andesite. The breccia tuffs may be unimodal, bimodal, or polymodal. The texture of Unit M7 varies from polymodal breccia flow to unimodal autobreccia. Unwelded ash flow breccia is present in some portions and contains dacitic blocks from 6 cm to 1 m in diameter in a matrix of ash and pumice lapilli. The ash-flow breccia may have extruded along fractures associated with a cauldron rim (Cas and Wright, 1987).

The welded ash-flow breccia tuff matrix is hypocrystalline with seriate plagioclase, alkali-feldspar, and montmorillonitized glass. Portions contain pale-pink to grey, hydrothermally altered lithic fragments containing minor augite and hornblende. Hydrothermally altered fragments of andesite contain abundant plagioclase, augite, hornblende, and opaque oxides. The highly altered groundmass of the andesite fragments is hematite-stained and veined with chalcedony.

Dacitic andesite is a common clast type in the ash-flow breccia. The dacitic andesite is a seriate, crystal-rich hypocrystalline rock with glomerophyric hornblende and pyroxene and an intersertal to hyalopilitic texture. Phenocrysts are plagioclase with diameters of from 2 to 10 mm. Hypersthene and augite xenocrysts are intensely fractured. Some plagioclase is replaced by pyroxene. Phenocrysts of quartz and biotite are rare. The groundmass constitutes 32% of the rock and consists of brown glass with crystallites. Groundmass crystals include plagioclase, aegirine augite, apatite, zircon, and rutile. The unit includes an andesite breccia dated 11.4 ± 2.6 Ma (Table 1).

Marine deposits of Miocene age (Unit M8)

Marine sedimentary units are exposed over an 8 km^2 area in Arroyos I through IV, which trend approximately perpendicular to the strike of the beds (Plate I). Detailed measured sections presented by Cassidy (1989) are summarized in Figure 3. Arroyos IV and II correspond to arroyos A and B of Weaver (1979, 1981). Units M8a to M8d are, in part, laterally equivalent facies.

Marine sedimentary breccia (Unit M8a)

Unit M8a is approximately 100 to 250 m thick and consists of sparsely fossiliferous, massive to poorly bedded, marine sedimentary breccia. It was deposited unconformably on a high-relief surface on Miocene volcanic rocks or on granitic basement at some localities (see cross section BB', Plate 1). Bedding is poorly defined and discontinuous, except for small local pockets of bedded sandstone. Clasts within the breccia consist primarily of angular to subrounded volcanic boulders up to 1 m in diameter. Granitoid clasts are present. The average clast diameter is 5 cm. The breccia is poorly sorted and largely clast-supported, with a matrix of silt to coarse sand particles. Megafossils include articulated, disarticulated, and fragmental oysters and pectinids. The fine-grained matrix of this unit was carefully examined for microfossils, but none were found.

Rhyolite and andesite flows (Unit M8b)

Flows and small pods of rhyolite and andesite are interbedded with unit M8a and between Units M8a and M8c. They contain phenocrysts of feldspar and quartz and vary in color from light red to gray. A 5–1-m-thick monolithologic debris flow located along Arroyo III (cross-section BB') was dated by Smith and collaborators (1985) at 12.9 ± 0.4 Ma.

Marine sandstone (Unit M8c)

Unit M8c is exposed in Arroyos I, II, and III and is 40 to 180 m thick. It consists predominantly of fine-grained to pebbly, fossiliferous sandstone and contains local thin, discontinuous beds of conglomerate. The conglomerate beds contain subrounded to rounded volcanic rock fragments, with an average clast diameter of 3 cm and a maximum diameter of up to 30 cm. Locally, they are inversely graded. Anomalous angular to subangular clasts are located near the base of the unit. Sandstone in Unit M8c is texturally immature and consists almost entirely of volcanic rock fragments. Megafossils include pectinids, oysters, barnacles, and echinoid spines. Microfossils include both benthic and planktonic foraminifers, calcareous nannofossils and ostracods (see Tables 8 and 10 for microfossils).

Marine conglomerate with ash beds (Unit M8d)

Unit M8d is the most extensive facies of Unit M8 and contains the highest concentration of megafossils. It is exposed in Arroyos I, II, III, and IV (Plate I) and has a minimum thickness of 160 m. It consists of interbedded conglomerate and texturally immature to submature sandstone with a high silt content. Conglomerate beds are laterally continuous, 0.3 to 1.3 m thick. Immature silty sandstone beds are discontinuous, and 4 to 10 cm thick. The finer sediment of Unit M8d is bioturbated. In Arroyo IV Unit M8d conglomerate is generally clast supported, commonly in 8 to 30-cm-thick beds, rarely to 60 cm thick. Clasts are subangular to subrounded volcanic rock, with a maximum diameter of 60 cm and average diameter of 1 cm. Clast imbrication is observed in several beds. The matrix ranges from silt to coarse-grained sand. Conglomerate beds are highly fossiliferous and contain articulated, disarticulated, and fragmented pectinids and oyster shells, corals and gastropod molds. Several channels filled with pectinid shells were observed (Figure 18). Interbedded silty sandstone beds are 3 to 8-cm thick, laterally discontinuous, and 30 to 90 cm in average length. Most sandstone beds are poorly sorted, pebbly, and highly fossiliferous; some contain horizontal and vertical burrows (1–2 cm diameter). The contact between Unit M8d and the overlying ash-flow tuff is an angular unconformity.

Ash flow tuff (Unit M9)

Unit M9 is an ash-flow tuff (ignimbrite) capping Cerro Starship (Plate 1 and Figure 2). A sample was dated at 11.2 ± 1.3 Ma by Gastil and Krummenacher (1977) (Table 1). Samples of younger dikes collected by Cassidy and Neuhaus were dated at 4.16 ± 1.8 Ma (S-16) and 5.67 ± 0.17 Ma (F-316). The basal unit of Cerro Starship is a 2-m-thick pumice. It is overlain by a breccia flow (average 3 m thick), a dacite vitrophyric welded tuff (4 to 6 m thick), and a crystal-rich, white to tan, apparently effusive rhyolite (8 m thick). Total thickness of the ignimbrite succession is 45 m. The upper flow can be described as a sanidine-rich vitrophyre with a hyalopilitic texture. Minerals include ferroaugite, hornblende, biotite, hypersthene, and plagioclase. A groundmass of glass with crystallites constitutes 80% of the rock. No source caldera has been identified, suggesting the ash flow tuff came from the area of the present gulf.

Rhyolite flows and dikes (Unit M10) and fluvial conglomerate (Unit M11)

Small, flat-lying, hematite-red rhyolite in the the form of pods and coulees intrude and overlie the predominantly tilted Units M1 through M8. The flows appear to be both low-density crystal-rich (phyric) rhyolite and high-density aphyric rhyolite with eutaxitic texture. Such styles of rhyolitic extrusion and intrusion are associated with shallow subterranean magma chambers that produce numerous small pods and flows instead of a large eruption (Middlemost, 1985). These rhyolites are predominantly banded (eutaxitic) hematitic cryptocrystalline vitrophyres. Phenocrysts compose only 1 to 3% of the rock and include alkali feldspar, plagioclase, strongly pleochroic hypersthene, and biotite. Groundmass contains abundant chalcedony (30 to 40%), glass (45%), hematite (5%), magnetite (2-5%), and a trace of biotite. A rhyolite dike dated at 3.7 ± 0.9 Ma by Gastil and Krummenacher (1977) crosses Arroyo I near its mouth (Plate I). A rhyolite coulee on the east side of Cerro Starship was dated at 5.67 ± 0.46 Ma (sample 51A). Rhyolite cutting Unit M8a yielded an Ar/Ar age of 9.02 ± 1.18 Ma (Figure 4 and Table 1).

The rhyolite dikes of Unit M10 contain phenocrysts of hypersthene, sodic plagioclase and sanidine in an orthophyric to glomerophyric groundmass. The groundmass is 50% glass and contains crystals of alkali feldspar, aegerine augite, secondary calcite, chalcedony, opaque oxides, and amygdules of zeolite.

Flat-lying fluvial conglomerates of Unit M11 are interbedded with extrusive rhyolite in the southeastern portion of the study area. Southeast of the study area, the flat-lying fluvial conglomerate (Unit 11) is capped by an 18 km^2 field of dacitic ignimbrite containing a basal pumice lapilli layer overlain by a vitrophyre. The ash-flow tuff contains 3 to 4 mm alkali feldspar phenocrysts in a black glass groundmass. A K-Ar date of 5.61 Ma (Sample 239W) had high atmospheric argon and, therefore, shows a very large age uncertainty (Table 1).

PLEISTOCENE

Marine terraces

Coastal and lowland marine terraces are $CaCO_3$-cemented and rich in microfossils and megafossils, which Stump (1975) identified as Pleistocene in age. The deposits form a thin cap across the western corner of the study area and a narrow terrace along the coast (Plate I).

QUATERNARY

Stream terraces and alluvial deposits

Stream terraces located along Arroyos II and IV consist of unsorted pebble breccias and pebble conglomerate (Plate I).

SEDIMENTS, STRUCTURES AND DEPOSITIONAL ENVIRONMENT, UNIT M8 MARINE STRATA

Fan-delta deposits

Fan-deltas are "alluvial fans that prograde into standing bodies of water from adjacent highlands" and generally consist of wedge-shaped prisms of conglomeratic sediment that cover less than 1 km^2 and are less than a 1.5-km thick (Ethridge and Wescott, 1984). The Isla Tiburón sequence has a maximum preserved thickness of 1,500 m and covers approximately 8 km^2.

The marine sedimentary section of the southwestern corner of Isla Tiburón contains characteristics typical of both shelf- and slope-type fan deltas (Ethridge and Wescott, 1984). Both typically coarsen upward, but the sequence is better defined in the shelf-type model; conglomerates in Arroyo IV display this trend. Many individual beds are inversely graded, and although average clast diameter stays fairly constant throughout this section, maximum clast diameter increases from 4 cm near the bottom of the section to 30 cm near the top. Upsection, average and maximum clast diameters are generally greater, but no smooth trend toward more coarse material was observed. This poorly defined coarsening-upward trend seems to fit the slope-type fan delta model. Slope-type fan deltas typically have a marine-nonmarine transition zone characterized by fossiliferous conglomerate and sandstone that are well-sorted and horizontal, with seaward-dipping imbricated clasts. In contrast, clast imbrication in Arroyo IV, Unit M8d, is away from the direction of dip.

Fan delta deposits worldwide are texturally immature to submature, as are those of southwest Isla Tiburón; they suggest close proximity to the source area (Ethridge and Wescott, 1984). All of the rock types within the conglomerate crop out within 3 km. Many of the beds are inversely graded, suggesting deposition on steep proximal slopes of the fan delta (Nemec and Steel, 1984). Textural maturity tends to decrease upsection, with clasts varying from rounded to subrounded near the base and subangular to subrounded near the top. This variation could represent a change in source proximity or progradation of the fan. Remnants of pinnid (pen shell) beds and other organisms in growth position are evidence against classifying Unit M8d as a debris flow (Figure 16).

Ephemeral flood deposits

Most of the marine section is well sorted, with some atypical "boulder beds" that contain generally sub-angular clasts that vary widely in size: maximum diameters measure as much as 60 cm. Such "flashy" flood deposits (Nemec and Steel, 1984) can result from marine deposition by ephemeral floods. A few beds within Unit M8 in Arroyo IV are texturally very immature, unfossiliferous, and dominated by conglomerates with subangular clasts. Such deposits are generally conformably overlain and underlain by fossiliferous units and could be the products of ephemeral floods.

Fan delta fringe deposits

Units M8c and M8d contain beds of fossiliferous sandstone that vary from fine to coarse grained and contain subrounded to rounded clasts. Some are bioturbated, and none show diagnostic sedimentary transport structures. Most contain microfossils, which indicate deposition at no more than 50 to 150 m of water. This is consistent with fan-delta fringe deposits or sandstones deposited on the prodelta slope.

Clasts

All of the units contain outsized clasts, the isolated megaclasts of Nemec and Steel (1984). The presence of these outsized clasts may result from more coarse material being trapped within fully turbulent subaqueous gravity flows when the sediment freezes as a fairly uniform dispersion (Nemec and Steel, 1984).

Clast imbrication away from the direction of dip is present throughout the section and is well developed in Arroyo IV. Fifty clasts from each of seven individual beds were analyzed. Cassidy (this paper) concluded that the clasts were oriented during deposition in the subaqueous portion of a fan-delta and that the paleocurrent directions were in the range of S5°E to S60°W.

DISCUSSION

The lack of a significant amount of very fine grained deposits seems to indicate that the debris flows that compose the majority of this unit belong to the category of cohesionless gravity flows (Nemec and Steel, 1984). The majority of the beds in Arroyo IV are less texturally mature, contain less well-sorted subangular to subrounded clasts, and have a higher matrix content than the beds in other portions of the section.

This ungraded fossiliferous conglomerate could be the result of deposition at a submarine slope break under hydraulic jump conditions (Nemec and Steel, 1984).

STRUCTURE

Isla Tiburón lies east of a major Gulf of California transform fault that separates it from Isla Esteban to the south; it is within the Coastal Tilt Domaine of Stewart and Roldán-Quintana (1994). The study area has only one main fault system, possibly a continuation of the La Cruz fault (Gastil and Krummenacher, 1977), which crosses the southern edge of the island (Figure 1). The fault trends north to northwest in Arroyo II and has no more than a few hundred meters of right lateral displacement.

Stratigraphic units in the area generally show greater dip with greater age (Neuhaus *et al.*, 1988):

Unit M1a redbeds (early Miocene):	40-55° north
Unit M3 lapilli tuff (19 Ma):	16° north
Unit M4 basalt (19-15 Ma):	15-23° northwest
Unit M8 conglomerate (12-15 Ma):	15-20° northeast
Unit M10 ignimbrite (11 Ma):	4-8° northwest
Younger volcanic units:	horizontal

Exceptions to the above occur at Ensenada Blanca, where redbeds seem to dip more steeply as a result of faulting associated with volcanic intrusion (Plate 1). Elsewhere in the western area, redbeds and basalts are horizontal, apparently because they directly overlie granitic basement that has remained relatively stable.

The widespread tilting in the southwestern corner of Isla Tiburón may result from normal faulting associated with regional extension. Gastil and Krummenacher (1977) noted that most normal faults of the coastal Sonoran region and southwestern Arizona trend northwest-southeast, suggesting a predominantly northeast-southwest extension direction (Boehm, 1987). Similar faulting associated with Basin and Range extension occurred throughout the area surrounding the Gulf of California as far south as Nayarit, Mexico (Henry, 1989; Henry and Aranda-Gómez, 1992). Normal faults may be tied at depth to southwest-dipping detachment surfaces inclined toward the center of the gulf (Gastil and Fenby, 1991). In this model, most beds dip northeastward, away from the center of extension.

K-Ar GEOCHRONOLOGY (Table 1 and Figure 4)

Gastil and Krummenacher (1976) provided the first K-Ar dates on Miocene volcanic rocks for Isla Tiburón and adjacent coastal Sonora. Additional K-Ar dates were obtained by Krummenacher (*in* Neuhaus, 1989), Smith and collaborators (1985), Damon (*in* Neuhaus, 1989), and unpublished work by Shafiqullah and Ferrar.

Gastil and Krummenacher's regional map of Isla Tiburón and coastal Sonora between Puerto Lobos and Bahía Kino shows calc-alkaline rocks, largely andesite to rhyolite, having attitudes that differ with age. Rocks older than 9 Ma are nearly everywhere tilted; those less than 9 Ma are generally flat-lying. Subsequent work has shown that the southwestern corner of Isla Tiburón contains rocks that range more widely in both age and composition than those found by Gastil and Krummenacher (1976, 1977) in coastal Sonora.

As part of this study, 19 K-Ar and three Ar-Ar dates were obtained from 21 samples of 10 different volcanic units from southwest Isla Tiburón (locations shown on Plate 1). Dating was performed at the Baylor Brooks Institute of Isotope Geology, San Diego State University; the University of Arizona Isotope Geochemistry Laboratory; the USGS in Menlo Park, California; and Queens College, Ontario (Ar-Ar).

For subsequent theses Neuhaus (1989) and Cassidy (1989) collected mineral samples to date the volcanic units of the entire stratigraphic sequence (Table 1). For the rocks underlying the marine section, K-Ar ages agree with those reported in Gastil and Krummenacher (1977) and are consistent with the mapped stratigraphic succession. Unpublished dates obtained from Krummenacher and Damon (K-Ar), and Farrar (Ar/Ar) in this study are also in agreement. The date of sample 284 (17.7 Ma) showed that the strata of Unit M8 rest on considerable topographic relief (units M8a and M8b are in depositional contact with 15 to 17.6 Ma andesite and rhyolite). Sample 276 in Unit M7 is an andesite breccia (believed to be extrusive) immediately underlying Unit M8a and dated at 11.44 ± 2.61 Ma. The USGS laboratory in Menlo Park obtained a K-Ar date of 12.9 ± 0.4 Ma (sample number B2BS1260P from Unit M8b; Smith *et al.*, 1985). This locality is near a minor fault that may be part of the De la Cruz fault system, but the amount of offset, less than 500 m, does not displace the dated volcanic rock appreciably from the underlying marine strata. The apparent conflict with the Smith sample (being older and apparently upsection), located within or just below Unit M8b, can be explained by overlapping error bars that indicate close ages within the limits of analytical error.

In hopes of reproducing the date on the capping rhyolite of Cerro Starship reported in the 1976 study, Neuhaus and Cassidy collected rhyolite from the ridge and obtained a K-Ar age of 4.16 ± 1.81 Ma on feldspar (sample S10 on Plate 1, and Table 1). Because rhyolite dikes line up with the ridge, and are probably present on it, Neuhaus and Cassidy concluded that they had collected a younger dike rock. They obtained a second sample, 51F, from airfall strata immediately above the tilted marine strata. Shafiqullah (*in* Cassidy, 1989) obtained an age of 5.67 ± 0.46 Ma on this sample (sample 51F, Table 1).

To reconfirm the Smith K-Ar date (B2BS1260P), on a debris flow stratigraphically within the marine section, Neuhaus and Cassidy searched for other volcanic horizons with datable material. There are many horizons of bedded ash within the marine section, however crystals are generally not

Table 1. K-Ar and Ar-Ar data for volcanic rocks of southwestern Isla Tiburón.

Potassium/Argon Age Data

Sample number	K (Av %)	Rad Ar m/g-10^{-10}	At Ar (%)	Age (Ma)	Unit
150 W *	1.369	0.455	69	19.1 ± 0.6	M2
1 H +	0.577	0.2064	26.1	20.5 ± 0.5	M2
15 F +	1.945	0.7137	55.1	21.0 ± 0.5	M1b
274 W *	1.520	0.4904	55.07	18.52 ± 0.68	M3b
145 W *	0.994	0.3089	29	17.80 ± 0.6	M3b
223 W *	0.960	0.2956	72.48	17.67 ± 1.4	M3b
223 F +	1.000	0.3307	38.1	19.0 ± 0.4	M3b
252 F +	1.286	0.3964	17.2	17.7 ± 0.5	M3b
106 W *	1.798	0.5885	53.99	15.30 ± 0.54	M3b
237 F +	2.383	0.7218	27.4	17.4 ± 0.4	M5
219 W *	1.845	0.4805	82.88	14.96 ± 2.17	M6
272 W *	1.523	0.4040	54.17	15.24 ± 0.54	M5
216 W *	1.713	0.4448	64.18	14.92 ± 0.8	M10
275 W *	2.958	0.3138	82.24	6.11 ± 1.81	M11
51 F +	2.923	0.2876	62.5	5.67 ± 0.17	M9
10 W *	2.581	0.1865	93.53	4.16 ± 1.81	dike, M9
239 W *	1.727	0.1683	97.91	5.61 ± 7.89	**
B2BSJ 260 P•	0.463	1.032	76	12.9 ± 0 .4	M8b
2B-27 *	4.63	0.9230	48	11.2 ± 1.3	M9

Argon/Argon Age Data

	K (approx %)	Ar39 ΣPA (%)	Age	Unit
5 P Δ	0.22	86.6	9.02 ± 1.18 plateau	Dike cutting Unit M8a
276 F Δ	0.33	77.7	11.44 ± 2.61 plateau	M7
284 H Δ	0.41	86.3	17.68 ± 0.15 plateau 17.91 ± 0.38 integrated	M5

*Krummenacher, San Diego State, California
+ Damon and Shafiqullah, U. Arizona
• Smith, USGS
Δ Farrar, Queens University, Ontario, and Renne, Institute of Human Origins
H: hornblende; P: plagioclase; F: feldspar; W: whole rock
**to the east of mapped area

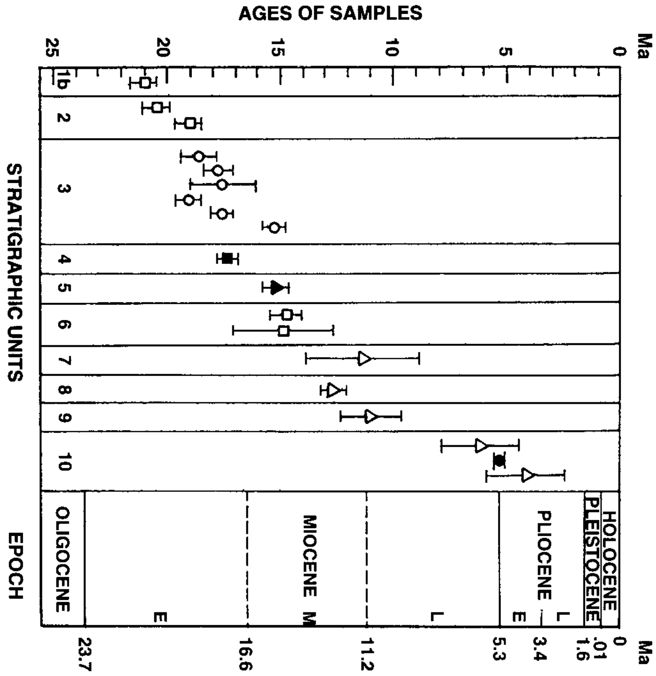


Figure 4. Potassium/Argon and Argon/Argon ages. Graph of K-Ar and Ar-Ar volcanic rock dates plotted against stratigraphic units (M numbers on Plate I). Data are shown on Table 1. Time scale from the Decade of North American Geology. (Modified from Neuhaus, 1989, fig. 6). Open circle: basalt; open square: andesite; black square: latite; open triangle: rhyolite; black triangle: basaltic andesite.

adequately preserved. A volcanic dike (Sample 5P) dated by Ar/Ar as 9.02 ± 1.10 Ma (Table 1) indicates that Unit M8a, the sedimentary breccia, was already in place by that time.

Southeast of the mapped area is a sequence of nonmarine conglomerate and sandstone strata containing dacite and rhyolite sills and flows unconformably overlying all older strata, including the tilted marine strata (Unit M8). This unit is capped by a flat-lying dacite ignimbrite that covers about 18 km^2 (Gastil and Krummenacher, 1976). An exposure near the base of the nonmarine sequence yields an age of 6.11 ± 1.31 Ma (sample 375W, Table 1). These dates for flat-lying volcanic rocks suggest that the strata deposited after 5 or 6 Ma are nonmarine and untilted.

GEOCHEMISTRY

MAJOR ELEMENT CHEMISTRY OF VOLCANIC ROCKS (Table 2 and Figures 5–10)

Major element chemistry for the southwestern corner of Isla Tiburón volcanic rocks is shown in Table 2. The data show generally linear trends on Harker diagrams (Figures 5 and 6). Basalts, with the exception of one sample, plot alkalic. The balance of the suite is composed of andesite, dacite, and rhyolite (Figure 6) (Kuno, 1968). The MgO-FeO*-Al_2O_3 ternary diagram (Figure 8) (Pearce *et al.*, 1977) discriminates tectonic environments for rocks with silica between 50 to 60%; appropriate the southwestern corner of Isla Tiburón rocks plot in the orogenic field except for one basalt, which plots in the "Ridge and Floor" field.

MgO vs. TiO_2 and Ti vs. Zr (Figures 9 and 10) have been plotted to compare the southwestern corner of Isla Tiburón volcanic rocks with those of other localities around the northern part of the Gulf of California, including middle Miocene samples from the Alverson Formation (Gjerde, 1982), Jacumba volcanics (Hawkins, 1970), and Chocolate Mountain volcanics (Crowe, 1978). All Imperial Valley/Salton Trough localities display chemistries overlapping those of the "oceanic" and "continental" crusts (Mehegan *et al.*, 1989; Herzig,

Table 2. Major and selected minor elements, weight percent and ppm, from southwest Isla Tiburón, Gulf of California, Mexico.

Sample number	Unit symbol	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
150	M1B	59.2	1.00	16.65	4.77	0.07	3.17	6.94	3.48	1.66	0.29	3.20	100.38
1	M1B	58.5	1.02	16.66	7.88	0.06	3.75	6.38	3.06	2.00	0.27	2.40	99.50
202	M1B	59.1	1.04	16.36	5.01	0.07	4.00	7.22	3.01	1.87	0.27	2.46	100.39
66	M2	60.06	0.62	16.34	4.46	0.11	2.22	6.60	3.19	2.95	0.25	4.40	100.19
130	M2	58.25	0.64	17.5	5.43	0.11	1.58	6.28	3.66	2.23	0.23	4.10	99.99
274	M2	60.17	0.56	16.5	4.53	0.07	2.95	4.87	3.34	3.13	0.22	2.53	99.35
129	M3	50.9	1.01	15.2	6.86	0.13	9.85	8.02	3.13	2.40	0.49	2.40	100.43
106	M3	48.9	1.27	14.0	7.69	0.15	8.68	8.82	3.31	1.95	0.73	2.69	100.73
274	M3	48.0	1.38	13.4	7.68	0.14	11.32	9.04	2.85	1.86	0.91	3.11	99.65
145	M3	49.3	0.95	15.8	7.81	0.15	10.86	8.53	3.73	1.10	0.38	0.73	99.38
252	M3	48.8	0.94	15.7	7.82	0.13	10.82	8.67	3.48	1.36	0.37	1.55	99.67
223	M3	50.3	0.89	15.35	7.54	0.14	10.5	8.40	3.29	1.07	0.27	2.65	100.41
221	M3	51.2	1.10	15.56	7.26	0.13	8.87	7.94	3.38	2.29	0.49	2.09	100.26
237	M4	61.95	0.69	17.35	4.10	0.07	2.04	4.91	3.23	3.67	0.27	1.06	99.37
272	M5	54.75	1.03	17.85	6.61	0.10	4.47	7.55	3.10	1.78	0.29	1.98	99.51
159	M5	55.49	1.00	16.8	5.76	0.07	6.54	8.01	3.53	1.38	0.30	1.13	100.05
11	M5	57.1	0.93	17.48	5.8	0.11	5.45	6.95	3.72	1.66	0.34	0.86	99.74
242	M5	59.4	0.75	15.9	4.61	0.05	5.13	6.21	3.68	2.51	0.26	1.18	99.71
219	M5	58.29	1.09	16.50	5.27	0.08	3.82	6.94	3.32	1.84	0.34	1.62	99.11
263	M6	58.71	0.69	16.3	4.82	0.08	3.11	6.16	3.89	2.14	0.23	1.56	98.24
216	M6	60.87	0.70	12.3	4.49	0.09	3.48	5.62	3.96	2.03	0.23	1.51	100.26
84	M6	63.1	0.53	16.04	3.80	0.07	2.64	5.27	3.46	2.41	0.21	1.35	99.33
276	M7	69.10	0.38	16.00	2.67	0.044	*1.45	4.22	*5.33	1.29	0.12	0.33	100.60
76	M9	67.7	0.44	15.4	3.03	0.06	0.82	2.43	5.10	2.45	0.10	2.07	99.58
76	M9	70.3	0.34	14.8	2.33	0.03	0.82	1.93	4.29	3.95	0.09	1.34	100.26
51	M9	72.6	0.33	13.7	3.12	0.06	0.64	1.36	4.34	3.65	0.07	0.56	100.46
275	M9		0.42	14.3	2.73	0.06	0.73	1.74	4.74	3.61	0.09	0.48	99.11
10	M9	69.6	0.31	14.5	2.32	0.05	0.90	1.67	4.27	3.43	0.08	3.50	100.62
4.164	M9	71.9	0.22	14.2	1.81	0.04	0.79	1.35	4.14	3.78	0.06	2.09	100.42
239	M10	62.2	1.04	15.9	6.45	1.5	1.75	3.99	4.48	2.05	0.33	2.04	100.30
64	M10	72.2	0.41	14.3	2.87	0.05	0.70	1.51	4.46	3.82	0.08	0.46	100.87
5	M10	70.19	0.43	14.12	2.81	0.045	•0.24	1.84	*6.28	3.45	0.08	0.62	100.21

*may be high; •may be low

Sample number	Unit symbol	Rb	Sr	Ba	Zr	Sample number	Unit symbol	Rb	Sr	Ba	Zr
150	MIB	—	—	—	—						
1	M1B	40.6	1314	614	308	11	M5	—	864	1648	314
202	M1B	44.4	1272	518	312	242	M5	—	—	—	—
66	M2	—	—	—	—	219	M5	—	—	—	—
130	M2	—	—	—	—	263	M6	54.8	781	1591	219
274	M2	68.9	662	1119	178	216	M6	49.3	840	1576	224
129	M3	—	—	—	—	84	M6	—	—	—	—
106	M3	—	1195	1257	520	276	M7	—	—	—	—
274	M3	40.5	1211	1538	602	76	M9	—	—	—	—
145	M3	69.3	—	—	—	51	M9	—	—	—	—
252	M3	44.2	721	827	276	275	M9	120	136	1169	277
223	M3	28.55	563	703	234	10	M9	—	—	—	—
221	M3	29.81	—	—	—	4.164	M9	131.6	100.9	1300	178
237	M4	60.0	970	760	281	239	M10	59.5	250	742	340
272	M5	—	911	—	—	64	M10	126	111	1115	331
159	M5	41.5	—	—	—	5	M10	—	—	—	—

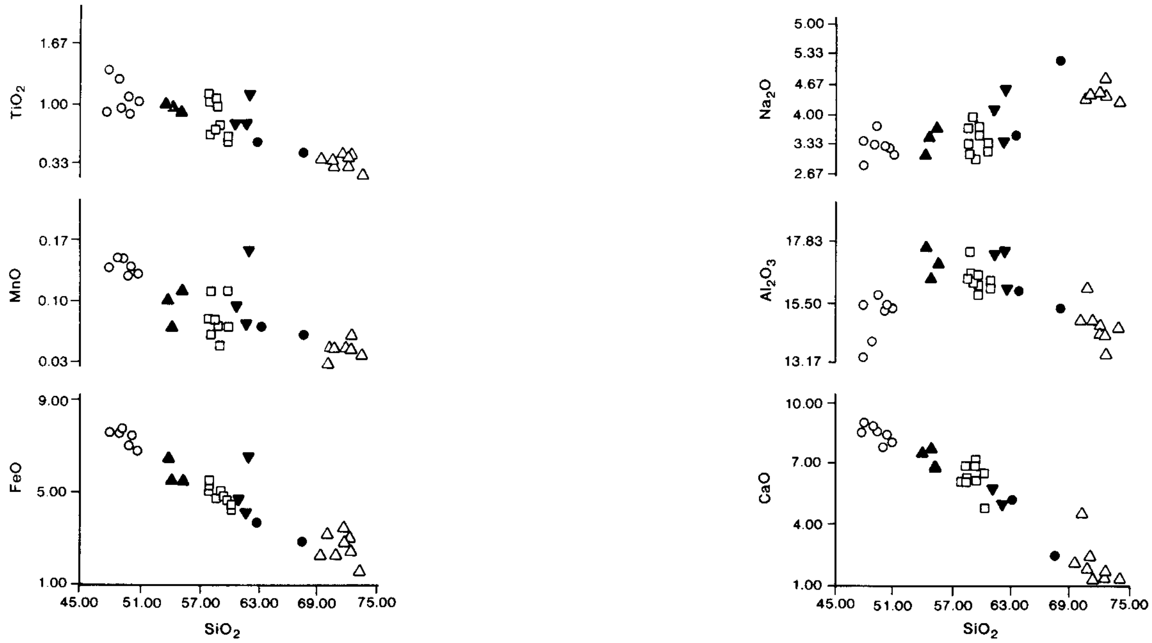


Figure 5. Harker diagrams for titanium, manganese, iron, sodium, aluminum and calcium. Open circle: basalt; black circle: dacite; open square: andesite; black triangle: basaltic andesite; open triangle: rhyolite; inv. black triangle: dacitic andesite.

1990; Sawlan, 1991). Basalts of the Alverson Formation and the Jacumba area plot in the oceanic portion of the diagram primarily as a result of their high MgO contents. Basalt chemistries of the southwestern corner of Isla Tiburón are consistent with Basin and Range type basalts (Leeman and Rogers, 1970).

In looking at volcanic geochemistries covering an interval of 15 Ma in an area that was alternately or perhaps contemporaneously undergoing detachment-style extension, arc volcanism, and finally rift-transtension, one might expect changes in the chemical character of the erupted volcanic rocks consistent with changes in the tectonic environment. Early volcanism of the southwestern corner of Isla Tiburón (19 to 21 Ma) is characterized by the eruption of both alkaline basalt and subalkaline andesite. Later eruptions are subalkaline (Figure 10), and the youngest volcanic rock analyzed (sample 51a) plots tholeiite on the basis of FeO/MgO - SiO_2 (Miyashiro, 1974).

The most obvious pattern is the trend toward more siliceous volcanic rock with time; Harker diagrams for iron, calcium, and aluminum illustrate the apparent relationship between all of the volcanic rocks (Figures 5 and 6). Data are consistent with mantle-derived alkaline basalt and andesite, subsequent dacite and rhyolite differentiates, with a new pulse of mantle-derived tholeiite starting about 5 Ma.

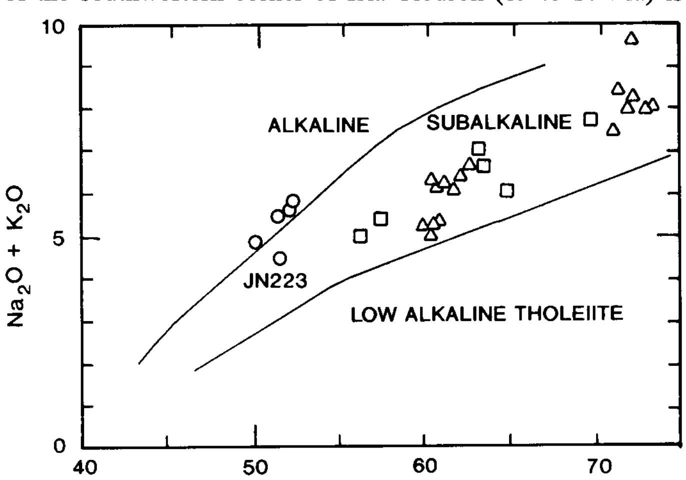


Figure 6. Alkali vs. silica. Fields given for alkaline, subalkaline, and low alkaline tholeiite after Irvine and Barager (1971) and Kuno (1968). (After Neuhaus, 1989, fig. 10). Open circle: basaltic andesite; open square: andesite; open triangle: rhyolite. Sample JN 223 is subalkaline and contains greater amounts of plagioclase than other basalts analyzed.

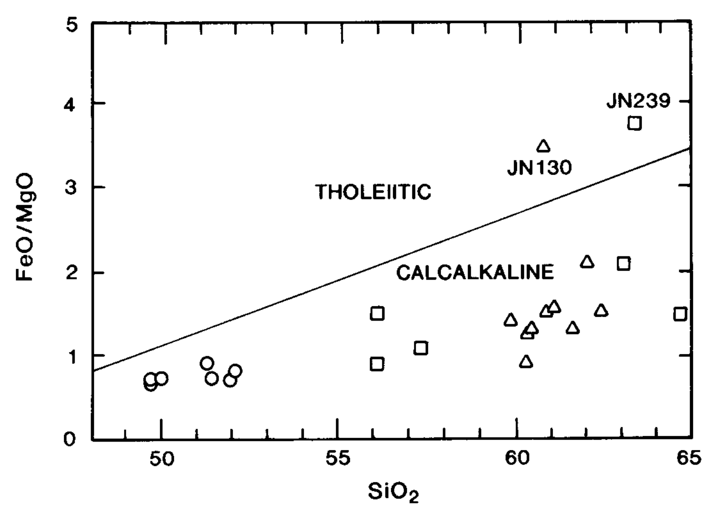


Figure 7. FeO*/MgO/SiO_2, separation into calc-alkaline and tholeiitic fields after Miyashiro (1974). FeO* = total iron as FeO. Open circle: basalt; open square: andesite; open triangle: rhyolite. The southwestern Isla Tiburón volcanic suite has primarily a calc-alkaline trend, with the exceptions of two tholeiitic samples: JN 130 (Unit M1b) and JN 239, a dacite ash flow tuff dated at 4.16 ± 1.81 Ma (Neuhaus, 1989, fig. 3b).

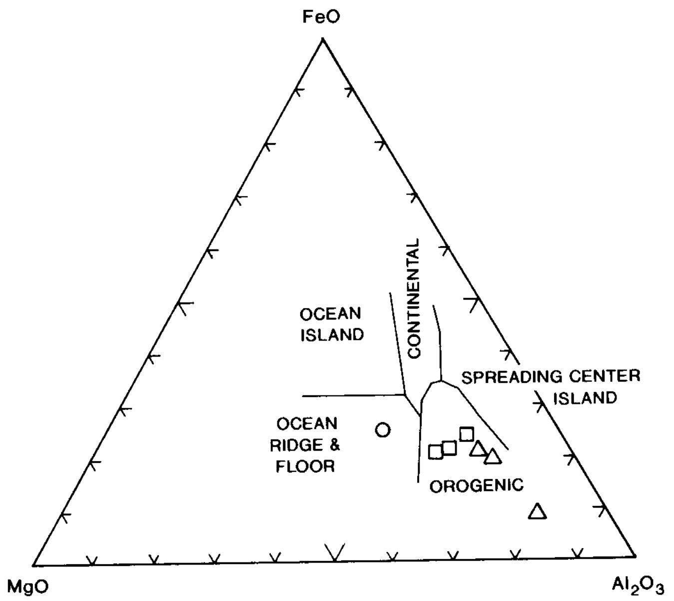


Figure 8. MgO, FeO*, Al_2O_3 fields interpreted for tectonic origins of basalts and andesites (after Pearce *et al.*, 1977): FeO* is total iron expressed as FeO (after Neuhaus, 1989, fig. 14). Open circle: basalt; open square: andesite; open triangle: rhyolite.

STRONTIUM ISOTOPE INITIALS (Table 3)

The low Sr initial of sample JNA-1 suggests that this andesite was a primary (mantle-derived) melt. Such low initial andesite could be a result of crystal fractionation and M2 andesite (Sr_i=0.7031) could have formed basaltic andesite (Sr_i=0.7034). The dacitic andesite, with a Sr_i of 0.7047, could be rhyolitic magma contaminated by low initial andesite (0.7031). The Sr initials are compatible with contamination of a mantle wedge enriched by hydrous fluids from the subducted slab, the upper portions of which include sediment and hydrated basalt. Sr_i initials of southwestern Isla Tiburón are consistent with those for Basin and Range rocks across Baja California and Chihuahua (0.7044 to 0.7050), which show no evidence of significant continental crust interaction (Cameron *et al.*, 1980; Cameron and Cameron, 1981).

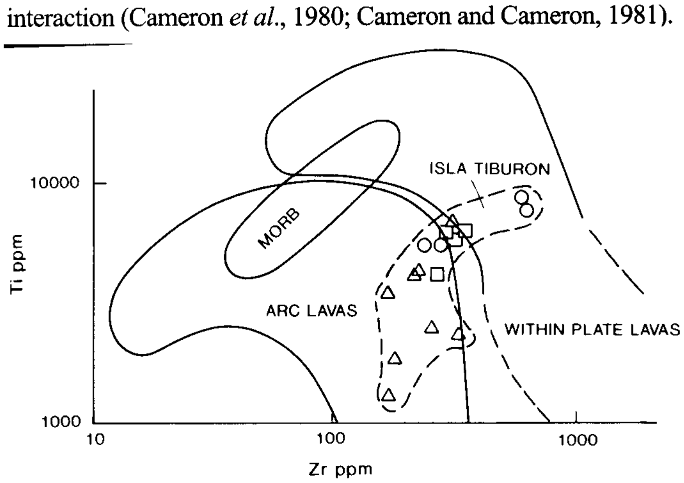


Figure 9. Titanium vs. zirconium (after Pearce, 1982). Covariation diagram showing fields of within plate and arc lavas, compared to data for mid-ocean ridge basalt (MORB) volcanism and southwestern Isla Tiburón, Sonora, Mexico (Neuhaus, 1989, fig. 17). Open circle: basalt; open square: andesite; open triangle: rhyolite.

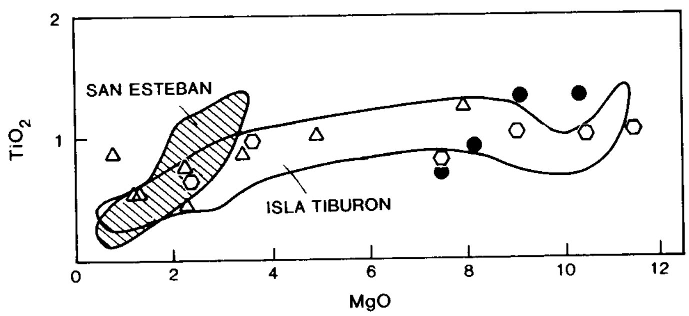


Figure 10. MgO plotted against TiO_2 to compare fields of volcanic rocks from southwestern corner of Isla Tiburón, Sonora, Mexico, with those of other northern Gulf localities. Isla San Esteban is shown in oblique line pattern; Chocolate Mountains rocks are shown as triangles; the San Felipe area of Baja California is shown as octagons; the Alverson Formation of Coyote Mountains as circles (after Herzig, 1990); additional data from Sawlan and Smith (1984), master's theses by Desonie (1985) and Gjerde (1982). McDougall and others (in press, fig. 1) include a map that shows these areas.

RARE EARTH ELEMENTS (Table 4 and Figure 11)

A middle Miocene basalt, a middle Miocene andesite, and a latest Miocene rhyolite were analyzed for rare earth elements and normalized according to Boynton and Wack (1984) (Table 4). Although the andesite and basalt represent the earlier "arc" tectonic framework and the rhyolite represents the late rift-spreading tectonics, the characters of the profiles are very similar (Figure 11). The presence of a europium anomaly for only the arc andesite suggests that the early basalt and late rhyolite are both derived from a depth below the stability of plagioclase, whereas the middle Miocene andesite is a plagioclase-depleted differentiate of the basalt.

GEOLOGIC HISTORY

Redbed deposition occurred in the early Miocene in the Isla Tiburón area. Sediment transport directions suggest that the source region for these deposits was to the northeast. Similar redbed deposition occurred in southwestern Arizona through much of the early to middle Tertiary during a period of intense block-faulting and erosion (Eberly and Stanley, 1978).

Table 3. Strontium isotope data, southwestern Isla Tiburón.

whole rock sample	map unit	Sr initial	Rb (ppm)	Sr (ppm)	Sigma	SEM
JNA1	M3	.70311	29	1327	.00024	.00008
274	M4	.70501	72	1383	.00027	.00009
223	M4	.70557	19	595	.00012	.00004
272	M6	.70340	24.6	1102	.00020	.00007
216B	M8	.70467	40.5	884	.00018	.00006
275	M11	.70497	121	107	.00016	.00005
G2-16	M11	.70463	120	53	.00023	.00008

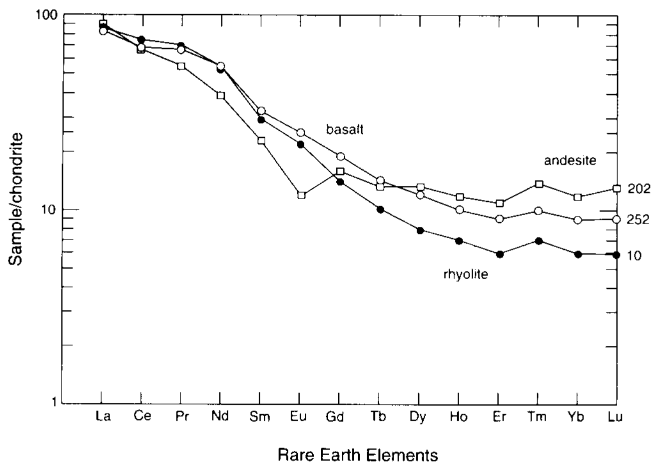


Figure 11. Spider diagram showing normalized rare earth element analyses for three rocks from southwestern Isla Tiburón, Sonora, Mexico. Normalization according to Boynton and Warck (1984). Black circle: rhyolite; open circle: basalt; open square: andesite.

Volcanism on the southwestern corner of Isla Tiburón began around 21 Ma with the extrusion of hornblende andesite. Similar "medium K" andesite is found along the eastern side of Baja California from 25 to 10 Ma (Sawlan and Smith, 1984; Hausback, 1984). The belt of medium-K andesite extends from Baja California Sur near La Paz north to the Imperial Valley, California, and eastward into Sonora (Gastil *et al.*, 1979). The 21–19 Ma andesite of the southwestern corner of Isla Tiburón (alkali-lime index = 61; Neuhaus, 1989) has a similar age and chemistry.

A majority of this arc deposition (Unit M3b) is believed to have occurred 18-22 Ma (Gastil *et al.*, 1979). Hausback (1984) has characterized the belt as an arc (alkali-lime index = 60) consisting largely of andesitic flows and lahars and rhyolitic ash-flow tuffs. The principal basaltic volcanism on the southwestern corner of Isla Tiburón occurred from 19 to 15.5 Ma. These basalts are predominantly olivine-augite alkaline basalt, with minor subalkaline olivine and quartz normative basalt.

Alkaline and tholeiitic basalt volcanism (Figures 6, 12) is believed to correspond to the onset of extension of the Basin and Range and the formation of the protogulf (Sawlan and Smith, 1984; Christiansen and Lipman, 1972; Stock and Hodges, 1989; Hausback, 1984; Henry, 1989; Henry and Aranda-Gómez, 1992).

Boehm (1982) placed the time of incipient Basin and Range extension, which formed a pre-protogulf nonmarine structural trough in northeastern Baja California, at 17 to 15 Ma on the basis of major changes in transport direction (from westward to eastward) and deposition of a thick sequence of lacustrine sediments. Alkaline basalt of the northern gulf area is very similar to that of the southwestern corner of Isla Tiburón, not only in age and mineralogy, but also in markedly high Mg, Ba, Sr, and K (Gjerde, 1982). The Alverson Formation of western Imperial County contains alkaline and subalkaline basalt, as well as basaltic andesites similar in mineralogy, chemistry, and age to those of the southwestern corner of Isla Tiburón. These and other basalts in the northern gulf region are similar to "Basin and Range basalts" in their age and their predominantly alkaline olivine basalt composition. The basalts also share high percentages of incompatible elements, intergranular and intersertal textures, and associated basaltic andesite "differentiates" (Leeman and Rogers, 1970).

Basin and Range type basalt originates from high H_2O magmas (2%) and may be derived through low percentage melting of a spinel or plagioclase peridotite parent material at 25 to 55-km depth (Green and Ringwood, 1968; MacGregor, 1968; Leeman and Rogers, 1970). Basalts exposed on the southwestern corner of Isla Tiburón contrast with the average Basin and Range olivine alkaline basalts of Leeman and Rogers (1970) in that they have slightly higher MgO, K_2O, and SiO_2, slightly less CaO and TiO_2; and more incompatible elements. The high and variable abundances of incompatible elements and high MgO of the Isla Tiburón-type rocks suggest that a refractory mantle had later been enriched by metasomatic processes, possibly involving hydrous fluids of a subducted slab (Sawlan and Smith, 1984). Subsequently, andesitic to dacitic pyroclastic flows erupted between 15 and 11 Ma on Isla Tiburón, possibly from remnant heat of basaltic volcanism and extensional thinning. These eruptions were likely the final stages of the medium-K arc along the eastern Baja California peninsula and then-adjacent Sonora and are concordant with the initiation of the marine incursion recorded on Isla Tiburón (Smith, 1991b). Pyroclastic parent melts were forming in a caldera-like depression (southeastern part of area), and pyroclastic explosions shed tuffaceous material into the marine basin. K-Ar dates put the timing of initial marine deposition in the Isla Tiburón area at mid-middle Miocene (marine beds lie both above and below a volcanic debris flow dated at 12.9 ± .4 Ma).

Table 4. Rare earth elements, actual values in ppm, from volcanic rocks, southwest Isla Tiburón.

Sample number	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
10	29.08	62.34	6.75	24.66	4.67	0.94	4.35	0.70	4.30	0.91	0.6	0.70	0.60	0.60
202	27.41	59.41	8.52	33.82	5.71	1.70	3.98	0.54	2.84	0.54	0.9	0.10	0.90	0.90
252	28.04	58.05	8.22	34.33	6.43	1.90	5.35	4.35	0.77	0.11	0.14	0.12	0.12	0.13

Sample number 10 = rhyolite; 202 = andesite; 252 = basalt.

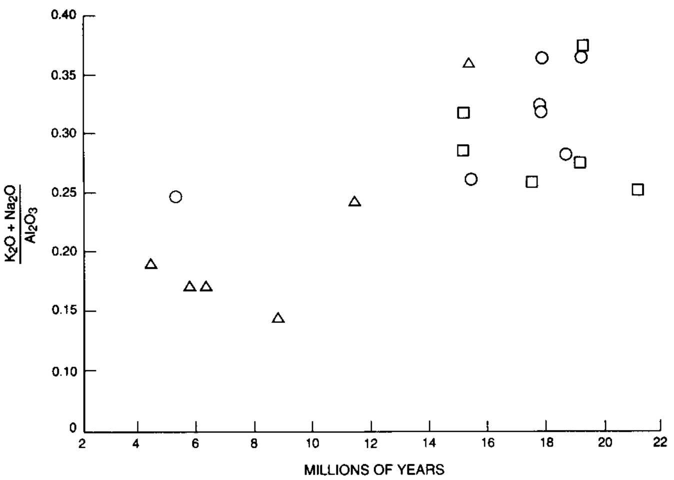


Figure 12. Na_2O and K_2O/Al_2O_3 plotted against rock age. Open circle: basalt; open square: andesite; open triangle: rhyolite.

Still younger "high K" rhyolite coulees, flows, and crystal dikes (4 to 6 Ma) are high in iron and appear to contain a transitional "oceanic rift" character. These rhyolites reflect changes associated with the propagation of a new oceanic rift along the Gulf of California depression, approximately 4.5 Ma ago (Sawlan and Smith, 1984).

The youngest volcanic bed on the southwestern corner of Isla Tiburón, a late Miocene (?) dacite ash-flow tuff plots on the tholeiitic portion of the Miyashiro (1974) diagram (Figure 7). The high FeO and TiO_2 and low MgO suggest that this dacite is "oceanic" in character, as associated with magmas of the modern Gulf (leaky transforms and spreading centers) (Batiza *et al.*, 1979). The northwest-southeast extension of the southwestern corner of Isla Tiburón appears to have begun around 15 to 16 Ma when red beds and basalts were tilted by extension-induced normal faulting (Boehm, 1987; Henry, 1989). Similar extensional features are documented in northeastern Baja California, where normal faults suggest east-west extension began between 17 and 9 Ma (Dokka and Merriam, 1982; Stinson, 1990). Henry (1989), Stock and Hodges (1989), and Henry and Aranda-Gómez (1992) detail the full development of Basin and Range extension in the Gulf of California and adjacent mainland Mexico beginning *ca.* 12 Ma.

MEGAFOSSIL PALEONTOLOGY

OVERVIEW

Marine fossils at Isla Tiburón are an important component of the reference section that documents the earliest incursion of seawater by 12.9 Ma into the northern area of the ancient gulf. Megafossils identified to species level are Miocene in age based upon their presence in radiometrically constrained formations elsewhere in the ancient Gulf of California and their stratigraphic occurrence with and below dated volcanic rocks at Isla Tiburón. They do not include any exclusively Pliocene forms, and some are phylogenetically ancestral to younger Pliocene species. Radiometric ages for volcanic rocks associated with fossiliferous members of Unit 8 further refine the Isla Tiburón assemblage as late middle or early late Miocene in age. These data together with other stratigraphic and paleontologic evidence indicate multiple seawater incursions in the ancient northern gulf, including the Salton Trough, in the Miocene and Pliocene.

Megafaunal and microfaunal ages are not in complete agreement for Unit 8 marine rocks on Isla Tiburón. Although the megafossils are Miocene, their chronostratigraphic ranges alone are not known precisely enough to distinguish between late middle and early late Miocene, the more refined age indicated by associated volcanic rocks. Microfossils from Unit M8c (see discussion below) are no older than late Miocene (7 to 9 Ma), suggesting possibilities of different facies, reworking, or time-transgressive taxa.

MEGAFOSSIL RECORD

Invertebrate megafossils at Isla Tiburón are most abundant in the youngest part of Unit M8d, near the mouth of Arroyo IV (loc. 83T2 = 87JS3), but present to common throughout the marine section in units M8d and M8c. The faunal list in Table 8 represents but a fraction of the diverse shallow water faunule that lived in the northern gulf during the late middle or late Miocene. Identifications are hampered by poor preservation in all but the pectinids and oysters, and by shells as delicate as potato chips. External molds in horizons of crumbling pebble conglomerate are difficult to cast, whether in the field or the laboratory. In addition to the mollusks discussed here (Table 5), Unit M8d contains the colonial coral *Solenastrea fairbanksi* (Vaughan), an unidentified solitary coral, and unidentified echinoids now in the collections at the University of California, Berkeley.

This report is based on fossils identified mainly from the literature and collected from 1983 to 1987, and on the redetermination of taxa reported in earlier papers by Weaver (1979, 1981), Stump (1981) and Smith (1991c). Fossil localities are plotted on Plate I (see equivalency list thereon). Representative taxa are illustrated in Figures 13, 14 and 15.

TERTIARY CARIBBEAN FAUNAL AFFINITIES

Like the fauna in the older members of the Imperial Formation near Whitewater and the Coyote Mountains in the Salton Trough of California, the mollusks from Unit M8d have strong Tertiary Caribbean affinities, a connection recognized by Vaughan (1900, 1917) between the ancient northern gulf and the Caribbean. Isla Tiburón has species in common with the faunas of the Springvale Formation of Trinidad (Jung, 1969), the Gatun Formation of Panama (Woodring, 1957), the Gurabo Formation of the Dominican Republic (Maury, 1917), and the Tuxpan Formation of Veracruz, Mexico (Perrilliat,

Table 5. Marine Mollusks from Isla Tiburón (Unit M8d except as noted; locality abbreviations as for Figures 13, 14, 15).

Gastropods	**Tiburón locality**	**Age**	**Other occurrences**	**Remarks, ecology, references to figures**
Crucibulum sp.	87JS3 [=83T2 =USGS M9117]			Internal molds of cap-shaped shell with internal cuplike support; lives limpet-like on hard substrates, intertidal to 30 m, some species 60–200 m. Several specimens with crenulate margins like modern *Crucibulum scutellatum* (Wood). (Figure 13h, i)
Latirus sp.	87JS3 [=83T2 =M9117]			Internal mold of a fragment that agrees in proportions, profile and structure with *L. concentricus* (Reeve) *in* Keen (1971, p. 613, fig. 1328)
Melongena melongena subspecies *consors* (Sowerby), fragment	83T2 [= 87JS3 = USGS M9117]	Miocene in the Pacific, Miocene to Recent in the Caribbean	Tertiary Caribbean, including Trinidad, BWI (Maury, 1917); Panama (Woodring, 1970); Baja California: Cabo Trough and La Purísima area (Smith, 1984; 1989)	Illustrated in Smith (1984, 1989). Early middle Miocene in the Isidro Formation, La Purísima, B.C.S., living in the West Indies (Smith, 1991c)
Strombus obliteratus Hanna	87JS3 [= 83T2 = USGS M9117]	Miocene	Cabo Trough, Trinidad Formation and unnamed unit east of Santa Anita, B.C.S.; Coyote Mts., CA, Imperial Formation (CAS 682, UCR 7267)	Internal molds with two distinctive rows of prominent tubercles on body whorl (Figure 15c)
Strombus sp. cf. *S. galeatus* Swainson	83T2			Specimen is mainly an internal mold, 12.5 cm high (incomplete and lacking expanded adult body whorl and outer lip. See Keen (1971, p. 421, fig. 609). Lives on intertidal sand and rubble, and among rocks, to depths of 45 m; throughout the Gulf of California to Ecuador (Kerstitch, 1989)
Terebra sp. cf. *T. robusta* Hinds	87JS3			Absence of sculpture suggests a shell like *T. robusta* Hinds, 1844 (see Keen, 1971, p. 682, fig. 1560), which lives intertidally to 90 m from Baja California to the Galapagos Islands
Turritella sp. cf. *T. altilira* Conrad	83T2, 87JS2, 87JS3		*Turritella altilira* stock is represented in the southern Tertiary Caribbean Province, in the Michoacán Basin, Ferrotepec Formation (Perrilliat, 1987), the Cabo Trough, B.C.S. (Smith, 1991c), and in California by *T. imperialis*	Both *Turritella altilira* and *T. imperialis* have distinctive bicarinate whorls, but fragments of internal molds cannot be distinguished. *T. altilira* is illustrated in Woodring, 1957, pl. 23

Pelecypods	**Tiburón locality**	**Age**	**Other occurrences**	**Remarks, ecology, references to figures**
"Aequipecten" plurinominis (Pilsbry and Johnson)	87JS3 = USGS M9117	Miocene	Cabo Trough, E of Santa Anita, B.C.S.; Panama, Gatun Formation; Dominican Republic, Gurabo Formation; Coyote Mts., Imperial Formation	*"Aequipecten" muscosus* (Wood) of earlier lists, this species has scaly fine macrosculpture on its 16–17 ribs, in interspaces and on auricles. Specimen from the type Imperial Formation identified as *Pecten sancti-ludovici* Anderson and Martin by Hanna (1926) is different from the holotype of that taxon from central California. *"Aequipecten" plurinominis* (Pilsbry and Johnson) may be ancestral to *"A." corteziana* (Durham) and related to *"A." canalis* (Brown and Pilsbry) from the Isidro Formation, La Purísima area, B.C.S. (Figure 13a, b)
Anadara spp.	87JS3			Internal molds
Arca (*Arca*) sp. cf. *A.* (*A.*) *suspecta* Olsson	87JS3			Internal molds having a long, straight hinge,beaks close to the anterior end; 2 cm high 5.5–6 cm long

Table 5. Marine mollusks from Isla Tiburón—Continued.

Pelecipods	Tiburón locality	Age	Other occurrences	Remarks, ecology, references to figures
Argopecten circularis subspecies *calli* (Hertlein)	83T2 87JS4	Miocene	Cabo Trough, type locality near Santiago, B.C.S.; Trinidad Formation	Illustrated in Moore (1984, p. 35, pl. 10, fig. 2). Hard to distinguish from *A. demiurgus,* but Tiburón specimens of *A. c. calli* attain 5 cm ht, 5.5 cm length and have wider interspaces. *A. circularis* (Sowerby) lives intertidally among rocks and gorgonians at San Felipe, B.C., has been dredged in 11–26 m. It lives from the Gulf of California and Isla Cedros to Peru (Gemmell *et al.,* 1987)
Argopecten demiurgus (Dall)	87JS3, 87JS4, 87JS21, 83T6	Miocene	Trinidad, West Indies, Springvale Formation (Maury, 1925)	Ancestral form to modern calico scallops referred to *Argopecten gibbus* (Linnaeus) in the Caribbean and western Atlantic, *A. circularis* (Sowerby) in the eastern Pacific. Like the living species, it seems to have been gregarious, water in beds at depths of 2 to 370 m. The Tiburón specimens are characterized by having 17–18 ribs in each valve, equally convex shells. Allen and Costello (1972) summarize temperature, salinity, substrate and spawning data for *A. gibbus* (Linnaeus) in the Gulf of Mexico. (Figure 13c, d, e, g)
Atrina stephensi Hanna	87JS20	Miocene	Coyote Mts. and Whitewater River areas, CA, Imperial Formation (Powell, 1986)	Examples of pen shells, *Atrina* and *Pinna,* are illustrated in Moore (1983) and Hanna (1926). Isla Tiburón specimens have very little surface sculpture, look more like the western Atlantic to West Indian taxon *A. serrata* (Sowerby) than living Gulf of California species. Eastern Pacific Atrinas live in 1–125 m (Keen, 1971)
Barbatia sp.	87JS3			Living species are byssate on hard rock and rubble.
Cardita sp. cf. *C. matima* Olsson	87JS6		Whitewater River area, Riverside Co., CA (Powell, 1986); Costa Rica, Gatun Formation	Probably the same as *Cardites crassicostata* (Sowerby) of Powell (1986). The largest fragment from Isla Tiburón is 5.5 cm high, 6 cm long; the nodulated ribs become wrinkled near the ventral margin. Carditids tend to live under rocks in shallow water, attaching by byssal threads (Keen, 1971). (Figure 15e)
Euvola? sp.	87JS15; 83T12; 87JS13;	Units M8c, M8d		Thin and fragile, like a potato chip, and hard to preserve. Right valves more convex than in *Euvola keepi,* umbonal angle very wide, hinge not straight, auricles bent away from line of commissure. (Figure 14b, c, e, f, g, j)
Euvola keepi (Arnold)	83T2= 87JS3	Miocene to early Pliocene	Coyote Mts., CA, Imperial Formation; San Felipe, B.C.; Santa Rosalía, Boleo Formation; Cabo Trough, Trinidad Formation [as *E. refugioensis* (Hertlein)]	Tiburón specimens do not attain gigantic size of the San Felipe shells, which reach 13.4 cm high, more than 13 cm in length. Some of the specimens are articulated (were buried alive), most are broken. It ranges in age from Miocene to Pliocene. (Figure 14h, i, and Moore, 1984, pl. 30, figs. 5, 6.)
Flabellipecten carrizoensis (Arnold)	87JS3, 83JS12, 87JS15	Miocene; Units M8c, M8d	Coyote Mts., CA, head of Garnet Canyon, Imperial Formation; Santa Rosalía, basal Boleo Formation	Convex right valves bear 18, commonly medially sulcated, rectangular ribs, left valves planoconvex, with 16 rounded ribs. Probably ancestral to *F. bosei* (Hanna and Hertlein), which has more ribs and occurs in the overlying Tirabuzón Formation near Santa Rosalía. Several species from the Gulf of California range from 100–375 m in depth. (Figure 13f, 14a and Moore, 1984, pl. 31, figs. 4, 6.)
Glycymeris (Glycymeris) sp. cf. *G. (G.) gigantea* (Reeve, 1843)	83T2			Specimen is 7.2 cm high, 7.2 cm long and seems not to have any radial ribbing
Hyotissa haitensis (Sowerby)	87JS2, 87JS3	Miocene to Recent	La Purísima area, B.C.S., Isidro Formation; Tertiary Caribbean, including Trinidad (Maury, 1917), Panama, Colombia, Dominican Republic; living, western and Indo-Pacific	Illustrated in Smith (1984) and Moore (1987). Lives in 3–60 m in the Gulf of California to Ecuador, also in the Western and Indo Pacific
Lyropecten tiburonensis Smith	83T2, 83T2,	Miocene	Whitewater River area; Coyote Mts., CA, Imperial Formation, Latrania Member (88JS9; CAS 683; UCR 7267, UCR 5042)	A few disarticulated fragments found at Arroyo IV locality (Smith, 1991a); abundant large specimens in the southeastern Coyote Mountains. (Figure 14d)

Table 5. Marine mollusks from Isla Tiburón—Continued.

Pelecipods	Tiburón locality	Age	Other occurrences	Remarks, ecology, references to figures
Panopea sp.	87JS3			Internal mold of two-valved specimen, 6.5 cm high and 10 cm long, buried in substrate; modern *Panopea globosa* Dall lives 2-3'deep in sandy mud, in water depths up to 60 m. (See Keen, 1971, p. 273, fig. 699)
Pinna latrania Hanna	87JS2	Miocene	Coyote Mts., CA, at head of Garnet Canyon [USGS 3922]; Whitewater River area, Riverside Co., CA, Imperial Formation (Powell, 1986)	Illustrated in Hanna (1926) and Moore (1983), Pinnas have similar habitats to Atrinas but differ in shell shape, the presence of an anterior keel, and adductor muscle scar. The Tiburón Pinnas were in living position, the Atrinas were not. *Pinna rugosa* (Sowerby) lives intertidally to 30 m, Gulf of California to Peru; living assemblages from the Bay of La Paz are discussed by Arizpe-C. (1995)
Pycnodonte (Crenostrea) veracruzana Perrilliat	87JS12 = USGS M9162	Miocene	Type locality is Veracruz, Mexico, Tuxpan formation (Perrilliat, 1994)	A large, thick shelled, circular oyster common at "Anfiteatro Ostrea" and described from the middle Miocene Tuxpan Formation of northern Veracruz. (Figure 15g)
Spondylus sp. A cf. *S. bostrychites* Guppy	83T1, 83T2, 87JS4, 87JS12, 87JS19	Miocene	Lion Canyon section, west of Whitewater River, Riverside, Co., CA [CAS 548]. McDougall and others (in press) report late Miocene microfossils of 7.4–6.04 Ma from six referred places at Cabazon and Whitewater, CA, Imperial Formation; Santa Rosalía, Boleo Formation [84JS24]	The taxon is characterized by nearly equal valves, macrosculpture varying from short, broken spines to long, well developed flat ones, and four orders of spines. Probably closely related to the Tertiary Caribbean species *S. bostrychites* Guppy and the modern *S. americanus* Hermann, which lives in the Gulf of Mexico and off the Carolinas to Brazil in 30–150' (9–45 m) (Abbott, 1974). (Figure 15d)
Spondylus sp. B [= S. *bostrychites* Guppy of Hanna, 1926 (not of Guppy)]	Isla Tiburón, float from Arroyo IV		Coyote Mountains, CA, Imperial Formation, Latrania Sand Member (Hanna, 1926) (UCMP 738 and LACM 9802)	Ancestral form of a phylogenetic series that includes a spondylid represented in Pliocene rocks west of San Felipe, Baja California and Pleistocene beds on Isla Coronado *(S. victoriae* Durham). A descendant, *S. ursipes* Berry, was described from Isla Ángel de la Guarda. See Hanna (1926) and Moore (1987)

At least half a dozen species of oysters, some recognizable from other formations in the northern Gulf of California, have yet to be identified. Additional megafossils are listed in Stump (1981); unidentified echinoids were deposited in the collection at the University of California, Berkeley. At least two species of barnacle that are missing the diagnostic opercular plates *(fide* V. Zullo, 1991, written communication) were sent to the Los Angeles County Museum of Natural History. Corals are represented by *Solenastrea fairbanksi* (Vaughan) and an unidentified solitary coral.

1994). This Tertiary Caribbean aspect is not found in Pliocene assemblages of the Gulf of California.

Melongena melongea subspecies *consors* (Sowerby) is a Caribphile, a taxon that is extinct in the Pacific but living in the West Indies. It occurs in Baja California Sur in the well-constrained middle Miocene Isidro Formation near La Purísima (Smith, 1984) and in the lowest part of the Miocene Trinidad Formation, member A, in Arroyo Trinidad in the Cabo Trough (Smith, 1989).

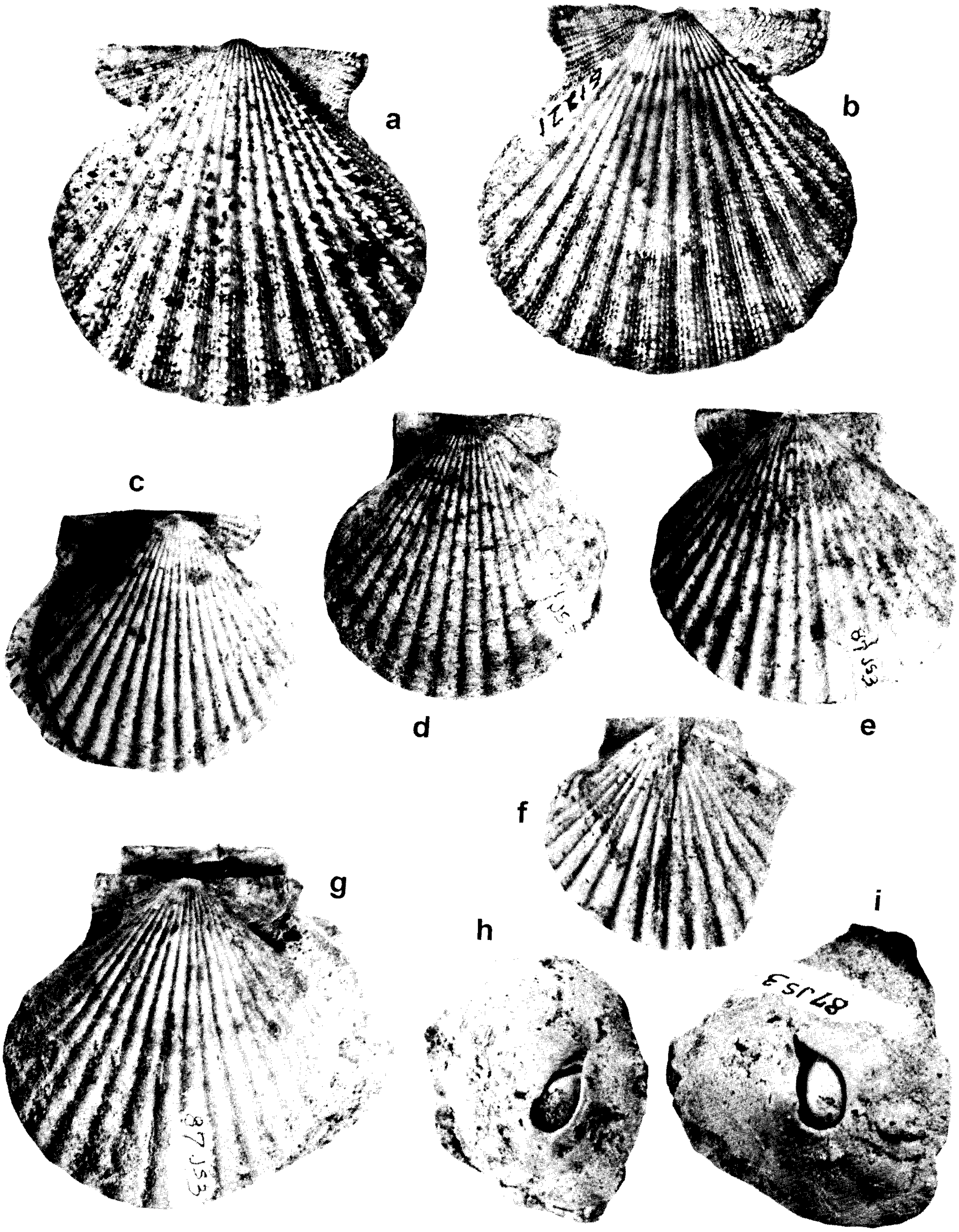
One internal mold of *Turritella* sp. cf. *T. imperialis* Hanna indicates the presence of an indeterminate species of the Tertiary Caribbean *T. altilira* (Conrad) stock, which is Miocene to Pliocene.

ABSENCE OF PLIOCENE MEGAFOSSIL INDEX SPECIES

The Isla Tiburón assemblage contains none of the well established Pliocene index species found in many deposits from the Islas Tres Marías, Isla Cerralvo, the Marquer Formation of the Loreto basin, the upper Tirabuzón Formation and the Infierno Formation of the Boleo basin, and an unnamed marine conglomerate with coquina in the Bahía de

Figure 13. Common Miocene marine mollusks buried alive, Isla Tiburón, Sonora, Mexico.* All are from marine conglomerate Unit M8d, locality 87JS3 = USGS M9117, Plate I, locality 3. 13*a, b—"Aequipecten" plurinominis* (Pilsbry and Johnson). LV, RV, hypotype USNM 422805. Ht 4.8 cm, lth 4.9 cm. [locality CAS 61221 = 87JS3]. *"Aequipecten" muscosus* (Wood) of Smith, 1991c, fig. 4f. 13*c, d, e, g—Argopecten demiurgus* (Dall). Figure *c,* RV, hypotype IGM 7508, ht 4.2 cm, lth 4.3 cm. Figure *d,* RV, hypotype IGM 7509, ht 5.1 cm, lth 5 cm. Figure *e,* LV, hypotype IGM 7510, ht 5.2 cm, lth 5.5 cm. Figure *g,* RV, hinge of LV, hypotype USNM 492050, ht 5.7 cm, lth 5.8 cm. Figure 13*f—Flabellipecten carrizoensis* (Arnold). LV, hypotype IGM 7511, ht 4.1 cm, lth 4.3 cm (incomplete). Figure 13*h, i— Crucibulum* sp., internal molds, apical view of limpet-like rocky substrate gastropods. Figure *h,* hypotype IGM 7512, greatest diameter 4 cm. Figure *i,* hypotype USNM 492051, greatest diameter 3.2 cm.

*Abbreviations: RV, right valve; LV, left valve; ht, height; lth, length; USNM, U.S. National Museum, Washington, DC; IGM, Instituto de Geología, catálogo 2 of UNAM, Universidad Nacional Autónoma de México, México, D.F.; CAS, Academy of Sciences, San Francisco, CA; UCMP, University of California Museum of Paleontology, Berkeley, CA; UCR, University of California, Riverside, CA; USGS M, Geological Survey, Menlo Park, CA, Cenozoic Register.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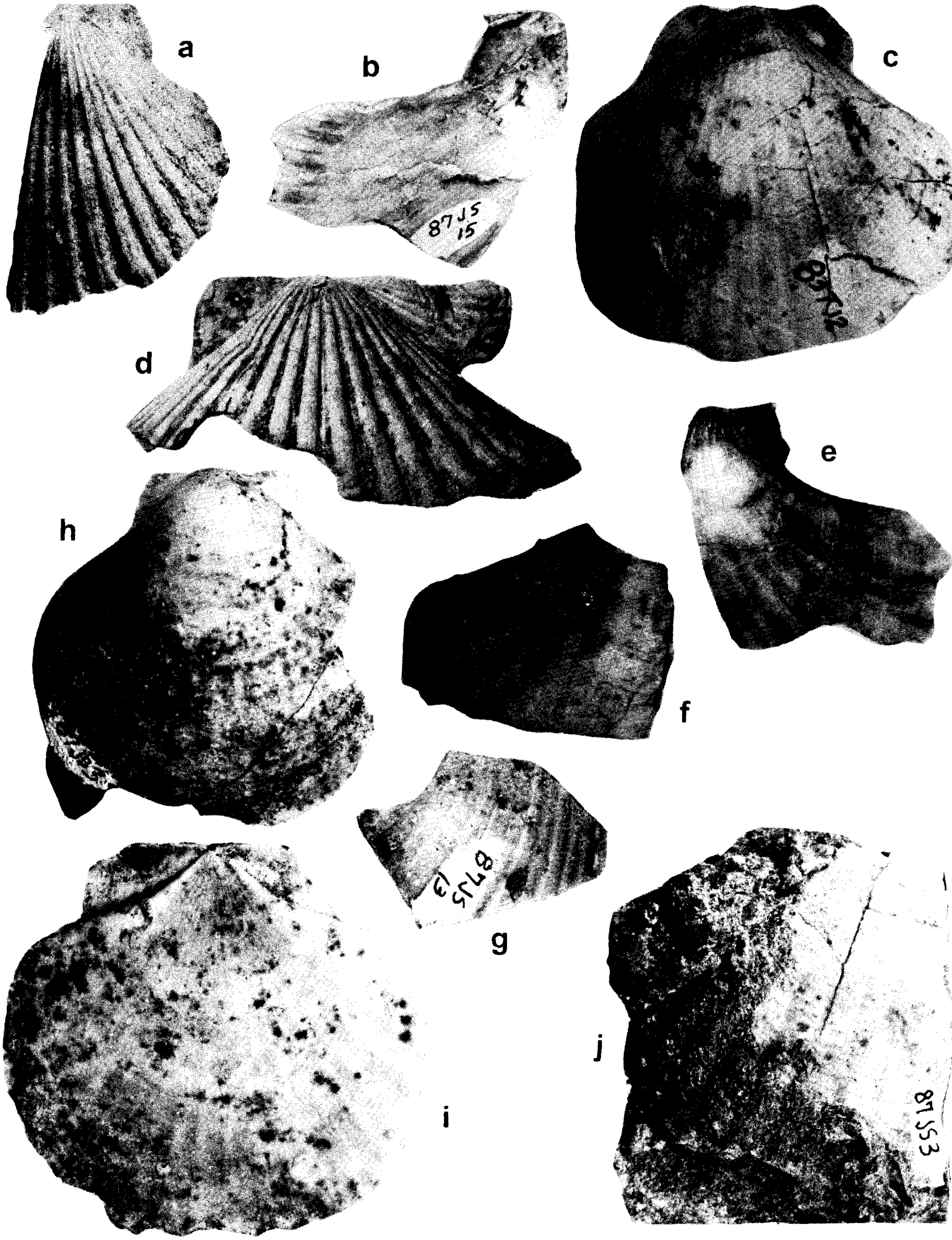
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Guadalupe area, Baja California (specimens collected by G. Axen). Those Pliocene taxa include *"Aequipecten" dallasi* (Jordan and Hertlein), *"A." woodringi* (Olsson), *Argopecten abietis* (Jordan and Hertlein), *A. revellei* (Durham), and *Leopecten bakeri* (Hanna and Hertlein), and the Pliocene to Recent species *Nodipecten arthriticus* (Reeve), *N. subnodosus* (Sowerby), and *Argopecten circularis* (Sowerby).

Several taxa suggest the Isla Tiburón flabellipectinids and spondylids are ancestral forms to species found in Pliocene rocks in the Boleo basin and San Felipe, B.C.; these phylogenetic sequences require more and better preserved samples for confirmation. Phylogenetic relationships between *"Aequipecten" plurinominis* (Pilsbry and Johnson) and the younger *"A." corteziana* (Durham) and between *Flabellipecten carrizoensis* (Arnold) and *F. bösei* (Hanna and Hertlein) are also suspected.

STRONTIUM ISOTOPE DATA FROM MOLLUSCAN SHELLS

Molluscan samples from Isla Tiburón and other northern gulf localities were submitted for Sr isotope dates to R.E. Denison, who interpreted their ages from the curves of De Paolo and collaborators (1986). Ages were interpreted as Miocene, mainly middle Miocene to early late Miocene, although some plot as old as early Miocene, >15 Ma. Data are shown in Tables 6 and 7.

Most of the specimens from Isla Tiburón were pectinids that appeared fresh, although they were associated in Unit M8d with other mollusks represented by dissolved aragonitic shells and internal molds. It is possible the pectinids were also altered.

Table 7 summarizes Sr data for selected formations in the northern Gulf. The marine conglomerate of Isla Tiburón is unique, whereas the sediments are more alike among the basins of eastern Baja California.

ENVIRONMENT OF DEPOSITION OF UNIT M8D

A number of articulated free-swimming pectinids indicate a living assemblage that was buried alive in the cobble to boulder conglomerate of Unit M8d. All indicate shallow water, fully marine conditions, not a mangrove or brackish water environment. Two species of scallops with articulated valves are found together but represent different habitats: abundant Argopectens (*Argopecten demiurgis* Dall) and less common, fragile, spinose *"Aequipecten" plurinominis* (Pilsbry and Johnson). The former was gregarious, living in beds like modern calico scallops (*A. gibbus* [Linnaeus] in the Caribbean, *A. circularis* [Sowerby] in the Pacific Panamic) at intertidal depths to 26 m. Near the mouth of Arroyo IV large numbers of pectinids are concentrated in channels (Figure 18). They include Tertiary Caribbean taxa such as *"Aequipecten" plurinominis* (Pilsbry and Johnson) (= *"A." muscosus* Wood of Smith, 1991c) as well as endemic early Gulf taxa such as *Lyropecten tiburonensis* Smith.

Further up Arroyo IV and down section, a small stand of pen shells is preserved in living position, their valves gaping and extending several centimeters above the former substrate/water interface (Figure 16). Once thought to live only in sandy habitats, some Pinnas are now known to prefer cobbles and rubble in which they anchor themselves by byssal threads. Other organisms found in living positions include the large infaunal clam *Panopea* sp. and some oysters, although the hill of disarticulated shells at "Anfiteatro Ostrea" (Figure 17) is not a living assemblage.

CORRELATION

On the basis of molluscan taxa identified to the species level, Unit 8Md correlates with the following ancient gulf formations: the Imperial Formation near Cabazon and Whitewater, in the northern Salton Trough of California; the Imperial Formation, Latrania Sand Member, in the northern and southern Coyote Mountains, California; the basal Boleo Formation in the Boleo basin near Santa Rosalía, B.C.S.; and the basal Trinidad Formation and an unnamed sandstone east of Santa Anita, B.C.S. in the Cabo Trough. Associated radiometrically dated units and/or microfossils indicate a Miocene age for all but the section at Santa Anita, which has not been examined for microfossils and which contains no volcanic rocks. These localities are shown in Smith (1991c).

Correlation with the Imperial Formation is complicated by the controversy over its age. Recent work by McDougall and coworkers (in press) recognizes multiple marine incursions in the ancient northern gulf at *ca.* 4 Ma and 6 to 7 Ma, represented by sections of the Imperial Formation, and 8 to 9.5 Ma, represented by the Fish Creek Gypsum (Dean, 1996). This

Figure 14. Late middle Miocene pectinids, southwestern Isla Tiburón, Sonora, Mexico [localities shown on Plate 1; abbreviations as for Figure 13]. 14*a*—*Flabellipecten carrizoensis* (Arnold). RV, hypotype IGM 7513, ht 5 cm, lth 3.5 cm, incomplete. Locality 87JS15, white sandstone facies of Unit M8d, Arroyo I. 14*b, c, e, f, g, j*—*Euvola (?)* sp., [called "the potato chip pecten" because of its extreme fragility]. Figures *b, e*, internal, external views, RV fragment, hypotype USNM 492052, showing flared umbonal region, smooth, unsculptured surface, angular hingeline. Ht 3.9 cm, lth 4.2 cm, incomplete. Locality 87JS15, white sandstone facies of Unit M8d. *Figure c*, RV, hypotype USNM 492053, ht 5.7 cm, lth 6 cm. Very worn shell showing internal ribbing not seen in better preserved specimens. Locality 83T12 = 83T6 = USGS M 9162. Figure *f*, fragment, hypotype USNM 492054, exterior view, showing smooth surface, barely perceptible internal radial ribs. Ht 3.8 cm, greatest length 4.1 cm, locality 87JS15, white sandstone facies of Unit M8d. Figure *g*, fragment, hypotype USNM 492055, internal view, showing ribbing. Ht 2.9 cm, lth 3.8 cm, locality 87JS13, white sandstone facies. Figure *j*, RV fragment, hypotype IGM 7514, ht 5.7 cm, lth 6 cm. Locality 87JS3, marine conglomerate Unit M8d. Figure *d*, *Lyropecten tiburonensis* Smith. RV, fragment, holotype CAS 61215.01, ht 4.5 cm, lth 8.7 cm, incomplete. Hinge length 4.6 cm. Locality CAS 61215 = U.S. Geological Survey M9117, marine conglomerate Unit M8d. Figure 14*h, i*, *Euvola keepi* (Arnold). Figure *h*, hypotype IGM 7515, ht 5 cm, lth 5.2 cm. Figure *i*, LV, hypotype IGM 7516, showing subdued radial ribs. Ht 5.8 cm, lth 6.5 cm. Both specimens from locality 87JS3 = USGS M9117, marine conglomerate Unit M8d.


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e
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g

Table 6. Strontium isotope data from molluscan shells from Isla Tiburón and other northern Gulf reference areas. Determinations by R.E. Denison (see also Table 7).

Mobil sample	**Region**	**JSmith locality [1]**	**$^{87}Sr/^{86}Sr$ [2]**	**Δsw[3]**	**Specimen, freshness**
8476-2	Isla Tiburón	83T2[= 87JS3 = USGS M9117]	0.708113±37	-96.0	Pecten fragments, some chalky, Unit M8d
8478	Isla Tiburón	87JS13	0.708818±29	-25.5	Very fresh oyster, Unit M8d
8481	Coyote Mountains, CA	88JS9 [= Kidwell 88GSD119]	0.708988±26	-8.5	Pecten fragments, fresh, from the Imperial Formation
8490	Boleo Basin, B.C.S.	84JS24 [= 81JTS4 =USGS M9036]	0.708559±39	-51.4	Pecten, chalky but generally fresh, from the Boleo Formation
8491	Boleo Basin, B.C.S.	84JS23 [= USGS M9035 = LACM 4828]	0.708897±35	-17.6	Pecten, mostly fresh, some patina, from the Tirabuzón Formation
8494	Arroyo Matomí, B.C.	11/87JS5 [= JStock VC-87-96]	0.708860±31	-21.3	Pecten, very fresh, tan, bored, from the Puertecitos Formation
8496	Arroyo Matomí, B.C.	11/87JS9	0.708704±29	-36.9	Pecten, thin, some chalky patina, from the Puertecitos Formation

[1]Additional locality numbers of S.M. Kidwell, University of Chicago; U.S. Geological Survey, Menlo Park, CA, Cenozoic register; J.M. Stock, California Institute of Technology, Pasadena, CA.

[2]Based on NBS-987 = 0.71014

[3]$\Delta sw = {}^{87}Sr/{}^{86}Sr$ unknown - $^{87}Sr/^{86}Sr$ modern seawater [0.709073] x 10^5

explains the long-standing disagreements among authors arguing for a Pliocene or Miocene age for the Imperial Formation, and the importance of making correlations on the basis of species having precise geographic and chronostratigraphic data. Key areas for correlation are, north to south, the Cabazon and Whitewater areas, northernmost Salton Trough, the Fish Creek/Vallecitos Mountains, and the Coyote Mountains, both the headwaters of Garnet Canyon on the north and at Alverson Canyon, the type section of the Imperial Formation, Latrania Sand member, and other outcrops to the south and southeast. Of these, the Isla Tiburón megafossils are found only in the older sections of the Imperial Formation. They are unknown in the Pliocene, post-Colorado River deltaic facies of the Imperial Formation mapped by Winker (1987) and Winker and Kidwell (1986) in the Fish Creek/Vallecitos Mountains, and regarded by them as ~ 4.3 Ma on the basis of paleomagnetic data.

MICROFOSSILS

FORAMINIFERA

Microfossil samples were collected from various locations in Unit M8c to establish the age and depositional environment of these sediments. Only five samples yielded identifiable foraminifera. The highest diversity and best preserved assemblages were found in samples 1 and 62, whereas assemblages in Cassidy samples 98, TT69 and TT1 are marked by poor preservation and consequent lower diversity (Table 8). Ranges of key planktonic species and one distinctive benthic species collectively indicate an age range of uppermost Miocene to lower Pliocene for Unit M8c. Foraminiferal assemblages also indicate deposition occurred at inner to outer neritic water depths between 50 and 150 m in a shelf to shelf-edge setting.

Figure 15. Marine molluscan species represented at Isla Tiburón, Sonora, Mexico. (Abbreviations as for Figure 13). 15*a, b*—*Atrina* sp. Figure *a*, in living position, internal mold with some salmon-colored shell preserved on the right, characteristic ridges near the beak area. Hypotype IGM 7517, ht 11 cm, lth 9 cm, inc. Figure *b*, plan view, hypotype IGM 7518, greatest diameter 6.5 cm. Both, locality 87JS20, marine conglomerate Unit M8d. 15*c*—*Strombus obliteratus* Hanna. Side view, hypotype UCR 7267, internal mold. Ht 5 cm. Locality UCR 7267, Imperial Formation, Alverson Canyon area, southern Coyote Mountains, CA. Similar specimens come from Isla Tiburón, marine conglomerate Unit M8d. 15*d, f*—*Spondylus* sp. RV, LV, hypotype USNM 492056, ht 11.3 cm, lth 9.5 cm, locality 87JS19, marine conglomerate Unit M8d. A deformed specimen was collected from the Lion Canyon area, northeast of Cabazon, Riverside County, CA (CAS collection). 15*e*—*Cardita* sp. cf. *C. matima* Olsson. Fragment, hypotype IGM 7519, ht 5.3 cm, lth 4.6 cm, showing characteristic concentric flanged lamellae. Locality 87JS6, marine conglomerate Unit M8d. 15*g*— *Pycnodonte (Crenostrea) veracruzana* Perrilliat. Hypotype IGM 7520, ht 11.5 cm, lth 14.4 cm, locality 87JS12. Marine conglomerate Unit M8d.

Table 7. Summary of strontium isotope and megafaunal data, southwestern Isla Tiburón and other reference areas in the northern Gulf of California.*

***Area* and stratigraphic unit**	**Sample No. JSmith, *Mobil* (Institutional locality no., if any)**	**Age interpreted from Sr isotope data (R.E. Denison, written communication, 1991)**	**Comments**
Southwestern Isla Tiburón, Sonora			
M8d Conglomeratic facies	83T2=87JS3 *Mobil 8476-2* Plate I, fossil locality 3	Late middle Miocene, *ca.* 15.2–16 Ma	Highest part of the section of fossiliferous marine conglomerate, the "main megafossil locality" in Arroyo IV nearest the beach
M8d White sandstone facies within marine conglomerate	87JS13 *Mobil 8478* Plate 1, fossil locality 13	Early late Miocene, *ca.* 10.5–11.5 Ma	Facies overlain unconformably by 11.2 ±1.3 Ma ash flow cap (Gastil and Krummenacher, 1977)
Arroyo Matomí area, NW of Puertecitos, B.C.			Area of the Puertecitos Embayment and Volcanic Province, currently under investigation by J. Stock, California Institute of Technology, Pasadena, CA; Arturo Martín-Barajas, CICESE, Ensenada, B.C., and colleagues (Stock *et al.*, 1991)
Puertecitos Formation, Matomí Mudstone Member (Martín-Barajas *et al.*, 1997) [= unnamed mustard beds, Pmy of Stock *et al.*, 1991]	11/87JS5 *Mobil 8494* [=J. Stock loc. VC-87-96]	Late Miocene	Fossils in the Puertecitos Formation include *Amaea edwilsoni* DuShane and *Amusium* sp. that are also found in the Tirabuzón Formation, latest Miocene to early to middle Pliocene, at Santa Rosalía, B.C.S. None of the Isla Tiburón species are present in the Puertecitos Formation, which is also represented by a dredged sample from the Gulf of California between Isla San Esteban and Isla San Lorenzo (Los Angeles County Museum of Natural History locality 12542), from 28°37.0' N, 112°43.2'W, at 200 m depth, collected by L.T. Findley and K.H. Holtschmit, ITESM-Guaymas. The dredged sample is from 37 km S30°W of the mouth of Arroyo IV, and 4 km E of Isla San Lorenzo
Yellow beds, coquina and white sandstone	11/87JS9 *Mobil 8496*	Latest middle Miocene	*Euvola* and *Turritella* fragments, infaunal clams present but they do not indicate precise age
Coyote Mountains, Imperial County, CA			Latrania Sand samples dated for this study are not from the type locality but from *ca.* 9 km east-northeast of it, in the Painted Gorge 71/2' Quadrangle, CA, Sec. 5, T 16 S, R 10 E [JSmith locality 88JS9]
Imperial Formation, Latrania Sand Member	88JS9 *Mobil 8481* [= Kidwell 88GSD-119]	Miocene/ Pliocene boundary, *ca.* 5 Ma	Important, highly fossiliferous reference locality in the south-eastern Coyote Mountains. Sediments are pre-Colorado River deltaic deposits (Kerr and Kidwell, 1991; Winker, 1987). Same *Lyropecten tiburonensis* Smith, *Spondylus* species as at Isla Tiburón, Unit M8d
***Boleo Basin, Santa Rosalía,* B.C.S.**			
Tirabuzón Formation [=Gloria Formation of Wilson, 1948 and authors]	84JS23 *Mobil 8491* [= USGS M9035, LACM 4828]	Near Miocene/ Pliocene boundary	Locality is 4-km north of Santa Rosalía, west side of Mexico. Although lithologically different, this unit correlates with the "mustard beds" of Stock and others (1991) near Arroyo Matomí. Foraminifer and shark data indicate that the Tiburón Formation was deposited about 3 miles offshore, in depths of 200–500 m. Fossils include meter-long *Gyrolithes* burrows, early and middle Pliocene mollusks that include morphologic descendants of pectinids found in the underlying Boleo Formation and early to middle Pliocene foraminifers (Carreño, 1981, 1982) and sharks (Applegate and Espinosa-A., 1981); late Miocene benthic foraminifers are present at its base (McDougall, 1996, personal comm.)
Boleo Formation, basal coquina	84JS24, 81JTS4 *Mobil 8490* [= USGS M9036]	Near early/ middle Miocene boundary	Abundant mollusks with Tertiary Caribbean affinities occur in the basal coquina that is draped over a basaltic andesite submarine vent dated at 12.3–12.5 Ma (Smith, 1991c, Table 1; Smith, 1991b). Coquina is 200 m downsection from the *cinta colorada* marker bed, which is dated at 6.76 Ma (Holt and others, in press) Molluscan index species in common between the Isla Tiburón conglomerate (Unit M8d) and the Boleo Formation include *Spondylus* spp. A and B, *Flabellipecten carrizoensis* (Arnold), and *Hyotissa hyotis* (Linnaeus)

*Strontium data interpreted according to De Paolo (1986). Epoch boundaries as in Smith (1991c): Pliocene/late Miocene, 5 Ma; late Miocene/middle Miocene, 10 Ma; middle Miocene/early Miocene, 18 Ma. Table 5 shows isotope data on which this table is based.

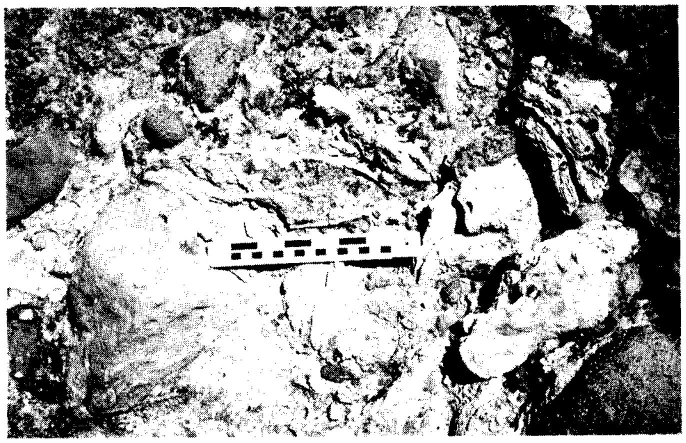

Figure 16. Dipslope in marine conglomerate Unit M8d exposing large oysters and a cross section of a pinnid clam in life position in rubble. Fossil locality 87JS2, shown as #22 on Plate I.

Figure 18. Channel filled with concentrations of Pecten shells, marine conglomerate Unit M8d in Arroyo IV near fossil locality #3 shown on Plate I. Area in photographs is 1 meter across.

PLANKTONIC SPECIES

The most abundant taxon in all four samples is *Globigerinoides obliquus*. This species ranges from earliest Miocene Zone N5 to early Pleistocene Zone N22 according to Blow (1979) and Kennett and Srinivasan (1983) whereas Bolli and Saunders (1985) restrict its range to early Miocene Zone N8 through early Pliocene Zone N19. Also present is *Globigerinoides extremus* which, according to Kennett and Srinivasan (1983), ranges from the top of late Miocene Zone N16 to the top of late Pliocene Zone N21. More recently, Berggren, Kent and collaborators (1995) have correlated the first appearance of *G. extremus* with a radiometric age of 8.3 Ma and its last appearance at 1.77 Ma within early Pleistocene Zone N22. The more conservative taxonomic approach of Bolli and Saunders (1985) is preferred, with these authors placing the last appearance of *G. extremus* in the early portion of late Pliocene Zone N21, approximately correlative with a radiometric age of 3-2.5 Ma. The occurrence of *G. bulloideus* in samples 1B, 62, and 98 further constrains the age to latest Miocene-early Pliocene as this species is thought to be restricted to Zones N17B to N19 and correlative with a radiometric age of 6.2 through 4 Ma (Kennett and Srinivasan, 1983). The co-occurrence of *Globoquadrina venezuelana* also points to an age no younger than early Zone N19 or *ca.* 4 Ma.

Figure 17. "Anfiteatro Ostrea," view from northeast of hill in upper Arroyo III, fossil locality 87JS12 = USGS M9162 shown as #12 on Plate I. Marine conglomerate Unit M8c, with abundant disarticulated oysters and spondylids representing a death assemblage. Strontium isotope data indicate this is not an open seawater environment.

Specimens of keeled *Globorotalia* in two samples most closely resemble *G. limbata* which ranges from middle Miocene Zone N14 through late Pliocene Zone N21 (Kennett and Srinivasan, 1983); this species is considered synonymous with *G. pseudomiocenica*. Other specimens show an affinity to *G. pleisiotumida* which is thought to range from late Miocene Zone N17A through early Pliocene Zone N19. One poorly preserved specimen was tentatively identified as *G. anfracta*, a species which ranges from earliest Pliocene Zone N18 to Recent.

A single poorly preserved specimen in sample TT1 was identified as *Pulleniatina primalis* which ranges from late Miocene Zone 17B to late early Pliocene zone N20 (Kennett and Srinivasan, 1983) with Berggren, Hilgren and others (1995) and Berggren, Kent and others (1985) placing its first appearance at 6.4 Ma and its last appearance at 3.65 Ma.

Thus, established ranges of the most age diagnostic planktonic species identified suggest a late Miocene (Zone 17B) - early Pliocene (Zone N19) age for Unit M8c, correlative with a radiometric age range of *ca.* 6.4 to 4 Ma.

BENTHIC SPECIES AND THE SIGNIFICANCE OF Amphistegina gibbosa

The majority of benthic foraminifera identified in samples from Unit M8c (Table 8) range in age from Miocene to Recent and are currently living in the Gulf of California (Bandy, 1961; Phleger, 1964); hence, they are of little value in defining the precise age of these deposits. Alternatively, the presence of the tropical shallow water species *Amphistegina*

Table 8. Distribution of Foraminifera, Neogene marine Unit M8c, Isla Tiburón, Gulf of California, Mexico.[1]

Planktonic Foraminifera

Planktonic species	**1B**	**62**	**98**	**TT69**	**TT1**	**Imperial Formation**	**Santiago Diatomite**
Globigerina sp. cf. *G. apertura* Cushman		x		x			§
Globigerina decoraperta Takayanagi & Saito		x	x			∞‡	
Globigerina falconensis Blow		x					
Globigerina quinqueloba Natland			x				§
Globigerina woodi Jenkins	x	x				∞‡	
Globigerinella sp.		x					
Globigerinoides bollii Blow	x	x			x		
Globigerinoides bulloideus Crescenti	x	x	x				
Globigerinoides conglobatus (Brady)		?					§
Globigerinoides extremus Bolli & Bermudez	x	x	x	x	x	∞‡	§
Globigerinoides obliquus Bolli	x	x	x	x	x	∞‡	§
Globigerinoides ruber, s.l. (d'Orbigny)	x	x			x	∞‡	§
Globoquadrina venezuelana (Hedberg)	x	x		x			
Globorotalia sp. cf. *G. anfracta* (Parker)		x					
Globorotalia sp. aff. *G. limbata* (Fornasini)	x		x				
Globorotalia menardii, s.l. (Parker, Jones, & Brady)	x	x					§
Pulleniatina primalis Banner & Blow					?		§

Benthic Foraminifera

∞ = taxon also represented in Whitewater River area Imperial Formation; ‡ = also at Cabazon section, Imperial Formation, near San Gorgonio Pass, California (McDougall *et al.,* in press).

Benthic species		**1B**	**62**	**98**	**TT69**	**TT1**	**Imperial Formation**
Amphistegina gibbosa d'Orbigny		x		x			∞‡
Bolivina alata effusa Cushman & Todd			x				
Bolivina pisciformis Heron-Allen & Earland		x					
Bolivina spp.			x	x	x		
Buccella sp.			x				
Bulimina auriculata Bailey			x				
Cancris auricula (Fitchel & Moll)			x				
Cassidulina cushmani R.C. and K.C. Stewart			x				
Cassidulina delicata Cushman						x	∞‡
Cibicides mckannai Galloway & Wissler		x					
Cibicides sp. cf. *C. reflugens* Montfort		x	x				
Cibicides sp.		x			x	x	
Elphidium crispum (Linné)		x					∞‡
Elphidium sp.			x				
Eponides antillarum (d'Orbigny)		x	x	x	x		
Florilus basispinata (Cushman & Moyer)		x	x	x	x		
Florilus miocenica stella (Cushman & Moyer)		x	x			x	
Florilus sp.				x			
Gaudryina sp.		x					
Guttulina sp.			x				
Hanzawaia americanus (Cushman)		x	x				
Hanzawaia (Cancris) *bertheloti* (d'Orbigny)			x	x	x		
Hanzawaia concentrica (Cushman)		x		x			
Hanzawaia nitidula (Bandy)		x	x		x	x	∞‡
Hanzawaia (Cancris) panamensis (Natland)			x				
Hanzawaia (Cancris) panamensis (Natland) var. A		x	x				
Lenticulina sp. aff. *L. americanus* (Cushman)	x						
Lenticulina sp. aff. *L. calcar* (Linné)		x	x	x		∞‡	
Lenticulina limbata (Linné)	x						
Lenticulina spp.		x	x	x			
Loxostomum bradyi (Asano)				x		∞‡	
Marginulina papillata Coryell and Rivero	x						
Planulina ariminensis (d'Orbigny)	x						
Planulina ornata (d'Orbigny)	x	x			x	∞‡	

Table 8. Distribution of Foraminifera, Neogene marine Unit M8c, Isla Tiburón, Gulf of California, Mexico[1]—Continued.

Benthic species	**1B**	**62**	**98**	**TT69**	**TT1**	**Imperial Formation**
Pullenia salisburyi R.E. and K.C. Stewart	x					
Rotorbinella turbinata (Cushman)		x				
Siphotextularia sp. aff. *S. affinis* (Fornasini)		x				
Textularia sp.	x	x	x			
Trifarina spp.	x	x				
Uvigerina excellens Todd		x				
Uvigerina proboscidea Schwager	x					∞‡
Valvulineria inflata (d'Orbigny)	x					

[1]Recorded in terms of presence (x) or absence; use of pre-picked faunal slides precluded accurate assesment of relative abundances; symbol "?" represents a questionable identification based on a single poorly preserved or broken specimen.

Analysis by James C. Ingle, Jr., Department of Geological and Environmental Sciences, Stanford University, of M. Cassidy samples from marine Unit M8c.
§ = identified from the Trinidad Formation, Santiago Diatomite Member, Cabo Trough, by Carreño (1992), who regards the age of that unit as latest Miocene to Pliocene. ∞, ‡ = present at Cabazon and Whitewater River sections, respectively, of the Imperial Formation near San Gorgonio Pass, California (McDougall *et al*, in press).

gibbosa is of special importance for both age determination and correlation with other Neogene marine sequences in the Gulf of California and along the adjacent Pacific Coast. A recent study by McDougall and others (in press) has reinterpreted the age range of this distinctive species within the Gulf of California and the adjacent Pacific Ocean as latest Miocene-early Pliocene and highlighted its usefulness for correlation in this region.

Amphistegina gibbosa is a Miocene to Recent Atlantic-Caribbean species commonly associated with modern coral reef and carbonate bank environments in this region. This species migrated into the Pacific during warm climatic periods of the Miocene and Pliocene but became extinct in the Pacific following step-wise closure of the Panamanian seaway in Pliocene time compounded by cooling climate and local paleoceanographic changes (Crouch and Poag, 1979; McDougall *et al.*, in press). Although Crouch and Poag (1979) and Keller and others (1989) favor a latest Pliocene age for final closure of the Isthmus of Panama, evidence from mollusks and foraminifera collected in this area indicates effective closure occurred in the early Pliocene *ca.* 3.5 Ma (Duque-Caro, 1990; Coates *et al.*, 1992; Collins, 1993; Jackson *et al.*, 1993) with *A. gibbosa* restricted to the Atlantic-Caribbean province thereafter.

Amphistegina gibbosa has been recorded (as *A. lessonii* and *A. gibbosa*) from the lower through upper Miocene La Boca and Gatun formations and in the upper Miocene through Pliocene Bocas del Toro basin in Panama (Blacut and Kleinpell, 1969; Coates *et al.*, 1992; Collins, 1993) and from Deep Sea Drilling Project sites west of Panama (McDougall, 1985). The youngest occurrences of the species along the Pacific Coast of North America were reported by Crouch and Poag (1979) in what they considered lower and upper Pliocene bank top deposits in the Continental Borderland of southern California.

Natland (1950) first reported *A. gibbosa* (recorded as *Amphistegina* sp.) in the Carmen Formation exposed on Carmen and Monserrate islands in the central Gulf of California and originally dated as middle Pliocene on the basis of molluscan fossils (Durham, 1950). Later, the species was recorded in lower Pliocene (Zone N19) sediments of the Imperial Formation in the Fish Creek Wash section of the Vallecito Mountains, California (Ingle, 1974) and from the lower Imperial or Split Mountain formation in the same area by Quinn and Cronin (1984). *Amphistegina gibbosa* also occurs within the Balleto Road section on María Madre Island in the southernmost Gulf of California (McCloy *et al.*, 1988), where it is dated as early Pliocene (Zone N19) on the basis of well preserved planktonic foraminifera.

Most recently, McDougall and others (in press) reported the occurrence of *A. gibbosa* in the Imperial Formation exposed in the San Gorgonio Pass area in the northern Salton Trough, California and dated the enclosing sediments as uppermost Miocene in age (*ca.* 6.5 to 6.04 Ma), based on ranges of associated planktonic foraminifera, radiometric dates on adjacent volcanic units, and correlation with the eustatic sea level curve of Haq and others (1987) and North Pacific Neogene climatic warm event W10 of Keller and Barron (1983). These authors also undertook revaluation of the early to latest Pliocene ages assigned to the occurrences of *A. gibbosa* in the southern California Borderland and in the Gulf of California. McDougall and others (in press) concluded that associated planktonic and benthic microfossils and the stratigraphic contexts of the reported occurrences of *A. gibbosa* in these latter areas allow a latest Miocene-early Pliocene age range for all of these deposits and preclude a latest Pliocene age as reported by Crouch and Poag (1979). Similarly, these same authors reinterpret the middle Pliocene ages previously assigned to *A. gibbosa* in the central Gulf of California (Durham, 1950; Natland, 1950; Ingle, 1974) as representative of "late Miocene to early

Pliocene Zones N17 and N18 based upon the presence of *Globoquadrina humerosa* and morphotypes transitional to *G. dutertrei*". Based on this revaluation of evidence, McDougall and others (in press) now consider that *A. gibbosa* became extinct in the Gulf of California and southern California area no later than 4.3 Ma.

Given the collective latest Miocene (N17) through early Pliocene (N19) age range of *A. gibbosa* in the southern California Borderland, the Salton Trough, and the Gulf of California, the presence of this species in Unit M8c points to the same age range for this occurrence and supports the similar age based upon associated planktonic species.

FORAMINIFERAL AGE

Both planktonic and benthic foraminifers found in samples from Unit M8c provide evidence of an uppermost Miocene-early Pliocene age. In particular, the co-occurrence of *Globigerinoides bulloideus* together with *G. extremus*, *Globoquadrina venezuelana*, *Globorotalia limbata*, and the tentative identifications of *G. anfracta* and *Pulleniatina primalis* suggest deposition occurred no earlier than late Miocene Zone N17 and no later than early Pliocene Zone N19. In addition, two general aspects of these planktonic assemblages also support a late Miocene-early Pliocene age including (1) the abundance of *Globigerinoides obliquus* which correlates with the Zone N18-N19 abundance pattern of this species in the María Madre island sequence (Carreño, 1985; McCloy *et al.*, 1988) and at DSDP Site 475 in the mouth of the Gulf of California (Ingle, in preparation) and (2) the fully tropical character of the assemblages which is consistent with the established patterns of latest Miocene and early Pliocene climatic warming known to be accompanied by northward expansions of tropical faunas in the eastern North Pacific (Ingle, 1973; Crouch and Poag, 1979; Keller and Barron, 1983).

The composition of the benthic assemblages in the Unit M8c samples also supports a late Miocene-early Pliocene age, in particular the presence of *Amphistegina gibbosa*. Although this distinctive species is present in lower Miocene strata in Panama, it does not appear in higher latitudes (*i.e.*, higher than 20° N) along the Pacific Coast until migration occurred in conjunction with the climatic warm events of the latest Miocene and early Pliocene. The presence of *A. gibbosa* is consistent with the occurrence of this species in other latest Miocene-early Pliocene deposits within the Gulf of California and Salton Trough, and favors this age range for at least a portion of the Tiburón marine sequence.

COMPARISON OF ISLA TIBURON DATA WITH THOSE OF PUNTA MITA, NAYARIT

The tropical-subtropical composition of the benthic foraminiferal faunas recovered from Unit M8c stands in clear contrast to the more temperate character of early late Miocene foraminifera identified in outer neritic marine sediments exposed at Punta Mita, Nayarit, located north of Puerto Vallarta in the southeastern Gulf of California (Table 9). The marine sediments exposed at Punta Mita are intercalated with and immediately underlain by volcanic rocks radiometrically dated (K-Ar) as 10.2 and 11.1 Ma (Jensky, 1975; Gastil *et al.*, 1978).

Of special significance, the benthic foraminifers present in the Punta Mita sequence include taxa which are common to early and middle late Miocene temperate faunas in California, allowing their assignment to the provincial Mohnian stage of Kleinpell (1938, 1980), based on the presence of *Bolivina decurtata*, *B. goudkoffi*, *B. hughesi*, *Bulimina uvigerinaformis*, *Cassidulina panzana* and other species. Although foraminifers found at Punta Mita represent a similar depositional environment to faunas recovered from Unit M8c on Isla Tiburón, the species composition of the two faunas is completely different, emphasizing the difference in age and implied climatic settings of these faunas. The established presence of early late Miocene benthic foraminiferal faunas typical of the California province within the Miocene Gulf of California suggests elements of these faunas should have been recovered in the Tiburón sequence, if present. The neritic faunas found in the Isla Tiburón Unit M8c lack benthic species characteristic of the provincial Miocene Luisian or Mohnian faunas of California. Moreover, both the planktonic and benthic foraminifers found in Unit M8c represent tropical-subtropical conditions and are typical of latest Miocene-earliest Pliocene age faunas reported elsewhere within the Gulf of California from deposits exposed near San José del Cabo, Loreto, Isla Carmen and Isla María Madre, and from the Imperial Formation in the Salton Trough (Natland, 1950; McCloy *et al.*, 1988; Carreño, 1992; McDougall *et al.*, in press).

In summary, correlation of established ranges of planktonic foraminifers with the paleomagnetic and radiometric scales and reevaluation of the age range of *Amphistegina gibbosa* in southern California and the Gulf of California by McDougall and others (in press) suggest deposition of Unit M8c occurred some time between 6.2 and 4.3 Ma, spanning the Miocene/Pliocene boundary (Berggren *et al.*, 1985; Berggren, Hilgren *et al.*, 1995; Berggren, Kent *et al.*, 1995). We are unable at this time to explain the discrepancy between ages based on microfossils and those based on megafossils collected from other horizons in Unit M8 and radiometric ages on rocks that overlie those sediments.

DEPOSITIONAL ENVIRONMENT BASED ON FORAMINIFERA

Species composition of benthic foraminiferal assemblages and the relatively high abundance of planktonic species in Cassidy samples 1B, 62, 98, TT1, and TT69 (Table 8) are characteristic of an outer shelf (*e.g.*, outer neritic) to shelf-edge environment. The dominance of *Globigerinoides* and the presence of keeled species of *Globorotalia* in the accompanying

Table 9. Foraminifera in an unnamed upper Miocene marine siltstone, Punta Mita, Nayarit, Mexico.[1,2,3]

Planktonic Species:

Globigerina angustiumbilicata (Bolli)
Neogloboquadrina continuosa (Blow)
Orbulina suturalis (Bronniman)

Benthic Species:

Angulogerina sp.
Bolivina californica Cushman
Bolivina cf. *decurtata* Cushman
Bolivina foraminata R.E. and K.C. Stewart
Bolivina granti Rankin
Bolivina hughesi Cushman
Bolivina aff. *imbricata* Cushman
Bolivina mulleri Kleinpell and Tipton
Bolivina spp. (juveniles)
Buliminella brevior Cushman
Buliminella curta Cushman
Buliminella elegantissima (d'Orbigny)
Cassidulina panzana Kleinpell
Dentalina sp.
Elphidium sp.
Epistominella reliziana (Kleinpell)
Galliherina uvigerinaformis (Cushman and Kleinpell) - broken specimens
Globobulimina sp. (broken specimens)
Hansensica julticamerata (Kleinpell)
Uvigerina aff. *hootsi* Rankin

[1]Foraminifera processed and identified by J.C. Ingle. Sample collected by J.W. Durham (Durham sample no. 10239) in a sequence of interbedded basalts and marine siltstones exposed at Punta Mita, Nayarit, Mexico and described by Jensky (1975).

[2]Established age ranges of the three planktonic species identified allow an early Miocene age (Zone N8 through basal Zone N17) following Kennett and Srinivasan (1983) and Bolli and Saunders (1985). The assemblage of benthic species is typical of the provincial Mohnian State of California with the presence of *G. uvigerinaformis* placing the sample in the lower half of this stage following the original species ranges and zonal definitions presented by Kleinpell (1938). Later work by Kleinpell (1980) and Finger (1992) indicates this assemblage can be assigned to the late middle Mohnian Stage or the upper part of the *G. uvigerinaformis* zone of Kleinpell (1938). Using diatom biostratigraphy, Barron (1986) has established that the Mohnian Stage spans the mid to late Miocene and that the upper part of the *G. uvigerinaformis* zone can be correlated with a radiometric age range of *ca.* 11 to 8.4 Ma. Jensky (1975) and Gastil and others (1978) reported a K-Ar date of 10.3 ± 0.8 Ma for a basalt interbedded with the marine siltstones yielding the microfauna listed above, a date which places these rocks in the lower upper Miocene according to correlations of Berggren, Hilgren and others (1995), and Berggren, Kent and others (1995).

[3]The composition of the foraminiferal assemblage in this sample is representative of deposition in an upper bathyal or upper slope environment at a water depth between 150 and 500 m (Ingle and Keller, 1980).

planktonic assemblages point to deposition under tropical conditions, as does the presence of the benthic species *Amphistegina gibbosa* based upon its modern habitat (Crouch and Poag, 1979). The common occurrence of *Cibicides mckannai*, *Hanzawaia bertheloti*, *H. nitidula*, *H. panamensis*, *Florilus* spp., *Planulina ornata*, *Trifarina* spp., *Lenticulina* spp., and marginal occurrences of costate *Uvigerina excellens* represent an outer shelf biofacies virtually identical to Recent faunas found between depths of 50 and 150 m off the Pacific coasts of Central America and Mexico, including the southern Gulf of California (Bandy and Arnal, 1957; Bandy, 1961; Phleger, 1964; Ingle and Keller, 1980). Species presumably redeposited from shallower inner shelf and littoral environments include *Elphidium crispum* and *Bucella* sp. The presence of broken, worn and well preserved specimens of *Amphistegina gibbosa* also indicates redeposition of shallow water material from a nearby carbonate-rich setting based on the common occurrence of this taxon in tropical-subtropical reef, near-reef, and banktop settings and at depths of 10 to 100 m in the Recent Caribbean-Atlantic province.

In summary, the composition of benthic foraminiferal assemblages and the relatively high abundances of planktonic foraminifers in samples from Isla Tiburón Unit M8c indicate deposition of these sediments occurred in an outer shelf to shelf-edge environment at water depths not exceeding 150 m. Species composition of both benthic and planktonic assemblages indicates that sustained tropical surface temperatures prevailed during deposition as opposed to the seasonal alternation of temperate and subtropical temperatures characterizing the Isla Tiburón area today.

These interpretations of age and depositional environment of course only apply to those portions of the Isla Tiburón marine unit which yielded foraminifera (*i.e.*, Unit M8c). Continental and insular shelf sequences are notoriously rich in hiatuses and it is likely that the Isla Tiburón sequence contains several unconformity-bounded units representing littoral through shelf environments representing a range of ages. Only further sampling and good fortune with respect to fossil recovery will resolve these sorts of questions.

CALCAREOUS NANNOPLANKTON

Four samples from Unit M8c contained calcareous nannoplankton, yielding thirteen species identified by Stanley A. Kling of Micropaleo Consultants, Encinitas, CA (Table 10). One sample (locality 87JS16, Table 6) contains a few poorly preserved specimens tentatively identified as *Discoaster brouweri?*, which ranges from Miocene to Pliocene. More precise age information is provided by the presence of both *Dictyococcites antarcticus* and *D. productus*. The two species are differentiated by a size change which takes place at the Miocene-Pliocene boundary. *Dictyococcites productus* is the smaller of the two and ranges in age from the Miocene-Pliocene boundary through the Pliocene. *Dictyococcites antarcticus* is the larger species and ranges in age from at least the middle Miocene to the Miocene-Pliocene boundary. The occurrence of both species in the same samples (M. Cassidy locality 62 and 87JS16) indicates an age close to the Miocene-Pliocene boundary (Stanley A. Kling, 1987, written communication).

Table 10. Calcareous Nannoplankton from marine conglomerate Unit M8c.

Taxon	Abundance in sample 87JS16
Braarudosphaera bigelowi	R
Calcidiscus leptoporus	F
Coccolithus pelagicus	R
Dictyococcites antarcticus	R
Dictyococcites productus	R
Discoaster spp.	R
Helicosphaera carteri	R
Reticulofenestra haqii	R
Sphenolithus abies	A
Sphenolithus moriformis	R
Sphenolithus neoabies	F
Thoracosphaera sp.	R

R = rare; F = frequent; A = abundant
Analysis of sample 87JS16 [Plate I, fossil locality 16] by Stanley A. Kling, Micropaleo Consultants, Encinitas, CA. Sample is from white sandstone facies mapped as Unit M8c, fairly high in the section on the northeastern flank of Cerro Starship and below the unconformity and ash flow cap dated at 11.2 ± 1.3 Ma. Age of the nannoplankton assemblage is "probably early Pliocene, zone indeterminate".

Two other samples from the Isla Tiburón marine unit collected by Ingle in 1983 (samples TI-83-15 and TI-83-17) were submitted to specialists Stanley A. Kling and Richard Boettcher of Micropaleo Consultants. Although neither sample yielded specific guide fossils, they contain floras composed of abundant *Sphenolithus abies* and *Calcidiscus leptoporus*, along with *Braarudosphaera bigelowi*, *Helicosphaera carteri*, *Coccolithus pelagicus*, and *Reticulofenestra pseudoumbilicata*, and other taxa. Both Mr. Peter Miller of Chevron USA and the paleontologists from Micropaleo Consultants, Encinitas, Calif., independently assigned a late Miocene-early Pliocene age range to these floras, with earliest Pliocene favored.

CONCLUSIONS

Southwestern Isla Tiburón contains a critical reference section for the northern Gulf of California east of the Pacific and North American plate boundary. Rocks include Cretaceous granitic basement overlain by Neogene volcanic and sedimentary units spanning a period of 16 m.y., from 21 to 5 Ma. The sequence corresponds in general to the end of subduction and arc volcanism and the beginning of extensional tectonics and rifting at about 12 Ma. A unique 1.5-km thick, mainly marine, fossiliferous conglomerate documents the presence by 12.9 ± 0.4 Ma of a marine "proto-gulf" which pre-dates the formation of the modern gulf by sea floor spreading and transform faulting beginning 6–5 Ma. The oldest marine unit recognized may correlate with facies in the Cabo Trough, the Boleo Basin near Santa Rosalía, and parts of the Salton Trough of California.

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