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SEDIMENTOLOGY AND STRATIGRAPHY OF THE UPPER MIOCENE EL BOLEO FORMATION, SANTA ROSALÍA, BAJA CALIFORNIA, MEXICO

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ABSTRACT

The transtensional Upper Miocene Santa Rosalía basin, located in the east-central part of the Baja California Peninsula, consists of almost 500 m of non-marine to marine sedimentary deposits, and interbedded tuffaceous beds. The Santa Rosalía basin is a NW-SE elongated fault-bounded depocenter that records the sedimentation from Upper Miocene to Pleistocene time. The sequence is divided in El Boleo, La Gloria, Infierno and Santa Rosalía Formations. The lower most stratigraphic unit is the El Boleo Formation, a 200 to 300 m thick section composed in its lower part by a 1 to 5 m thick basal limestone and gypsum bodies followed by 170 to 300 m of clastic coarsening upward fan-delta, marine and nonmarine deposits. The upper clastic part of the El Boleo Formation show intraformational unconformities, synsedimentary folds and faults, and unidirectional sedimentary structures. These occur in at least three well organized upward coarsening cycles (90-100 m thick). Each cycle represents a prograding fan-delta deposit formed probably as consequence of large and repeated vertical movements of the basin floor with respect to the source areas. This activity is related to the early stage of the opening of the Gulf of California. Each cycle started with the deposition of a unit composed by laminar fine-grained sediments accumulated in an extensive area covered by shallow standing fresh water with periodic introduction of subaqueous debris flows. Each fine unit hosts Cu-Co-Zn ore bodies in the Santa Rosalía mining district. Lateral and vertical facies changes are present in each depositional cycle, involving proximal coarse sandstone and conglomerates through fine sandstone characterized by planar and low angle cross bedding, alternating with siltstone and mudstone with ripple lamination. Early, during the formation of the Santa Rosalía basin, two ancient depocenters located north-northwest and south-southeast of the basin were developed. These depocenters were filled by sediments during the first cycle, and were separated by a ridge formed by the volcanic rocks of the Comondú Formation.

Keywords: Sedimentology, Stratigraphy, Upper Miocene, El Boleo Formation, Santa Rosalía, Baja California, Mexico

RESUMEN

La cuenca de Santa Rosalía se localiza en la parte centro-este de Baja California, alargada en dirección NW-SE y limitada por fallas, las cuales estuvieron activas desde el Mioceno Tardío hasta el Pleistoceno. La cuenca de Santa Rosalía se desarrolló en un ambiente de esfuerzos transtensionales y fue rellenada por casi 500 m de depósitos marinos y no marinos, con capas de tobas interestratificadas en su parte inferior. La secuencia está dividida de abajo hacia arriba en las Formaciones El Boleo, La Gloria, Infierno y Santa Rosalía. La Formación El Boleo tiene un espesor entre 200 y 300 m, y es dominada en su parte inferior por sedimentos marinos transgresivos y cuerpos evaporíticos seguidos por sedimentos clásticos en su gran mayoría no marinos con texturas progradacionales, características de un ambiente fluvio-deltáico cercano a una línea de costa. Esta secuencia clástica alcanza espesores entre 170 y 300 m, y presenta al menos tres ciclos de sedimentación bien organizados, con depósitos de grano grueso hacia la cima, con espesores entre 90 y 100 metros. Cada ciclo representa una secuencia progradacional producida probablemente por las repetidas etapas de subsidencia del piso de la cuenca de Santa Rosalía durante el inicio de la apertura del

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Golfo de California. Cada ciclo inicia con la depositación de sedimentos finos laminares en cuencas extensas con introducción periódica de flujos subacuosos de detritos. Las facies finas de cada ciclo hospedan los cuerpos estratiformes de Cu-Co-Zn del distrito minero de Santa Rosalía. Cambios de facies, tanto laterales como verticales, están presentes en cada ciclo, variando de conglomerados y areniscas de grano grueso en facies próximas a areniscas de grano fino, caracterizadas por estratificación cruzada de bajo ángulo y estratificación planar, alternando con limolitas y lodolitas finamente laminadas en facies distales. Al inicio de la formación de la cuenca de Santa Rosalía, se desarrollaron dos depocentros antiguos localizados al norte-noroeste y al sur-sureste de la cuenca; estos depocentros fueron rellenados por sedimentos correspondientes al primer ciclo deposicional y estuvieron separados por un alto topográfico formado por las rocas volcánicas de la Formación Comondú.

Palabras clave: Sedimentología, Estratigrafía, Mioceno Superior, Formación El Boleo, Santa Rosalía, Baja California, México

INTRODUCTION

The Gulf of California was formed during Late Miocene time, when Baja California rifted from mainland Mexico along the Gulf of California transform-rift. Structural and tectonic details of the opening of the Gulf of California have been described in different models (Hamilton, 1961; Atwater, 1970; Karig and Jensky, 1972; Dickinson and Snyder, 1979; Spencer and Normark, 1979; Mammerickx and Klitgord, 1982; Stock and Hodges, 1989; Lonsdale, 1989, among others). Volcanism associated to the eastward subduction of the Farallon Plate beneath western North America, and the geochemistry of the volcanic products, has been documented in eastern Baja California and western Sonora (Gastil *et al*., 1979; Sawlan and Smith, 1984; Dorsey and Burns, 1994; Sawlan 1991), and volcanism associated with the opening of the Gulf of California present in Baja California, western Sonora and Sinaloa has been mentioned by Gastil and collaborators (1979), and Batiza (1978).

In The Santa Rosalía basin, N-S striking normal faults and NNW-SSE to NW-SE dextral-slip and oblique faults have been recognized in the younger sediments, and have been related to a clockwise rotation of the direction of extension from NE-SW to E-W associated to San Andreas strike-slip motion (Angelier *et al*., 1981).

During the opening of the Gulf of California, the east-central side of Baja California Peninsula was affected by Late Miocene to Plio-Quaternary NE-SW to ENE-WSW extension followed by E-W to ESE-WNW extension (Angelier *et al*., 1981; Stock and Hodges, 1989; Zanchi, 1994). Both movements reactivated old NNW-SSE faults in large parts of this area. This extensional regime was responsible for the tilting of large blocks, and the formation of large and deep individual basins. Some of these basins have been studied in detail, including the Santa Rosalía basin (Wilson, 1948; Wilson and Rocha, 1955), the Ánimas and Los Ángeles basins (Gastil *et al*., 1975), the Laguna Salada basin (Axen and Fletcher, 1998; Walker, 1989), and the Loreto basin (Zanchi, 1994; Umhoefer and Stone, 1994; Umhoefer and Stone, 1996). All of these basins are located along the western Gulf side, and aligned along NNW-SSE faults.

Our work is concentrated in the Santa Rosalía basin, with emphasis on the sedimentological and tectonic history to constrain the early evolution of the Gulf of California. In this work, we report new information from detailed stratigraphic studies of 65 drill cores, and several measured stratigraphic sections and geochemical data from the El Boleo Formation, which contains a well preserved sedimentary section and ore deposits formed during the early rifting of the Gulf. This paper focus on the facies architecture of the El Boleo Formation, which proved new insight on basin subsidence and sedimentation in the early Gulf of California rifting.

GEOLOGICAL SETTING

The Santa Rosalía basin is bounded to the north-northwest by the Plio-Quaternary volcanic field of Tres Vírgenes and La Reforma Caldera, to the west-southwest by the Mid-Miocene Comondú volcanic rocks that make up the Sierra Santa Lucía, and to the east by the Gulf of California (Figure 1).

The oldest rock in the Santa Rosalía area is a biotite quartz-monzonite dated at ca. 91 Ma (Schmidt, 1975) (Figure 1). It corresponds to the southeastern continuation of the Cretaceous Peninsular Ranges Batholith (Gastil, 1983; Silver and Chappel, 1988; Silver *et al*., 1969), and crops out on the Las Palmas creek and La Reforma caldera, 15 and 35 km north and northwest from the Santa Rosalía basin, respectively. Locally, the sedimentary fill of the Santa Rosalía basin unconformably overlies volcanic rocks of the Comondú volcanic rocks, which consist of more than 1 km thick subaerial andesitic and basaltic flows, tuff, breccia, agglomerate, and tuffaceous sandstone dated between 24 and 11 Ma (Sawlan and Smith, 1984). These rocks define a medium-K calc-alkaline suite typical of active continental margins (Sawlan and Smith, 1984). The Comondú volcanic rocks lie in erosional discordance on the biotite quartz-monzonite basement. In the Las Palmas creek, there is a 2-3 m thick weathered zone at the contact, formed by sub-angular, coarse-grained to pebble-sized biotite quartz-monzonite conglomerate, overlain by a reddish colored, medium-grained, moderately sorted sandstone with cross bedding. Similar

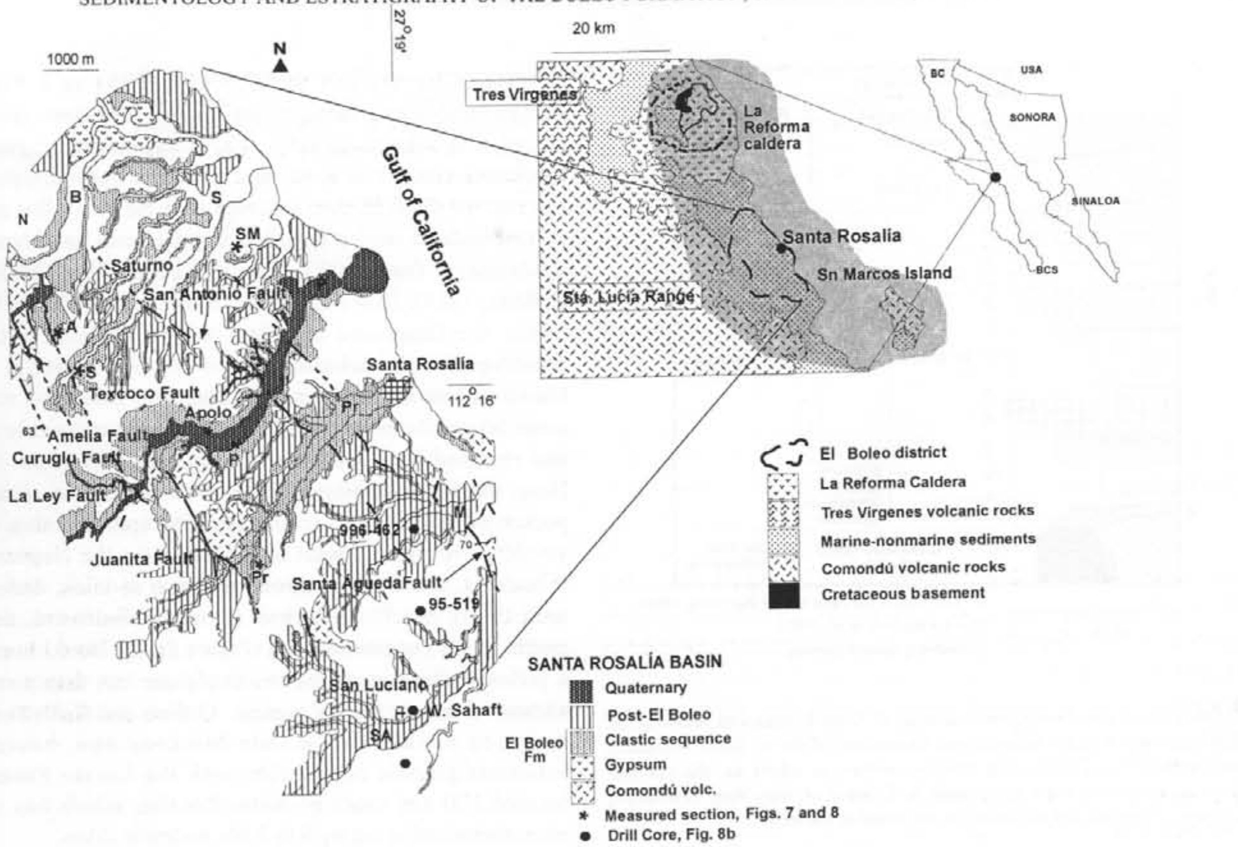

Figure 1. Simplified geological map after Wilson and Rocha (1955), showing the main rock types in the Santa Rosalia basin and the major structures in the mining district. B = El Boleo, N = Neptuno, A= Amelia, S = Soledad, SM = Santa Martha, P = Purgatorio, Pr = Providencia, M = Montado, SA = Santa Águeda. Insert shows the location of the Santa Rosalía mining district and a regional geologic setting. Abreviations are: BC = Baja California, BCS = Baja California Sur.

fluvial sandstone rest above the crystalline basement in the Loreto area (Gastil *et al.*, 1979).

In the Santa Rosalia area, one kilometer west of the mouth of the Purgatorio creek (Figure 1), a 0.5 to 1.0 m thick, white ash and pumice tuff, composed by 1 cm angular pumice fragments and lesser amounts of angular Comondú Formation clasts in an ashy matrix rest unconformably on the Comondú volcanic rocks (Figure 2). The origin of this tuff is unknown, but its chemical composition and petrographic characteristics are different from those of the typical Comondú Formation volcanic rocks. Recently this unit have been dated with ages ranging from 9.96 to 7.91 Ma (Conly, 1999).

From Upper Miocene and continuing into Pliocene, the Santa Rosalía basin began to subside rapidly and to accumulate detritus from adjacent uplifted blocks of the Comondú volcanics. The El Boleo Formation is a 250-350 m thick unit that consists mostly of sandstone, siltstone and conglomerate, and minor limestone and gypsum beds in its lower part (Figure 2).

Continued subsidence of the Santa Rosalía basin permitted periodic incursions of seawater into the basin, with the consequent deposition of the La Gloria, Infierno and Santa Rosalía Formations (Figure 2). The La Gloria Formation unconformably overlies the El Boleo Formation, and it is best exposed along the coast and in local areas, where it unconformably overlies the Comondú volcanic rocks. The age of the La Gloria Formation is Early to middle Pliocene (Ortlieb and Colletta, 1984). The La Gloria Formation has a maximum thickness of 60 m along the coastal area, and it thins and pinches out inland. It grades inland from shallow marine fossiliferous clastic rocks to non-marine conglomerates and sandstones that locally rest on a basal conglomerate (Wilson and Rocha, 1955) (Figure 2).

The La Gloria Formation is unconformably overlain by the 20-30 m thick Upper Pliocene Infierno Formation (Wilson, 1948), which consists of fossiliferous marine sandstone grading southwestward to continental conglomerate. The geographic distribution of this unit is the same as the La Gloria Formation. On the basis of fossil evidence, Ortlieb and Colletta (1984) determined that the deposition of Infierno Formation could be as young as early Pleistocene (Figure 2).

The Infierno Formation (Figure 2), is unconformably overlain by the Pleistocene Santa Rosalía Formation (Wilson, 1948). The Santa Rosalía Formation is 10-15 m thick, and consists mostly of calcareous fossiliferous conglomerate. Ortlieb and Colletta (1984) described this formation as a Pleistocene marine terrace, consisting of fossiliferous sandstone and non marine conglomerate, grading to continental breccia and conglomerate landward.

The continental and marine stratigraphic sequence that fills the Santa Rosalía basin records at least five episodes of

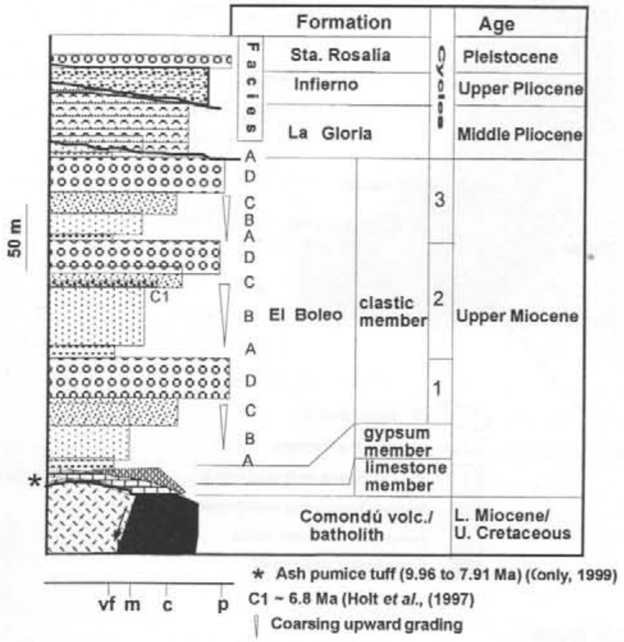

Figure 2. Generalized stratigraphic column of Santa Rosalía area, showing the three members (Clastic, Gypsum and Limestone) of the El Boleo Formation and various facies within the clastic member, as where as the cyclical division. Grain-size scale abbreviated as follows: vf- very fine, m-medium, c-coarse, p- pebbles (all the facies are described in the text).

seawater incursions from Upper Miocene (El Boleo Formation) to recent (marine terraces of Santa Rosalía Formation). At least early during the formation of the Santa Rosalía basin, the clasts of the El Boleo Formation were derived from the Comondú volcanic rocks, from a source located west of the basin.

STRATIGRAPHY OF THE EL BOLEO FORMATION

The El Boleo Formation in the Santa Rosalía basin was described in some detail by Wilson and Rocha (1955). They recognized the conglomerate beds that underlie the ore bodies in the mining district, and considered the fine and coarse units respectively above and below the conglomerates as tuffaceous sandstone. In this paper, we propose that the El Boleo Formation consists of three informal members, from the base to top: the limestone, gypsum, and clastic members (Figure 2).

LIMESTONE MEMBER

The lowermost member of the El Boleo Formation consists of an extensive, thinly bedded, reddish-gray marine, in places fossiliferous, limestone resting unconformably on an irregular rugged, weathered surface developed on the Comondú volcanic rocks. However, in some places west of El Boleo creek (Figure 1), this unit rests above a talus conglomerate composed of volcanic debris. Locally, the lower member crops out as crusts with almost vertical dips above the Comondú volcanic rocks (Figure 3). This unit was initially described by Wilson and Rocha (1955) as a Pliocene manganiferous and ferrugineous impure limestone grading in places into calcareous tuffs. The basal limestone ranges in thickness from 1 to 6 m, and becomes less fossiliferous towards the Gulf. In most outcrops near the coast, this member corresponds to brown calcareous, tuffaceous sandstone with unidentified fossils (Wilson and Rocha 1955; Ortlieb and Colletta, 1984). However, west-northwest of the Santa Rosalía basin, the limestone is a dark-brown coquina with well preserved fossils including pecten and oysters set in a dark brown calcareous sandy matrix. There are small and scattered areas where the basal limestone has been pervasively altered and replaced by silica (jasper), iron, and manganese oxides. Here, the basal limestone contains incomplete to completely preserved fossils, and is cross-cut by sporadic thin calcite veinlets. North-northwest of the basin, in the Neptuno area (Figure 1), the basal limestone is 1 to 6 m thick, dark-brown with thinly interbedded chert horizons. Gulfward, near the mouth of the Purgatorio creek (Figure 1), the basal limestone is a yellow tuffaceous calcareous sandstone less than 1 m thick, without apparent fossils content. Ortlieb and Colletta (1984) assigned to this unit a Late Miocene age, based on a lithostratigraphic correlation with the Loreto Formation, located 100 km south of Santa Rosalía, which has similar microfauna and is cut by 6 to 7 Ma andesitic dikes.

GYPSUM MEMBER

The gypsum member in the Santa Rosalía basin range in thickness from a few meters to more than 60 m. The gypsum member is composed of white, reddish and gray colored massive to distinctly banded gypsum beds. This member forms extensive blankets that overly both the basal marine limestone and Comondú volcanic rocks. The gypsum beds are interbedded with thin horizons of clastic material and locally contain small stains of iron oxides. The size and shape of these bodies is variable and range from large horizontal and extensive beds (hundreds meters size) to small mounds (tenths of meters size), which wedge out rapidly as seen in the Montado-Santa Águeda creek, southeast of Santa Rosalía, El Boleo creek and Neptuno area.

The distribution and extent of the stratified gypsum atop the Comondú volcanic rocks and basal limestone in the Santa Rosalía basin suggest that it was deposited in isolated, partially closed basins during a marine transgressive event.

CLASTIC MEMBER

Detailed stratigraphic studies of the clastic member of the El Boleo Formation show a wide variety of lateral and vertical facies changes, local unconformities, synsedimentary faults, sedimentary structures, and local eastward unidirectional transport direction structures. This clastic section can be subdivided in five distinctive lithofacies, which

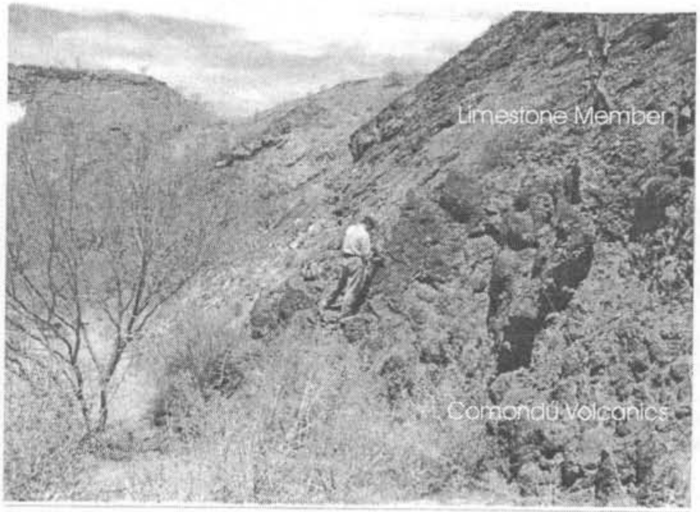

Figure 3. Steeply dipping crust of basal limestone overlying the tilted Comondú Volcanic rocks in the west side of the basin along the El Boleo creek.

correspond to distinct fan-delta deposits of a series of progradational episodes occurred in an alluvial system in response to periods of basin floor subsidence (Figure 2). The lithofacies nomenclature for the progradational clastic sequence in the El Boleo clastic member follows the Miall's code system (1978) (Table 1).

Facies A

Facies A occurs above facies D in the west part of the Santa Rosalía basin and on facies B and C gulfward. In the lower part of the sequence, facies A is consistently formed by undisturbed and unfossiliferous beds of 0.25 to 0.50 m thick, internally laminated calcareous mudstone. This calcareous mudstone is partially overlain by 1 to 20 m light red, laminated claystone-siltstone. Distinctively, the laminated claystone-siltstone interval is partially to totally brecciated, with angular clasts, 1 to 5 cm in diameter, chaotically rotated, in a matrix lithologically identical to the clasts (Figure 4a). Small dark angular grains of organic carbonaceous material are erratically distributed in the matrix and in the breccia clasts. Wilson and Rocha (1955) identified carbonized plants and petrified wood, partially replaced by chalcocite in facies A (they named this facies as *manto 3*), and reported a low proportion of organic carbon in five samples (averaging 0.2%). Volcanic glass shards are present in the matrix and in the breccia clasts. The upper contact of the breccia zone within the claystone-siltstone interval is irregular and sharp in the west part of the Santa Rosalía basin, and increasingly gradational toward the Gulf of California.

Facies A ranges in thickness from 0.6 to 3 m in the upper cycle of the El Boleo Formation. In the western Santa Rosalía basin, this facies frequently is a 1 m thick, internally laminated, non-calcareous, light colored tuffaceous mudstone horizon near its base. Immediately above, there is a 2.5 m thick, monomictic breccia, formed by angular sandstone-siltstone clasts in a matrix with the same composition as the fragments (Figure 4b). In some places, this breccia is pervasively altered to clay and contains abundant jasper accompanied by iron and manganese oxides. To the south-southeast of the basin, in Santa Águeda and Montado area, this facies was not found. Gulfward, this facies presents a 7-8 cm thick gypsum bed. Immediately above, there are 0.8 m thick dark tuffaceous-sandy beds with large penetrative spots of manganese oxides (Figure 4c). The presence of carbonized material, together with laminated character of facies A (claystone-siltstone), with a thin calcareous mudstone at its base, and interbedded sandstone and siltstone horizons, indicate accumulation under reducing conditions in a standing water body, likely shallow lakes. These strata are coeval with ash falls in the basin, which produced tuffaceous deposits.

Facies B

Facies B range in thickness from 20 to 70 m (Figure 2). This facies consists of predominantly light red, subangular to subrounded, sandstone and siltstone, containing one or more of the following sedimentary structures: crudely inverse grading, ripple cross lamination, horizontal to sub-horizontal lamination, planar low-angle cross lamination, and massive structureless bedding (Figure 5a). The low-angle cross bedded sets are less than 5 cm thick, and are discordant and cut by thin planar stratification. Frequently, this facies contains lenticular bodies up to 1m thick and a few meters long of coarse-grained sandstone. Toward the Gulf, facies B becomes richer in thinly-bedded shale, which appears as horizons less than 1 m thick. Compositionally, the sandstone grains consists of broken crystals of feldspar (40 %), hornblende (< 2%), biotite (< 2%), opaque minerals (< 0.5 %) and volcanic grains (< 20 %) set in 15% matrix.

Facies B frequently overlies the Comondú volcanic rocks western of the basin, and facies A near the coast. The internal sedimentary structures of this facies, the alternance of thinly bedded fine-grained sandstone-siltstone-mudstone and their extensive lateral distribution, suggest that this facies was deposited into a subaqueous lower fan-delta flood basin environment.

Facies C

Facies C in the El Boleo clastic member ranges in thickness from 20 to 30 m (Figures 2 and 5b). This facies is composed of fine to medium-grained poorly sorted, gray-purple sandstone. Facies C contains 1-2 m thick interbedded lenticular bodies of pebble-cobble conglomerate in its lower part. Clasts are subrounded and poorly sorted and derived from the Comondú volcanic rocks. These conglomeratic bodies are more frequent toward the upper part of Facies C. Sedimentary structures in this facies include: low-angle cross stratification,

Table 1. Summary of lithofacies in the clastic sequence of the El Boleo Formation.

Facies	Miall Facies*	Description	Interpretation
D	Gh, Gm, Gt	Disorganized, moderately sorted pebble-cobble conglomerate: imbrications, partially clast supported, horizontal bedding	Waning-stage channels, gravelly bride stream, longitudinal bars
C1	—	Well sorted, rounded grains, poor matrix, low cross bedding	Channelized high energy, and intertidal deposits
C low cross bedding, fine-coarse	St, Sm shallow braided channels	Coarsing upward grading, sandstone, scour channels, roots	Waning-flood deposit,
B	Sr, Sh	Finely stratified, fine sandstone to siltstone with lamination, planar and low cross bedding. Ripples	Waning-state channels and interchannels deposits
A	F1	Fine laminar, tuffaceous clay-siltstone	Lacustrine or waning flood deposits

structureless beds, scoured channels, trough cross strata, coarsening-upward grading beds, dewatering structures, hummocky cross stratification, and 1 to 3 cm long white irregular tubes, randomly distributed in the upper part of this Facies. Facies C lies unconformably above the basal limestone in the western part of the basin and overlies Facies C1 in the center of the Santa Rosalía basin. Westward, in the center part of the Santa Rosalía basin, there are thin horizons of this facies interbedded toward the base of facies D, indicating a gradual transition between these two facies. The overall geometry of facies C is lenticular, pinching out gulfward. Westward this facies contains local intercalations of lenticular, laminated, brown-reddish sandstone with scattered pebbles of volcanic rocks derived from the Comondú sequence. Petrographically, is composed of plagioclase and feldspar (> 40%), and angular, poorly sorted clasts of andesite and basaltic-andesite (< 20%) and minor but conspicuous pumice sand grains (4 to 6%), and between 15 % of matrix. Based on its physical characteristics such as structureless, poorly sorted, angular, fine to coarse sandstone beds with planar cross beds, and interbedded pebbly conglomerate in small channels, Facies C is interpreted as waning-flood deposits in shallow braided channels.

Facies C1(marker bed)

Facies C1 consists of a 2 to 3 m thick of dark reddish, well sorted and rounded, coarse pebbly sandstone with low-angle cross bedding, planar cross bedding, and local bioturbation (Figure 5c). This facies is known in the district as *Cinta Colorada*, and lies unconformably above facies B and underlies facies C, but laterally grades into facies C. At its base it contains scoured channel fills of pebble-cobble clasts, and commonly has interbedded lenses 25 to 35 cm long and 3 cm thick consisting of subangular, poorly sorted, granule-pebble conglomerate. This facies crops out in the west-central part of the Santa Rosalía basin and wedges out gulfward. Petrographically, this facies consists of well rounded, fine-grained volcanic detritus (more than 90%) coated with a thin layer of hematite, with less than 2% of diagenetic matrix composed mainly of clay minerals. The restricted distribution of Facies C1 together with its internal structures, suggest that this could correspond to a subaqueous-subaereal channelized high energy deposit. The low angle cross bedding, well sorting and rounded grains seem correspond to intertidal sand bars, possibly as a result of a rapid incursion of seawater.

Facies D

Facies D occurs three times within the clastic member (Figure 2). It is a 20 to 40 m thick disorganized, partially clast-supported, cobble-boulder conglomerate (Figures 5b and 5d). The clasts are predominantly derived from the Comondú volcanic rocks, and no lithological distinction can be made among them. Clast sizes range from a few cm to 0.5 m diameter. The conglomerate has channelled bases and is most often apparently massive or shows low angle cross-stratification. It also shows primary sedimentary structures,

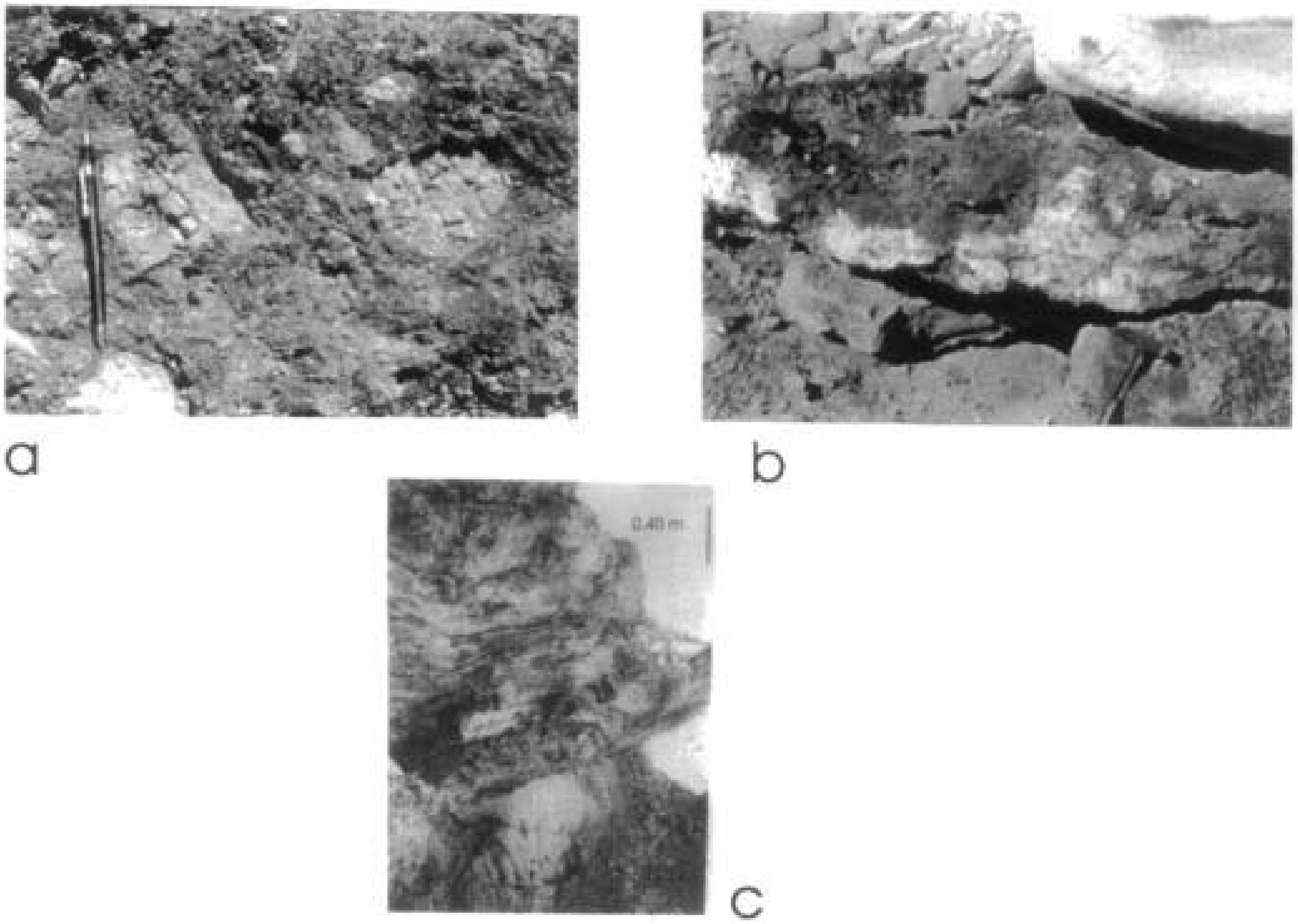

Figure 4. a) Facies A, showing the monomictic breccia in the upper claystone-siltstone interval, with angular clasts in a matrix of the same composition. The pencil is 15 cm long. b) Facies A in the upper part of the clastic sequence on the west side of the Santa Rosalía basin, showing the breccia texture with high penetration of silica, manganese and iron oxides on Purgatorio Creek. c) Facies A near the coast, with the gypsum and laminar sandstone-siltstone beds in the bottom, and dark dusty sandstone in the upper part.

indication of textural trends are almost absent. Sporadic imbricated clasts indicate provenance from the west, and a crude fining upward grading. Lenses of gray-purple, pebble sandstone of facies B are regularly interbedded, giving it a better stratification. These horizons are more frequent toward the top of the stratigraphic column in cycles 2 and 3of facies D (Figures 2 and 5b). This unit has a sharp flattened lower contact with facies C, observed in the center and the western side of the Santa Rosalía basin. In areas closer to the coast, Facies D overlies Facies B, and pinch out toward the Gulf. The distinctive poor organization, lenses of pebbly sandstone with a crude cross stratification, sporadic imbrication, and broad distribution, suggest scour channel filled by longitudinal high-energy gravel bar deposits in a braided streams system during floods (Miall, 1978).

DEPOSITIONAL SYSTEM

The basal limestone is best exposed in the west side of the Santa Rosalía basin, although isolated outcrops are also widespread in the east side of the basin, which have been uplifted by faults. To the north-northwest of the Santa Rosalía basin, in the Neptuno area, this unit is present and continue north-northwest to the Lucifer area, 12 km north of Santa Rosalía, where it partly forms the base of the Lucifer manganese ore deposit. The distribution and lithological characteristics of the basal limestone and gypsum lithofacies at the base of the El Boleo Formation indicate a first marine incursion during the early stage of the Santa Rosalía basin. The Late Miocene age of the basal limestone (Ortlieb and Colletta, 1984) and the age of ca. 7 Ma at the base of the clastic

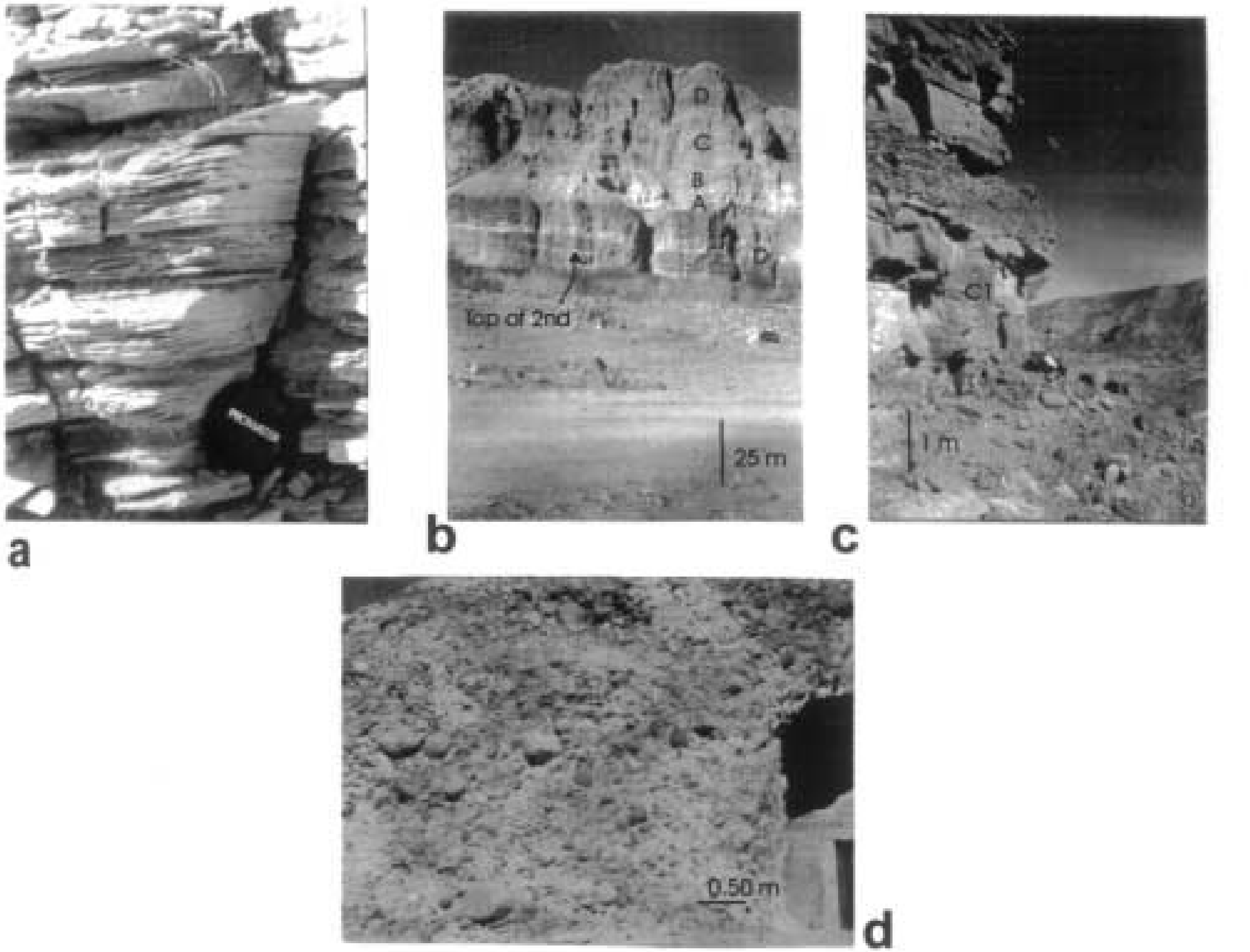

Figure 5. a) Close up of facies B, in the Purgatorio creek, showing ripple cross lamination and horizontal or subhorizontal lamination. b) Part of the clastic sequence of the El Boleo Formation, showing the conglomeratic facies D underlying the fine grained facies A and grading to coarse facies to the top from facies A to C, on the north side of Purgatorio creek. c) Facies C1, showing lenses of pebble conglomerate interbedded within well sorted, rounded conglomeratic sandstone. d) Facies D, showing disorganized, partially grain supported, poorly sorted, cobble-boulder conglomerate, with sporadic imbricated structures.

sequence above the limestone (Holt et al., 1997) suggest a rapid and extensive marine transgression prior to deposition of the Upper part of the El Boleo Formation. The basal limestone, in the west side of the Santa Rosalía basin, overlies the basement paleo-relief with original mainly high-angle to vertical dips (Figure 3). Wilson (1948) interpreted this position due to steep initial topography, where organisms were adhered to the slopes of the volcanic rocks as they were engulfed by the sea. In the same way, Chorowicz and Lyberis (1984) compared the deposition of crusty limestone in the Suez Gulf and Gulf of California, and suggested that the almost vertical dips of the basal limestone in both cases, correspond to a submarine crust deposited on steep slopes contemporaneous to rifting.

Gypsum beds were deposited in two different areas within the Santa Rosalía basin (Wilson and Rocha, 1955). One area is located south-southeast of Santa Rosalía, in the vicinity of the Montado and Santa Águeda creeks (Figure 1). Another area is located 5-7 km north-northeast of Santa Rosalía, where a series of opened folds crop out in the Soledad and El Boleo creeks. These small exposures continue north-northwest in the Neptuno area as gypsum mounds. Some of them are up to 15 meters high, aligned along a NE-SW direction, which suggests a control by faults. A third thick gypsum bed crops out 5 km southeast from Santa Rosalía, on San Marcos Island (see inset, Figure 1). The wide distribution of gypsum beds in the Santa Rosalía basin, suggests that it was deposited in partially closed extensive basins. The large positive values of $\delta^{34}S$ (+22.82 and +21.35‰) on two gypsum samples collected in the basin by Ortlieb and Colletta (1984), support the closed basin environment hypothesis.

to 3 from the base to the top (Figure 2). Each cycle consists of a 90 to 100 m thick coarsening upward sequence. Each cycle starts with the fine grained facies A, which hosts the Cu-Co-Zn ore bodies (*mantos*) in the district, and ends with the deposition of conglomerate of facies D (Figure 2). A fourth cycle is present in some parts west of Santa Rosalía basin, but it has been eroded and unconformably covered by the La Gloria Formation. The lowest part of the first cycle is not well exposed, although, in the west side of the basin close to the contact with the basal limestone (Figure 6), there is a complete early clastic sequence. The fine grained facies of the first cycle where is poorly exposed, and commonly replaced by manganese oxide and silica. The distribution of this fine facies is restricted and exposed mostly in contact with the Comondú volcanic rocks (Wilson and Rocha, 1955).

On the basis of lithofacies distribution and detailed studies on drill holes (Ochoa, 1998), two separate ancient depocenters elongated NW-SE and limited by faults can be distinguished (Figure 7). These depocenters were named north and south basins, and together form the large composite Santa Rosalía basin. The south basin has an area of ~12 km^2 and is located in the central-northwestern side of the Santa Rosalía basin, between Purgatorio and La Soledad creeks. South basin includes the facies A, B, C and D of the first cycle, and only facies A of the second cycle. All these facies indicate a single large fan-delta, which prograded to the east, with minor input of material from the Providencia creek area (Figure 8a). The ~10 km^2 south basin in the southeastern part of the Santa Rosalía, is deeper than north basin, and is almost completely covered by the La Gloria Formation. All facies descriptions in the south basin are from drill core studies. Mostly of the core studied were drilled in the center of the basin, cutting only the upper part of the sequence, and none of them reached the bottom of the basin. Ochoa (1998), described the upper part of the sequence that fill the south basin and included the facies B and C in the first cycle, and facies A of the bottom of second cycle. Recently, with more detailed drill core descriptions made out by geologists of Minera Curator in the south basin, indicate that the lithofacies described by Ochoa (1998) could correspond to facies B and C of the second cycle, and facies A to the bottom of third cycle (Escandón, personal communication), suggesting the presence of cycle 1 at the bottom of the south basin. The facies distribution and sedimentary structures in south basin indicate that sediments correspond to a separate large fan-delta, which prograded from an area south-southwest of Santa Águeda creek to the northeast (Figure 8b). Both basins were partially divided by a N-S striking ridge formed by the Comondú volcanic rocks, which was higher than the contiguous basins. We interpret this topographic high as a secondary *en échelon* structure, oblique to the main fault system oriented NW-SE.

The detailed studies, which are the basis of the stratigraphic sections in the Figures 6 and 9, and the paleogeographic reconstruction shown in Figure 7, supply

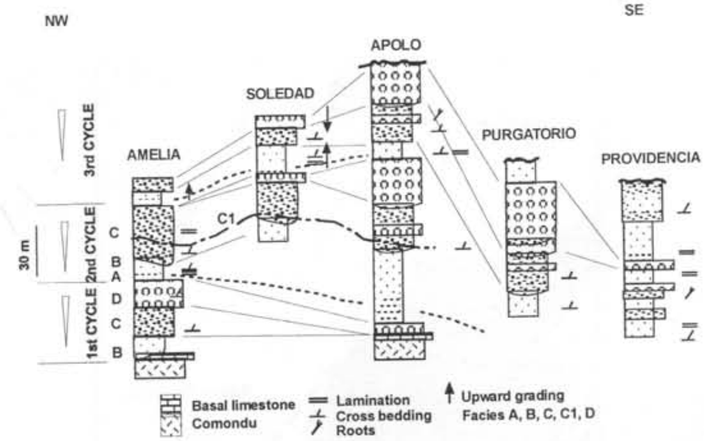

Figure 6. Stratigraphic columns in the west side of the Santa Rosalía basin. The different sections show the distribution of the distinct facies that conform the clastic member of the El Boleo Formation. Note the lateral distribution of all facies, and the position of facies A (ore bodies) atop facies D. The stratigraphic columns location is shown in Figure 1.

evidence for the facies distribution suggested in Figure 9. The figure depicts the earliest depositional cycle with a clear progradation to the northeast, with proximal gravelly braided-stream deposits (facies C and D), grading into distal interchannel flood plain deposits (facies B) in an early time during the development of the Santa Rosalía basin.

TECTONIC DEVELOPMENT OF THE SANTA ROSALÍA BASIN

Large N-S and NNW-SSE structures were outlined by Wilson and Rocha (1955) in the Santa Rosalía basin, and a kinematic analysis of these structures was carried out by Angelier and collaborators (1981), who determined that most faults in the Santa Rosalía basin are normal faults dipping to the west, with some dextral strike-slip component. In the same study, the authors found a consistent NW-SE pattern of faulting affecting rocks as old as Comondú volcanic rocks and as young as El Boleo, La Gloria and Infierno Formations, suggesting an E-W to ESE-WNW extension during Late Miocene to at least Pleistocene. Subsequent variation in the direction of extension was illustrated by Angelier and co-workers (1981), with a consistent E-W to ESE-WNW extension affecting Pliocene rocks of the La Gloria and Infierno Formations, and with a clear increase of strike-slip component relative to dip-slip movement. A similar kinematic analysis was carried out by Zanchi (1994) in the Loreto basin, with similar results. Zanchi (*op. cit.*), defined two important periods of deformation in the Loreto basin: 1) a Basin and Range extension, with consistent NW-SE trending system and a NE-SW extension related to the opening of the Protogulf of California (Late Miocene), and 2) a transtensional period with related E-W extension characterized by strike-slip faults and subordinated thrust faults together with dip-slip superposed on the Basin and Range pattern, with extension E-W related.

Since the Upper Miocene, the N-S, NW-SE faults were periodically reactivated (Angelier *et al.*, 1981). In the Santa

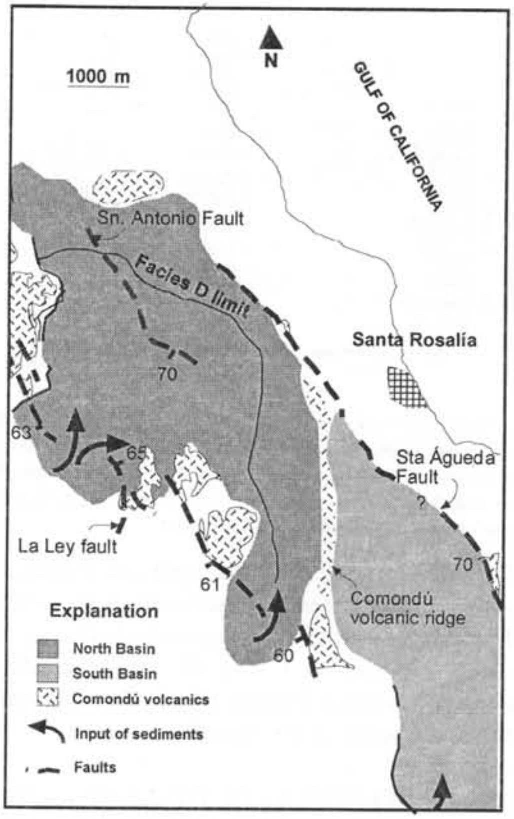

Figure 7. A simplified paleogeographic map before ~6.8 Ma by Holt and others (1997). Distinction of the south and north basins, limited by major structures.

Rosalía area, large and small blocks were slightly tilted to the east, acting as traps for the deposition of sediments coming from the west. The mean normal slip along most of the structures ranges between 40 and 60 m, with a maximum value exceeding 110 m along the Santa Águeda fault. All these faults were active during the filling of the basin and generated a complicated process of sedimentation, with abrupt lateral and vertical facies variations during the formation of the Santa Rosalía basin.

The age of initiation of the Santa Rosalía basin is poorly constrained and was regarded as Early Pliocene by Wilson and Rocha (1955), considering the fauna just above the basal limestone in the clastic sequence of the El Boleo Formation. A Late Miocene age for the bottom of the El Boleo Formation, and an Early Pliocene age for the top were proposed by Ortlieb and Colletta (1984), based on comparative fauna in the Loreto basin. On the basis of this hypothetic age, Angelier and collaborators (1981) suggested that the whole area, including the Santa Rosalía basin, has acted as a complex NW-SE trending transform-extensional zone since the Late Miocene-Early Pliocene. The different geological and sedimentological features of the El Boleo Formation, as well as the age of the basal limestone, suggest repeated subsidence of the Santa Rosalía basin since the Late Miocene. Recently, Holt and collaborators (1997), determined a $^{40}Ar/^{39}Ar$ age of 6.76 ± 0.90 Ma for the *cinta colorada* (facies C1), deposited 150 m above the top of the Comondú volcanics. Besides, they estimated an age of 7.1 ± 0.05 Ma for the bottom of the El Boleo Formation, and 6.21 ± 0.06 Ma for its top, on the basis of magnetostratigraphic correlations. These data yield a sedimentation rate of 28 ± 4 cm/1,000 a.

All these data suggest that Santa Rosalía basin has been active at least since Late Miocene time, slightly before 7 Ma until Pliocene time.

VOLCANISM IN THE EL BOLEO FORMATION AND THEIR TECTONIC IMPLICATION

Most of the El Boleo clastic sequence was derived from the erosion of the Comondú sequence. Petrographic studies show that the rocks located above and below the muddly sandstone at the bottom of each cycle were not transported far from their source area and present only minor subsequent diagenetic changes. The fine-grain and laminated distal facies are formed by fine sand with angular crystals mostly composed of unaltered plagioclase, feldspar, biotite, amphiboles, and minor amounts of volcanic lithics. Clay minerals sometimes make up more than 10% of volume. In some places, the crystals have been reworked and partially subrounded. Near the coast line, the fine-grained sediments contain more than 5% in volume of very fine volcanic glass shards, which have been reworked and incorporated within the clastic sediments during the same fluvial regime. The coarse material which corresponds to proximal-mid distal deposits (facies C and D), are poorly sorted and indicate proximity to the source area. Volcanic glass shards are conspicuous in facies C.

The physical characteristics of the finest grain facies A at the bottom of each cycle that hosts the different Cu-Co-Zn ore bodies (*mantos*), indicate its deposition during a quiet epoch with minor input of clastic material from inland. Stable isotope studies of carbonates and oxygen isotopes from the laminar calcareous mudstone in the bottom and sulfide minerals from the ore bodies (facies A), show introduction of seawater into the basins and mixing with freshwaters and anoxic conditions during the formation of the ore bodies. Petrographic studies in the more productive facies A show a major presence of volcanic glass. Fresh to devitrified glass is present as angular grains in the matrix and in the breccia clasts. All of these observations indicate that volcanic activity probably occurred during the deposition of facies A, at least during the formation of the first sedimentary cycles.

In the Santa Rosalía basin, there are vestiges of acidic volcanism near the mouth of the Purgatorio creek. An ash-pumice tuff rest directly above the Comondú volcanic rocks and beneath the basal limestone (Figure 2). As was mentioned above, the deposition of this tuff marked a radical change in composition of the volcanism in the Santa Rosalía area, passing from medium-K calc-alkaline andesitic lavas of the Comondú volcanic rocks to acidic ash-pumice tuff. A similar

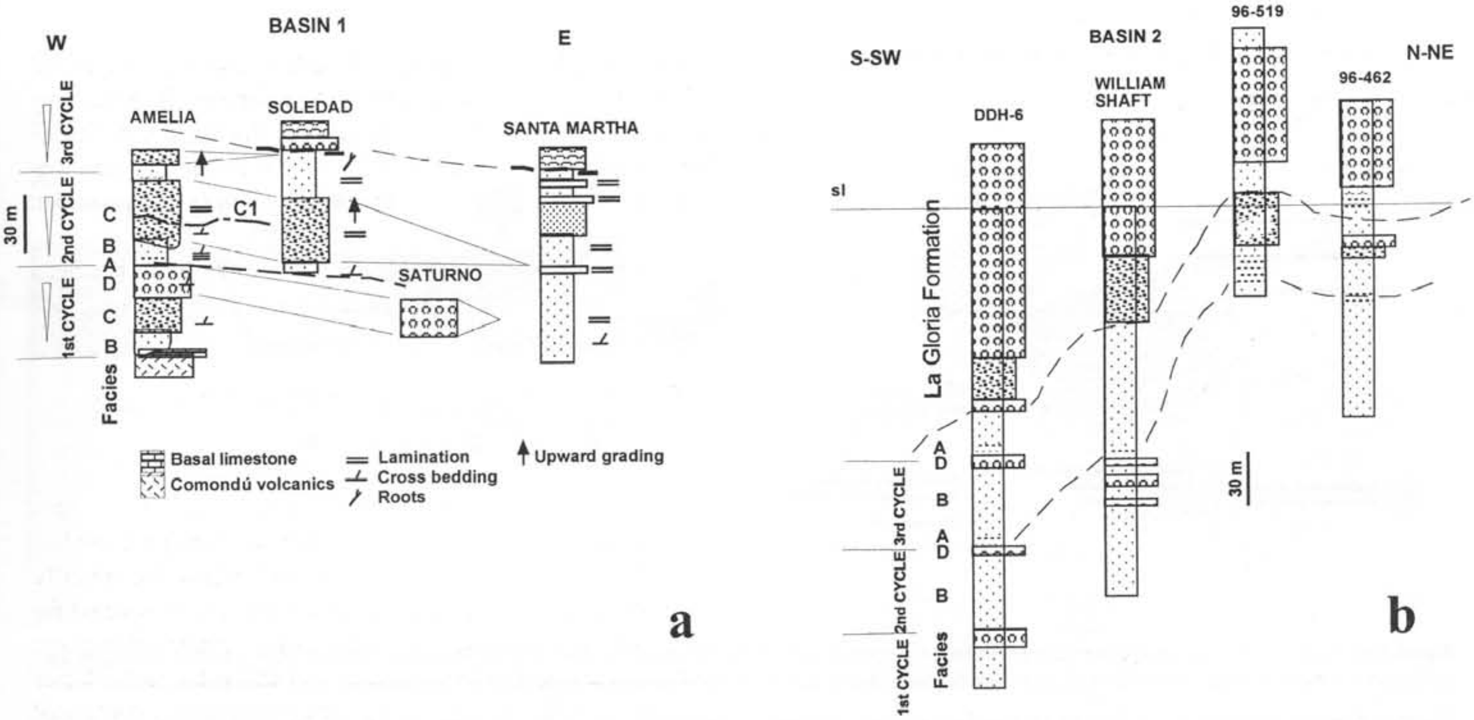

Figure 8. a), and b) Stratigraphic columns in the north and south basins respectively, showing the distribution of the different facies from inland to Gulfward. Note the variation coarse grain grading to fine grained facies to the east. (The holes are located in Figure 1)

pattern was noted by Sawlan and Smith (1984) in northern Baja California Sur.

The post 10 Ma calc-alkaline magmatism in the Santa Rosalía area is atypical for extensional regimens and apparently it is not related to subduction zone. However, the large volume of the volcanic and subvolcanic rocks in the La Reforma and Tres Vírgenes areas, surrounding the Santa Rosalía basin, have calc-alkaline affinity (Schmidt, 1975; Demant, 1981) as well as the pliocenic volcanism of San Esteban island (Desonie, 1992). This could indicate a continued descent of the slab below Baja California, at least 10 Ma after the culmination of subduction on the west side of Baja California. On the other hand, tholeiitic basalts related to the opening of the Gulf of California have been well documented and described by Sawlan and Smith (1984) as an extensive *ca.* 10 Ma tholeiitic basalt province in the northern Baja California Sur, with vents located beneath of the Gulf of California; those tholeiitic basalts are not present in the Santa Rosalía basin.

DISCUSSION

The cyclicity of the clastic sequence of the El Boleo Formation is probably due to repeated subsidence of the basin floor produced by NW-SE and N-S faulting during the early stages of the opening of the Gulf of California. Although the general pattern of basin filling was a progradation of fan deltas from the west-southwest, in detail, there is a systematic east-southeast thickening of the sequence in the south basin (Figure 9b), which suggests that it was an asymmetric transtensional basin. This lateral movement corresponds to dextral-normal faults related to the opening of the Gulf, which were active since Late Miocene, being more frequent during the Late Pliocene to Holocene times (Angelier *et al.*, 1981; Zanchi, 1994). In a simple way, the sedimentary cycles of the El Boleo were produced by active prograding phases in a fluvial fan-delta environment. The large input of sediments from inland during the constructional phases of the fan-delta, together with the tectonic instability and rapid subsidence of the basin floor, originated drastic vertical and lateral changes that might explain the absence of fossils in most of the clastic El Boleo Formation sequence, although field evidence indicates that this clastic sequence passes into a marine environment gulfward with the presence of fossiliferous interbeds. The formation of extensive monomictic breccia within facies A (ore bodies) is an enigma, but field description of these breccias have shed light on their origin. The ore bodies have a large areal distribution, present variable thickness, from few centimeters to more than 10 m; the breccia contains fragments only of the fine-grained facies, and the matrix is of the same composition as the clasts. Frequently, local synsedimentary structures such as slumping breccia and small folds are present within this lithofacies. The breccia formation is poorly understood, although by its large extension and continuity might have been originated by large flood movement of poorly consolidated fine-grained sediments carried into the basin as consequence of earthquake and fault activation. This could explain the sharp contact with the laminar calcareous mud in the bottom, and the irregular contact at the top of the same facies. In the same way, the volcanic glass shards present in the matrix and in the clasts of the breccia suggest volcanism coeval to the formation of the breccia. The presence of similar breccia structures into the

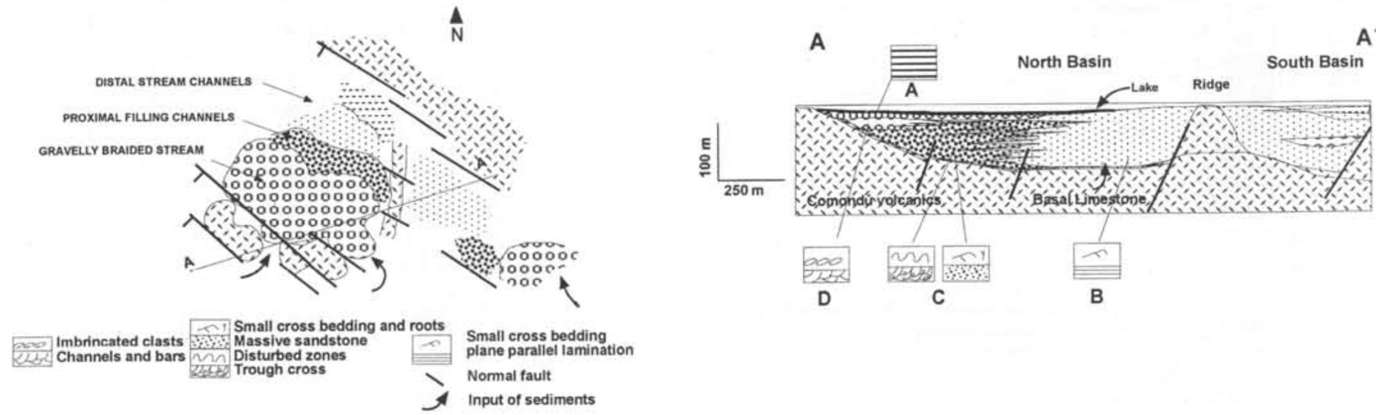

Figure 9. a) Simplified paleogeographic reconstruction for a time period early in the history of a single cycle. b) Schematic SW-NE (A-A´) section looking to the northwest in the Santa Rosalía basin. Both figures show the dominant structures and facies during an early stage of development of the Santa Rosalía basin.

distinct fine grained facies of the El Boleo Formation, suggest the same conditions of breccia formation during a short period of earthquakes and coeval volcanism in closed or partially closed basins.

The age of The El Boleo Formation has been bracketed between Late Miocene and early Pliocene age (Ortlieb and Colletta, 1984). Recently, Holt and collaborators (1997) dated the *cinta colorada* facies C1, at 6.76 ± 0.90 Ma, by $^{40}Ar/^{39}Ar$ method on plagioclase from a tephra deposit. Their field description and interpretation for this unit is in disagreement with our observations, because the *cinta colorada* was described in distinct places as an intertidal sand deposit. However, this date is in agreement with the proposed age of the El Boleo Formation based on fossils (Wilson and Rocha, 1955; Ortlieb and Colletta, 1984), and the calculated age for the bottom of the El Boleo Formation by Holt and collaborators (1997) is slightly younger than the age of the felsic tuff above the Comondú volcanic rocks reported by Conly (1999).

With this scenario, the formation of the Santa Rosalía basin has been linked to the opening of the Gulf of California since 10 to 8 Ma. Tholeiitic volcanism related to the opening of the Gulf of California is absent in the Santa Rosalía area. Post 10 Ma calc-alkaline volcanism, coeval to or younger than the Santa Rosalía basin formation, differs from subduction related andesitic to dacitic rocks and may correspond to partial melting of a metasomatized mantle trigged by the thermal event related to the opening of the Gulf of California, or may be related to the partial melting of subducted eastern Pacific plate slabs (Bellon *et al.*, 2000).

CONCLUSION

The stratigraphic and sedimentological characteristics of the El Boleo Formation indicates a fluvial fan-delta environment. At least three sedimentary cycles were involved during the deposition of the El Boleo Formation, where each cycle corresponded to an upward coarsening transgressive-regressive sequence, likely produced by the tectonic instability during the evolution of the Santa Rosalía basin.

The fine-grained facies in the bottom of each cycle host the Cu-Co-Zn ore bodies in the district that are known as *mantos*. The facies A regularly contains calcareous, laminar, fine sediments at the bottom overlain by tuffaceous claystone-siltstone horizons, which are commonly brecciated (monomictic breccia). On the basis of its physical characteristics, facies A has been interpreted as tuffaceous horizons with interbedded subaqueous debris flows deposits in shallow standing fresh water bodies. Introduction of seawater and mixing was probably produced by subsidence of the floor of the Santa Rosalía basin. The interpretation of brackish water bodies for facies A is consistent by carbon and oxygen isotope studies by Ochoa (1998).

The sedimentological characteristics, such as intraformational and local unconformities, folds, synsedimentary faults and cyclicity in the sequence, together with geochemical evidence, indicate the invasion of seawater into non-marine Santa Rosalía basin and suggest intermittent subsidence events of the margin during the early evolution of the Santa Rosalía basin and the early stage of the opening of the Gulf of California.

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