CENOZOIC VOLCANIC AND TECTONIC EVOLUTION OF BAJA CALIFORNIA SUR, MEXICO

Brian P. Hausback
Department of Geology and Geophysics
University of California
Berkeley, CA 94720

ABSTRACT

Tertiary to Recent volcanic and sedimentary rocks in Baja California Sur record the geologic events caused by the interactions of lithospheric plates, notably the transition from subduction to strike-slip motion between the North American and adjacent oceanic plates.

As the Farallon Plate was subducted beneath North America during the early Tertiary, Baja California was a stable marine continental shelf receiving volcanic detritus from the active Sierra Madre Occidental calc-alkaline volcanic arc in western Mexico. Volcanic activity migrated westward and arrived along what is now eastern Baja California about 24 m.y. ago accompanied by uplift of the Baja platform.

Calc-alkaline volcanism dominated the geologic events in Baja California Sur from 24 m.y. to about 12 m.y. The focus for this volcanic activity lay along the eastern margin of the present peninsula of Baja California. The volcanic and volcaniclastic materials that constitute the Isidro and Comondú Formations were shed to the west from the arc, first onto a shallow marine shelf, then onto a network of volcanic and detrital nonmarine fans built across Baja California. These arc-related volcanic rocks range from andesitic flows and lahars to rhyolitic ash-flow tuffs. The abundance of rhyolitic volcanics generally decreases to the north from the Bahía de La Paz region.

Subduction ceased off Baja California by 12 m.y. ago, closely followed by the extinction of the Comondú volcanic arc. Consumption of the Farallon Plate resulted in the juxtaposition of the Pacific Plate with Baja California along the Tosco-Abreojos fault. Lack of depositional units above the Comondú volcanics indicates a separation of the peninsula from the easterly volcanic and sedimentary sources probably due to graben formation along the locus of a proto-Gulf of California.

Coeval with the development of the proto-Gulf of California, a series of basalts yielding dates from 12.4 to at least 0.47 m.y. erupted from widely distributed local sources in Baja California Sur. These largely alkalic basalts are associated with the extensional structural regime and further document the transition from the earlier period of calc-alkaline volcanism that accompanied the mid-Tertiary subduction.

Structurally, the southern Baja California Peninsula was a generally stable continental margin during the Miocene arc volcanism. One major discontinuity, the La Paz Fault, was active prior to the Miocene and evidence shows that normal, east-side down, and left-lateral strike-slip motion has occurred along this structure from the late Miocene to possibly Recent times.

INTRODUCTION

The southern portion of the Baja California Peninsula provides an excellent opportunity to study the genesis, growth and extinction of a well exposed Tertiary volcanic arc. To date, most models of the tectonic evolution of this continental margin are based on offshore magnetic, bathymetric and seismic geophysical data, with few constraints from the terrestrial geology. This study focuses on the volcanology, geochronology and geochemistry of the Cenozoic stratigraphy in the southern portion of Baja California Sur(fig. 1) in order to correlate the geologic consequences of lithospheric plate interactions and to help define the geologic events resulting from these plate motions.

The major focus of this report is the Comondú Formation of Baja California Sur. Detailed studies of the Comondú and the associated stratigraphy were undertaken in the La Paz area, with reconnaissance north and south of this area through most of figure 1. In addition, detailed work in the area surrounding La Purísima has been completed (McLean and Hausback, 1984).

The physiography of the southern peninsula is dominated by the Sierra de la Giganta, an elongate northwest-trending, asymmetrically-shaped mountain chain. Several peaks along the rugged Sierra crest reach elevations of over 1000 meters. The position of the divide averages less than 10 kilometers from the eastern shoreline resulting in a precipitous Gulf of California escarpment, and a western flank gently draining to the Pacific Ocean (fig. 2). The elevation of the Sierra declines gently to the south until the mountains disappear into the lowlands of the La Paz area and then abruptly rise again to form the Sierra de la Laguna of the Cabo(Cape) province.

PREVIOUS WORK

Geologic reconnaissance of the southern peninsula was undertaken by several early explorers who concentrated their studies on the marine sedimentary stratigraphy of the region: Gabb (1882), Darton (1921), Heim (1922), and Beal (1948). More recently, McFall (1968) described the Comondú volcanics of the Bahía Concepción area. Gastil and others (1979) described the geochemistry and geochronology of the circum-gulf volcanic rocks on a reconnaissance basis. This study amplifies and reinterprets Gastil's record of volcanism for Baja California Sur between Bahía Concepción and La Paz.

STRATIGRAPHY

The deserts of Baja California Sur contain a well exposed succession of Cenozoic volcanic and sedimentary rocks that record the geologic events of this active plate margin. The prominent Sierra de la Giganta is built of the largely undeformed volcanic and volcaniclastic rocks of the Miocene Comondú Formation. Along the western and eastern margins of the Sierra there are local exposures (figs. 1 and 3) of underlying Tertiary marine sediments. Exposures of the basement rocks are restricted to the periphery of the southern peninsula and make up most of the rugged Cabo province.

Pre-Tertiary Basement

The basement of Baja California Sur is similar to that found in the Peninsular Ranges batholith of Alta California, U.S A. and Baja California Norte. This batholith is composed of a chain of Mesozoic granitic bodies and accompanying metasedimentary roof pendants structurally sutured to a western belt of oceanic crustal rocks.

Pre-Tertiary basement rocks are sparsely exposed in Baja California Sur, although the southern tip of the peninsula, the Cabo province, is dominated by exposures of Pre-Tertiary, mostly Mesozoic, basement terrains (Gastil and others, 1978). Exposures of basement outside the Cabo province in the southern part of the peninsula occur primarily along the coasts in isolated exposures. McFall (1968) reported 78 m.y. granodiorite at Bahía Concepción (locality 1, fig. 1). Northwest of Loreto exposures of tonalite have yielded a date of 144 m.y. (locality 2, fig. 1; Gastil and others, 1978; Chávez, 1978). The nature of the basement below Arroyo La Purísima, northwest of Loreto (locality 3, fig. 1), is indicated by partially melted xenoliths of diorite and gneiss in a young basalt flow. Between Loreto and La Paz, at Punta San Telmo (locality 4, fig. 1), there are exposures of meta-sediments, "schists and gneisses" (Diaz, 1977). Exposures of Mesozoic ophiolitic and island-arc rocks are present on Isla Santa Margarita, Isla Magdalena, the Viscaino Peninsula and Isla Cedros along the west coast of the Peninsula (Blake and others, this volume). The southernmost Cabo province structural block, sutured to the peninsula by the north-south trending La Paz fault, is a highland of Mesozoic crystalline rocks containing

in Frizzell, Virgil A. Jr., ed., 1984, **Geology of the Baja California Peninsula**: Pacific Section S.E.P.M., Vol. 39, p. 219-236

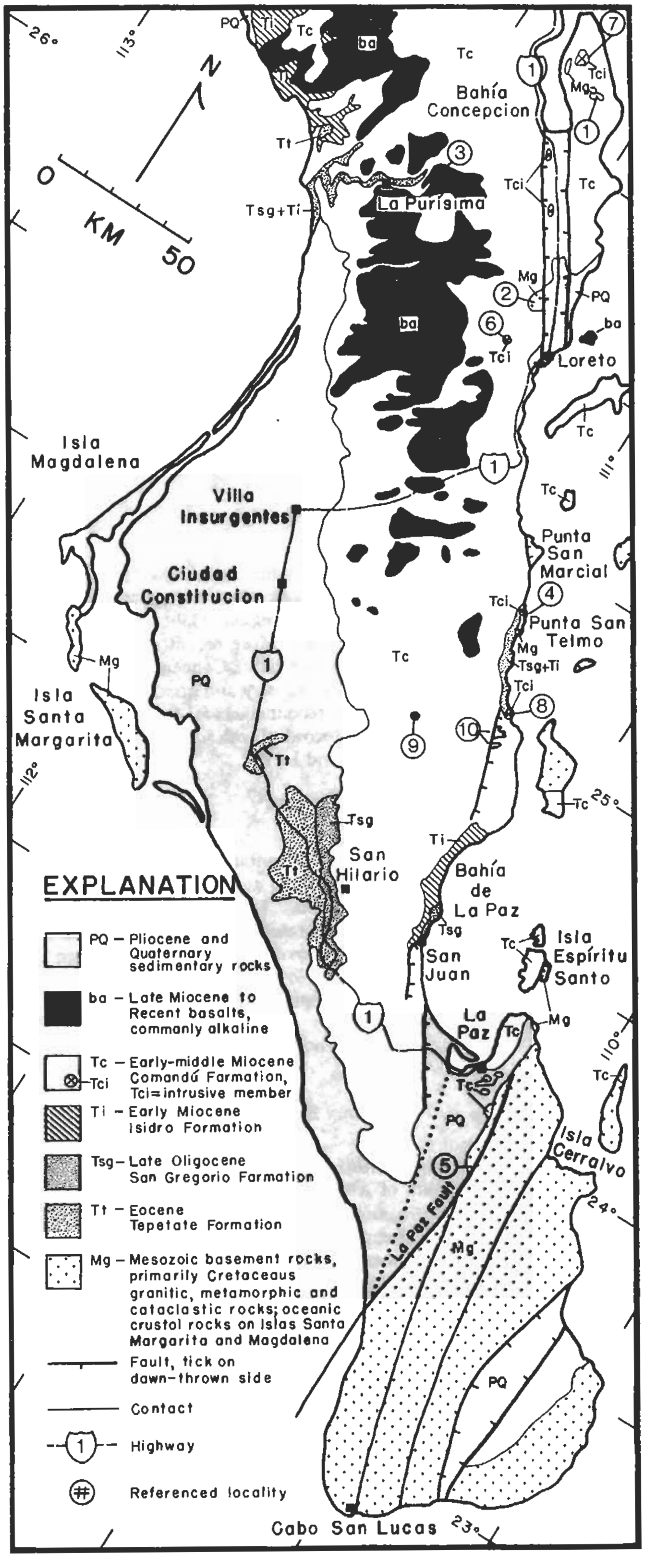


Figure 1. Generalized geologic map of Baja California Sur; modified from Mina (1957), McFall (1968), and Chávez (1978).

numerous metamorphic pendants. Potassium-argon dates on the granitic rocks of the Cabo block yield ages of 70 to 109 m.y., including a biotite granite that yields 93 m.y. ages by both the K-Ar and U-Pb methods (Frizzell, V.A., Ort, K., and Mattinson, J.M.; written comm., 1983). A layered hornblende diorite along the La Paz fault zone yields a K-Ar date of 115 m.y.(locality 5, fig 1). Gastil and others (1976, 1978) report additional 70 to 98 m.y. K-Ar ages as well as two Paleozoic age determinations from the Cabo block.

The Cretaceous marine sedimentary rocks of the Eugenia and Valle Formations overlie the crystalline basement. These rocks crop out only on the Viscaino Peninsula north of the study area and are similar to the Great Valley Sequence of Alta California, probably formed from materials shed from the exposed Mesozoic batholithic highland.

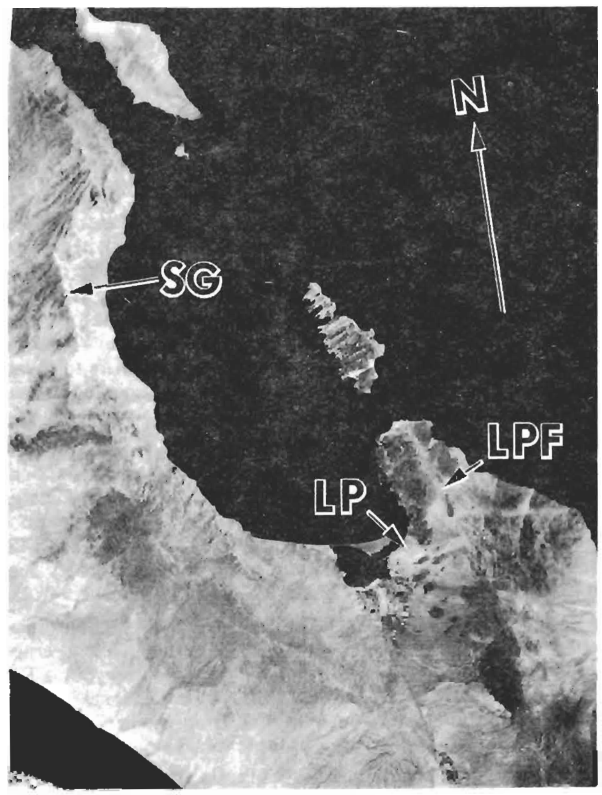


Figure 2. Landsat image of the Bahiá de La Paz region; crest of the Sierra de la Giganta (SG), La Paz (LP), La Paz Fault (LPF).

Tepetate Formation

The Cretaceous rocks of Baja California Sur are overlain by lower Tertiary marine sedimentary rocks, of which the oldest encountered in this study is the Tepetate Formation (Heim, 1922). The Tepetate is exposed only on the western side of the Peninsula in two areas: west of the Bahía de La Paz, and considerably farther north in Arroyo Mesquital, northwest of La Purísima. Cursory examination of the sandstones show them to be foram-bearing feldspathic wackes derived mainly from a granitic source with little or no volcanic detritus. These sandstones commonly contain abundant *Discocyclina*, a disk-shaped foraminifera up to 1 cm or more in diameter. The microfauna of this formation were studied by Knappe (1974) who concluded that this sequence of sandstone and shale is the result of upper bathyal to mid-bathyal slope deposition during the early Eocene.

Salto Formation

Localized subaerial volcanic activity on the eastern side of Baja California may have occurred prior to and possibly coeval with marine deposition of the San Gregorio Formation, the stratigraphic unit generally found overlying the Tepetate Formation. McFall (1968) reported an age of 28.1 ± 0.9 m.y. for a tuff in what he refers to as the Salto Formation which he considers to be the oldest portion of his "Comondú Group" at Bahía Concepción. Gastil and others (1979) report a date of 27.5 ± 0.8 m.y. on a basalt within the marine sedimentary section north of San Juan de la Costa. In addition, a subaerially deposited ash-flow tuff near Punta San Telmo, probably lying stratigraphically below the San Gregorio Formation, yields a date of 28.0 ± 0.7 m.y. In each case these volcanic units are associated with cross-bedded red sandstones. Although widely dispersed, these essentially coeval Oligocene volcanic rocks and cross-bedded sandstones of the Salto Formation constitute a pre-Comondú portion of the Tertiary stratigraphy localized along the eastern margin of Baja California Sur that is slightly older than or coeval with the San Gregorio Formation.

San Gregorio Formation

The San Gregorio Formation (Beal, 1948) unconformably overlies the Tepetate Formation and is well exposed on the east and west sides of the Sierra de la Giganta west of Bahía de La Paz, as well as in limited exposures in several arroyo bottoms in the La Purísima region. These rocks have also been referred to as the Monterey (and Monterrey) Formation due to their lithologic similarity to the younger Miocene Monterey Formation of Alta California (Darton, 1921; Heim, 1922; Mina, 1957; Escandón, 1978; Ojeda, 1979). The exposed thickness of the formation is about 100 m in Arroyo San Hilario (Ojeda, 1979), 127 m at San Juan de la Costa (Escandón, 1978) and at least 72 m in the La Purísima area. In the La Purísima region the formation consists of a sequence of interbedded, commonly phosphatic, silicious shale, diatomite, pelletoidal phosphatic sandstone and rhyolite tuff. In the San Hilario area the lithologies are similar but less diagenically silicified than at La Purísima. The Gulf coast exposures at San Juan de la Costa (fig. 4) of the San Gregorio Formation contain tuffaceous sandstone, siltstone (mildly diatomaceous), ostracod-bearing sandstone, and pelletoidal phosphatic sandstone (commonly containing abundant shark teeth and marine mammalian bones). The presence of abundant smooth-shelled ostracods probably indicates an estuarine brackish water environment (Pokorný, 1978). This, together with abundant marine mammalian bones, rare solitary corals, pelecypod coquinas, and local cross- bedding, strongly suggests deposition of much of the San Gregorio Formation at San Juan de la Costa in a shallow marine, nearshore environment. The occurrence of coquinas and cross-bedding increases upward in the San Juan de la Costa section, perhaps indicating a gradual uplift. In the La Purísima region the benthic foram assemblage indicates that the San Gregorio Formation was deposited at upper bathyal depths of 2000-1500 m (McLean, Barron, and Hausback, 1984), and is directly overlain by the shallow marine Isidro Formation, suggesting either an abrupt period of uplift or a gap in the depositional record.

Pebble conglomerates in the upper 15 m of the San Gregorio Formation at San Juan de la Costa contain metamorphosed volcanic pebbles. These pebbles are strongly silicified, well-rounded clasts of welded rhyolite tuff, andesite, white (vein ?) quartz, and minor quartzo-feldspathic sandstone. These rocks contain local groundmass sericite and epidote, locally replacing plagioclase. This meta-volcanic pebble component appears in the upper San Gregorio Formation, extends through the Isidro Formation and terminates in the lower Comondú Formation. The occurrence of the meta-volcanic pebble conglomerates is widespread throughout the study area, notably found at the base of the Isidro Formation in all known exposures. The pebbles were probably shed westward onto the Baja California shelf from uplifted exposures of the middle Cretaceous to Eocene volcanic complex developed along the western Mexican mainland.

The age of the San Gregorio Formation has been a topic of debate for the better part of a century but is now known to be late Oligocene. Early workers in the region (Darton, 1921; Heim, 1922; Beal, 1948; Mina, 1957) suggested ages ranging from Eocene to mid-Miocene, primarily based on lithologic similarity to the Monterey Formation of Alta California. Vanderhoof (1942) discovered fossil remains of the sea cow *Cornwallius* resulting in the first concrete evidence of an Oligocene age. Hausback (1982) determined a K-Ar radiometric age of 25.5 m.y. (late Oligocene) on biotite from a tuff bed in the San Gregorio Formation at Arroyo San Hilario. Four additional tuffs in the San Gregorio Formation in the La Purísima area have yielded K-Ar dates ranging from 27.2 to 23.4 m.y. (table 1), consistent with their relative stratigraphic position. In addition to radiometric evidence, diatoms at La Purísima indicate a late Oligocene age for the formation (McLean, Barron, and Hausback, 1984). Well preserved coccoliths, *Cyclicargolithus abisectus* (Müller) and *dictyococcites bisectus* (Hay and others), from the same Arroyo San Hilario locality as the dated biotite-bearing ash also indicate a late Oligocene age for the San Gregorio Formation (David Bukry, written comm., 1982). Furthermore, Shelton Applegate (pers. comm., 1983) suggests that the shark fauna in the Arroyo San Hilario exposure of the San Gregorio Formation is of Oligocene age.

The dates on silicic ashes of the San Gregorio Formation show them to be coeval with voluminous calc-alkaline volcanism of the adjacent Sierra Madre Occidental of western Mexico. McDowell and Keizer (1977) and McDowell and Henry (1983) document the occurrence of a voluminous north-south elongate volcanic arc in the Sierra Madre Occidental that may have given rise to distal water-laid ashes such as those deposited in the San Gregorio Formation. This volcanic arc was active from 32 to 23 m.y. ago, during which time it gradually migrated toward the western edge of the continent.

Isidro Formation

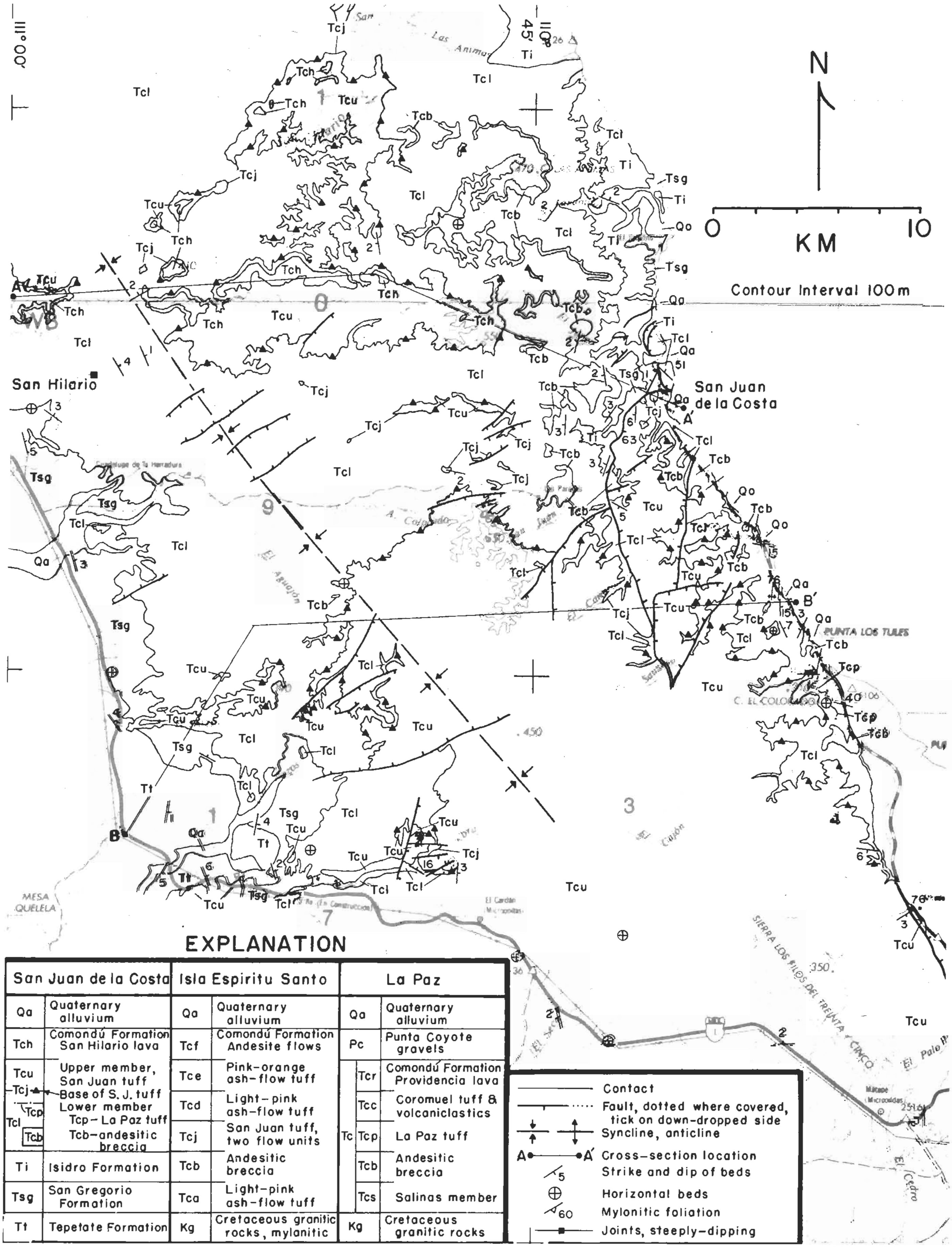
Deposition of the Isidro Formation (Heim, 1922) marks the initiation of local volcanism in eastern Baja California during earliest Miocene time. Along the Gulf coast, at San Juan de la Costa, this formation is composed of a 37 m section of green-colored water-lain tuff, pebbly sandstone, oyster coquina and conglomerate intercalated with reworked pink tuff (fig. 6). This locally intense green color is due to clinoptilolite (Edward Montgomery, pers. comm., 1981) coatings on grains and is apparently restricted to the marine deposits.

On the west side of the Sierra de la Giganta, in the San Hilario area, the Isidro Formation is only about 15 to 25 m thick, mainly composed of pebble conglomerate and sandstone, contains minor pelecypod debris, and lacks primary volcanic deposits. This thin unit has been included with the lowermost Comondú Formation in figure 3.

The northernmost exposures of the Isidro Formation near La Purísima are composed of bioturbated yellow to brown fine-grained tuffaceous sandstone and siltstone that attain a stratigraphic thickness of up to 80 m. Pelecypod, gastropod and barnacle fossils are locally abundant. Cross-bedding indicates strong current action similar to occurrences of these rocks to the south. The fossil and sedimentological data suggest neritic water depths, probably of a lagoonal depositional environment; (Judy Smith, this volume). Field relations indicate that the Isidro Formation interfingers with the nonmarine lowermost Comondú Formation.

The age of the Isidro Formation is well constrained by K-Ar dates on the enclosing stratigraphy. In Arroyo San Hilario the Isidro Formation unconformably overlies the San Gregorio Formation which contains a 25.5 m.y. ash bed. In the San Juan de la Costa area the Isidro beds are overlain by the lowermost Comondú formation containing tuffs dated at 21-22 m.y. (fig. 5). Further north in the La Purísima region the Isidro Formation unconformably overlies San Gregorio beds as young as 23.4 m.y. and at Purísima Vieja, 16 km northwest of La Purísima, the Isidro Formation grades vertically upward into nonmarine Comondú beds containing a 14.5 m.y. basalt flow. So, it appears that in the Bahía de La Paz region the Isidro Formation is lówermost Miocene, between 25.4 and 22 m.y. but in the La Purísima region the Isidro probably has a longer age span of lower to middle Miocene, between 23.4 and 14.5 m.y. Undoubtedly, the Isidro is, in part, coeval with the Comondú Formation and probably represents the shallow marine equivalent of the Comondú.

Figure 3. Following page. Geologic map of the Bahiá de La Paz region. Note that the thin Isidro Formation on the west side of the Sierra de la Giganta has not been mapped and is included with the lower member of the Comondú Formation. On the west side of the Bahía de La Paz only the base of the San Juan tuff has been mapped; its bulk is included in the Tcu member.


N
0 KM 10
Contour Interval 100m
San Hilario
San Juan de la Costa
PUNTA LOS TULES
C. EL COLORADO
MESA QUELELA
SIERRA LOS FILOS DEL TREINTA Y CINCO
EXPLANATION
San Juan de la Costa
Qa Quaternary alluvium
Tch Comondú Formation San Hilario lava
Tcu Upper member, San Juan tuff
Tcj Base of S. J. tuff
Tcl Lower member
Tcp Tcp – La Paz tuff
Tcb Tcb – andesitic breccia
Ti Isidro Formation
Tsg San Gregorio Formation
Tt Tepetate Formation
Isla Espiritu Santo
Qa Quaternary alluvium
Tcf Comondú Formation Andesite flows
Tce Pink-orange ash-flow tuff
Tcd Light-pink ash-flow tuff
Tcj San Juan tuff, two flow units
Tcb Andesitic breccia
Tca Light-pink ash-flow tuff
Kg Cretaceous granitic rocks, mylonitic
La Paz
Qa Quaternary alluvium
Pc Punta Coyote gravels
Tc
Tcr Comondú Formation Providencia lava
Tcc Coromuel tuff & volcaniclastics
Tcp La Paz tuff
Tcb Andesitic breccia
Tcs Salinas member
Kg Cretaceous granitic rocks
Contact
Fault, dotted where covered, tick on down-dropped side
Syncline, anticline
A A′ Cross-section location
Strike and dip of beds
Horizontal beds
Mylonitic foliation
Joints, steeply-dipping

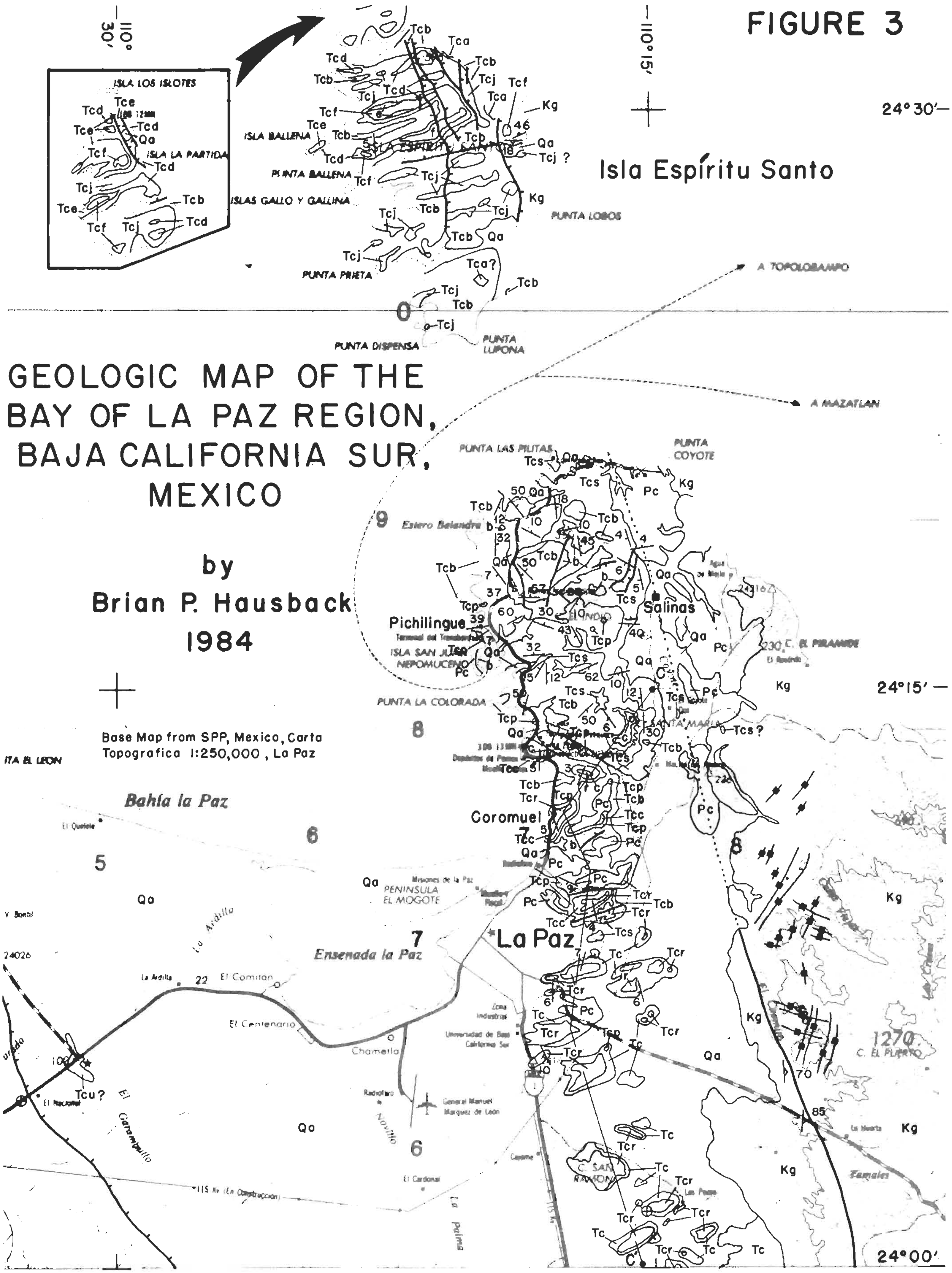


FIGURE 3
GEOLOGIC MAP OF THE BAY OF LA PAZ REGION, BAJA CALIFORNIA SUR, MEXICO
by
Brian P. Hausback
1984
Base Map from SPP, Mexico, Carta Topografica 1:250,000 , La Paz
Isla Espíritu Santo
ISLA LOS ISLOTES
ISLA LA PARTIDA
ISLA BALLENA
PUNTA BALLENA
ISLAS GALLO Y GALLINA
PUNTA LOBOS
PUNTA PRIETA
PUNTA DISPENSA
PUNTA LUPONA
A TOPOLOBAMPO
A MAZATLAN
PUNTA LAS PILITAS
PUNTA COYOTE
Estero Balandra
Pichilingue
Salinas
ISLA SAN JUAN NEPOMUCENO
PUNTA LA COLORADA
Bahía la Paz
Coromuel
PENINSULA EL MOGOTE
La Paz
Ensenada la Paz
El Comitan
El Centenario
Chametla
C. SAN RAMON
C. EL PIRAMIDE
C. EL PUERTO
110° 30′
110° 15′
24° 30′
24° 15′
24° 00′

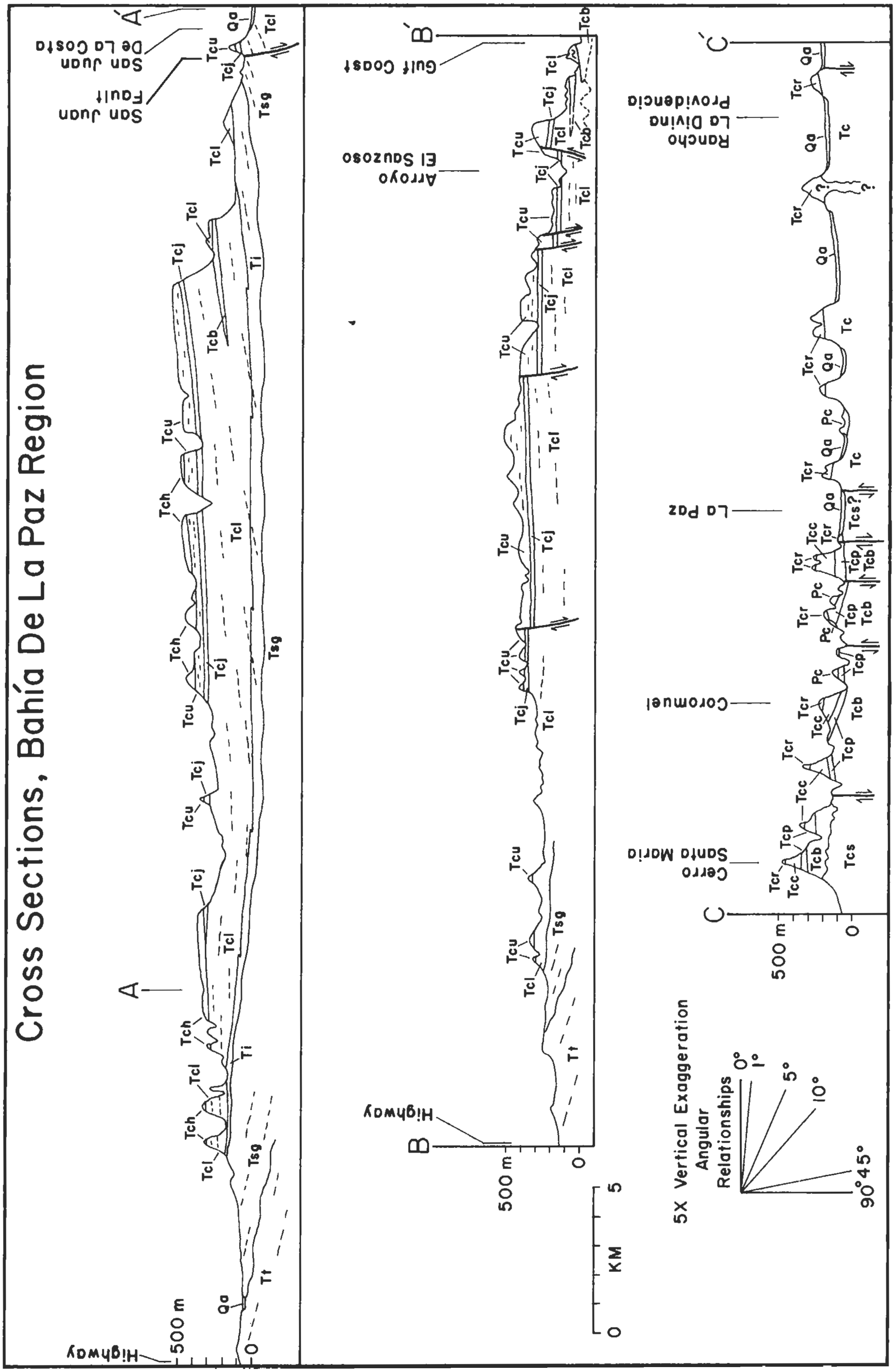


Figure 4. Cross sections to accompany figure 3.

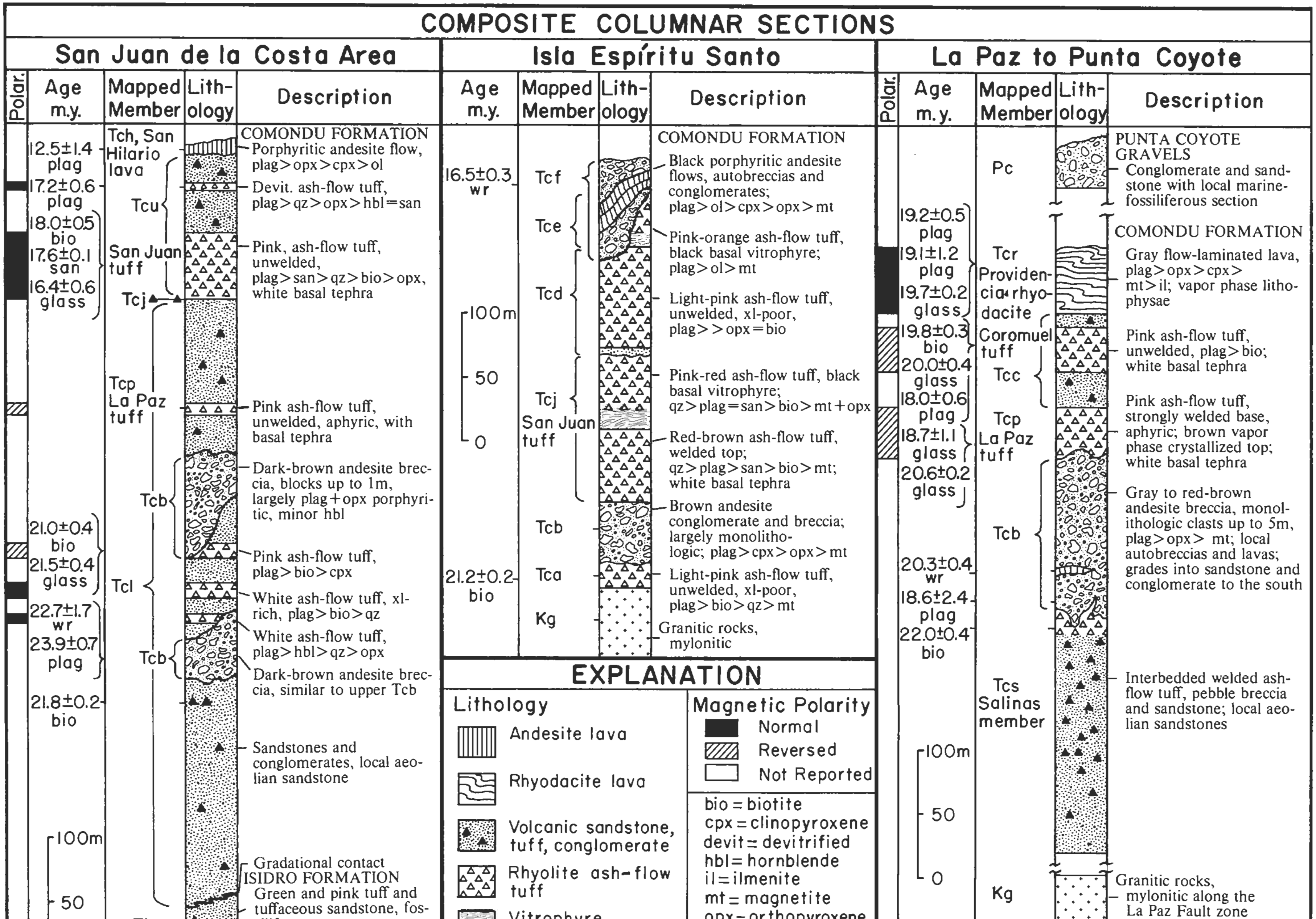


Figure 5. Generalized stratigraphic sections for the Bahía de La Paz region.

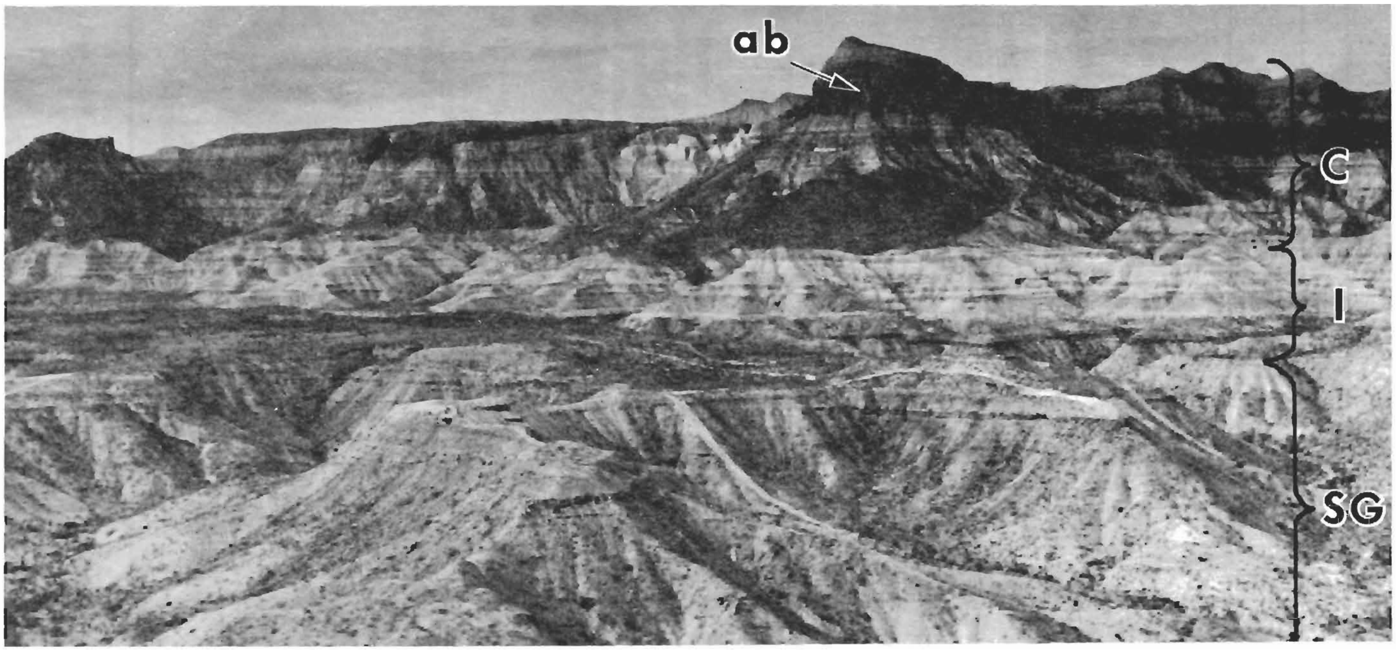


Figure 6. Aerial view to the west of the San Juan de la Costa area showing nearly flat-bedded stratigraphy; San Gregorio Formation (SG), Isidro Formation (I), and lower part of the Comondú Formation (C) including a prominent cliff-forming andesitic breccia or lahar (ab).

Comondú Formation

The Comondú Formation was named by Heim (1922) for the volcaniclastic sandstones and conglomerates exposed in the deep canyon walls at the village of Comondú, west of Loreto. Heim stated that the Comondú Formation thickened to the east and included "basaltic breccia" in the crest of the Sierra de la Giganta at Cerro Giganta. Prior to Heim's work the Comondú Formation was informally known as the Mesa Sandstone (Gabb, 1882, and Darton, 1921). More recently, the Comondú designation has been liberally applied to the entire Miocene sequence of volcanic and volcaniclastic rocks of the Sierra de la Giganta (Beal, 1948; Mina, 1957). This study restricts the name Comondú Formation to the Miocene arc-derived silicic and intermediate composition volcanics and volcaniclastics that make up the bulk of the Sierra de la Giganta and excludes the late Miocene and younger capping basalt flows related to post-arc rifting.

The widespread Comondú Formation dominates the geology of Baja California Sur. The formation overlies the Isidro Formation and in most exposures the transition is gradational from the shallow marine Isidro beds to the subaerially deposited Comondú strata. Comondú rocks extend as far south as La Paz and are exposed continuously to just north of the 28th parallel, north of which equivalents are found discontinuously through Baja California Norte and into eastern Alta California and Arizona (Glazner and Supplee, 1982). To the west the distal sandstones of the Comondú Formation thin across the gentle Pacific slope and generally disappear beneath Quaternary alluvium before reaching the western shore; to the east, the massif of the Comondú rocks, 1500 m or more in thickness at numerous localities, is sharply truncated by the Gulf of California escarpment. The Comondú Formation is described below in detail for the Bahía de La Paz region and in reconnaissance fashion to the north.

Lithologies

The Comondú Formation is composed of interbedded volcanic sandstones and conglomerates, rhyolitic ash-flow tuffs, and andesitic lahars and lava flows (fig. 5). The most abundant of these are volcanic sandstone and conglomerate. These immature, fragmental, brown to gray rocks form lensoidal to tabular beds often displaying planar laminations with thin interbeds of tuffaceous siltstone. The sandstones and conglomerates are composed of disaggregated volcanic rocks: poorly-sorted bubble-wall shard glass, crystal fragments, and andesitic to rhyolitic lithic debris. Trough cross-bedding, massive bedding and reverse-graded bedding are common. Frequently, the sandstones and conglomerates are rich in pumice pebbles and the sandstones support outsized rounded cobbles and boulders of andesite. These features suggest braided stream and debris flow depositional mechanisms. The Comondú Formation lacks fossil remains and was probably deposited as a set of detrital fans on the western flank of a north-south chain of volcanoes.

The next most abundant lithologies in the La Paz region are the rhyolite ash-flow tuffs which are interbedded throughout the Comondú Formation. The tuffs comprise about 75 percent of the stratigraphy on Isla Espíritu Santo, 20 percent at San Juan de la Costa, but are absent west of San Hilario suggesting easterly source areas for the tuffs. Individual flow units range from 6 to at least 77 meters in thickness. The ash-flow deposits are commonly pink-colored, massive, pumicious, crystal-vitric, poorly welded tuffs with basal airfall tephras. On Isla Espíritu Santo the ash-flow tuffs contain welded portions with black basal vitrophyres up to 15 m thick. Only one major ash-flow tuff in the La Paz section, the newly named La Paz tuff, is strongly welded and none are strongly welded in the San Juan de la Costa section. One of the largest of these tuffs, the San Juan tuff (newly named for its exposures at San Juan de la Costa), has a reconstructed volume of at least 31 km^3 of uninflated rhyolitic magma exposed west of Bahía de La Paz (57 km^3 of expanded 1.37 g/cm^3 tuff; assuming magma density of 2.5 g/cm^3). Accounting for the rifted easterly portion of this tuff, the original magma volume was *at least* 55 km^3, similar in magnitude to the volume of the climactic eruption of Crater Lake caldera in Oregon (Bacon, 1983).

Based on phenocryst mineralogy, Sr, Rb and Zr trace element geochemistry (fig. 7) and magnetic stratigraphy constrained by K-Ar geochronology, two general tuff correlations can be made between the three geographically separated areas in the Bahía de La Paz region (figs. 3 and 5). The prominent San Juan tuff appears on Isla Espiritu Santo as one or both of the associated flow units of member Tcj. Also, the thick, welded La Paz tuff can be found just south of San Juan de la Costa as a distal, thin, unwelded ash-flow tuff.

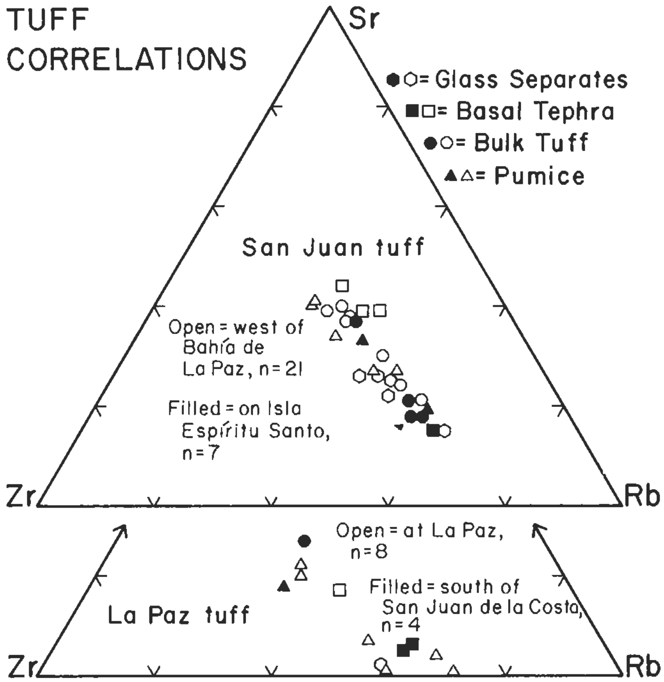


Figure 7. Sr, Zr, Rb trace element correlation data for the San Juan tuff in the San Juan de la Costa region west of Bahía de La Paz and on Isla de Espiritu Santo; also the La Paz tuff in the La Paz area and in the coastal section south of San Juan de la Costa. Analyses by X-ray fluorescence.

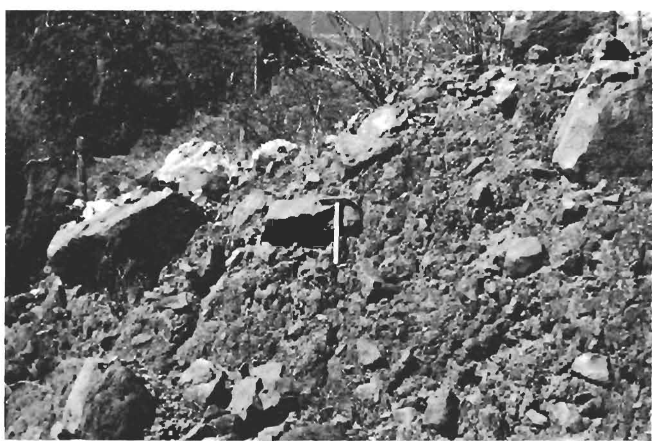


Figure 8. Outcrop of an andesitic lahar in the lower Comondú Formation of the San Juan de la Costa area. The hammer is 0.5m long for scale. Note the matrix-supported angular blocks and the massive to poorly-stratified character of the deposit.

The final major category of Comondú rock types are the genetically associated andesitic lahars and lava flows. The lahars form massive tabular sheets up to about 40 m in thickness and locally grade into lava flows (autobreccias). The lahars consist of breccias of largely monolithologic hypersthene andesite with angular clasts commonly up to 1 m or more in diameter. The clasts float in a groundmass of gray to brown, poorly sorted, sand-sized andesitic detritus (fig. 8). The lahars locally fill deep paleochannels. Where these lahars overlie tuff and tuffaceous sandstone the extreme invertèd density relationship frequently has resulted in the formation of large-scale, probably syndepositional, loading structures -- blocks (commonly tens to hundreds of meters in dimension) of lahar sinking into what must have been unconsolidated sandstone, and the sandstone flaring upward into the andesite bodies as large dike-like structures. Local baked and silicified zones along the base of the breccia units and in the immediately underlying tuffaceous sandstones indicate that these andesitic breccias were emplaced at high temperatures. The andesite breccias are thus probably the result of hot volcanic debris flows associated with strato-volcanic eruptions. Laterally the breccias grade into conglomerates and sandstone units.

Transport Directions

The sedimentary and volcanic transport directions of the Comondú Formation deposits are derived from several lines of evidence and indicate divergent directions between the La Paz and San Juan de la Costa areas (fig. 9). Clast imbrications and cross-bedding indicate fluvial transport of the Comondú sandstone and conglomerate to the west near San Juan de la Costa area, and to the south in the La Paz area. Lateral fining of andesitic breccia and maturation into conglomerate and sandstone occur along these same directions. In addition, isopachs of the prominent San Juan tuff show a general thinning to the west and indicate a source area to the east of the present Gulf shoreline, probably to the east of the Isla Espíritu Santo. Similar facies gradations of the andesitic clastic units between Loreto and Villa Insurgentes also indicate a southwesterly to westerly transport direction. In the La Purisima area, McLean and Hausback (1984) report fluvial Comondú transport directions to the south and southwest.

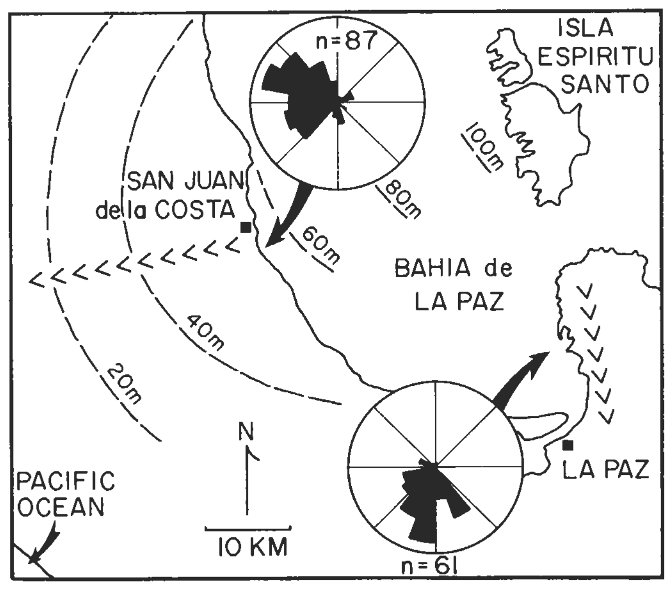


Figure 9. Compilation of Comondú Formation volcanic and sedimentary transport direction data. Rose diagrams determined from pebble imbrication and cross-bedding direction data in the lower Comondú Formation; >>>> indicates general fining direction of clastic andesitic units; dashed lines are isopaches of the San Juan tuff.

Throughout much of the Sierra de la Giganta the westward-sloping mesas are capped by lahars of andesitic breccia, conglomerate, and sandstone with well-preserved surface morphologies displaying low amplitude crescentic pressure ridges convex to the west, indicating transport in that direction. These debris flows once flooded down channels developed on the detrital fans built along the western flank of the Comondú volcanic chain. After deposition the dense, blocky flows became lithified and very resistant. Subsequent erosion of less competent surrounding sandstones has left these lahars as caps to many of the east-west elongate mesas.

In summary, the Comondú volcanic and volcaniclastic units were shed from volcanoes growing along the east side of what is now the Baja Peninsula onto the southern Peninsula along transport directions varying from west to south. The volcanics were first shed into a shallow marine environment, depositing the Isidro Formation and progressively built the Comondú subaerial volcanic and volcaniclastic apron westward across Baja California.

Facies Models

The volcanic and volcaniclastic rocks of the Comondú Formation display regular and predictable lateral gradations in grain size, lithologic assemblages, and welding of ash-flows. These variations can be applied to a nonmarine volcanic facies model developed by Vessel and Davies (1981). The facies, or assemblages, of an active continental stratovolcano are:

Volcanic Core Facies: lavas, airfall ash and colluvial deposits.

Proximal Volcaniclastic Facies: largely monolithologic volcanic breccias and airfall ashes.

Medial Volcaniclastic Facies: interbedded breccias, conglomerates, and coarse-grained sandstone.

Distal Volcaniclastic Facies: sandstone and conglomerate lithologies.

This model has been simplified for the Comondú Formation in this study by combining Vessel and Davies' proximal and medial facies into one facies, here called "proximal"(fig. 10). The core of the volcanic arc extended along the eastern margin of Baja California prior to rifting. The volcanic axis is presently offshore through southernmost Baja California and indications of its proximity are found in several localities along the east coast. Between Bahía Concepción and Loreto several hornblende-bearing hypabyssal andesitic porphyries cut the Comondú Formation. Because these stocks are coeval with Comondú eruptives (19.4 ± 0.9 m.y., locality 6, fig. 1; 20.0 ± 2.0 m.y., locality 7, McFall, 1968) and cut the lowermost part of the section, these intrusions and their associated dike systems probably represent subvolcanic Comondú magma chambers and feeders. This chain of porphyritic stocks along eastern Baja extends to the south where porphyries of similar lithology are found at Punta San Telmo (locality 4, fig. 1) and possibly at Los Dolores (locality 8, fig. 1).

The Pichilingue area, immediately north of La Paz, contains another portion of the volcanic core facies composed of andesite lavas grading into voluminous monolithologic breccias. In addition, a major welded tuff, the La Paz tuff, occurs there. This is the southernmost extension of the Comondú volcanic core facies exposed on the Peninsula as the zone is apparently truncated by the La Paz Fault. No outcrops of the Comondú Formation have been found during reconnaissance studies in the Cabo province. The northernmost tip of Isla Cerralvo, east of La Paz, contains a remnant capping exposure of a sequence of probable Comondú equivalent ash-flow tuffs, one of which is densely welded, and sedimentary rocks (J.G. Smith and M.G. Sawlan, pers. comm., 1983). The southern continuation of the volcanic core facies may have been offset along the La Paz Fault in a left-lateral motion (fig. 10), as suggested by offshore volcanic stratigraphy outlined by Normark and Curray (1968) and by recent seismic events (Molnar, 1973).

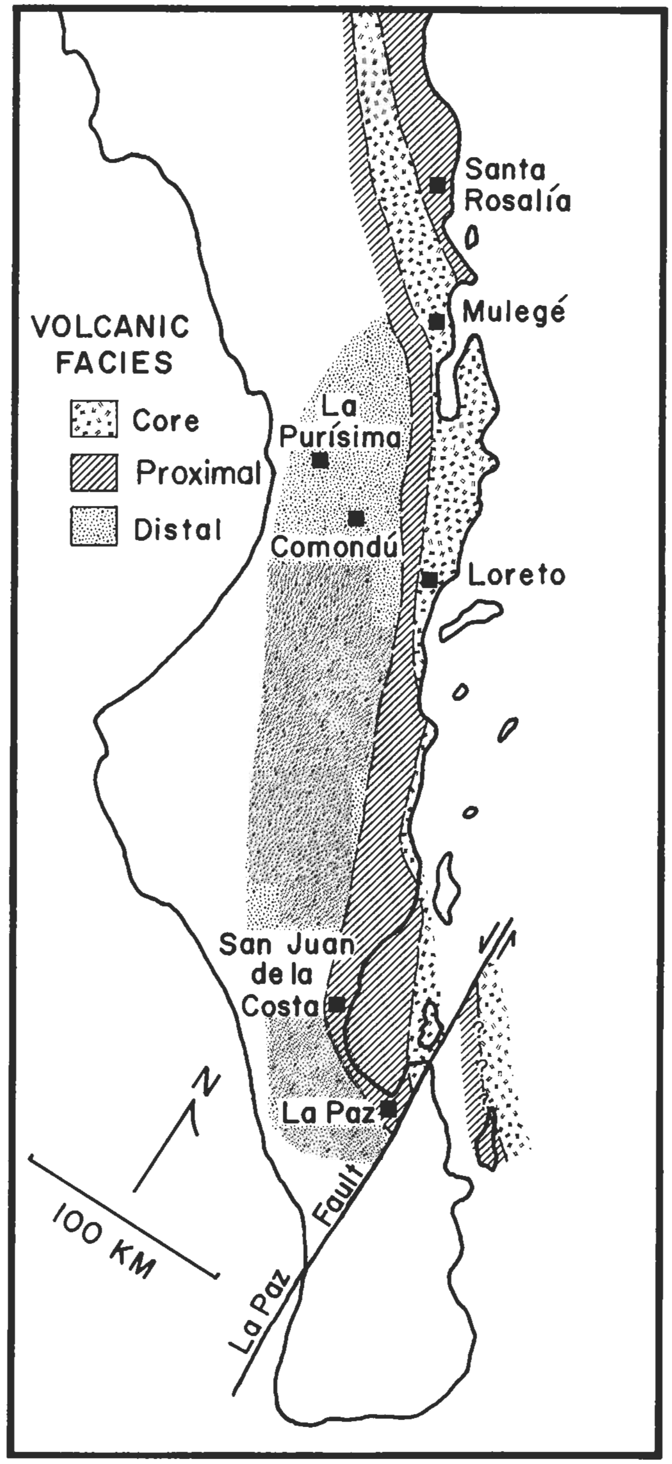


Figure 10. Generalized volcanic facies model of the Comondú Formation in Baja California Sur. Facies designations modified from Vessel and Davies (1981), see text.

On Isla Espíritu Santo the presence of andesite flows and several strongly welded ash-flow tuffs belonging to the core facies indicates a much nearer-source environment than to the west at San Juan de la Costa, where the proximal facies contains unwelded tuffs interbedded with a section of sandstone, conglomerate, and andesitic breccias. Further west, the Comondú stratigraphy is best characterized as distal facies containing mainly sandstones with few ash-flow tuffs, breccias, or coarse-grained conglomerates.

Table 1. Potassium Argon Age Data

Sample Number	Location Lat./Long.	Rock type	Mineral Dated	%K ± std. dev.	$^{40}Ar^{*}$ × 10^{-11} mol./gm	$^{40}Ar^{*}$ %	Age m.y. ± 2 std. dev.	Stratigraphic Unit/Comments
Late Miocene to Recent Basalts								
383-16-1	26°05'10"N 112°01'36"W	Alkalic Basalt	W.R.	3.087 ± 0.117	0.2503	4.4	0.47 ± 0.09	Canyon-Filling Flow, Rancho Escondido
383-8-1	26°16'36"N 112°02'18"W	Alkalic Basalt	W.R.	2.176 ± 0.092	0.3270	4.6	0.87 ± 0.13	Cinder Cone Flank Flow, NE of La Purísima
383-9-1	26°15'32"N 112°05'58"W	Alkalic Basalt	W.R.	2.585 ± 0.042	3.747	56.2	8.3 ± 0.3	Capping Flow between La Purísima & Paso Hondo
383-10-1B	26°29'08"N 112°07'40"W	Alkalic Basalt	W.R.	1.803 ± 0.041	3.492	56.9	11.1 ± 0.8	Canyon-Filling Flow A. San Gregorio
383-10-1A	26°29'08"N 112°07'40"W	Basalt	W.R.	0.948 ± 0.013	2.052	55.5	12.4 ± 0.4	Oldest Capping Flow A. San Gregorio
401	25°26'11"N 111°31'18"W	Alkalic Basalt	W.R.	3.584 ± 0.017	3.346	40.0	5.4 ± 0.1	N. side of Highway 32 km NE of Insurgentes
438	24°54'34"N 111°05'00"W	Alkalic Basalt	W.R.	3.961 ± 0.014	2.560	21.6	3.7 ± 0.1	5.5 km W of Los Torres
443	25°15'59"N 111°30'51"W	Alkalic Basalt	W.R.	3.096 ± 0.002	2.232	64.6	4.2 ± 0.1	Mesa Nombre de Dios, 26 km E of Insurgentes
Comondú Formation, West of Bahía de La Paz								
162	24°24'40"N 110°56'00"W	Andesite flow	Plag.	0.5096 ± 0.015	1.112	5.0	12.5 ± 1.4	Tch, San Hilario lava
Bj1	24°22'24"N 110°41'35"W	Rhy. ash-flow tuff	Plag.	0.9234 ± 0.0010	2.771	40.9	17.2 ± 0.6	Tcu, Devitrified tuff, San Juan de la Costa
28	24°21'37"N 110°41'31"W	Rhy. ash-flow tuff	Glass	4.731 ± 0.067	13.48	20.3	16.4 ± 0.6	Tcj, San Juan tuff
Bj2	24°21'37"N 110°41'51"W	Rhy. ash-flow tuff	Sanid.	8.179 ± 0.016	25.15	93.0	17.6 ± 0.1	Tcj, San Juan tuff, San Juan de la Costa
Bj2	24°21'37"N 110°41'51"W	Rhy. ash-flow tuff	Bio.	6.271 ± 0.070	19.68	41.8	18.0 ± 0.5	Tcj, San Juan tuff, San Juan de la Costa
38	24°20'44"N 110°40'42"W	Rhy. ash-flow tuff	Bio.	6.875 ± 0.070	25.15	86.2	21.0 ± 0.4	Tcl, 6 km S of San Juan de la Costa
178	24°26'49"N 110°46'55"W	Rhy. ash-flow tuff	Glass	4.353 ± 0.024	16.36	37.4	21.5 ± 0.4	Tcl, A. Tarabillas Prob. same as 38
425	24°19'08"N 110°39'05"W	Pumicious tuff	Bio.	6.555 ± 0.005	24.90	74.3	21.8 ± 0.2	Tcl, Coastal exposure N of A. Camarón
57A	24°18'22"N 110°39'02"W	Andesitic lahar, clast	W.R.	1.747 ± 0.039	6.923	41.5	22.7 ± 1.7	Tcb, N side of A. Sauzoso
57B	24°18'22"N 110°39'02"W	Andesitic lahar, clast	Plag.	0.743 ± 0.02	3.099	52.1	23.9 ± 0.7	Tcb, N side of A. Sauzoso
Comondú Formation, Isla Espíritu Santo								
286	24°28'49"N 110°23'00"W	Andesite flow	W.R.	1.733 ± 0.006	4.983	37.3	16.5 ± 0.3	Tcf, W side of Island
292A	24°31'25"N 110°20'33"W	Rhy. ash-flow tuff	Bio.	5.649 ± 0.035	20.86	78.1	21.2 ± 0.02	Tca, NE shore of Island
Comondú Formation, La Paz Area								
3	24°07'33"N 110°17'13"W	Rhyodacite lava	Plag.	0.7544 ± 0.02	2.509	24.9	19.1 ± 1.2	Tcr, SW end of Cerro Atravesado
239	24°10'20"N 110°16'36"W	Rhyodacite lava	Plag.	0.6921 ± 0.0053	2.318	80.5	19.2 ± 0.5	Tcr, 2 km NE of Cemetery
383	24°11'37"N 110°17'33"W	Rhyodacite Obsidian	Glass	3.848 ± 0.019	13.22	80.2	19.7 ± 0.2	Tcr, basal breccia, Coromuel
45	24°09'24"N 110°16'27"W	Rhy. ash-flow tuff	Plag.	0.531 ± 0.006	1.670	49.2	18.0 ± 0.6	Tcc, Coromuel Tuff, Quarry, NE La Paz
45	24°09'24"N 110°16'27"W	Rhy. ash-flow tuff	Bio.	5.684 ± 0.040	19.62	64.5	19.8 ± 0.3	Tcc, Coromuel Tuff, Quarry, NE La Paz
45	24°09'24"N 110°16'27"W	Rhy. ash-flow tuff	Glass	3.869 ± 0.032	13.48	65.5	20.0 ± 0.4	Tcc, Coromuel Tuff, Quarry, NE La Paz
119B	24°09'55"N 110°17'21"W	Rhyolite Pumice	Glass	4.394 ± 0.011	14.31	11.7	18.7 ± 1.1	Tcp, La Paz Tuff, N of Cemetery, NE La Paz
266	24°16'22"N 110°19'39"W	Rhyolite Tephra	Glass	4.462 ± 0.016	16.06	36.6	20.6 ± 0.2	Basal Tephra, La Paz tuff, Ferry Terminal
429	24°16'40"N 110°19'23"W	Andesite lava	W.R.	1.831 ± 0.014	6.477	76.2	20.3 ± 0.4	Tcb, E of Playa Pichilingue
Bj3	24°17'12"N 110°18'20"W	Andesitic lahar, clast	Plag.	0.1996 ± 0.0110	0.648	10.7	18.6 ± 2.4	Tcb, Directly above Bj4, Cerro El Indio

Table 1 -- continued

Sample Number	Location Lat./Long.	Rock type	Mineral Dated	%K ± std. dev.	$^{40}Ar^*$ × 10^{-11} mol./gm	$^{40}Ar^*$ %	Age m.y. ± 2 std. dev.	Stratigraphic Unit/Comments
Comondú Formation, La Paz Area, continued								
317	24°18'10"N 110°15'41"W	Rhy. ash-flow tuff	Bio.	6.159 ± 0.071	21.83	37.7	20.3 ± 0.5	Tcs, NW of Salinas (El Coyote), 50 m below Tcb
Bj4	24°17'12"N 110°18'20"W	Rhy. ash-flow tuff	Bio.	6.748 ± 0.060	25.89	68.1	22.0 ± 0.4	Tcs, S base of Cerro El Indio, top of Tcs
238	24°09'05"N 110°15'49"W	Rhy. ash-flow tuff	Plag.	0.398 ± 0.012	1.609	20.1	23.2 ± 1.6	Tcs, Base of hill at dump, S of quarry
394	24°08'32"N 110°16'16"W	Rhy. ash-flow tuff	Bio.	6.969 ± 0.042	30.48	50.6	25.0 ± 0.6	Tcs, base of small hill S of quarry
Comondú Formation, Loreto -- La Purísima Region								
383-11-1	26°18'41"N 112°10'11"W	Alkalic Basalt	W.R.	1.267 ± 0.052	3.189	57.4	14.5 ± 1.2	N side A. San Gregorio, Purísima Vieja
582-3-1	25°58'05"N 110°29'35"W	Andesitic porphyry	Hbl.	0.319 ± 0.004	1.081	16.7	19.4 ± 0.9	Old Loreto Grade; locality 6, fig. 1
San Gregorio Formation								
260	24°21'13"N 110°59'40"W	Rhyolite tuff	Bio.	6.881 ± 0.028	30.60	86.2	25.5 ± 0.4	A. San Hilario; previously pub. 25.4 ± 0.2 m.y.
28-3-8	26°07'00"N 112°11'02"W	Rhyolite tuff	Bio.	4.48 ± 0.01	18.34	73.7	23.4 ± 0.3	A. La Purísima, La Ventana
28-3-16	26°07'00"N 112°11'02"W	Rhyolite tuff	Glass	3.76 ± 0.03	15.71	85.9	23.9 ± 0.4	A. La Purísima, La Venetana
482-26-7	26°11'50"N 112°03'23"W	Rhyolite tuff	Bio.	6.76 ± 0.03	29.90	69.8	25.3 ± 0.3	A. La Purísima, Pump House area
HM-3-13	26°09'57"N 112°14'15"W	Rhyolite tuff	Glass	3.64 ± 0.04	17.28	92.7	27.2 ± 0.6	A. San Gregorio
383-5-3	25°18'56"N 110°57'09"W	Rhy. ash-flow tuff	Sanid.	6.366 ± 0.069	31.12	79.7	28.0 ± 0.7	Salto Fm, Punta San Telmo, upper of 2 tuffs
Basement Rocks								
22	23°51'40"N 110°10'20"W	Hornblende Diorite	Hbl.	0.273 ± 0.001	5.622	33.4	115 ± 2.4	Layered diorite, La Paz Fault zone

^{40}K decay constants: $\lambda e + \lambda e' = 0.581 \times 10^{-10}$/yr, $\lambda_\beta = 4.962 \times 10^{-10}$/year; ^{40}K/Total K = 1.167×10^{-4}. Abbreviations: W.R. = whole rock, Plag. = Plagioclase, Sanid. = sanidine, Bio. = biotite, Hbl. = hornblende, Rhy. = rhyolite, A. = arroyo, Fm. = Formation, * = radiogenic.

In several areas along the Baja Peninsula lateral facies variations in the Comondú Formation can be traced directly in outcrop. These gradations are commonly from core facies of coarse andesitic breccias, with or without lava flows, to proximal facies of coarse-grained conglomerates and sandstones, and finally to distal facies sandstones and finer-grained conglomerates. This gradation occurs along a southwesterly transect through most areas of the Sierra de la Giganta and is extremely well displayed in a southerly traverse from Pichilingue to La Paz.

Age

The Comondú Formation was deposited during the early to middle Miocene. Twenty-seven K-Ar radiometric dates on various volcanic minerals, glass and whole rock samples range from 25.0 to 14.5 m.y. and have detailed the chronology of this formation (table 1).

Several stratigraphic units were independently dated by using more than one component (mineral or glass separate). Biotite-glass pairs generally produced concordant ages. Because of this and their attendant high potassium contents, biotite and glass ages are considered the most reliable. Although sanidine ages are few because of the general dearth of this potassic phase in the rhyolites, they are also considered reliable. Plagioclase was dated twice in conjunction with other components; once from the Coromuel tuff, the other from the Providencia rhyodacite, both in the La Paz area. In these experiments the mean data on plagioclase is up to 9 percent younger than associated glass and biotite dates. Dalrymple and Lanphere (1969, p. 169) show several examples of dated volcanic biotite-plagioclase pairs in which the plagioclase is generally younger (up to 10%) than the biotite.

The oldest dates on the Comondú Formation in the Bahía de La Paz region are from rocks found in isolated exposures of the lowest stratigraphic unit in the La Paz area, the Salinas member (25.0 ± 0.6 m.y. biotite; 23.2 ± 1.6 m.y. plagioclase). Another older date of 23.9 ± 0.7 m.y. was determined from an andesite clast in the andesite breccias near San Juan de la Costa. These clasts are older than underlying tuffs, suggesting that older clasts in the lahar may have been inherited from previous volcanic events. It appears that voluminous mid-Tertiary volcanism along Baja California initiated about 25 m.y. ago, first depositing in a shallow marine environment (the Isidro Formation) followed by the accumulation of the subaerial Comondú Formation.

The bulk of Comondú volcanics in the La Paz region is from 25 to 17 m.y. old. However, younger andesitic lava flows of the Comondú unconformably cap the stratigraphies on the Isla Espíritu Santo and near San Juan de la Costa, and have whole rock ages of 16.5 m.y. and 12.5 m.y., respectively. Both of these younger flows comprise the present surface and were apparently never overlain by succeeding rock units, hence marking the end of the period of voluminous volcanic and volcaniclastic inundation of the southern Peninsula.

In the northern portion of Baja California Sur the Comondú Formation ranges from 22.9 ± 2.7 m.y. (Gastil, and others, 1979) to about 15 m.y. (Jim Smith, pers. comm., 1983). Thus, the activity of the Comondú volcanoes appears to be approximately synchronous along the length of Baja California Sur, although possibly older in the southernmost area by 1-2 m.y. Furthermore, the youngest date of the San Gregorio Formation in the northerly La Purísima area (23.4 m.y.) is younger than the oldest Comondú at La Paz, suggesting the possibility of a northward progression of volcanic events from La Paz to La Purísima.

Bulk Composition

The Comondú volcanics form a suite of lithologies ranging from low-silica andesite to high-silica rhyolite. The volcanic arc that existed along the present eastern shoreline of Baja California produced a far greater proportion of rhyolites in the Bahía de La Paz area than in the region to the north; rhyolite tuffs form a major part of the La Paz stratigraphy and become fewer in number northward, entirely disappearing from the section at Punta San Marcial. The Comondú Formation to the north is almost entirely andesitic with local rhyolitic ash-flow tuffs occurring east of Bahía Concepción. In the vicinity of La Paz and San Juan de la Costa the paucity of dacitic volcanic products results in a bimodal andesite-rhyolite sequence (fig. 11). This may be attributed to the fact that dacites tend to be associated with volcanic edifices in the form of domes and viscous lavas, uncommonly forming far-traveled fluid lavas or pyroclastic flows. With the Gulf of California east-side-down faulting of the majority of the volcanic vents in Baja California Sur the dacite component has been selectively removed.

The bulk composition of the Comondú suite in the La Paz region is typical of continental volcanic arcs. Major elements (table 2) are plotted against silica in figure 11. An alkali-lime index of 60 defines a calc-alkaline classification (Peacock, 1931). These analyses plotted on Miyashiro's (1974) FeO*/MgO vs. SiO_2 diagram also indicates a calc-alkaline classification. The Comondú volcanic chemistry plotted on an AFM diagram (fig. 12) displays a "differentiation" trend similar to that of the Cascade calc-alkaline continental arc volcanics, showing no iron enrichment.

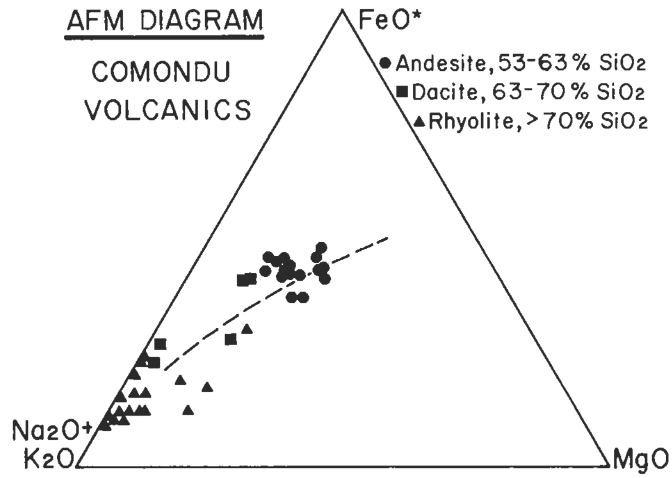


Figure 12. AFM diagram of the Comondú Formation volcanic rocks in the Bahía de La Paz region. For comparison, the dashed line is a summary of chemical data from lavas of the Cascade range of northwestern United States (Carmichael and others, 1974). FeO* is total iron reported as FeO.

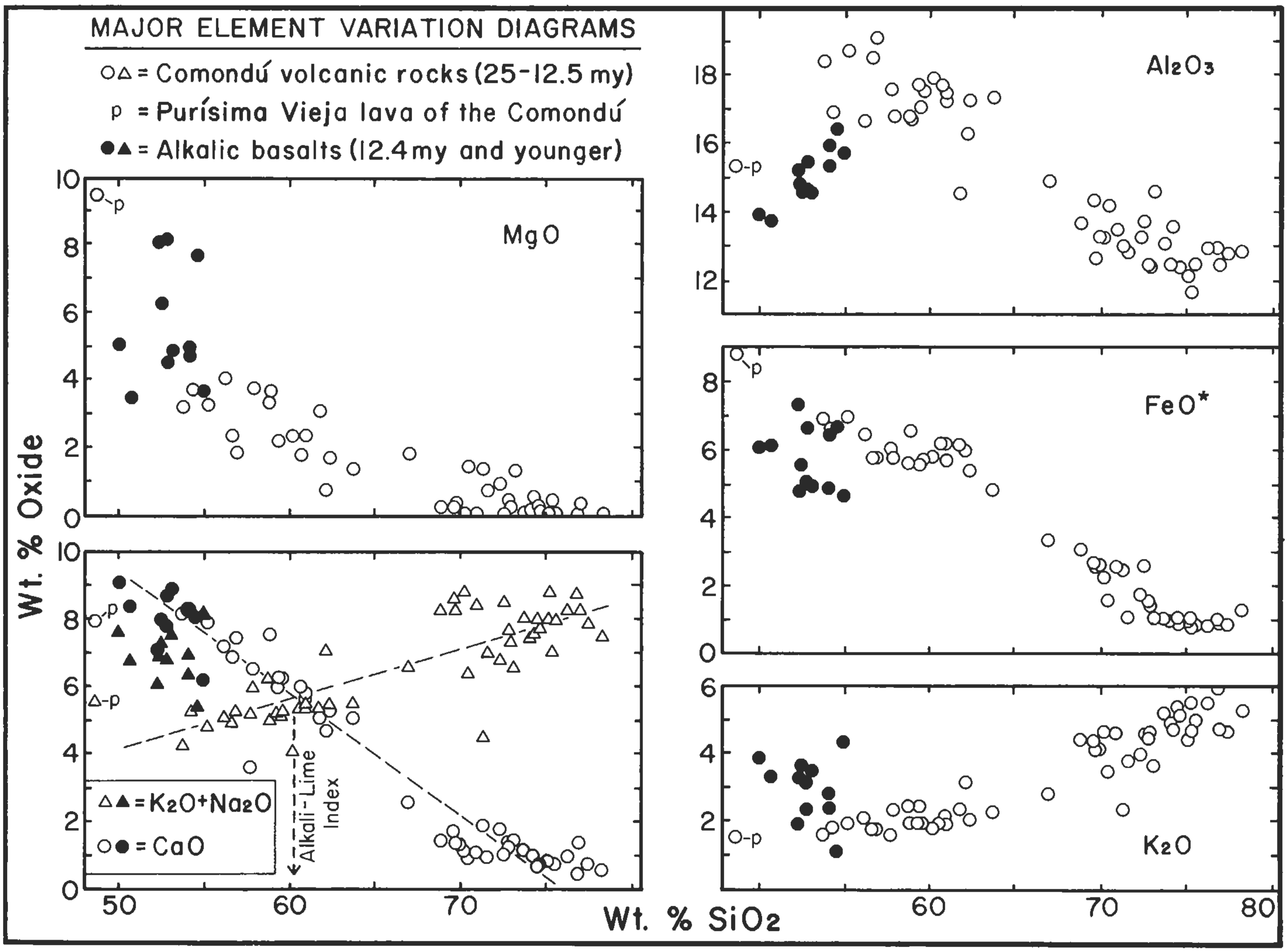


Figure 11. Major elemental oxides versus SiO_2 for volcanic rocks in Baja California Sur. Determinations from X-ray fluorescence methods. Note, the general difference in trends between the younger series of alkalic basalts and the older Comondú Formation. FeO* is total iron reported as FeO.

Young Alkalic Basalts

Unconformably overlying the Comondú Formation is a series of mid-Miocene to Holocene basalts that are clearly different from the older Comondú andesites and rhyolites. These basalts occur as canyon-filling flows as well as units capping the gently westward-tilted mesas of the Sierra de la Giganta and are most voluminous and widespread to the north of Punta San Marcial. The basalts occur sporadically in isolated exposures as far south as Los Torres (locality 9, fig. 1) but do not occur in the Bahía de La Paz region. They apparently issued from scattered local cinder cone source vents.

These basalts have completely different compositional signatures and trends compared to those of the Comondú volcanics, as indicated in figure 11. On the alkalies vs. silica classification of Kuno (1959) in figure 13, the basalts plot in the alkaline classification, off-trend from the Comondú calc-alkaline or high-alumina volcanic suite.

Petrographically, the alkali basalts are locally vesicular, fine-grained, gray to brown, holocrystalline intergranular lavas. They typically contain clinopyroxene and olivine microphenocrysts commonly set in a groundmass of sanidine, plagioclase, phlogopite, Fe-Ti oxides and (aenigmatite or priderite ?). These basalts are best classified as trachybasalts and are similar to Pliocene and Pleistocene minette lavas in the Colima Graben area near Guadalajara, Mexico (Allan and Carmichael, 1983). Associated with this primarily alkalic basalt sequence are units that are less alkaline, lacking the groundmass sanidine and phlogopite.

K-Ar ages of 12.4 m.y. to 0.47 m.y. (table 1) demonstrates that these lavas are younger than the entire Comondú Formation of Baja California Sur. At Purísima Vieja a 14.5 m.y. alkalic basalt is interbedded with Comondú volcanic sandstones. The similarity of this Comondú-age lava to the bulk composition of the younger alkalic basalts possibly suggests that it is a transitional eruptive unit between the older Comondú arc volcanics and the younger alkalic basalt series.

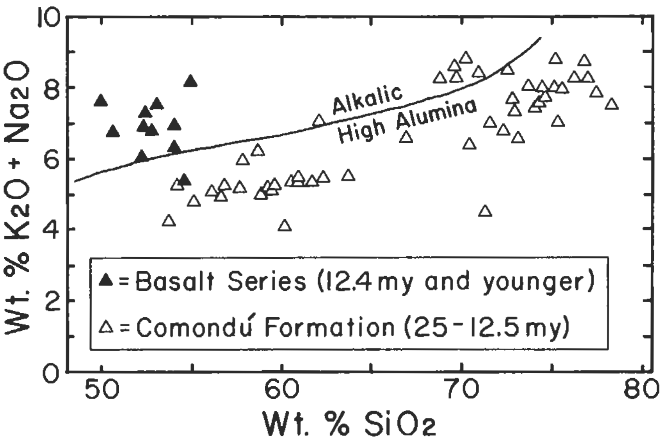


Figure 13. Alkalies versus silica for the volcanic rocks of Baja California Sur. Alkalic-High Alumina classification from Kuno (1959).

STRUCTURAL GEOLOGY

Baja California Sur is a coherent crustal block that has suffered little deformation since the early Tertiary. Generally, the topography of the southern Peninsula gently slopes to the west about 1°. The bedding of the Comondú Formation generally follows this westward dip, which probably represents the original depositional attitude of the volcaniclastics shed westward onto a broad network of alluvial fans draining the eastern chain of volcanoes.

Several deformational events occurred during the Tertiary, each resulting in minor warping of the stratigraphy. Contacts between the Tertiary formations are generally concordant but locally show angular discordances where the underlying formation has been folded into gentle flexures. The latter point is well-illustrated by the San Gregorio Formation which was gently deformed into north-trending open folds in

Table 2. Representative Analyses of Volcanic Rocks

Comondú Formation, San Juan de la Costa					
Member	Tch lava	Tcj pumice	Upper Tcb	Tcl Hbl-tuff	
Sample #	162	110B	176A	444	
SiO_2	57.84	73.74	55.18	66.94	
TiO_2	1.01	0.34	0.96	0.66	
Al_2O_3	16.79	13.03	18.68	14.90	
FeO^*	5.76	1.04	6.99	3.34	
MnO	0.09	0.04	0.13	0.07	
MgO	3.71	0.10	3.26	1.81	
CaO	6.40	1.14	7.86	2.59	
Na_2O	3.61	2.85	3.30	3.79	
K_2O	2.33	5.15	1.49	2.80	
P_2O_5	0.26	---	0.20	---	
Cl (ppm)	---	1420	---	9646	
Sr (ppm)	585	88	492	282	
Total Wt. %	97.86	97.54	98.10	97.89	
Comondú Formation, Isla Espíritu Santo					
Member	Tcf lava	Tce basal	Tcd tuff	Tcj pumice	
Sample #	288E	272A	283	274B	
SiO_2	56.12	69.61	72.91	74.11	
TiO_2	0.93	0.48	0.15	0.12	
Al_2O_3	16.68	14.32	12.46	12.47	
FeO^*	6.40	2.69	1.67	1.01	
MnO	0.12	0.05	0.05	0.04	
MgO	4.02	0.27	1.04	0.14	
CaO	7.17	1.69	1.45	1.09	
Na_2O	2.93	4.22	2.54	2.52	
K_2O	2.10	4.33	4.08	4.88	
P_2O_5	0.29	---	---	---	
Cl (ppm)	---	1409	1553	682	
Sr (ppm)	618	223	158	136	
Total Wt. %	96.82	97.80	96.52	96.46	
Comondú Formation, La Paz					
Member	Tcr lava	Tcc pumice	Tcp pumice	Tcb clast	Tcb lava
Sample #	113M	252B	195B	374C	429
SiO_2	70.96	74.21	75.65	60.94	60.64
TiO_2	0.48	0.10	0.04	0.75	0.76
Al_2O_3	13.48	13.59	11.92	17.20	17.70
FeO^*	2.59	1.07	0.92	6.12	6.19
MnO	0.05	0.07	0.03	0.09	0.09
MgO	0.08	0.56	0.07	2.00	1.79
CaO	1.10	0.95	0.52	5.72	5.96
Na_2O	3.77	2.82	2.65	3.54	3.46
K_2O	4.58	4.66	5.86	1.90	1.91
P_2O_5	---	---	---	0.17	0.22
Cl (ppm)	38	718	764	---	---
Sr (ppm)	167	122	6	429	434
Total Wt. %	97.11	98.11	97.74	98.47	98.76
Alkalic Basalt Series					
Locality	Insurgentes	Los Torres	La Purisima		
Sample #	443	438	383-9-1	383-8-1	
SiO_2	50.65	54.94	54.10	52.64	
TiO_2	2.05	1.80	0.90	2.13	
Al_2O_3	13.76	15.72	15.96	15.35	
FeO^*	6.11	4.67	4.89	6.43	
MnO	0.13	0.10	0.06	0.06	
MgO	7.72	3.63	4.97	4.68	
CaO	8.38	6.12	8.34	8.22	
Na_2O	3.46	3.80	4.11	3.98	
K_2O	3.30	4.32	2.80	2.38	
P_2O_5	1.36	1.03	0.43	0.98	
Cl (ppm)	---	---	---	---	
Sr (ppm)	3456	3827	2006	2628	
Total Wt. %	97.26	96.51	96.76	97.11	

Samples analysed by X-ray fluorescence, Univ. of Calif., Berkeley.

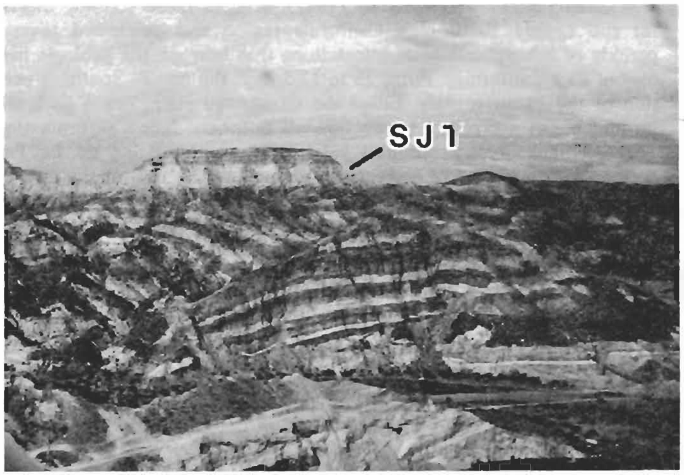


Figure 14. View to the northwest, at the mouth of Arroyo Sauzoso, south of San Juan de la Costa. Note, tilted lower Comondú Formation sandstone and tuff overlain by undeformed upper Comondú beds including the San Juan tuff (SJT).

Figure 15. View downstream in Arroyo Camarón, south of San Juan de la Costa. Note, contorted lower Comondú Formation sandstone and tuff.

the area of Arroyo La Purísima and was subsequently covered by the relatively flat-lying Isidro Formation. In the Bahía de La Paz region there is only the slightest regional warping of the Comondú, Isidro, San Gregorio, and Tepetate Formations.

There is clear evidence for localized syn-depositional deformation within the Comondú formation. In Arroyo La Purísima an abrupt angular discordance is present within the sandstone and conglomerate sequence. In the Bahía de La Paz region the undeformed upper Comondú rests unconformably upon locally intensely sheared and folded underlying tuffs and sandstones (figs. 14 and 15). This deformation is found in two areas: along the Gulf coast south of Arroyo Camarón and in Arroyo El Abra along the main peninsular highway near km 69 to the north of La Paz. Although deformational structures appear to be locally chaotic, slickensides measured on subhorizontal fault planes south of San Juan de la Costa roughly indicate a southwest-northeast shear direction. In addition, large detached lithic blocks along these subhorizontal fault planes show a general imbrication directed west to southwest along the Gulf coast and to the northwest (also perpendicular to local fold axes) in the Arroyo El Abra area. This deformation probably indicates a syn-depositional, generally westward gravitational sliding of immense slabs of lower Comondú Formation.

La Paz Fault

The La Paz Fault is a prominent strand of a major north-trending trans-peninsular fault system developed in the Cabo province. This fault juxtaposes the southern granitic Cabo province highland to the volcanic-dominated southern peninsula. The existence of the La Paz Fault was originally proposed by Beal (1948). Normark and Curray (1968) suggested that the fault was a wide structural zone with both left-lateral strike-slip movement and Quaternary normal, east-side-down movement based on bathymetric and offshore dredge-haul data in the southern cape area. Fault plane solutions for two 1969 earthquakes on this southern offshore extension indicate a large component of left-lateral motion on the La Paz fault (Molnar, 1973). Beal (1948) and Niemitz and Bishoff (1981) inferred the northerly extension of the La Paz fault along the major topographic escarpment of about 800 m height to the north of La Paz.

Geologic studies in the La Paz area substantiate the existence of this major fault zone. South of La Paz the fault is a single 2 km wide zone of sheared mylonitized granite and monzonite with local zones of hornblende cataclasite containing disseminated pyrite. These rocks, which must have been deformed beneath at least several kilometers of overburden, demonstrate the deep-seated nature of the fault and indicate that subsequent uplift and erosion has brought these lithologies to the surface.

North of La Paz the fault zone is hidden beneath a north-trending valley filled with apparently unfaulted Pliocene (?) and Quaternary alluvium and alluvial terrace gravels. At the north end of the Pichilingue peninsula the fault is covered by an undeformed sequence of alluvial conglomerates and sandstones known informally as the Punta Coyote gravels. The youngest portion of this conglomerate sequence contains a localized shallow marine assemblage with abundant pelecypod and gastropod fauna of late Pliocene to Recent age (Judy Smith, written comm., 1983). A coral from the marine portion of the Punta Coyote gravels has yielded a uranium-series date of 146,000 ± 9,000 years (Barney Szabo, written comm., 1984). The structurally undisturbed nature of these beds indicates that this portion of the La Paz Fault has probably been inactive since late Pleistocene time; however, Comondú Formation rocks near the fault zone are generally contorted, indicating post-middle Miocene fault movement. The relative inactivity of this portion of the fault zone is of great importance to the 200,000 people of La Paz who live directly downstream from a dam currently under construction astride the La Paz Fault. It must be reiterated that modern seismic events have been recorded on the offshore extension of this fault (Molnar, 1973).

A strand of the fault reappears on the eastern side of the Isla Espíritu Santo where it juxtaposes mylonitized granitic rocks on the east with the Comondú Formation on the west. At this locality ample evidence exists for post-Comondú normal fault movement along this structure. The island has an abrupt eastern escarpment and volcanic units resting atop the granitic basement have been vertically downdropped over 300 meters to the east.

The scarcity of Comondú volcanic deposits overlying the granitic basement to the east of La Paz, as well as the occurrence of sedimentary and volcanic transport directions parallel to the fault escarpment strongly suggest that the granitic area was already a highland during Comondú deposition, and therefore had been uplifted prior to the Miocene. During the Comondú volcanic period the granitic block probably formed a high relief valley wall, confining most of the volcanics to the La Paz area. The abrupt termination of volcanic core facies of the Comondú Formation against this granitic highland, without evidence of sub-volcanic intrusions into the granitic rocks, combined with observations south of La Paz cited above, suggest that the southern volcanic extension of the Comondú Formation has been translated to the north by left-lateral strike-slip movement of the La Paz Fault (fig. 10).

In summary, prior to the Miocene, the southern Cabo province was uplifted along the La Paz Fault forming an eastern granitic highland. After the Comondú Formation was deposited both an easterly downdropping and possibly left-lateral strike slip motion occurred along the fault. The timing of this post mid-Miocene fault movement in the La Paz area is poorly constrained and may, in part, continue to Recent times. Current activity is documented by earthquakes along the southern offshore extension of the fault.

Gulf Normal Faulting

An ubiquitous set of Gulf-downdropping normal faults cut the Baja Peninsula. These structures generally trend N15-35W with numerous arcuate extensions varying widely in orientation. The faults display local extensional brittle deformation, typically have sharp fault planes with steep easterly dips, and commonly die out along strike. The period of faulting appears to be entirely post-Comondú in age and activity probably continues to the present since the faults, in general, are morphologically young, and at least one cuts soils west of La Paz. The most prominent of these structures in the Bahía de La Paz region is the San Juan fault which has a vertical offset of about 0.5 km at San Juan de la Costa. South of Los Dolores, (locality 10, fig. 1). a major normal fault with a vertical offset of at least 100 m beheads the upper arroyo drainages at the Sierra crest, creating a series of internally-draining playa lakes. On Isla Espíritu Santo the abundant normal faulting merges in orientation with the La Paz Fault, suggesting that the post-Comondú normal offset along the La Paz Fault both on Isla Espíritu Santo and near La Paz is a reactivation of the old structure due to Neogene tensional stresses.

Associated with the northwest-trending normal faults is a conjugate series of faults and major joints trending N60-80E. These are nearly vertical structures with normal offsets up to 100 m or more. Best displayed in the La Paz and Isla Espíritu Santo areas, they slice the topography into a series of elongate tilted mesas.

TECTONICS

Interest in the tectonics of Baja California began with Alfred Wegner (1922), who proposed that Baja California had been originally attached to the Mexican mainland. Although the modern picture of the tectonic evolution of Western North America is based to a large extent on offshore geophysical data, an understanding of the onshore geology of Baja California contributes an integral and important part to this story.

McKenzie and Morgan (1969) and Atwater (1970) outlined the general tectonic evolution of western North America and concluded that during the early Tertiary the Farallon plate was being subducted beneath western Mexico. The collision of the Pacific-Farallon spreading ridge with the subducting North American-Farallon boundary (about 29 m.y. ago), created a zone of right-lateral, strike-slip faulting along the coastline that expanded both north and south, progressively converting the subducting plate boundary into a transform interplate shear zone.

Mammerickx and Klitgord (1982) detailed these tectonic events for the eastern Pacific-Baja California region and delineated several periods of lithospheric plate interactions that bear on the geologic history of Baja California. From 25 to 12.5 m.y. the narrow southern portion of the Farallon plate, called the Guadalupe plate, began to break up and began a pivoting subduction off Southern Baja California (fig. 16a). This geometry required subduction in the Bahía de La Paz region, with a northerly decreasing subduction rate toward the axis of rotation which was probably in northern Baja California. At 12.5 to 11 m.y. a major plate reorganization began (fig. 16b) and included the following: 1) the East Pacific Rise had rotated parallel with the western Baja coast; 2) subduction ceased synchronously along the length of Baja California Sur; 3) several fragments of the Guadalupe plate were stranded along the west coast; and 4) the right-lateral strike slip motion between Baja California and the Pacific Plate began along the Tosco-Abreojos Fault.

The period following this plate reorganization is one of great importance in understanding the process of detachment of Baja California from mainland Mexico. Geometrically, the Pacific plate was sliding northwestward with respect to North America. The Tosco-Abreojos Fault (fig. 17a) formed approximately 12.5 m.y. ago and became the transform fault boundary between the Pacific oceanic plate and the North American continental plate which included Baja California at that time. Transform faults such as these form parallel to the relative motion between adjoining plates, which, for the Pacific-North American plate movement at that time had an azimuth of about 325°. After the formation of this right-lateral fault 12.5 m.y. ago the azimuth of relative motion between the two plates progressively swung to the west (fig. 17b). This change resulted in an inability for the Tosco-Abreojos Fault to accommodate the entire interplate motion; the increasingly westward drift of the Pacific plate required either a reorientation of the boundary fault or attendant extensional motion. There is no evidence of a westward azimuth-shift of the Tosco-Abreojos Fault nor of rift basins opening along this structure. The necessary extension probably took place along the axis of the present Gulf of California -- initiating a proto-Gulf, or zone of graben formation. This would have been a likely locus for extension to occur since throughout the previous 10-12 m.y. it had been the core of the Comondú volcanic arc, therefore a zone of heated, intruded, fractured and generally weak crust. By 3.5 m.y. before present, most of the motion between the Pacific Plate and the Mexican mainland transferred from the Tosco-Abreojos Fault to the proto-Gulf, then developing along eastern Baja California. The Baja Peninsula was severed from North America and became sutured to the Pacific plate. Sea floor basalts began emerging in the spreading mouth of the Gulf of California, and a new set of more westwardly-oriented transform faults and spreading basins were generated along the evolving Gulf of California.

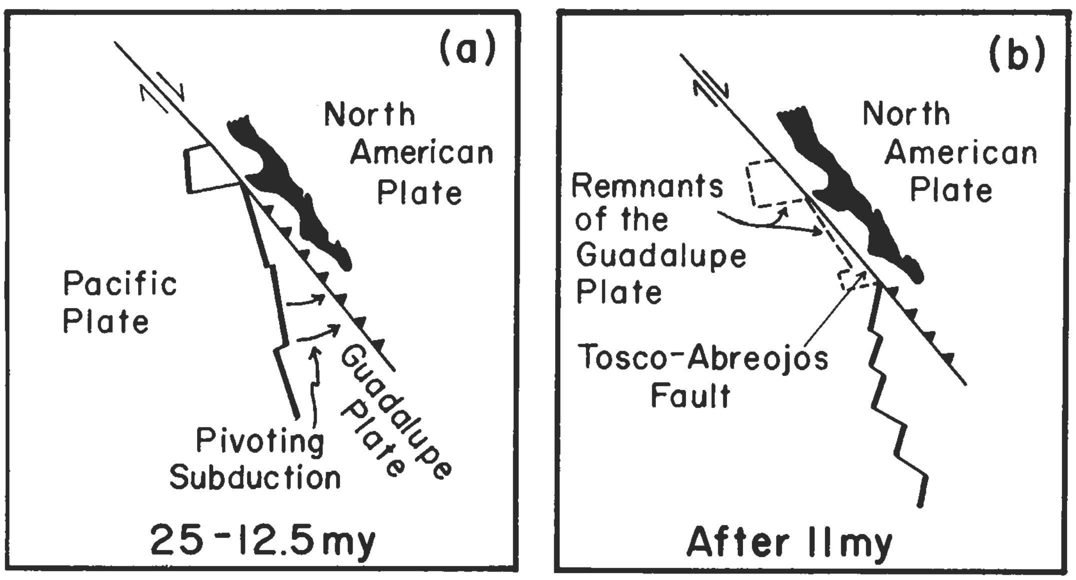


Figure 16. Evolution of plate organization off Baja California during the Miocene; modified from Mammerikx and Klitgord (1982). Thick line segments represent oceanic spreading ridges, connected by transform faults. Sawtooth-line indicates the axis of subduction with teeth on overriding plate.

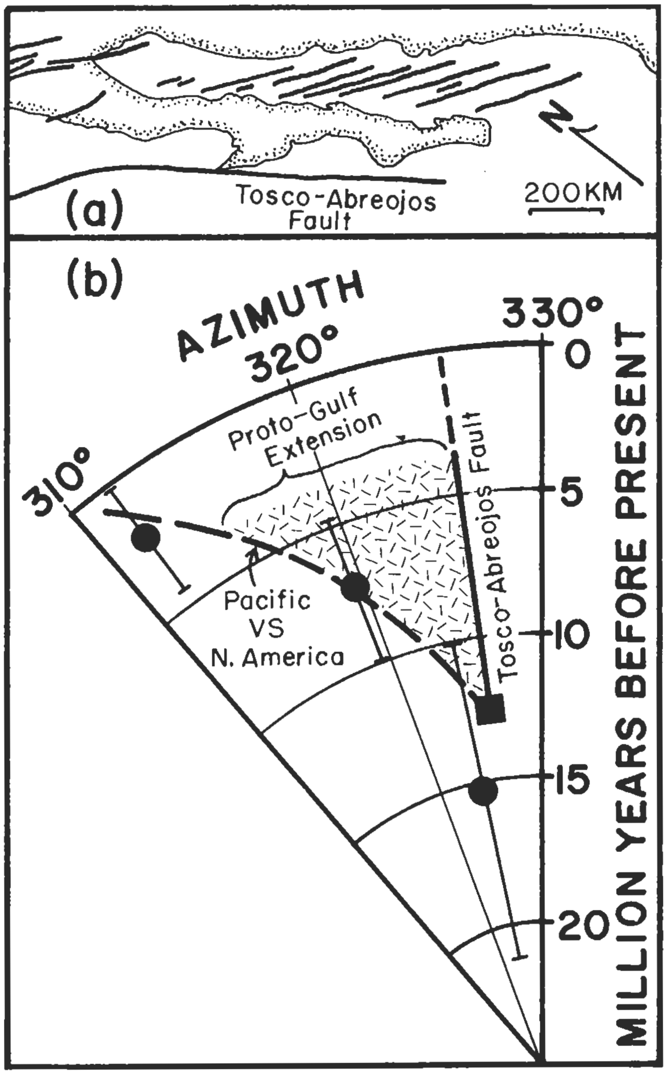


Figure 17. (a) Modern fault map of western Mexico showing the active transform fault system within the Gulf of California and the now relatively dormant Tosco-Abreojos Fault; after Spencer and Normark (1979). (b) Pacific versus North American Plate motion through time (dashed line). Data points with error bars from Blake and others (1978). The Tosco-Abreojos Fault initiated about 12.5 m.y. ago parallel to interplate motion (square). Since then, this plate motion has become more westerly directed requiring proto-Gulf extension (pattern) in addition to the Tosco-Abreojos Fault movement. By about 3.5 m.y. ago the Tosco-Abreojos Fault had become relatively inactive and the proto-Gulf rift system continued to evolve into the modern Gulf of California.

GEOLOGIC HISTORY AND INTERPRETATION

During the late Oligocene, Baja California Sur was a structurally stable marine shelf attached to western Mexico, shallowing eastward with a shoreline near the present Gulf of California coast. Upon this platform the San Gregorio shales, diatomites, and phosphorites were deposited, incorporating a large volume of silicic volcanic airfall ash erupted from the then active Sierra Madre Occidental volcanic arc. The focus of volcanic activity of the Sierra Madre was migrating westward and arrived in the vicinity of eastern Baja California at the onset of the Miocene epoch. Symptomatic with this westward volcanic migration was the crustal heating and uplift of western Mexico, including the Baja platform. Uplift generated the westward shedding of older volcanic basement detritus, recorded in Baja California as an influx of foreign meta-volcanic pebbles. The calc-alkaline volcanic chain arrived along what is now eastern Baja California about 24 m.y. ago, and quickly inundated the remnant shallow marine platform with a large volcanic-volcaniclastic apron along the length of the Baja Peninsula. With greater subduction rates in the south this arc produced large volumes of silicic volcanics, whereas the proportion of silicic volcanics decreased to the north where subduction was slower. By 16 m.y. ago volcanic activity began to wane and by 12.5 m.y., synchronous with the halt of subduction, the final products of the volcanic arc were shed onto the southern peninsula near San Juan de la Costa. Arc volcanism lasted until about 15 m.y. in the Loreto region and may have been transitional to the next phase of dominantly alkalic basalt volcanism. The demise of arc volcanism was nearly synchronous along Baja California Sur and reflects the proposed synchronous end of subduction along the entire length of Southern Baja California (Menard, 1978; Mammerickx and Klitgord, 1982). There is no indication of a progressively southward termination of volcanism as would have been predicted for a southerly migrating triple junction and sequential end of subduction from north to south. After subduction ceased, the boundary between the Pacific and North American plates became a major transform fault along the west coast of Baja with extension along this margin geometrically required. Lack of volcanogenic deposition onto the southernmost Baja Peninsula after 12.5 m.y. ago indicates a separation of the peninsula from easterly volcanic sources with probable graben formation along the axis of the then extinct chain of volcanoes. The formation of this proto-Gulf is well documented in the southernmost Gulf of California where, on Maria Madre Island, a major subsidence occurred after the deposition of mid-Tertiary volcanics and prior to the deposition of 8.5 m.y. marine diatomites (McCloy, 1982; McCloy and Ingle, 1985).

Alkalic basalts erupted along Baja California Sur coeval with, and probably as a result of the rifting of the proto-Gulf of California, extending from 12.4 m.y. to at least 0.47 m.y.

The southern Peninsula has generally been structurally stable throughout the Tertiary. The granitic Cabo province was probably already upthrown along the La Paz Fault prior to the early Miocene Comondú deposition. Post 12 m.y. movement along the La Paz Fault probably includes the downdropping of the Cabo block and significant left-lateral strike-slip faulting. The Gulf of California structural development has been accomplished along post-Comondú (post 12 m.y.) normal faults, likely active today.

ACKNOWLEDGEMENTS

Many people have helped and influenced me throughout my studies of Baja California. I would especially like to thank my advisor, Garniss Curtis, as well as Bob Drake and Joachim Hampel for their guidance, discussions and technical help throughout this project. My education at Berkeley has been vastly broadened through my interactions with several of my fellow graduate students: Mary Gilzean, Greg Harper, James Allan, Jim Luhr, Bill Chávez, and Alan Dieno, who have unselfishly supported me through thick and thin. My hat is off to Korda Cordes, my friend who skillfully engineered and typed this manuscript.

Fond memories of fieldwork in Baja are highlighted by the times that I have spent with my field partners: Hugh McLean, Andrew Arnold, and Tom Green. These fine folks have shared with me many a celestial desert evening of vagabond thoughts and have taught me much about Baja California. I would like to thank several other people: Clark Blake, Virgil Frizzell, David Howell, Jim Ingle, Ceil McCloy, Mike McWilliams, Mike Sawlan, Jim and Judy Smith, and Chris Utter of the U.S. Geological Survey and Stanford University who have assisted me in many ways and have seeded me with their true enthusiasm for life and science.

Logistical and financial support for fieldwork in Baja California has been generously provided by Ingenieros Guillermo P. Salas, Salvador Casarrubias, Hugo Cortez, and Antonio Castro of the Consejo de Recursos Minerales, as well as Ingenieros Francisco Escandón, Carlos Chacón, and Alfonso Martinez of Roca Fosfórica Mexicana, and Ingeniero Diego A. Córdoba of the Univérsidad Nácional Autónoma, Mexico. In addition, my work has been, in part, funded by the Geological Society of America, Penrose grants and the University of California.

REFERENCES

Allan, J.F., and Carmichael, I.S.E., 1983, Lamprophyric lavas in the Colima Graben, southwest Mexico: Geol. Soc. Amer., Abstracts with Programs, v. 15(6), p. 513.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geol. Soc. Amer. Bull., v. 81, p. 125-133.

Bacon, C.R., 1983, Eruptive history of Mount Mazama and Crater Lake Caldera, Cascade Range, U.S.A.: J. of Volcanology and Geothermal Res., v. 18, p. 57-115.

Beal, C.H., 1948, Reconnaissance of the geology and oil possibilities of Baja California, Mexico: Geol. Soc. Amer. Memoir, v. 31, 138 pp.

Blake, M.C., Jr., Campbell, R.H., Dibblee, T.W., Jr., Nilsen, T.H., Normark, W.R., Vedder, J.C., and Silver, E.A., 1978, Neogene basin formation in relation to plate-tectonic evolution of the San Andreas Fault system, California: Amer. Assoc. Petrol. Geologists, v. 62(3), p. 344-372.

Carmichael, I.S.E., Turner, F.J., and Verhoogen,J., 1974, Igneous petrology: McGraw-Hill, Inc., San Francisco, 739 pp.

Chávez, V.M., 1978, Estuido geológico general del area Loreto-Comondú-Bahía Concepción, Estado de Baja California, Sur: thesis, Escuela Superior de Ingenieria y Arquitectura, Mexico, D.F., 83 pp.

Dalrymple, G.B., and Lanphere, M.A., 1969, Potassium-argon dating principles, techniques and applications to geochronology: San Francisco, W.H. Freeman and Co., 258 pp.

Darton, N.H., 1921, Geologic reconnaissance in Baja California: J. Geology, v. 29, p. 720-748.

Díaz, R., 1977, Informe geologico preliminar del proyecto Tembabiche, B.C.S.: Roca Fosforica Mexicana, S.A. de C.V., company report, 26 pp.

Escandón, F.J., 1978, Bosquejo geológico de los depositos de fosforita de San Juan de al Costa, Baja California Sur: Roca Fosfórica Mexicana, S.A. de C.V., 22 pp.

Gabb, W.M., 1882,: Notes on the geology of lower California: Geological Survey of California, v. 2, Appendix H, p. 137-148, Cambridge Mass., John Wilson and Son, University Press.

Gastil, G., Krummenacher, D. and Minch, J., 1979, The record of Cenozoic volcanism around the Gulf of California: Geol. Soc. Amer. Bull, v. 90, p. 839-857.

Gastil, G., Morgan, G.J. and Krummenacher, D., 1978, Mesozoic history of Peninsular California and related areas east of the Gulf of California: (in) Howell, D.G. and McDougall, K.A. (eds.), Mesozoic paleogeography of the western United States: Soc. of Econ. Paleon. and Mineral., Pacific Coast Paleogeography Symposium 2, p. 107-115.

Glazner, A.F., and Supplee, J.A., 1982, Migration of Tertiary volcanism in the southwestern United States and subduction of the Mendocino fracture zone: Earth and Planetary Sci. Lett., v. 60, p. 429-436.

Hausback, B.P., 1982, Timing and nature of Tertiary tectonic and volcano-stratigraphic events in Southern Baja California, Mexico: Geol. Soc. Amer., Abstracts with Programs, v. 14(4), p. 171.

Hausback, B.P., 1983, An extensive volatile-charged rhyodacite flow, Baja California, Mexico: Geol. Soc. Amer., Abstracts with Programs, v. 15(5), p. 281.

Heim, A., 1922, Notes on the Tertiary of southern Lower California: Geol. Mag., v. 59(702).

Knappe, R., 1974, The micropaleontology of a section of the Tepetate Formation, Southern Baja California, and a paleobiogeographic comparison with equivalent foraminifera along the west coast of the United States: M.S. Thesis, Ohio University, 87 pp.

Kuno, H., 1959, Origin of Cenozoic petrographic provinces of Japan and surrounding areas: Bull. Volcanologique, v. 20, p. 37-76.

Mammerickx, J., 1980, Neogene reorganization of spreading between the Tamayo and the Rivera fracture zone: Marine Geophysical Researches, v. 4, p. 305-318.

Mammerickx, J., and Klitgord, K.D., 1982, Northern East Pacific Rise: Evolution from 25 m.y. B.P. to the present: J. of Geophysical Research, v. 87, no. B8, p. 6751-6759.

McLean, H., and Hausback, B.P., 1984, Reconnaissance geologic map of the La Purísima-Paso Hondo area, Baja California Sur, Mexico: U.S. Geol. Survey, Open File Report, no. 84-93.

McLean, H., Barron, J.A., and Hausback, B.P., 1984, The San Gregorio Formation of Baja California Sur, Mexico, is late Oligocene: Soc. Econ. Paleontologists and Mineralogists, Pacific Section, Abstracts with Programs, in press.

McCloy, C., 1982, Neogene foraminifera, stratigraphy, and depositional history of Isla Maria Madre; evidence of early marine conditions in the southern Gulf of California: Geol. Soc. Amer., Abstracts with Programs, v. 14(4), p. 213.

McCloy, C., and Ingle, J.C., 1985, Neogene foraminifera, stratigraphy, and depositional history of Maria Madre Island, Mexico: evidence of early Neogene marine conditions in the southern Gulf of California: in preparation.

McDowell, F.W., and Keizer, R.P., 1977, Timing of mid-Tertiary volcanism in the Sierra Madre Occidental between Durango City and Mazatlan, Mexico: Geol. Soc. Amer. Bull., v. 88, p. 1479-1487.

McDowell, F.W., and Henry, C.D., 1983, Late Cretaceous to Tertiary magmatic arcs in western Mexico and west Texas: Geol. Soc. Amer., Abstracts with Programs, v. 15(5), p. 302.

McFall, C.C., 1968, Reconnaissance geology of the Concepción Bay Area, Baja California, Mexico: Stanford Univ. Public., Geological Sci., v. 10(5), 25 pp.

McKenzie, D.P., and Morgan, W.J., 1969, Evolution of Triple Junctions: Nature, v. 224, p. 125-133.

Menard, H.W., 1978, Fragmentation of the Farallon plate by pivoting subduction: J. of Geology, v. 86, p. 99-110.

Mina, F., 1957, Bosquejo geologico del Territorio Sur de la Baja California: Asociacion Mexicana de Geologos Petroleros, Boletin, v. 9, p. 139-270.

Miyashiro, A., 1974, Volcanic rock series in island arc and active continental margins: Amer. J. Sci., v. 274, p. 321-355.

Molnar, P., 1973, Fault plane solutions of earthquakes and direction of motion in the Gulf of California and on the Rivera Fracture Zone: Geol. Soc. Amer. Bull., v. 84, p. 1651-1658.

Niemitz, J.W., and Bischoff, J.L., 1981, Tectonic elements of the southern part of the Gulf of California: Geol. Soc. Amer. Bull., part 2, v. 92, p. 360-407.

Normark, W.R., and Curray, J.R., 1968, Geology and structure of the tip of Baja California, Mexico: Geol. Soc. Amer. Bull., v. 79, p. 1589-1600.

Ojeda, J., 1979, Resumen de datos estratigraficos y estructurales de la Formacion Monterrey que aflora en el area de San Hilario, Baja California Sur: Geomimet, no. 100, p. 51-83.

Peacock, M.A., 1931, Classification of igneous rock series: J. of Geology, v. 39, p. 54-67.

Pokorný, V., 1978, Ostracodes, (in) Haq, B.U., and Boersma, A. (eds.), Introduction to Marine Micropaleontology: Elsevier, New York, 376 pp.

Spencer, J.E., and Normark, W.R., 1979, Tosco-Abreojos fault zone: a Neogene transform plate boundary within the Pacific margin of southern Baja California, Mexico: Geology, v. 7, p. 544-557.

Vanderhoof, V.L., 1942, An occurrence of the Tertiary marine mammal *Cornwallius* in Lower California: Am. J. Sci., v. 240, p. 298-301.

Vessel, R.K., and Davies, D.K., 1981, Nonmarine sedimentation in an active fore arc basin: Soc. Econ. Paleon. and Mineral., Special Pub., no. 31, p. 311-45.

Wegner, A., 1922, The origin of continents and oceans: Dutton, N.Y., ed. 3, 212 pp.