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Miocene-Pleistocene sediments within the San José del Cabo Basin, Baja California Sur, Mexico

Genaro Martínez-Gutiérrez
Departamento de Geología Marina, Universidad Autónoma de Baja California Sur, La Paz, Baja California Sur, Mexico 23080
Parvinder S. Sethi
Department of Geology, Box 6939, Radford University, Radford, Virginia 24142

ABSTRACT

The San José del Cabo Basin at the southern tip of the Baja California peninsula is considered a half-graben basin that formed in association with the opening of the Gulf of California. The basin consists of Tertiary-Quaternary sediments that range in age from middle Miocene to Pleistocene and accumulated in settings ranging from continental to marine. New formational names are proposed for the different sedimentary deposits. The formations studied include the La Calera, Trinidad, Refugio, Los Barriles, and El Chorro.

The La Calera Formation records the onset of sedimentation (terrestrial) within the basin as a result of middle Miocene block faulting. A marine transgression within the basin is recorded by the Trinidad Formation that conformably overlies the La Calera Formation. The transgression is attributed to subsidence that resulted from the development of a strike-slip zone at the mouth of the Gulf of California. A regressive phase was initiated within the San José del Cabo Basin during the lower Pliocene. Tectonic activity or slow subsidence within the basin marks the onset of a regression with shoaling and terrestrial deposition. → huh?

Late Pliocene listric normal faulting (San José del Cabo fault) affected the sedimentary sequence, producing a half-graben structure. The faulting produced terrestrial deposits of the Los Barriles Formation that consist of high-gradient, alluvial fan facies. Movement along the San José del Cabo fault continued by latest Pliocene through Pleistocene time.

During Pleistocene through Holocene time, alluvial sediments of the El Chorro Formation prevailed in the study area, reflecting the continued denudation of the La Victoria basement complex.

Lithologic evidence suggests that sediment accumulation in Pliocene-Pleistocene time was probably affected not only by sea-level change but also by local tectonism associated with syndepositional extension and transpression within the basin.

The objectives of this study are to interpret the depositional history of upper Miocene through Pleistocene sediments and to test the hypothesis that the basin developed through two tectonic stages (late Miocene extensional phase and Pliocene-Recent stage transform displacements).

INTRODUCTION

The San José del Cabo Basin contains continental and marine strata that range in age from early middle Miocene to Recent. The present work provides information to assume that the origin of the basin is associated with opening of the Gulf of California and formation of the Baja California peninsula. Development of both the gulf and the peninsula is related to a Tertiary-

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Quaternary rift system that originated about 10 Ma (Hausback, 1984; Stock and Hodges, 1989; Lonsdale, 1991). Sedimentary deposits of the San José del Cabo Basin contain distinctive tectonostratigraphic features associated with a rift-type basin.

One of the purposes of the present work is to characterize the sedimentary facies of the late Miocene to Pleistocene sediments and to relate their distribution to the unique structural setting associated with the Gulf of California. The overall objective of this study is to reconstruct the deposition of the late Miocene to Pleistocene formations and evaluate the effects of syndepositional extensional relative sea-level changes and basin subsidence.

The study area is located at the southern tip of the Baja California peninsula, Mexico (Fig. 1). The basin covers roughly 2,000 km^2, and includes the La Calera, Trinidad, Refugio, Los Barriles, and El Chorro Formations. The basin forms a north-south depression that is bounded on its western margin by the Sierra La Victoria and along the eastern margin by the Sierra La Trinidad.

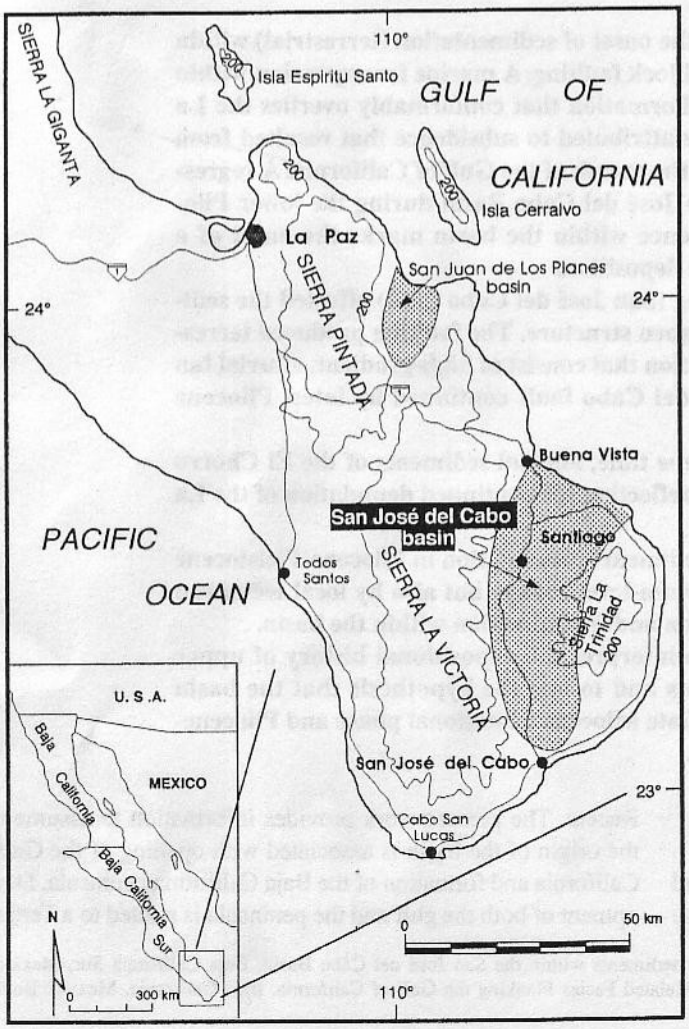

Figure 1. Location map of the study area.

PREVIOUS WORK

The basin was designated by different names: San José del Cabo region (Beal, 1948), Santiago–San José del Cabo region (Pantoja-Alor and Carrillo-Bravo, 1966), and San José del Cabo trough (McCloy, 1984). The study area is referred to as the San José del Cabo Basin in the present work because of its geologic features and geographic location.

The basin was the subject of only a few geologic reconnaissance investigations, most of which included it either as part of regional geologic summaries or focused on specific topics such as descriptive paleontology (Table 1).

Based on field reconnaissance, Beal (1948) proposed that the northern area of the San José del Cabo Basin was affected by a north-south–trending fault along the eastern front of the Sierra La Trinidad. He also recognized that the basin was depressed below sea level during Miocene and Pliocene time and that marine sediments may directly overlie granitic rocks. Mina (1957) assigned the name Salada formation to Pliocene marine deposits within the basin.

Hertlein (1925, 1966) provided some of the first detailed paleontological observations for the peninsular strata. He collected principally Tertiary fossils (mollusks), including some fossils from the "Salada formation" within the San José del Cabo Basin. Hertlein (1925) described some new species from the El Refugio locality (Fig. 2) to which he assigned late Miocene or early Pliocene ages.

Pantoja-Alor and Carrillo-Bravo (1966) mapped and described the formations that crop out in the San José del Cabo Basin. They correlated some volcanic rocks and continental deposits exposed in the study area with the volcanic deposits located at Sierra La Giganta (Comondú Formation) and the youngest marine deposits with the Salada Formation from the Purísima-Iray-Magdalena basin. They also proposed the informal name of Trinidad Formation for the oldest marine sedimentary strata that unconformably overlie what they named Comondú Formation (Table 1). They assigned a late Miocene age to the volcanic rocks and continental deposits on the basis of their similarity to the stratotype of the Comondú Formation. However, the Comondú Formation was not identified or observed.

McCloy (1984) studied the Tertiary sedimentary units that crop out in the study area. She included some stratigraphic sections, megafossils, and planktic foraminiferal data, concluding that sediments deposited in the basin correspond to alluvial and shelf deposits.

Subsequent workers utilized informal names proposed for the upper Miocene to Pliocene sediments (Mina, 1957; McCloy, 1984; Gaitán, 1986; Martínez-Gutiérrez, 1986). In the present work, new stratigraphic nomenclature is formally proposed for the San José del Cabo Basin, because names furnished by previous authors do not have type localities (Table 1). Among the new formation names are La Calera Formation, Refugio Formation, Los Barriles Formation, and El Chorro Formation. The name

TABLE 1. STRATIGRAPHIC TABLE OF UNIT NAMES OF EARLY WORKERS IN THE STUDY AREA*

	Epoch		Pantoja-Alor and Carrillo-Bravo, 1966	McCloy, 1984	Martínez-Gutiérrez, 1986	Smith, 1991	McCloy, in preparation†	This Study
Cenozoic	Pleistocene		Terraces and Coquina	Alluvium	Alluvium Post-Salada	Alluvium	Alluvium	El Chorro
	Pliocene	Late	Salada	Salada	Salada	"Salada"	Refugio	Los Barriles
		Early						Refugio
			Trinidad	Trinidad	Trinidad	Trinidad	Trinidad	Trinidad
	Miocene	Late	Comondú					La Calera
		Mid						Volcanic Rocks
		Early		Coyote Red Beds	Coyote Red Beds	?	Coyote	
	Ologocene					Coyote Red Beds		
	Eocene	L						
		M						
		E						
	Paleocene							
Mesozoic		Late	Granite	Granite	Granite	Granite	Granite	Granite-granodiorite
		Early						
	Jurassic							

*Martínez-Gutiérrez, 1994, produced a geologic map of a 1:100,000 scale. The geographic names derive from the topographic maps of scale 1:50,000 as edited by the Instituto Nacional de Estadística, Geografía e Informática (1983a through f).

†McCloy, C., 1997, Reconnaissance geologic map of the San Jose del Cabo trough, Baja California Sur, Mexico, Plates I and II: U.S. Geological Survey Open File Report, in preparation.

= No deposition. —·—·—·— = Unconformity

Trinidad Formation is formalized in this work by providing a neostratotype.

GEOLOGIC SETTING

The southern portion of the Baja California Sur state (south of about 24.5°N) is dominated by batholithic massifs that resemble northerly trending basins and ranges. The ranges are represented by the Sierra La Victoria and Sierra La Trinidad ridges, and the basins are represented by the San José del Cabo and San Juan de Los Planes Basins (Fig. 1). The basins contain Cenozoic nonmarine and marine sediments that range in age from late Miocene to Recent. Quaternary deposits consist of alluvial fans, braided river deposits, dunes, and beach deposits. The rocks that crop out at the southern tip of the Baja California peninsula are of igneous, sedimentary, and metamorphic. The igneous and associated metamorphic rocks are dated as pre-Tertiary and are thought to be of Mesozoic age (Gastil et al., 1978).

Two major crystalline complexes bound the San José del Cabo Basin: the La Victoria igneous-metamorphic complex on the west and the Trinidad igneous complex on the east. These two crystalline complexes are the sources of most of the sediments that filled the basin.

The La Victoria complex (identified as Kim, Fig. 2) consists of granite, granodiorite, tonalite, gneiss, schist, and mafic dikes (andesitic). Only regional geologic mapping (Lopéz-Ramos, 1973; Instituto Nacional de Estadística Geografía e Informática, 1987) and local geologic studies exist along the complex (Altamirano, 1972; Gastil et al., 1976; Aranda-Goméz and Pérez-Venzor, 1988; Ortega-Gutiérrez, 1982; Frizzell, 1984; Murillo-Muñetón, 1991; Carrillo-Chávez, 1991; and Sedlock et al., 1993). Gastil et al. (1976) estimated an age of Late Cretaceous (98.4 to 93.4 Ma) for the complex, using radiometric dating.

The La Trinidad complex (Kgr-grd, Fig. 2) has received minimal study and consists mainly of three major lithologic units: granite, granodiorite, and lava flows (rhyolitic). Gastil et al. (1976) assigned an age of Late Cretaceous–Early Tertiary (88.2 to 54.1 Ma) to the complex, based on radiometric dating.

Acid volcanic and volcaniclastic rocks of possible late mid-

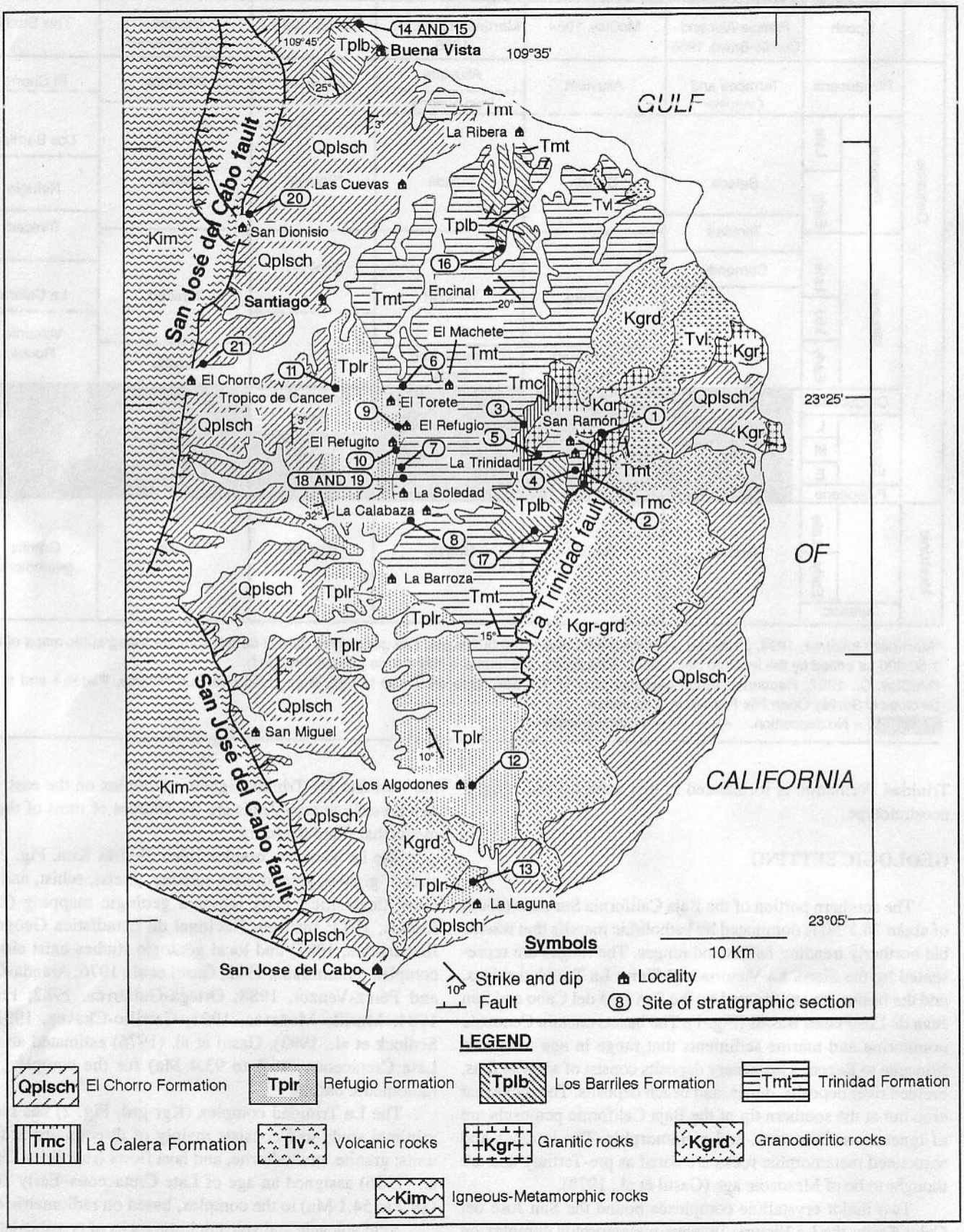

Figure 2. Generalized geologic map of the San José del Cabo Basin, adopted from Martínez-Gutiérrez (1994).

dle Miocene age also crop out at the northeastern margin of the San José del Cabo Basin.

METHODS

Twenty-one stratigraphic sections were measured within the San José del Cabo Basin (Fig. 2). Table 2 shows the characteristics of the sites as well as the purpose of measuring each section in terms of facies, paleocurrent indicators observed, and stratigraphic interval. The goal was to obtain more detailed information to characterize the facies of each formation, to infer the depositional processes associated with their accumulation, and to demonstrate the spatial relation among the sedimentary units.

Each stratigraphic section was measured, where possible, from the bottom to top. The thickness of individual beds in the stratigraphic sections shown is schematic. Composition, bedding, grain size, color, sorting, sedimentary structures (inorganic and organic), fossils, and paleotransport indicators were recorded in the field for each section (Fig. 3). Paleotransport indicators are not abundant. The indicators encountered with measurable transport azimuths include imbrication, cross-bedding (tabular and trough), channels, climbing-ripple marks, and groove marks. The azimuths of the paleocurrent indicators from each unit are plotted in rose diagrams.

RESULTS

La Calera Formation

The La Calera Formation (LCF) is the oldest sedimentary deposit and crops out at the eastern margin approximately 26 km east of Santiago. Pantoja-Alor and Carrillo-Bravo (1966) correlated this unit with the Comondú Formation cropping out near La Paz; however, the LCF lacks volcanogenetic rocks that characterize the Comundú Formation. McCloy (1984) proposed the informal name of Coyote Red Beds, yet the name of arroyo El Coyote does not appear on the topographic maps. The LCF is a distinctive red-colored deposit of conglomerate and sandstone.

The LCF is composed of about 25% conglomerate and 75% sandstone beds in a crudely "fining-upward" sequence. Conglomerate beds are concentrated mainly at the bottom of the sequence.

Exposures are restricted to a small downfaulted area of the La Trinidad complex. Based on its good exposures and easy access, we designate the stratigraphic section at arroyo La Calera, near La Trinidad, to be the type section (Fig. 2). Three columnar sections totaling 300 m were measured from this formation. The most complete and best-exposed interval is located at the intersection of arroyo La Trinidad and arroyo El Sauce (Fig. 4), where its thickness is about 130 m. The section of La Trinidad shows the sequence's general fining-upward trend.

The base of the LCF is characterized at all of these locations mainly by poorly sorted clast-supported conglomerate beds containing coarse pebbles and small cobbles.

The LCF grades from coarse to fine sandstone and from sandy conglomerate to conglomeratic sandstone (40 to 20% coarser clasts and 60 to 80% sand, respectively) at the locality of arroyo La Calera and La Trinidad. At the La Trinidad site, the LCF is composed of sandy conglomerate to pebbly sandstone with a conglomeratic content between 30 and 40% and a sandy content between 70 and 60%.

The top of the LCF is well exposed at the junction of arroyos La Calera and La Trinidad and is composed of medium to fine sandstone (pebbly arenite). Here, it grades upward into the fine-

TABLE 2. CRITERIA CONSIDERED FOR SELECTION OF SECTIONS

Site	Formation	Facies	Interval	Paleocurrent Indicators
1 San Ramón	La Calera	Alluvial	Bottom-middle	Fair
2 La Trinidad	La Calera	Alluvial	Middle-top	Good
3 Arroyo El Sauce	La Calera	Alluvial	Bottom-top	Fair
4 La Trinidad	Trinidad	Shallow marine	Bottom	Poor
5 Arroyo El Sauce	Trinidad	Shallow marine	Bottom-middle	Poor
6 El Torete	Trinidad	Outer shelf	Middle	Poor
7 El Rosarito	Trinidad	Inner shelf	Top	Good
8 La Calabaza	Trinidad	Shallow marine	Top	Poor
9 El Refugio	Refugio	Shallow marine	Bottom	Poor
10 El Refugito	Refugio	Shallow marine	Bottom-middle	Poor
11 Trópico de Cancer	Refugio	Shallow marine	Top	Good
12 Los Algodones	Refugio	Shallow marine	Bottom	Poor
13 Cerro La Laguna	Refugio	Shallow marine	Bottom-top	Fair
14 Arroyo Buenos Aires	Los Barriles	Alluvial	Bottom-top	Good
15 San Bartolo	Los Barriles	Alluvial	Bottom-top	Poor
16 El Encinal	Los Barriles	Alluvial	Bottom-top	Good
17 La Trinidad	Los Barriles	Alluvial	Middle	Poor
18 El Rosarito 1	Los Barriles	Alluvial	Bottom	Good
19 El Rosarito 2	Los Barriles	Alluvial	Bottom	Good
20 Arroyo San Dionisio	El Chorro	Alluvial	Bottom-middle	Poor
21 El Chorro	El Chorro	Alluvial	Bottom-top	Fair

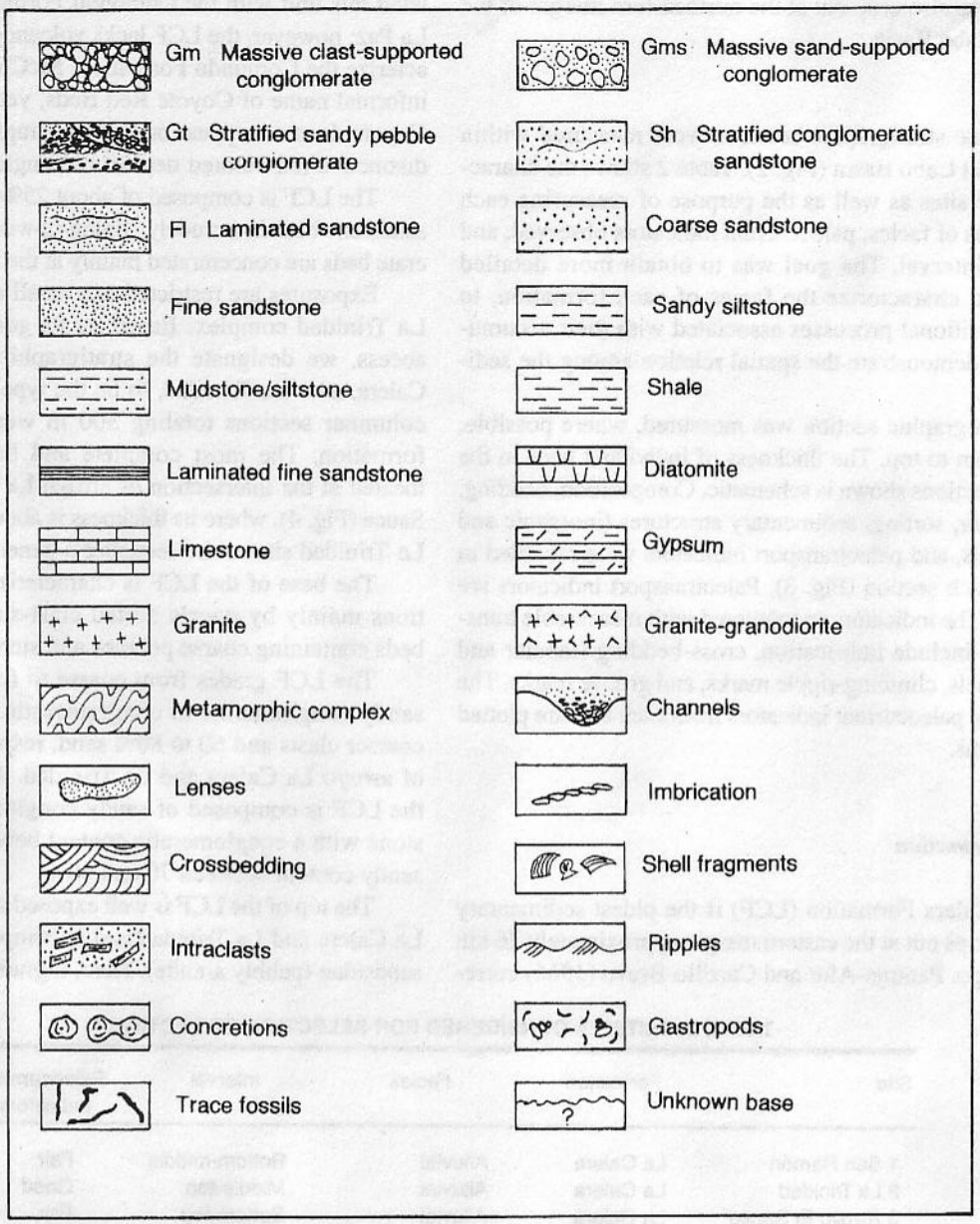

Figure 3. Lithofacies code and legend symbols for stratigraphic columns in Figures 4, 7, 8, 9, 11, 13, 14, 15, and 17.

grained sediments of the Trinidad Formation. The top of the LCF exhibits tabular stratification and massive stratification that ranges in thickness from 0.05 to ~2.0 m. Channels, scours, and clast imbrication are present in this part of the formation. At arroyo La Calera, channels and scours as well as slump structures in sandy beds are present. The clast composition of the La Calera Formation include granitic (69%), rhyolitic (20%), and pyroclastic (11%) rock fragments (Fig. 5) (Martínez-Gutiérrez, 1994).

Coarse-grained, poorly sorted, crudely stratified beds of sand-supported conglomerate punctuated by scour band lenses of clast-supported conglomerate indicate that the formation probably was deposited under alluvial conditions. Paleotransport indicators are scarce within the LCF; however, channels, trough cross-bedding, tabular cross-bedding, and imbrication were recorded from Sites 2 and 3 (Fig. 6). The indicators show that the flow patterns of these deposits had a west-northwest trend. Thus, clast types and limited cross-bedding converge to indicate that most of the La Calera clasts were probably derived from the adjacent La Trinidad complex and were transported generally northward during an initial depositional stage of the basin formation.

The age of the La Calera Formation remains undetermined. A reasonable age estimate is assigned using simple stratigraphic principles. The LCF unconformably overlies the La Trinidad basement complex and conformably underlies the Trinidad Formation. Rhyolitic lava flows of early Tertiary age

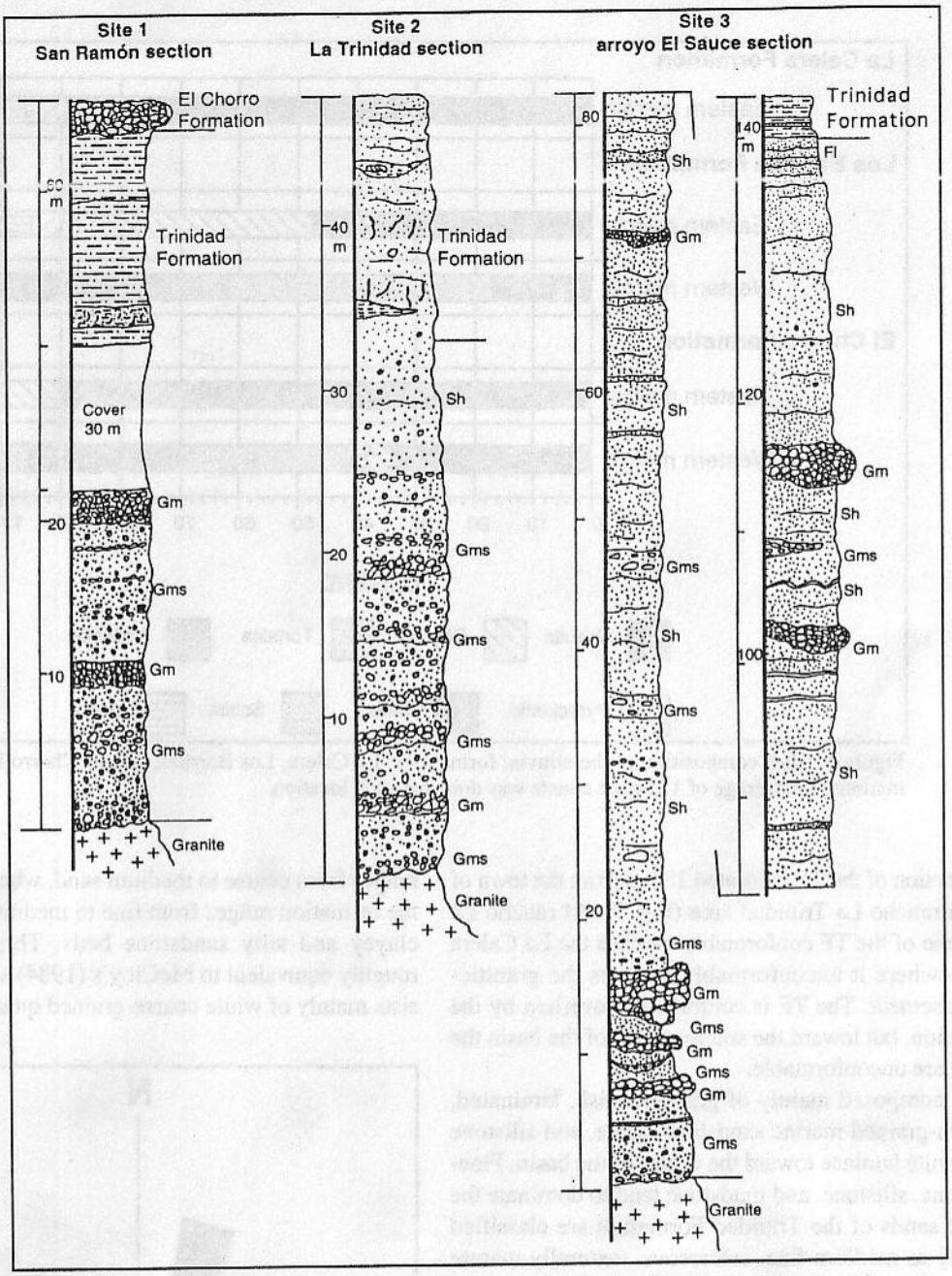

Figure 4. Stratigraphic columns of the La Calera Formation. See Figure 3 for legend.

overlie the Trinidad basement. An age of late Miocene based on megafossils and microfossils is assigned to the lower part of the Trinidad Formation (McCloy, 1984; Smith, 1989; Martínez-Gutiérrez, 1994). Therefore we estimate that the La Calera Formation could be middle-late Miocene in age. We propose the name of La Calera Formation and use it to designate the older, alluvial, basement-derived sequence within this basin.

Trinidad Formation

The Trinidad Formation (TF) was first described by Pantoja-Alor and Carrillo-Bravo (1966) and consists of greenish shale, mudstone, and sandstone that collectively represent the initial marine transgression. Marine fossils and marine trace fossils at the base of the unit provide evidence of marine deposition. The TF exhibits both vertical and lateral lithological changes from the northern to the southern region of the basin. No locality shows a complete stratigraphic section, but five stratigraphic columnar sections were measured (Fig. 2) to characterize typical facies and its lateral variations. The TF exhibits a prevalent northwest strike and dips southwest from 10 to 30°. Toward the eastern basin margin (the rancho La Trinidad area), the formation is slightly deformed into an antiform structure.

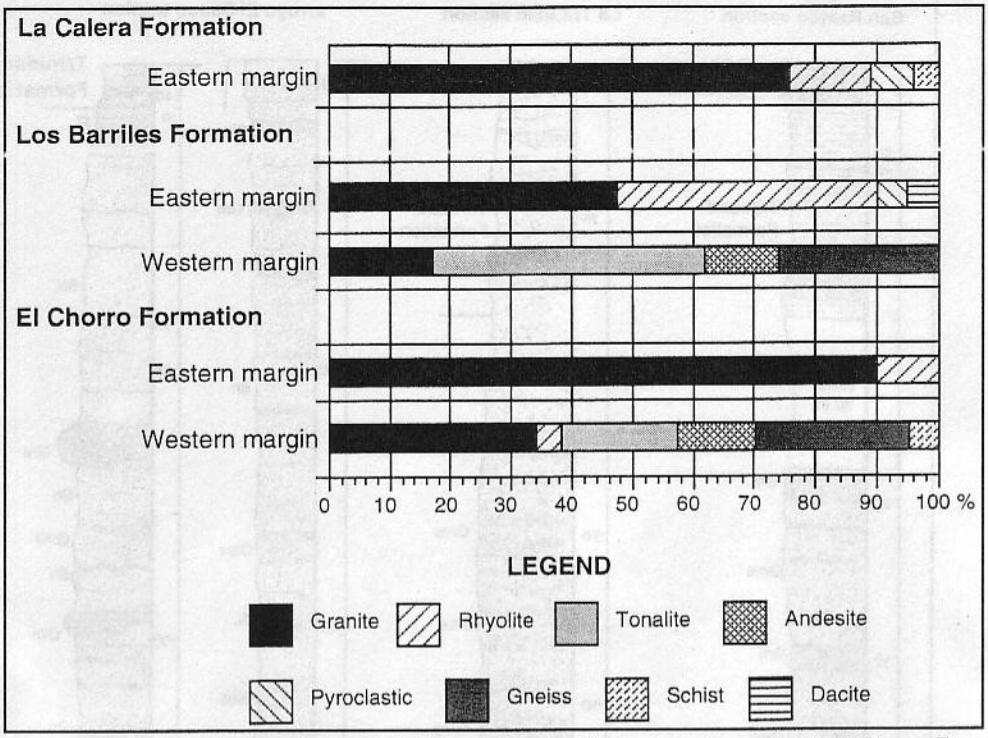

Figure 5. Clast composition of the alluvial formations: La Calera, Los Barriles, and El Chorro Formations. An average of 125 clast counts was done for each location.

The type section of the TF is located 28 km from the town of Santiago in the rancho La Trinidad area (Fig. 7). At rancho La Trinidad, the base of the TF conformably overlies the La Calera Formation; elsewhere it unconformably overlies the granitic-granodioritic basement. The TF is conformably overlain by the Refugio Formation, but toward the southern part of the basin the two formations are unconformable.

The TF is composed mainly of gray-greenish, laminated, fine- to medium-grained marine sandstone, shale, and siltstone and some diatomite laminae toward the center of the basin. Fine-grained sandstone, siltstone, and mudstone tend to dominate the formation. The sands of the Trinidad Formation are classified petrographically as medium-fine, calcareous, texturally mature arkose and consist mainly of angular to subrounded quartz, mica (mainly biotite), and K-feldspar grains and rare igneous and metamorphic rock fragments. An overall vertical trend is suggested for coarse-grained sandstone beds that grade upward into shale-siltstone with diatomite laminae, which grade near the top of the formation to coarse-to medium-grained sandstone beds. We estimate a total thickness of 400 m from the six stratigraphic sections.

To the west of the Sierra La Trinidad ridge (Fig. 1) toward the Sierra La Victoria ridge (Figure 1), the Trinidad Formation changes lithology. To better characterize the Trinidad Formation, it has been divided into three facies: lower, middle, and upper.

Lower facies. The lower facies is best exposed toward the eastern margin in the rancho La Trinidad area where it directly overlies the La Calera Formation. The grain size at the base ranges from coarse to medium sand, whereas at arroyo El Sauce the formation ranges from fine to medium sand that grades into clayey and silty sandstone beds. This basal sand facies is roughly equivalent to McCloy's (1984) subunit "A," which consists mainly of white coarse-grained quartzose sandstone, green

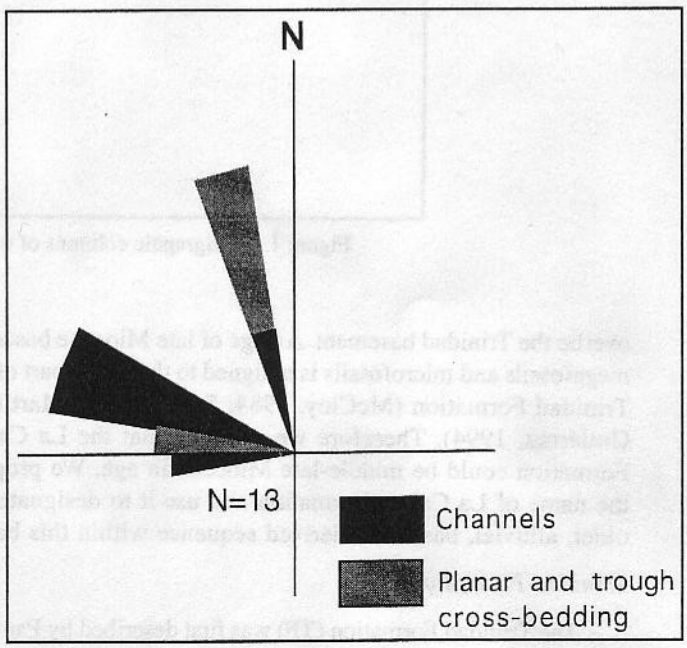

Figure 6. Rose diagrams showing paleocurrent azimuths measured in the La Calera Formation.

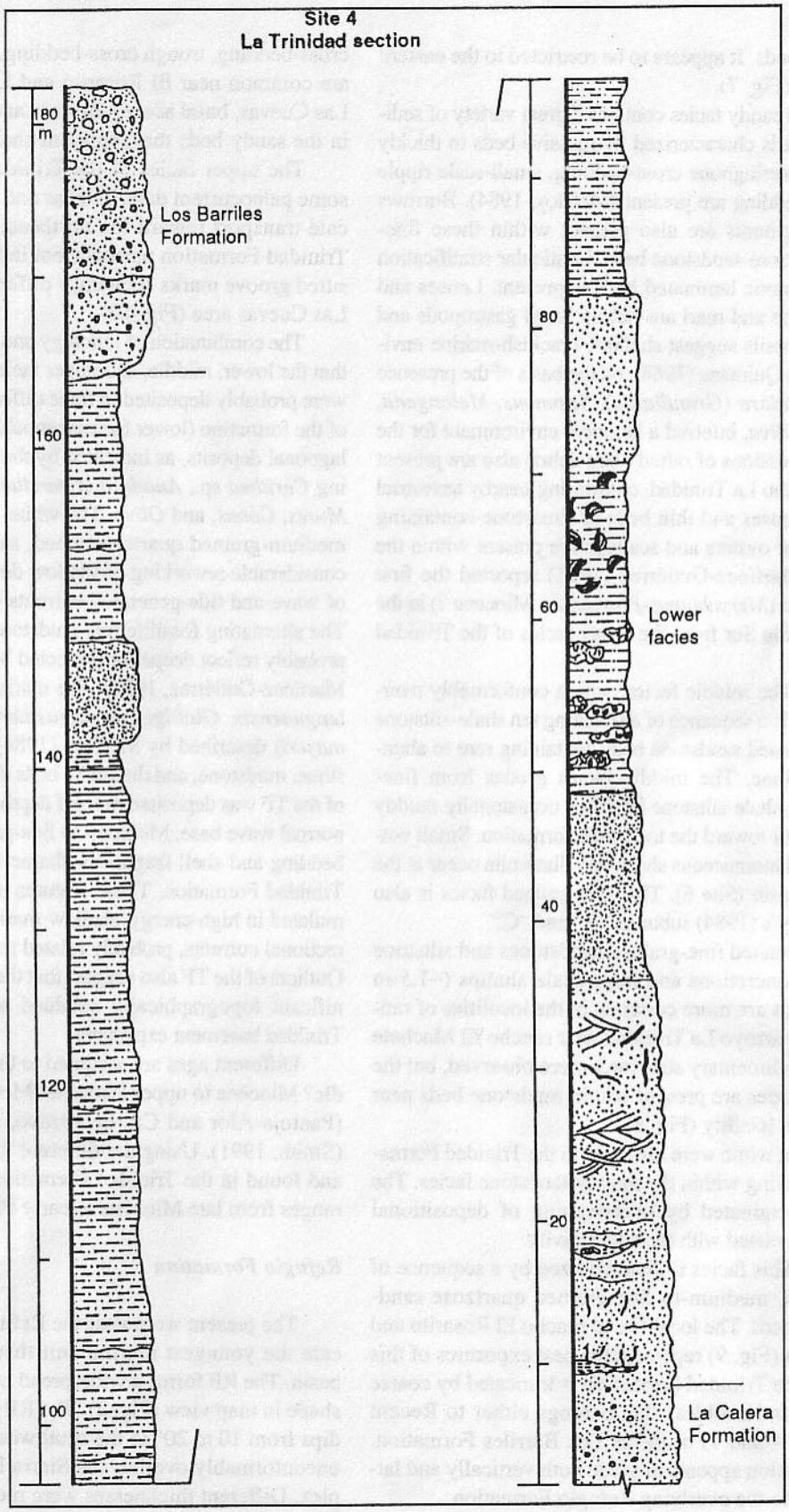

Figure 7. Stratigraphic columns of the Trinidad Formation, lower facies. See Figure 3 for legend.

siltstone, and shale beds. It appears to be restricted to the eastern portion of the basin (Fig. 7).

The basal quartz sandy facies contains a great variety of sedimentary structures. It is characterized by massive beds to thickly bedded sandstone. Herringbone cross-bedding, small-scale ripple marks, and planar bedding are present (McCloy, 1984). Burrows and fossil shell fragments are also present within these fine-grained, white, quartzose sandstone beds. Lenticular stratification within the shale-siltstone laminated beds is present. Lenses and thin beds of sandstone and marl are rich in fossil gastropods and pelecypods. These fossils suggest shallow, brackish-marine environments. Rodríguez-Quintana (1988), on the basis of the presence of *Cerithea* sp., *Anadara* (*Grandiarca*), *Strombus*, *Melongena*, *Murex*, *Conus*, and *Oliva*, inferred a lagoonal environment for the lower Trinidad. Impressions of rafted plant debris also are present at the locality of rancho La Trinidad, confirming nearby terrestrial habitats. Scattered lenses and thin beds of limestone containing small communities of oysters and scallops are present within the muddy sequence. Martínez-Gutiérrez (1991) reported the first horse jaw fossil found (*Merychippus-Pliohippus*, Miocene ?) in the state of Baja California Sur from the lower facies of the Trinidad Formation.

Middle facies. The middle facies, which conformably overlies the lower facies, is a sequence of alternating tan shale-siltstone laminae and fine-grained sandstone beds containing rare to abundant diatomite laminae. The middle facies grades from fine-grained sandstone to shale-siltstone laminae; occasionally muddy sandstone facies occur toward the top of the formation. Small outcrops of mudstone, diatomaceous shale, and diatomite occur at the central part of the basin (Site 6). This fine-grained facies is also equivalent to McCloy's (1984) subunits "B" and "C."

Massive to laminated fine-grained sandstones and siltstone beds contain rare concretions and large-scale slumps (~1.5-m width). These slumps are more common in the localities of rancho La Soledad and arroyo La Trinidad near rancho El Machete (Fig. 2). No other sedimentary structures were observed, but the remains of whale bones are present within mudstone beds near the rancho El Torete locality (Fig. 8).

Slumps of 1.5-m width were observed in the Trinidad Formation, generally occurring within the muddy sandstone facies. The slumps probably originated by overstepping of depositional slopes, possibly associated with tectonic activity.

Upper facies. This facies is characterized by a sequence of greenish to reddish, medium-to fine-grained quartzose sandstone and siltstone beds. The localities at rancho El Rosarito and rancho La Calabaza (Fig. 9) represent the best exposures of this facies. The top of the Trinidad Formation is truncated by coarse material (pebbles and cobbles) that belongs either to Recent alluvial fans (Sites 4 and 7) or to the Los Barriles Formation. The Trinidad Formation appears to grade both vertically and laterally southward into the overlying Refugio Formation.

The upper part of the TF exhibits massive (beds greater than 1.20 m in thickness) to thickly bedded coarse- to medium-grained sandstone that contains minor siltstone beds. Tabular cross-bedding, trough cross-bedding, and climbing ripple marks are common near El Rosarito and La Calabaza. In the area of Las Cuevas, basal scour, chevron, and groove marks are present in the sandy beds that represent shallow, sandy marine shoals.

The upper facies of the Trinidad Formation also yielded some paleocurrent data. Tabular and trough cross-bedding indicate transport toward the northeast and the south-southwest. Trinidad Formation paleocurrent indicators also included measured groove marks showing a different direction of flow in the Las Cuevas area (Fig. 10).

The combination of lithology and fossil assemblages indicates that the lower, middle, and upper facies of the Trinidad Formation were probably deposited in three different environments. The base of the formation (lower facies) probably corresponds to nearshore-lagoonal deposits, as indicated by the fossil assemblages containing *Cerithea* sp., *Anadara* (*Grandiarca*), *Strombus*, *Melongena*, *Murex*, *Conus*, and *Oliva*. The white, texturally mature, coarse-to medium-grained quartz-enriched, sandstone strata also suggest considerable reworking of shallow deposits by some combination of wave-and tide-generated currents or wind-generated currents. The alternating fossiliferous mudstone strata of the middle facies probably reflect deeper or protected bottom areas (McCloy, 1984; Martínez-Gutiérrez, 1994). The marine microfauna (*Globorotalia lenguaensis, Globigerina angustiumbilicata,* and *Globorotalia mayeri*) described by McCloy (1984) and the fine-grained sandstone, mudstone, and diatomite beds indicate that the middle facies of the TF was deposited in shelf depths slightly greater than that of normal wave base. Medium- to fine-grained sandstone with cross-bedding and shell fragments characterize the upper facies of the Trinidad Formation. These features indicate that the facies accumulated in high-energy, shallow marine waters affected by unidirectional currents, probably related to inner shelf shoals and bars. Outliers of the TF also suggest that the sea transgressed across significant topographically subdued areas of what are now La Trinidad basement exposures.

Different ages are assigned to the Trinidad Formation: middle? Miocene to upper Pliocene (McCloy, 1984), lower Pliocene (Pantoja-Alor and Carrillo-Bravo, 1966), and upper Miocene (Smith, 1991). Using the different fossil assemblages described and found in the Trinidad Formation, we estimate that the unit ranges from late Miocene to early Pliocene in age.

Refugio Formation

The present work uses the Refugio Formation (RF) to indicate the youngest marine unit that crops out throughout the basin. The RF forms a widespread outcrop belt and has a wedge shape in map view (Fig. 2). The RF strikes to the northwest and dips from 10 to 20° to the southwest. Toward the south, the RF unconformably overlies the Sierra La Trinidad basement complex. Different thicknesses were measured for the RF. Pantoja-Alor and Carrillo-Bravo (1966) measured a thickness of 80 m, whereas McCloy (1984) found a thickness of 280 m. Gaitán (1986) measured a thickness of about 360 m at the southern

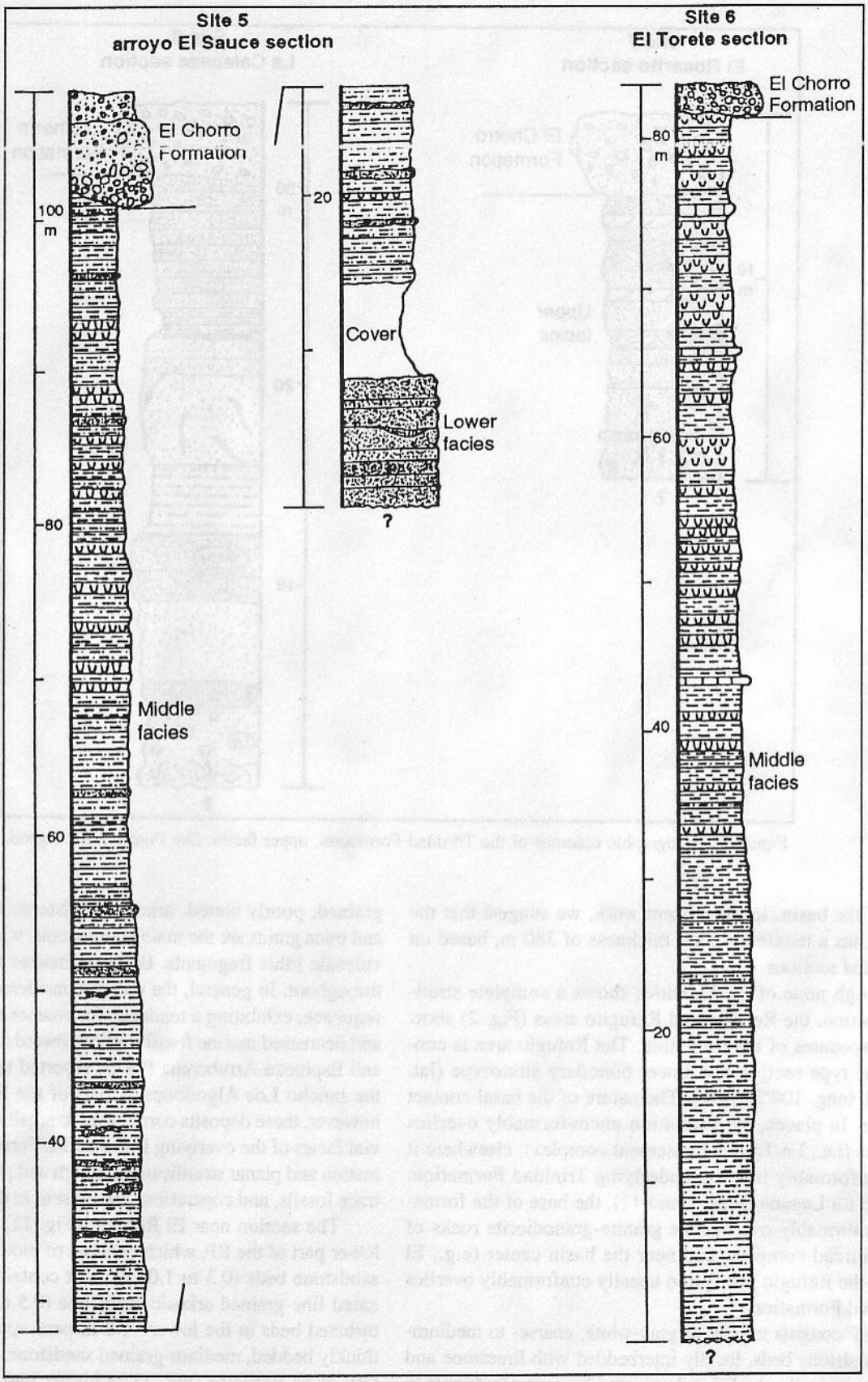

Figure 8. Stratigraphic columns of the Trinidad Formation, middle facies. See Figure 3 for legend.

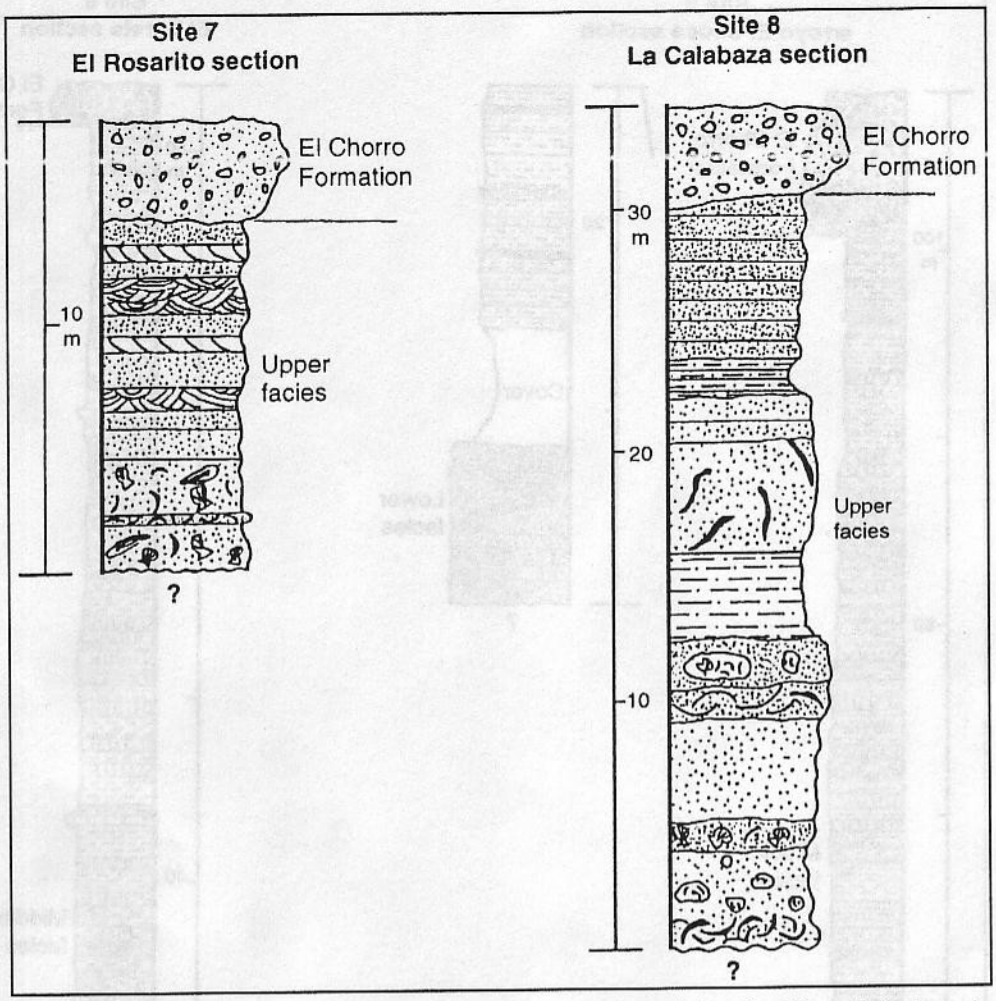

Figure 9. Stratigraphic columns of the Trinidad Formation, upper facies. See Figure 3 for legend.

portion of the basin. In the present work, we suggest that the formation has a maximum total thickness of 380 m, based on six measured sections.

Although none of the localities shows a complete stratigraphic section, the Refugio and Refugito areas (Fig. 2) show the best exposures of the formation. The Refugio area is considered the type section and lower boundary stratotype (lat. 23°24.1′N, long. 109°38.5′W). The nature of the basal contact is variable. In places, the formation unconformably overlies older rocks (i.e., La Trinidad basement complex); elsewhere it grades conformably into the underlying Trinidad Formation. Near cerro La Laguna (Figs. 2 and 11), the base of the formation unconformably overlies the granite-granodiorite rocks of the La Trinidad complex, and near the basin center (e.g., El Refugio), the Refugio Formation usually conformably overlies the Trinidad Formation.

The RF consists mainly of gray-white, coarse- to medium-grained sandstone beds, locally interbedded with limestone and shale. Lithologically, the RF is dominated by generally friable to weakly carbonate cemented, grayish-white, coarse- to medium-grained, poorly sorted, arkosic sandstone. Quartz, K-feldspar, and mica grains are the main components, with lesser amounts of volcanic lithic fragments. Brackish marine fossils are common throughout. In general, the unit is considered to be a regressive sequence, exhibiting a tendency for coarser sandstone grain size and decreased marine fossil content toward its top. Miller (1980) and Espinoza-Arrubarena (1979) reported terrestrial deposits at the rancho Los Algodones as part of the Refugio Formation; however, these deposits correspond to small outcrops of the alluvial facies of the overlying Los Barriles Formation. Parallel lamination and planar stratification, trough and planar cross-bedding, trace fossils, and concretions are present in the facies.

The section near El Refugio (Fig. 11) best represents the lower part of the RF, which consists of bioturbated fine-grained sandstone beds (0.3 to 1.00 m) that contain interbeds of laminated fine-grained arkosic sandstone (0.5 to 0.15 m). The bioturbated beds in the lower ~1.2 m pass upward into ~6.3 m of thickly bedded, medium-grained sandstone. At the adjacent section of El Refugito (Fig. 11) a higher part of the unit may be exposed. Here, the interval consists of a series of alternating

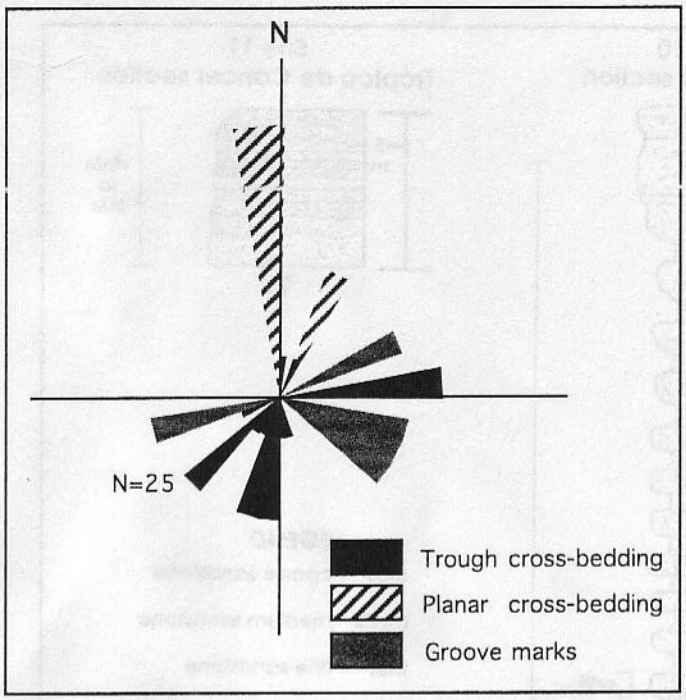

Figure 10. Rose diagrams showing paleocurrent azimuths measured in the Trinidad Formation, upper facies.

very coarse- and medium-grained white sandstone beds with thicknesses that range from 0.15 to 0.40 m. The medium-grained sandstone is moderately sorted and subrounded to rounded, whereas the very coarse-grained sandstone is poorly sorted and angular to subangular. The contact between beds is gradational, and some of the beds (both coarse and medium grained) fine upward. All sandstone beds have marine shell fragments, but no complete fossil shells are present. The top of the RF is exposed at Trópico de Cancer. It consists of commonly cross-bedded, texturally supermature, fine-grained sandstone.

The RF near rancho Los Algodones (Fig. 11) consists of ~30 m of massive, coarse-grained sandstone beds, unconformably overlying the Trinidad Formation. This sand is moderately sorted, with subrounded to rounded grains. It contains scattered whole and fragmented marine mollusks. Primary bedding is rarely preserved.

The arkosic sandstone is intercalated with siltstone and fossiliferous beds (coquina) at the Trópico de Cancer and cerro La Laguna localities. The sandstone beds are weakly cemented by $CaCO_3$, but in the cerro La Laguna area the base of the unit is strongly cemented by $CaCO_3$ and occasionally by SiO_2.

The southernmost section, cerro La Laguna, was originally measured by Gaitán (1986). Our unit description differs in terms of lithology from the northern exposures within the basin. Its base consists of white, carbonate- and silica-cemented, very coarse to coarse-grained quartzose sandstone that is moderately sorted and rounded to well rounded (similar to that at Site 12). The middle part of the RF consists of pinkish-gray limestone beds alternating with greenish-yellow siltstone beds that are overlain by fine-grained arkosic sandstone containing interbedded siltstone layers. The limestone beds contain shell fragments and lesser amounts of fine-grained sand. The upper part presents alternating deposits of yellowish-gray limestone and greenish-yellow siltstone beds. These alternating deposits are overlain by a white, coarse-grained, texturally mature to supermature, quartz-rich sandstone.

Tabular and trough cross-bedding measured in the RF at Trópico de Cancer (Fig. 12) suggests general southerly transport, probably in response to wave-and/or tidal-induced bottom currents. In contrast, older formations revealed paleotransport toward the west-northwest (Martínez-Gutiérrez, 1994).

The Refugio Formation is rich in fossils, including gastropods, pelecypods, arthropods, and marine vertebrates. Hertlein (1966) reports *Argopecten calli*, *Clhamys tamiamiensis grewingki*, *Euvola refugioensis*, *Pecten aletes*, *Striotsrea* sp., *Undulostrea megadon*, *Conus multiliratus*, *Ficus carbasea*, *Strombus obliteratus*, and *Amonia peruviana* at the rancho El Refugio locality. McCloy (1984) also includes *Pecten* (*Plagioctenium*) *calli* and *Pecten* (*Euvola*) *keepi*.

Smith (1991) states that the RF contains a Tertiary fauna of Caribbean affinity that is characterized by *Clementia dariena*, *Turritella abrupta fredeai*, *Florimetis tritinana*, *Cyathodonta gatunenis*, and *Raeta undulata*. Based on the fossil assemblage, Hertlein (1966) assigned an age of middle Pliocene to the Refugio Formation. Pantoja-Alor and Carrillo-Bravo (1966) designated a Pliocene age; McCloy (1984) assigned an upper Pliocene–Pleistocene age. Smith (1991), using the Caribbean affinities of Cenozoic marine mollusks from several Californian formations, suggests that "Salada Formation" (herein called the Refugio Formation) is a lower Pliocene unit. In this study an early Pliocene age is suggested for the Refugio Formation based on the fossil assemblage described by previous authors and by its conformable contact with the Trinidad formation.

The Refugio fossil assemblage described by Hertlein (1966) in the area of rancho El Refugio and rancho El Refugito suggests deposition in warm, shallow marine waters. Pantoja-Alor and Carrillo-Bravo (1966) interpreted the unit as a high-energy marine deposit with abundant turbidity currents. Based on megafossils (mollusks and gastropods), McCloy (1984) interpreted this formation as an inner shelf deposit in the El Refugio area that shoals upward into beach and lagoonal deposits in the Santiago area to the west. The presence of a coarsening-upward sequence, brackish marine fossils, and limestone beds suggests that the Refugio Formation was deposited in shallow marine waters as a regressive package in response to a sedimentary progradation.

Los Barriles Formation

The Los Barriles Formation (LBF) is typical of the conglomeratic deposits exposed along arroyo El Datilar at the western margin of the Sierra La Trinidad basement complex and

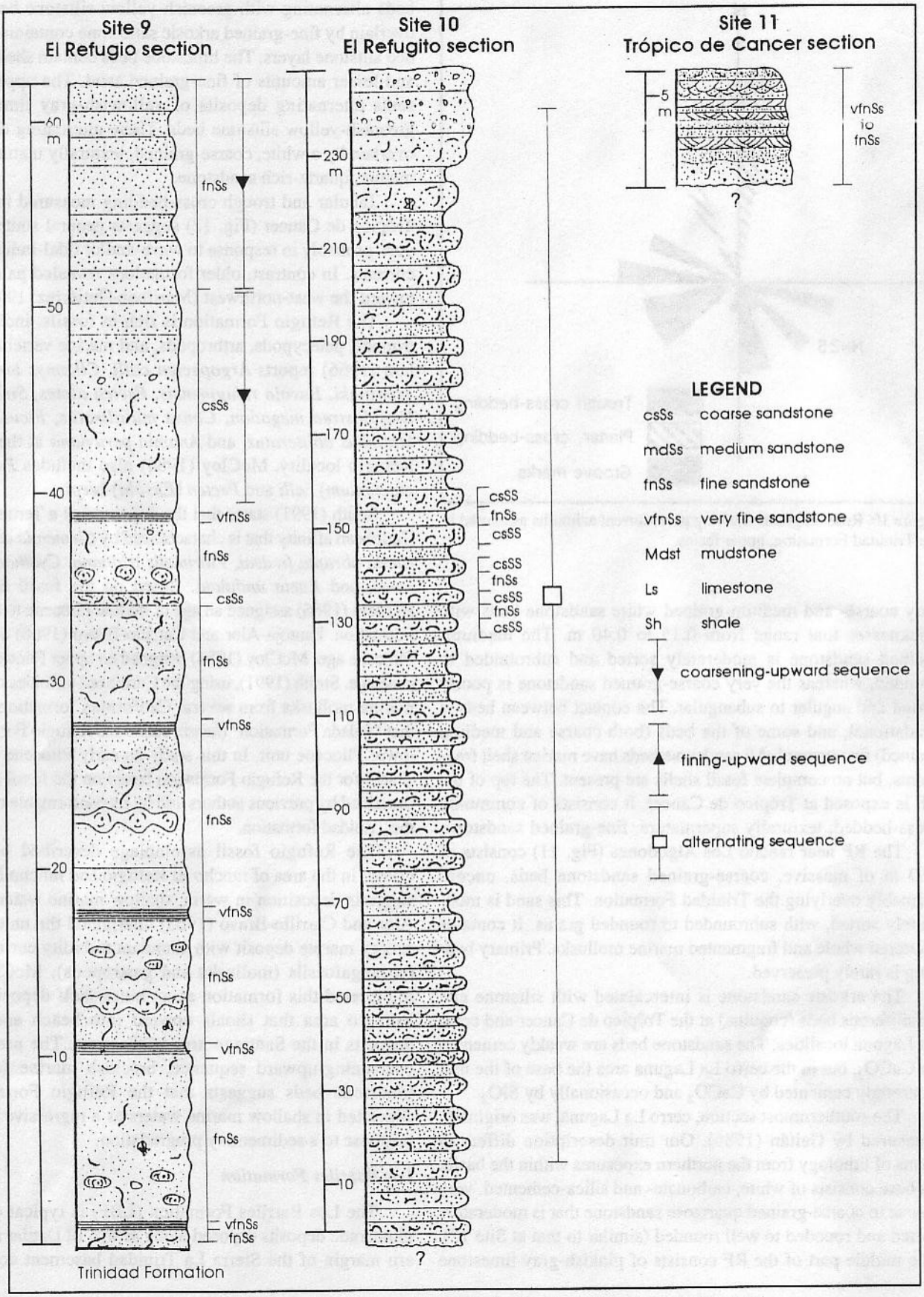

Figure 11. Stratigraphic columns of the Refugio Formation. See Figure 3 for legend.

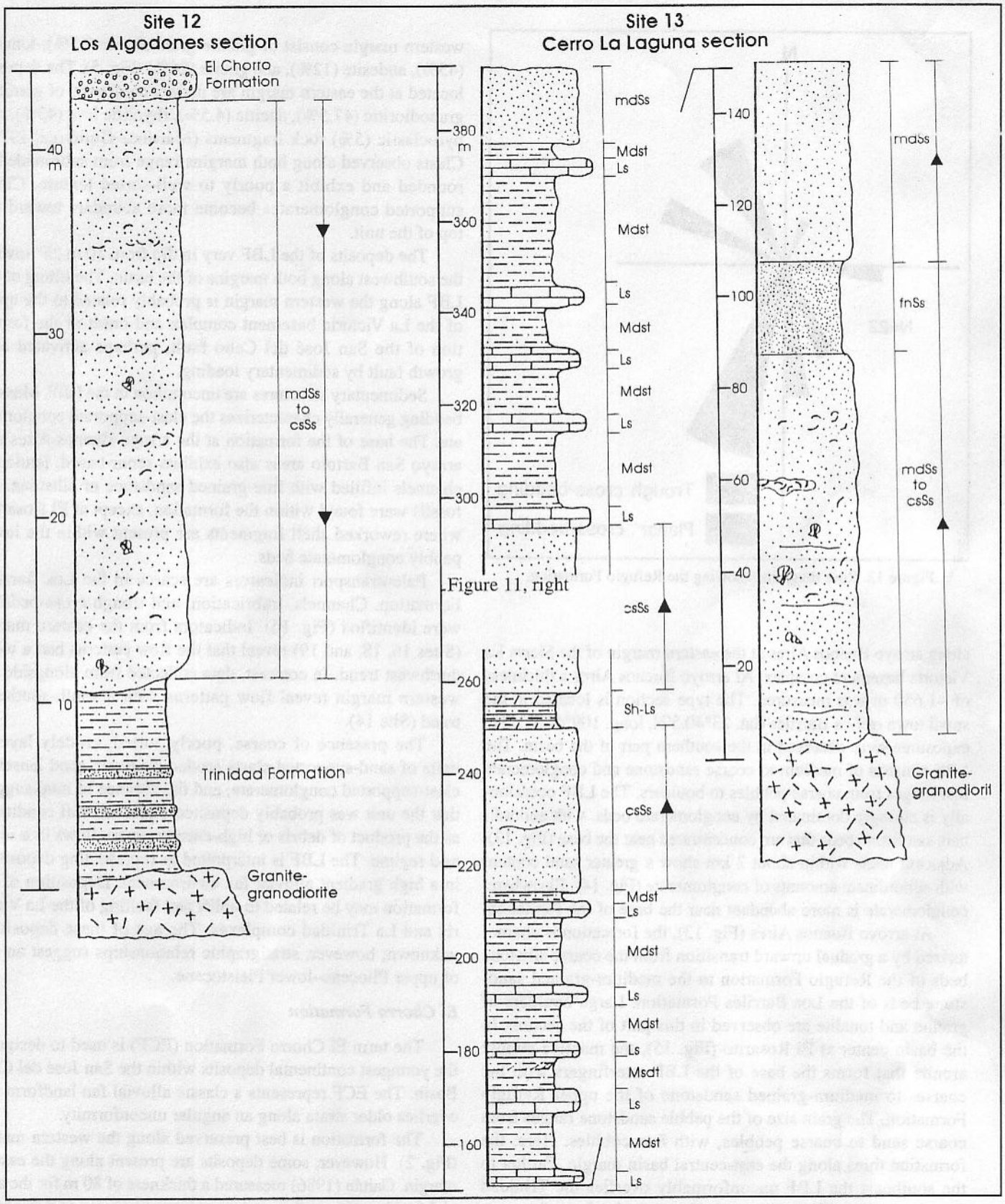

Figure 11, right

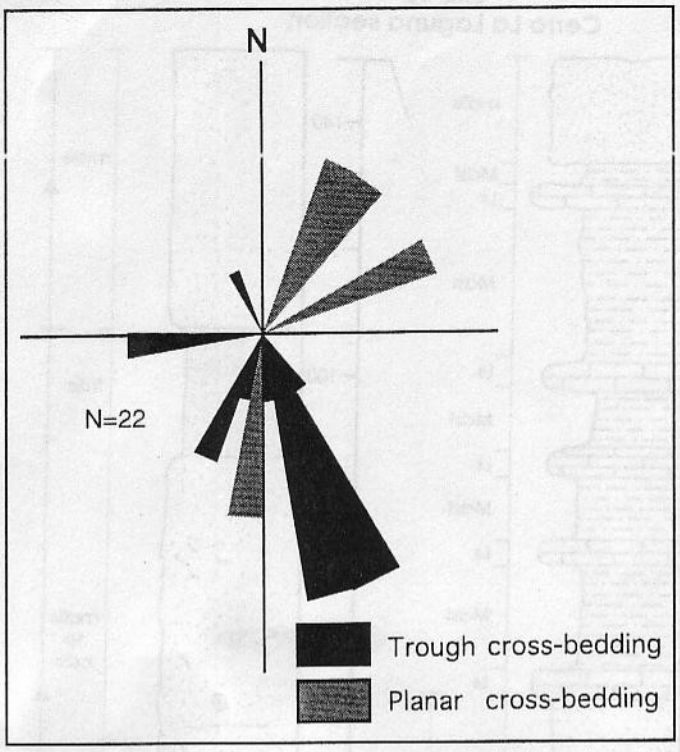

Figure 12. Rose diagrams showing the Refugio Formation.

along arroyo Buenos Aires at the eastern margin of the Sierra La Victoria basement complex. At arroyo Buenos Aires a thickness of ~1,650 m was measured. The type section is located in the small town of Los Barriles (lat. 23°40.5'N, long. 109°42'W). No exposures were observed in the southern part of the basin. The LBF consists of medium to coarse sandstone and conglomerate that ranges from coarse pebbles to boulders. The LBF occasionally is strongly dominated by conglomerate beds, with subordinate sandstone beds that are concentrated near the base (Fig. 13). Adjacent areas within about 2 km show a greater sand content with subordinate amounts of conglomerate (Fig. 14). Elsewhere, conglomerate is more abundant near the base of the formation.

At arroyo Buenos Aires (Fig. 13), the formation is characterized by a gradual upward transition from the coarse siltstone beds of the Refugio Formation to the medium-grained sandstone beds of the Los Barriles Formation. Large boulders of granite and tonalite are observed in this part of the section. In the basin center at El Rosarito (Fig. 15), the massive pebbly arenite that forms the base of the LBF interfingers with the coarse- to medium-grained sandstone of the upper Refugio Formation. The grain size of the pebble sandstone ranges from coarse sand to coarse pebbles, with few cobbles. Here, the formation thins along the east-central basin margin. Farther to the southeast the LBF unconformably overlies the Trinidad Formation (Fig. 15). In the north (Site 14), the formation conformably overlies Refugio strata; southward (Sites 18 and 19), they interfinger (fan-delta facies).

Larger clasts (pebbles and cobbles) of the LBF along the western margin consist of granite-granodiorite (17%), tonalite (45%), andesite (12%), and gneiss (26%) (Fig. 5). The deposits located at the eastern margin are mainly composed of granitic-granodioritic (47.5%), dacitic (4.5%), rhyolitic lava (43%), and pyroclastic (5%) rock fragments (Martínez-Gutiérrez, 1994). Clasts observed along both margins range from subrounded to rounded and exhibit a poorly to well-sorted texture. Clast-supported conglomerates become more abundant toward the top of the unit.

The deposits of the LBF vary in dip from 10 to 25° toward the southwest along both margins of the basin. The tilting of the LBF along the western margin is probably related to the uplift of the La Victoria basement complex and onset of the formation of the San José del Cabo fault, perhaps activated as a growth fault by sedimentary loading.

Sedimentary structures are uncommon in the LBF. Massive bedding generally characterizes the clast-supported conglomerate. The base of the formation at the arroyo Buenos Aires and arroyo San Bartolo areas also exhibits scour-based, lenticular channels infilled with fine-grained sandstone or siltstone. No fossils were found within the formation, except at El Rosarito, where reworked shell fragments are present within the lower pebbly conglomerate beds.

Paleotransport indicators are scarce in the Los Barriles Formation. Channels, imbrication, and trough cross-bedding were identified (Fig. 16). Indicators from the eastern margin (Sites 16, 18, and 19) reveal that the flow patterns had a west-northwest trend. In contrast, data collected from alongside the western margin reveal flow patterns with a south-southeast trend (Site 14).

The presence of coarse, poorly sorted, crudely layered units of sand-supported clasts eroded by scour, sand lenses of clast-supported conglomerate, and the absence of mud suggest that the unit was probably deposited under alluvial conditions as the product of debris or high-energy stream flows in a semi-arid regime. The LBF is interpreted as representing deposition in a high gradient alluvial fan environment. Deposition of the formation may be related to uplift and faulting of the La Victoria and La Trinidad complexes. The age of these deposits is unknown; however, stratigraphic relationships suggest an age of upper Pliocene–lower Pleistocene.

El Chorro Formation

The term El Chorro Formation (ECF) is used to designate the youngest continental deposits within the San José del Cabo Basin. The ECF represents a classic alluvial fan landform and overlies older strata along an angular unconformity.

The formation is best preserved along the western margin (Fig. 2). However, some deposits are present along the eastern margin. Gaitán (1986) measured a thickness of 80 m for the alluvial fan deposits on the western margin compared to a thickness of 2 to 4 m on the eastern margin. In this study, we measure a thickness of about 150 m at the localities described on the western margin (Fig. 17) and about 3 to 8 m for the deposits in the eastern

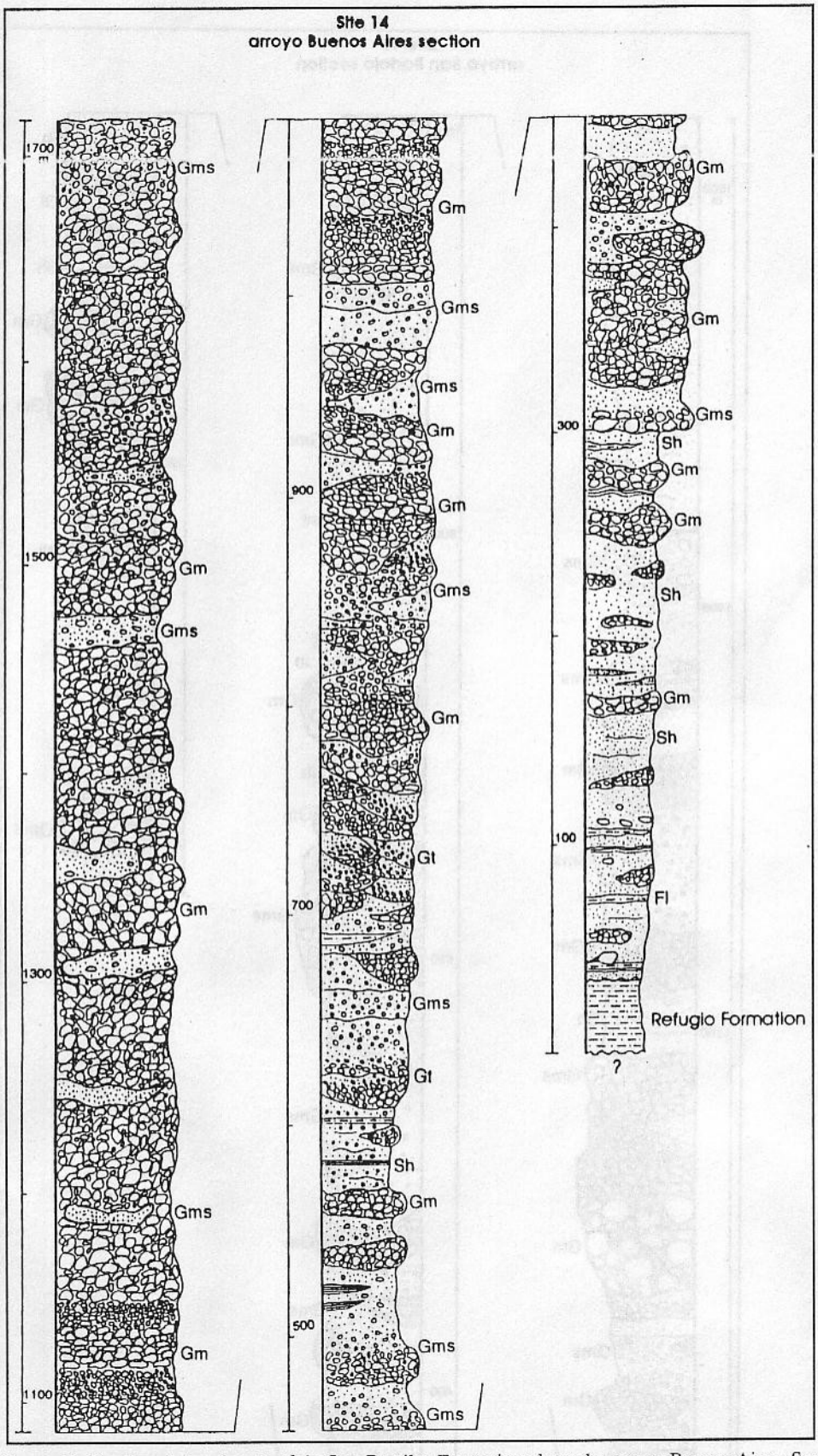

Figure 13. Stratigraphic columns of the Los Barriles Formation along the arroyo Buenos Aires. See Figure 3 for legend.

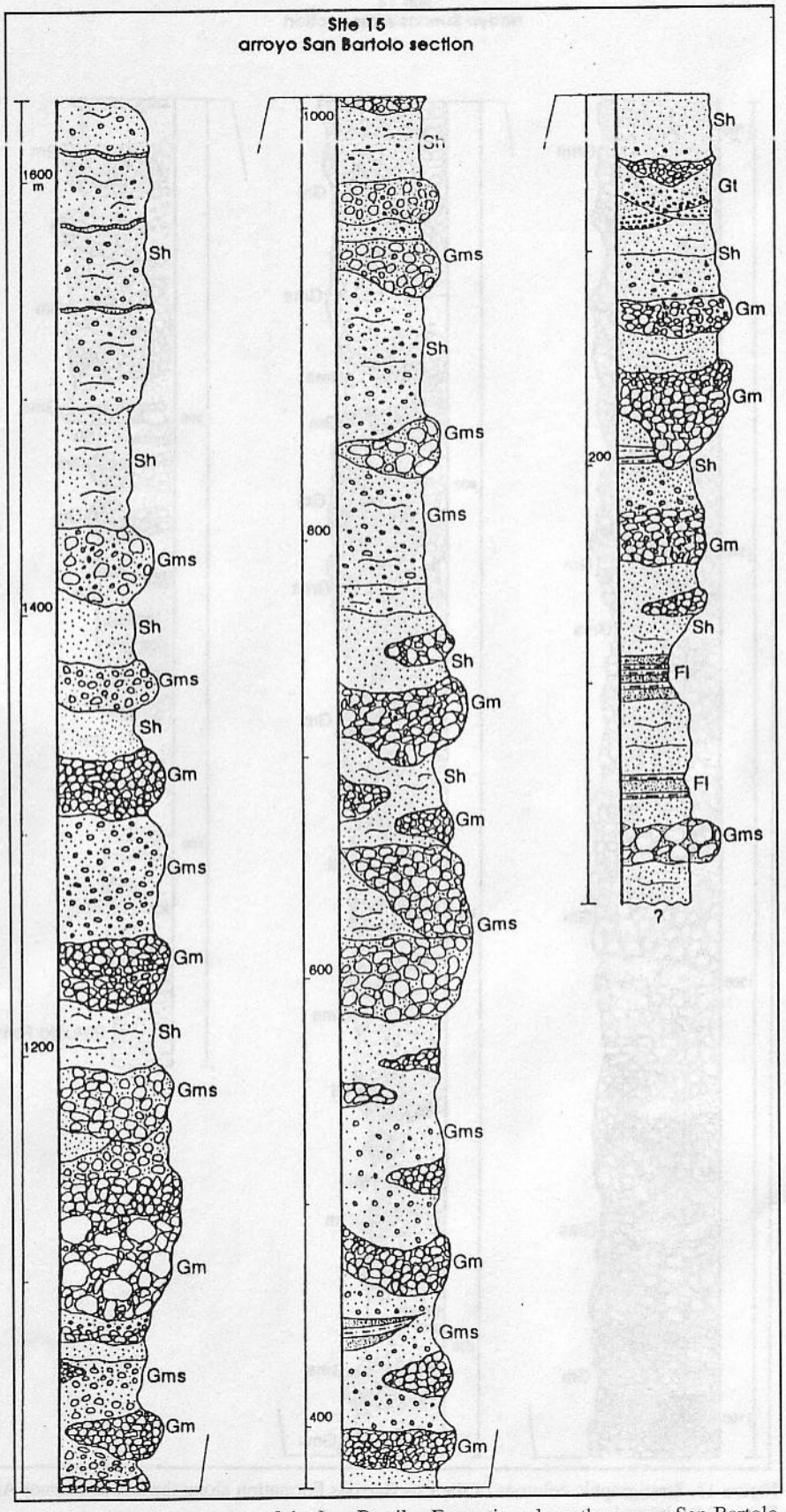

Figure 14. Stratigraphic columns of the Los Barriles Formation along the arroyo San Bartolo. See Figure 3 for legend.

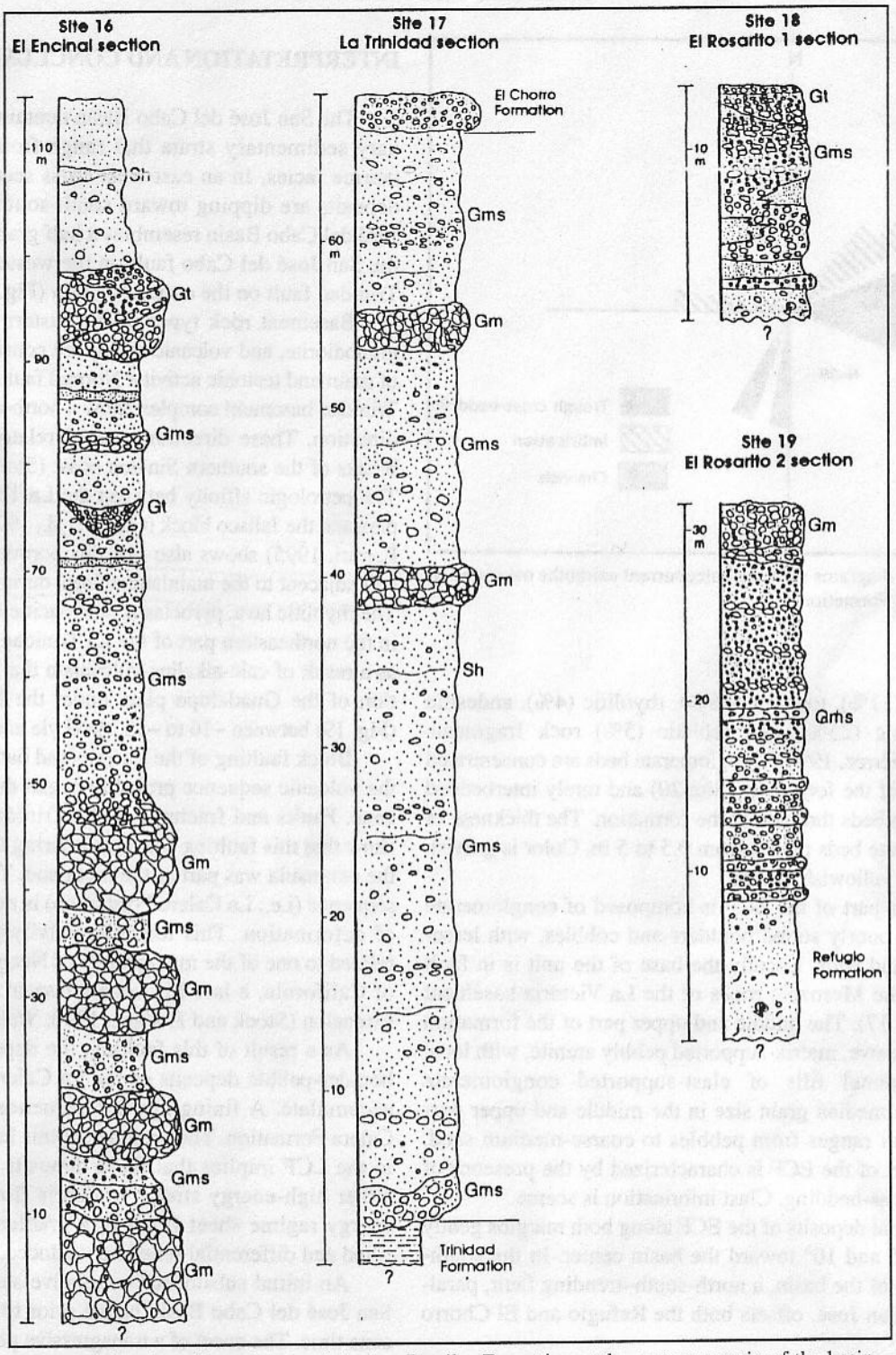

Figure 15. Stratigraphic columns of the Los Barriles Formation at the eastern margin of the basin. See Figure 3 for legend.

margin. The most complete stratigraphic sections measured are located near rancho El Chorro (section type, lat. 23°26.5′N, long. 109°48.5′W) and along arroyo San Dionisio (Fig. 17).

The El Chorro Formation is composed of nonmarine, coarse-grained sandstone and conglomerate. Lithic clasts range in size from coarse sand to boulders and vary from angular to subrounded. Clasts from the eastern margin and the western margin of the basin differ in composition. The eastern margin is composed of granitic (90%) and rhyolitic (10%) rock fragments (Fig. 5), whereas the western margin consists of granitic (23%),

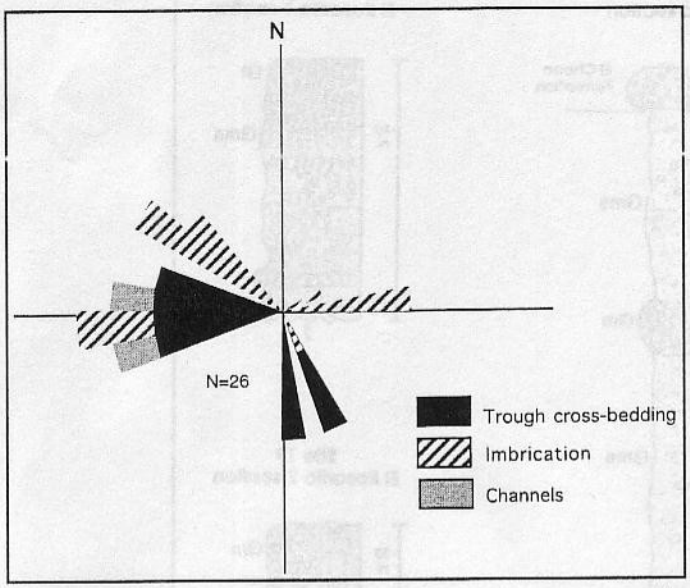

Figure 16. Rose diagrams showing paleocurrent azimuths measured in the Los Barriles Formation.

granodioritic (11%), tonalitic (19%), rhyolitic (4%), andesitic (13%), gneissic (25%), and schistic (5%) rock fragments (Martínez-Gutiérrez, 1994). Conglomerate beds are concentrated near the base of the formation (Site 20) and rarely interbedded with sandstone beds throughout the formation. The thickness of the conglomerate beds ranges from 0.5 to 5 m. Color is grayish orange or pale yellowish orange.

The lower part of the ECF is composed of conglomerate beds made of poorly sorted boulders and cobbles, with lesser amounts of sand beds. Locally the base of the unit is in fault contact with the Mesozoic rocks of the La Victoria basement complex (Fig. 17). The middle and upper part of the formation consists of massive, matrix-supported pebbly arenite, with local lens and channel fills of clast-supported conglomerate (Fig. 17). The median grain size in the middle and upper portion of the unit ranges from pebbles to coarse-medium sand. The upper part of the ECF is characterized by the presence of large-scale cross-bedding. Clast imbrication is scarce.

The alluvial deposits of the ECF along both margins gently dip between 5 and 10° toward the basin center. In the south-central region of the basin, a north-south–trending fault, parallel to arroyo San José, offsets both the Refugio and El Chorro Formations.

Indicators of transport direction are rare in the ECF. The few that were measured along Federal Highway 1 (Fig. 18) are consistent with the observable fan morphology and confirm that transport direction was predominantly eastward.

The El Chorro Formation is flat lying and most commonly lies in angular unconformity above older strata, including the La Calera, Trinidad, Refugio, and Los Barriles Formations. The ECF represents recent alluvial fan deposition with a probable age of upper Pleistocene–lower Holocene.

INTERPRETATION AND CONCLUSIONS

The San José del Cabo Basin contains Miocene to Quaternary sedimentary strata that range from alluvial to shallow marine facies. In an east-west cross section, the sedimentary deposits are dipping toward south-southwest, where the San José del Cabo Basin resembles a half graben that is bounded by the San José del Cabo fault on the western margin and the La Trinidad fault on the eastern margin (Fig. 2).

Basement rock types of the eastern margin (i.e., granite, granodiorite, and volcanic rocks) are considered to be a remnant of mainland tectonic activity. Normal fault traces in the Sierra La Trinidad basement complex show a north-northwest to northwest direction. These directions are correlated with the east tilted blocks of the southern Sinaloa coast (Stock and Hodges, 1989). The petrologic affinity between the La Trinidad basement complex and the Jalisco block (Gastil et al., 1978; Wallace et al. 1992; Ferrari, 1995) shows also that this portion of the peninsula was still adjacent to the mainland at least during lower Miocene time. The rhyolitic lava, pyroclastic, and dacitic lava rocks that crop out in the northeastern part of the La Trinidad complex accumulated as a result of calc-alkaline volcanism that resulted from subduction of the Guadalupe plate under the North American plate (Fig. 19) between ~16 to ~13 Ma (Lyle and Ness, 1991).

Block faulting of the La Trinidad batholithic basement and the volcanic sequence probably began during the middle Miocene. Faults and fractures in the Trinidad basement complex show that this faulting continued during the late Miocene when the peninsula was part of the mainland. The oldest sedimentary sequence (i.e., La Calera Formation) is not affected by this type of deformation. This tectonic activity presumably could be related to one of the main phases of Neogene rifting in the Gulf of California, a late Miocene phase of orthogonal east-west extension (Stock and Hodges, 1990; Wallace et al., 1992).

As a result of this faulting, the deposition of the massive boulder-pebble deposits of the La Calera Formation began to accumulate. A fining-upward sequence is evident in the La Calera Formation. The presence of this fining-upward sequence in the LCF implies that these deposits were associated with either high-energy stream to debris flows that grade to low-energy regime sheet flows or a gradient reduction as basins filled and differential relief was reduced.

An initial subsidence or relative sea-level rise within the San José del Cabo Basin began prior to or during upper Miocene time. The onset of a transgressive phase within the basin is recorded by marshy to shallow-marine deposits of the lower part of the Trinidad Formation (Fig. 20). The most prominent transgression is represented by the muddy and diatomaceous middle facies of the formation. The subsidence and transgression continued through the upper Miocene to lower Pliocene. The transgressive phase is explained in terms of a subsidence of the basin. A pre-8.2 Ma subsidence is also reported by McCloy (1987) where similar marine sediments at Isla María Madre indicate this event. The subsidence of the basin can be attributed to

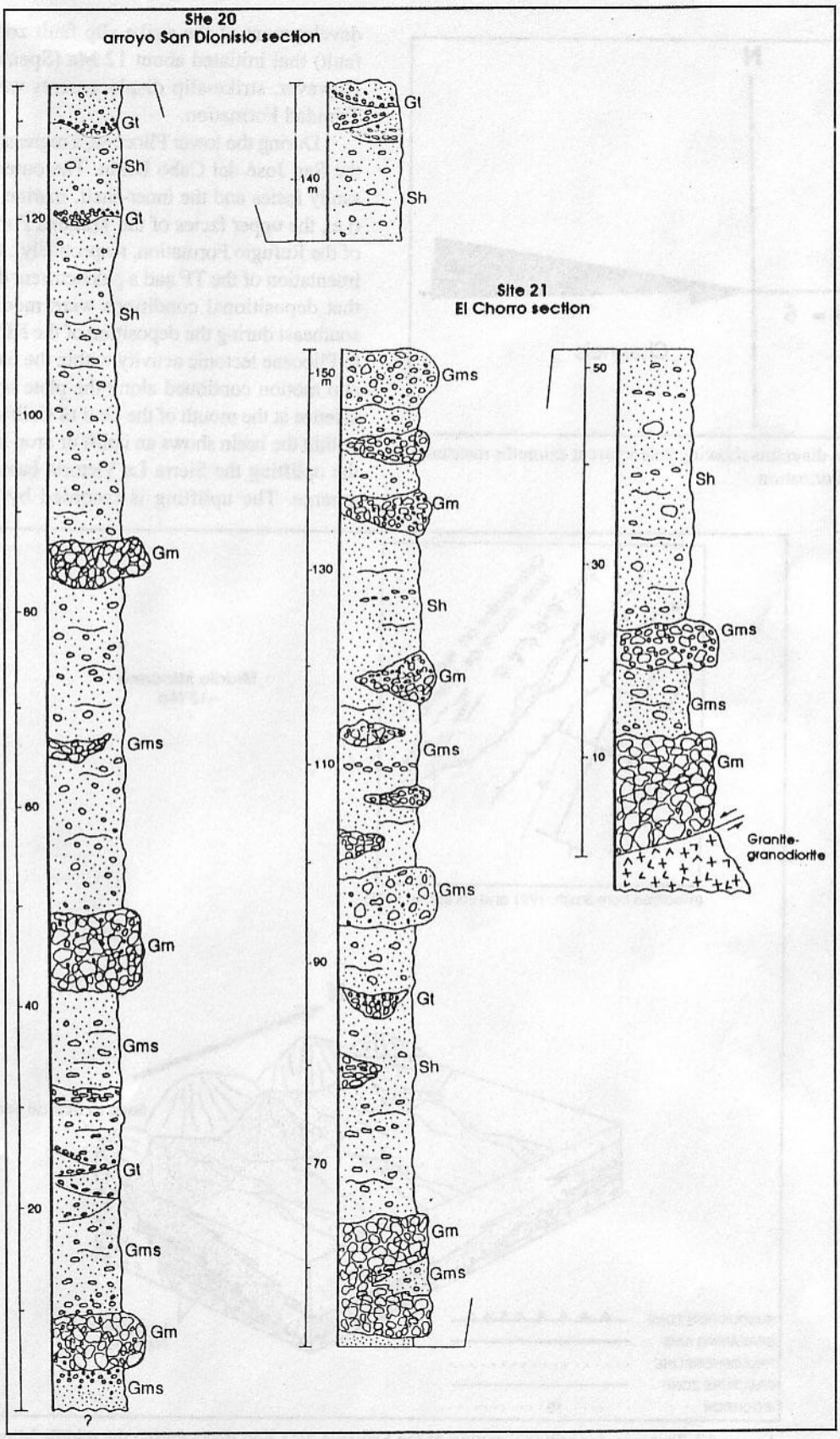

Figure 17. Stratigraphic columns of the El Chorro Formation. See Figure 3 for legend.

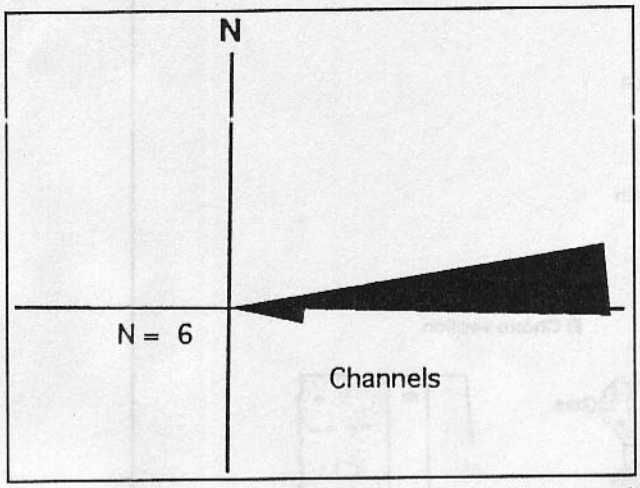

Figure 18. Rose diagrams showing paleocurrent azimuths measured in the El Chorro Formation.

development of the strike-slip fault zone (the Tosco-Abreojos fault) that initiated about 12 Ma (Spencer and Normak, 1979). However, strike-slip displacements were not observed in the Trinidad Formation.

During the lower Pliocene, a regressive phase initiated within the San José del Cabo Basin. The outer-shelf, marine, muddy-sandy facies and the inner-shelf, marine, sandy facies developed (i.e., the upper facies of the Trinidad Formation and lower facies of the Refugio Formation, respectively). Coarsening-upward sedimentation of the TF and a paleocurrent direction change indicate that depositional conditions were modified toward the south-southeast during the deposition of the RF. This variation is related to Pliocene tectonic activity within the basin. Although the strike-slip motion continued along the plate boundary, producing subsidence at the mouth of the Gulf of California, the geologic record within the basin shows an uplift or drop in sea level. As a result of the uplifting the Sierra La Victoria basement complex began to emerge. The uplifting is recorded by the coarsening-upward

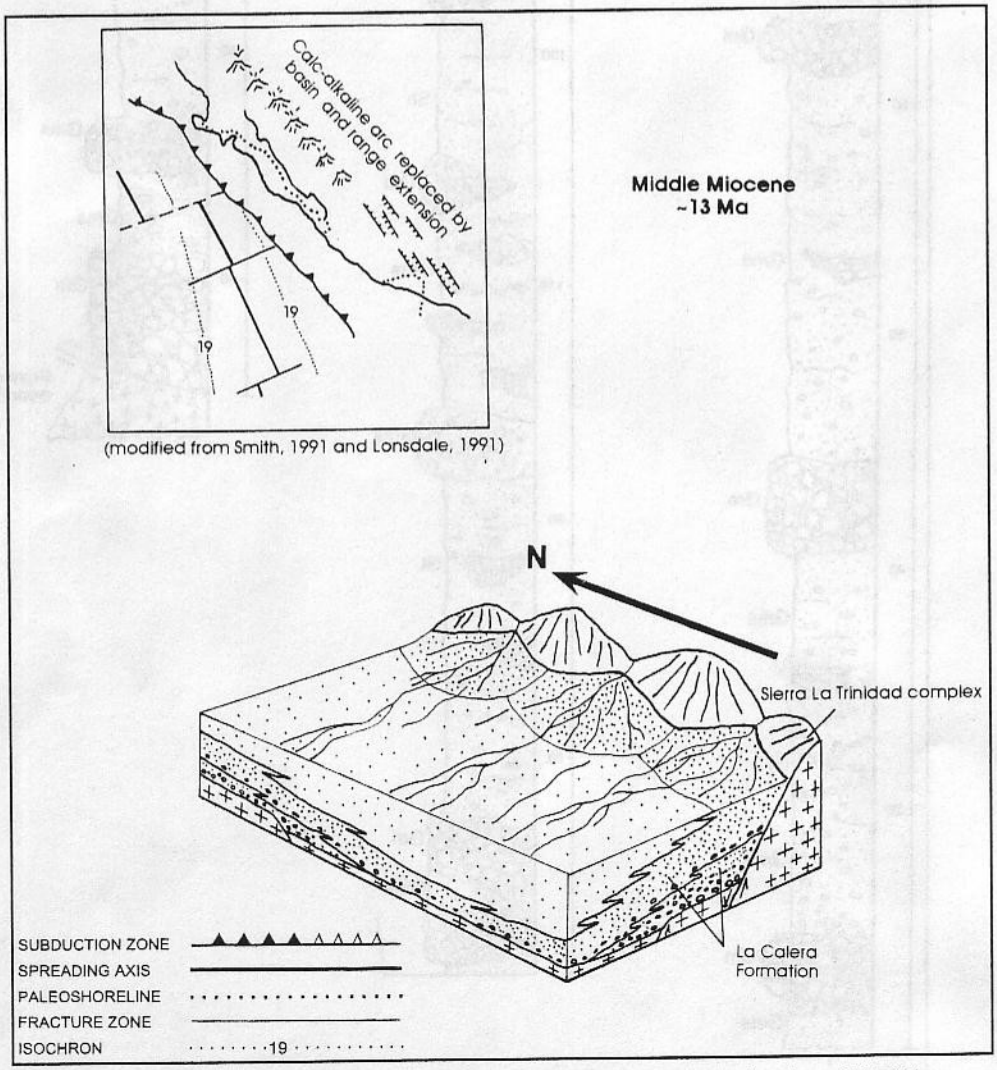

Figure 19. Tectonic-depositional setting of the San José del Cabo Basin during the middle Miocene. A block faulting of the Cretaceous-Tertiary batholithic basement and the volcanic sequence produced the alluvial sedimentation within the basin.

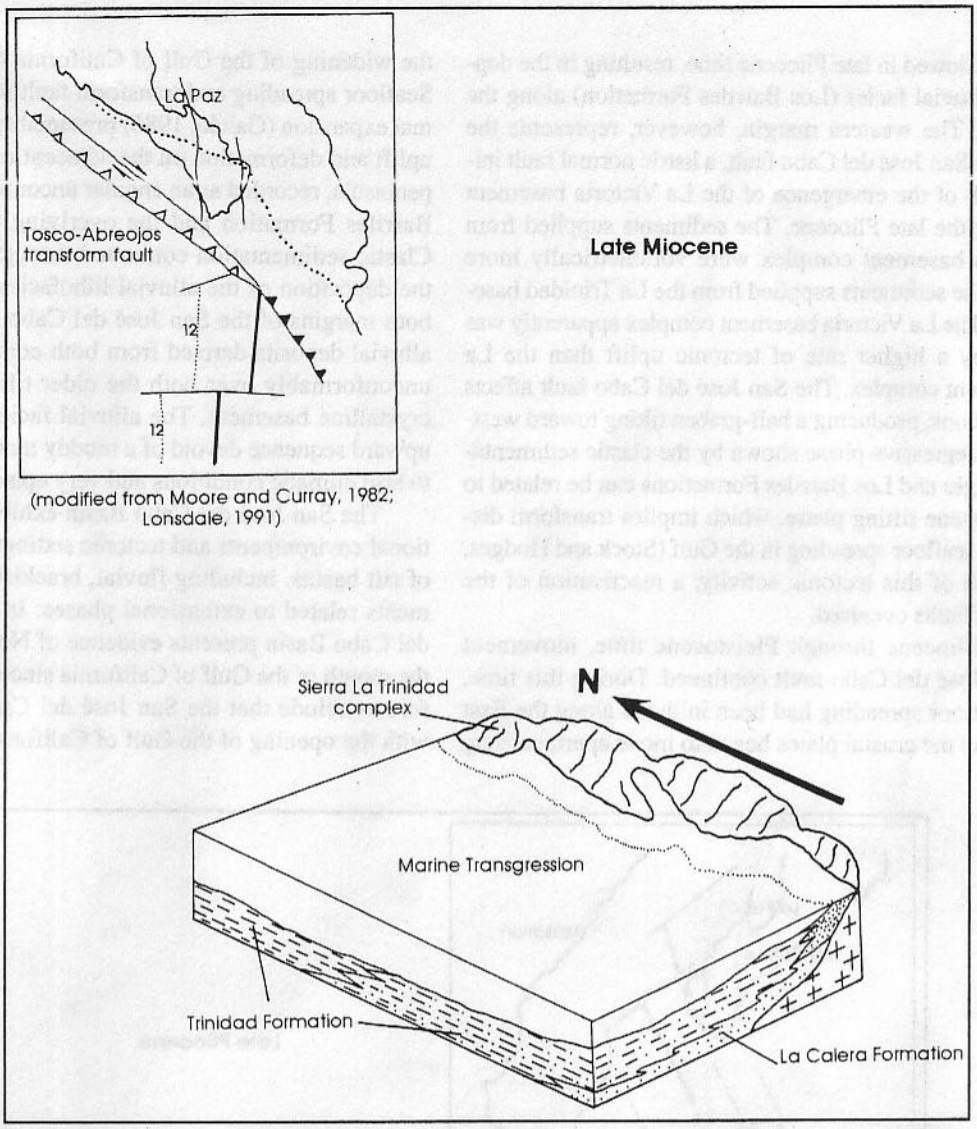

Figure 20. Tectonic-depositional setting during late Miocene time. A transgression occurs within the basin with the deposition of the Trinidad Formation. The transgressive phase is associated with a slip along basin-bounding faults. Key as on Figure 19.

nature of the Refugio Formation, which is only observable at the northern part of the basin; correlative strata in the southern part of the basin show evidence for deposition in a deeper water column (cerro La Laguna section).

Continued shoaling of the basin at the end of the late Pliocene, is evidenced by the shallow marine sandy facies of the Refugio Formation. This was perhaps due to tectonic uplift or a slowing subsidence at this time (i.e., the onset of deposition of the Los Barriles strata). The shoaling of the basin is recorded by the shallow marine sandy facies of the RF (Fig. 11). The shallow marine-lagoonal facies of the upper part of the RF that accumulated in the San José del Cabo area also suggests that a relative sea-level fall and/or tectonic uplift occurred. Paleocurrent data from the upper part of the RF indicate a general southward transport.

The transgressive and regressive phases that occurred within the basin do not coincide with the global sea-level curve (Haq et al., 1988). Therefore, we can assume that deposition within the basin was controlled by tectonism, presumably Miocene-Quaternary extension associated with rifting of the Gulf of California.

By late Pliocene time probably two tectonostratigraphic events occurred: (1) a continuation of the regressive phase that is represented by the change of the shallow marine deposits of the Refugio Formation to the terrestrial deposition of the Los Barriles Formation and (2) the continuation of uplift of the La Victoria and La Trinidad complexes that supplied sediments for deposition of the Los Barriles Formation. Both events apparently contributed to basin shoaling, marking the final phase of the marine sedimentation and heralding the onset of a terrestrial depositional environment on both sides of the basin (Fig. 21). Reactivation of the La

Trinidad fault followed in late Pliocene time, resulting in the deposition of the alluvial facies (Los Barriles Formation) along the eastern margin. The western margin, however, represents the formation of the San José del Cabo fault, a listric normal fault initiated as a result of the emergence of the La Victoria basement complex during the late Pliocene. The sediments supplied from the La Victoria basement complex were volumetrically more important than the sediments supplied from the La Trinidad basement complex. The La Victoria basement complex apparently was characterized by a higher rate of tectonic uplift than the La Trinidad basement complex. The San José del Cabo fault affects the older formations, producing a half-graben tilting toward west-southwest. The regressive phase shown by the clastic sedimentation of the Refugio and Los Barriles Formations can be related to the second Neogene rifting phase, which implies transform displacements and seafloor spreading in the Gulf (Stock and Hodges, 1989). As result of this tectonic activity, a reactivation of the basin-bounding faults occurred.

By latest Pliocene through Pleistocene time, movement along the San José del Cabo fault continued. During this time, continuous seafloor spreading had been initiated along the East Pacific Rise, and the crustal plates began to move apart, causing the widening of the Gulf of California (Lyle and Ness, 1991). Seafloor spreading and transform faulting associated with thermal expansion (Gaitán, 1986) presumably contributed to vertical uplift and deformation on the adjacent margins of the tip of the peninsula, recorded as an angular unconformity between the Los Barriles Formation and the overlying El Chorro Formation. Clastic sedimentation continued through the Pleistocene with the deposition of the alluvial lithofacies of the ECF alongside both margins of the San José del Cabo Basin (Fig. 22). These alluvial deposits derived from both complexes were deposited unconformably over both the older tilted formations and the crystalline basement. The alluvial facies shows a coarsening-upward sequence devoid of a muddy matrix, perhaps a response to arid climatic conditions and very episodic rainfall.

The San José del Cabo Basin exhibits a variety of depositional environments and tectonic settings that are characteristic of rift basins, including fluvial, brackish, and marine environments related to extensional phases. In addition, the San José del Cabo Basin presents evidence of Neogene plate motions at the mouth of the Gulf of California since ~12 Ma; we can therefore conclude that the San José del Cabo Basin is associated with the opening of the Gulf of California.

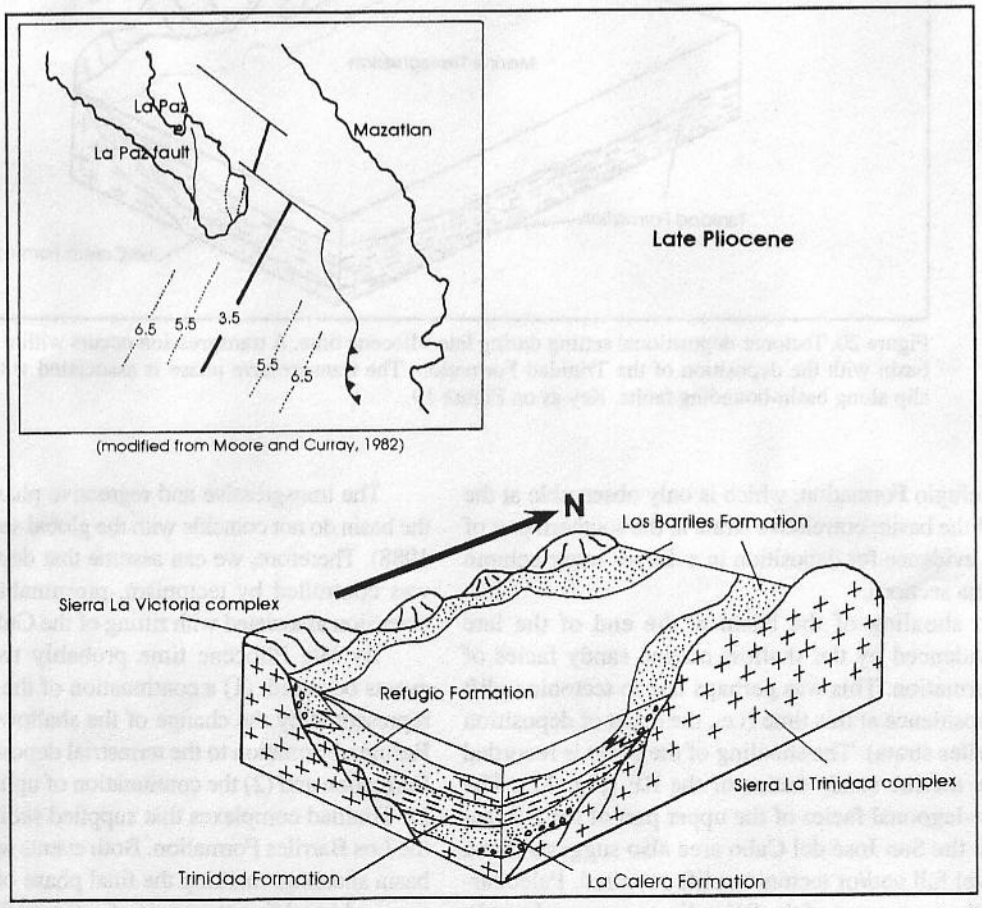

Figure 21. Tectonic-depositional setting during the Pliocene. A regressive phase began as a result of reactivation of the basin-bounding faults. The terrestrial sedimentation is represented by the Los Barriles Formation. Key as on Figure 19.

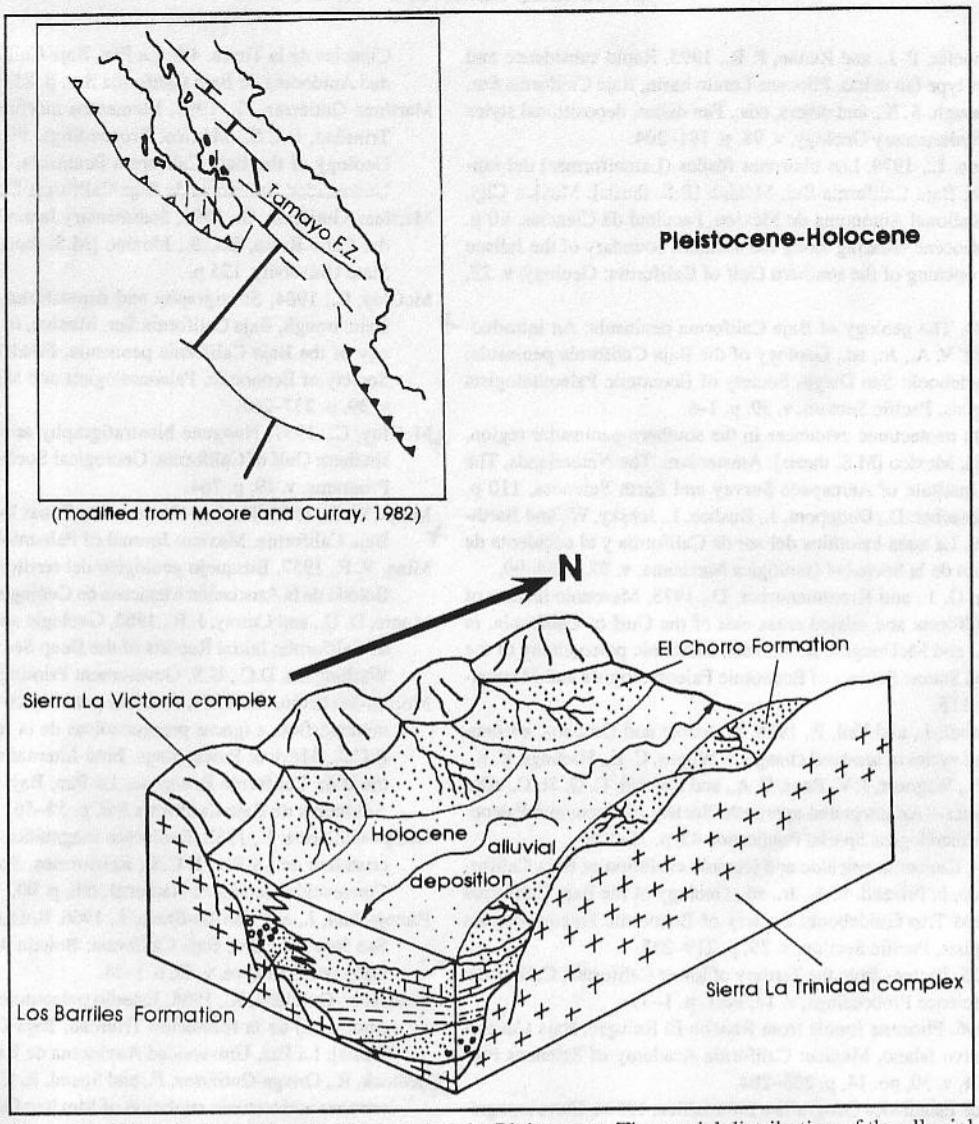

Figure 22. Tectonic-depositional setting during the Pleistocene. The spatial distribution of the alluvial units within the basin is like that of the present time. Key as on Figure 19.

In contrast to some other rift basins along the Gulf of California (e.g., Loreto basin and Santa Rosalia basin), the San José del Cabo Basin did not accumulate any volcanoclastic deposits (see Dorsey et al., 1995; Umhoefer et al., 1994). Moreover, the basin presents some sedimentologic and tectonic features that can be correlated with other Neogene basins along the Gulf of California, showing that they were formed by at least one late Miocene to Recent extensional phase (Stock and Hodges, 1989) that took place during the formation of the Gulf of California.

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