NEOTECTONICS AND PLIO-QUATERNARY VOLCANISM OF THE AREA OF SANTA ROSALIA, BAJA CALIFORNIA

FIELD TRIP No. 9 PREPARED FOR THE
GEOLOGICAL SOCIETY OF AMERICA
CORDILLERAN SECTION
1981 ANNUAL MEETING

MARCH 28-30

TRIP LEADERS:

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ROADLOG FOR THE SANTA ROSALIA FIELD TRIP

DAY ONE (March 28)

Time	Increment in Kilometers	
08:00 h.		Depart from Hotel Valle Grande, Hermosillo. Head south to Guaymas on the Highway 15.
	00.0	Cerro de la Campana with TV and microwave station relay:Paleozoic metamorphic limestones.
	6 to 46.5	Mesozoic granodiorite east of the Highway. To W Mid-Tertiary ignimbrite where is a shrive to the "Virgen de Guadalupe" west of the Highway.
	54	La Pintada - Mid Tertiary ignimbrites, dacites and rhyolites of the Sierra Libre.
	65.5	Estación de Microondas: Late - Mesozoic (?) altered and fractured andesitic rocks. Along the road to the "Estación microondas", volcanic series dipping eastward; dikes and sills of rhyolite and dacite intruding pyroclastites and ignimbrites (Cochemé, 1981).
	70 to 90	Thick dacitic flows.
	93	Cerro Huerfano: andesitic series overlapped by Tertiary basaltic flows.
	122	Fork to San Carlos: stay on Highway 15, to Guaymas.
	124.5	Turn off to the Estación de Microondas and to the airstrip of Guaymas. Thick Tertiary ignimbritic series. Guaymas city, built in a cauldron structure. Rocks consists of a calc-alkaline suite including basalts, trachyandesites, rhyodacites and ignimbrites (Johnpeer 1977).
11:30		Take off from Guaymas airport, Servicios Aéreos S. A. flight.
12:00		View of Isla Tortuga, the only tholeiitic basalt volcano of the Gulf of California, (Batiza, 1977, 1978). Easternmost part of the island is downthrown along a NE-SW main fault. This volcanic structure lies NW of the Guaymas Basin, a spreading center recently studied through DSDP Leg 64 (Curray and Moore, 1979; Moore and Curray, 1979), and with a submersible (Londsdale and Lawver, 1980). Dolerite sills and dikes intrude thick young sedimentary sequences.

12:15 h.

General view of the coast north of Santa Rosalía. From N to S: Sierra de Santa Ana (Miocene Comondú Group), the central block of Cerro La Reforma encircled by the rim of the La Reforma caldera (10 km diameter), the gently sloping southern flank of the caldera, and the Santa Rosalía Basin; in the background the high cone of the Tres Virgenes.

- At Cabo Virgenes, spectacular sequence of staircase marine terraces cutting Pliocene volcanics. The banks of Arroyo Las Palmitas and the Las Minitas locality show dioritic intrusive bodies (dated 1.37 $\pm$ 0.5 m.y., Schmidt and others, 1977).

- In the Arroyo La Reforma: Pliocene grey ashes and prismatic lava flows (30 m thick) with pillows.

- Yellow non-welded tuffs related with ignimbritic eruptions are conspicuous on the SW flank of Cerro La Reforma.

- The outer part of the rim is capped with Early (?) Pleistocene scoriaceous basalt flows.

- Between the La Reforma Caldera and the Tres Virgenes volcano, wide plateau composed of ignimbritic tuffs covered with alluvium.

- The two peaks N of the 3 Virgenes cone consists of dacitic andesitic flows. The 3 Virgenes Volcano results from viscous dacitic flows.

  Recent volcanic activity (Ives, 1962) is evidenced by several dark basaltic flows. Light-colored pumices and ashes can be seen all around the Tres Virgenes Volcano.

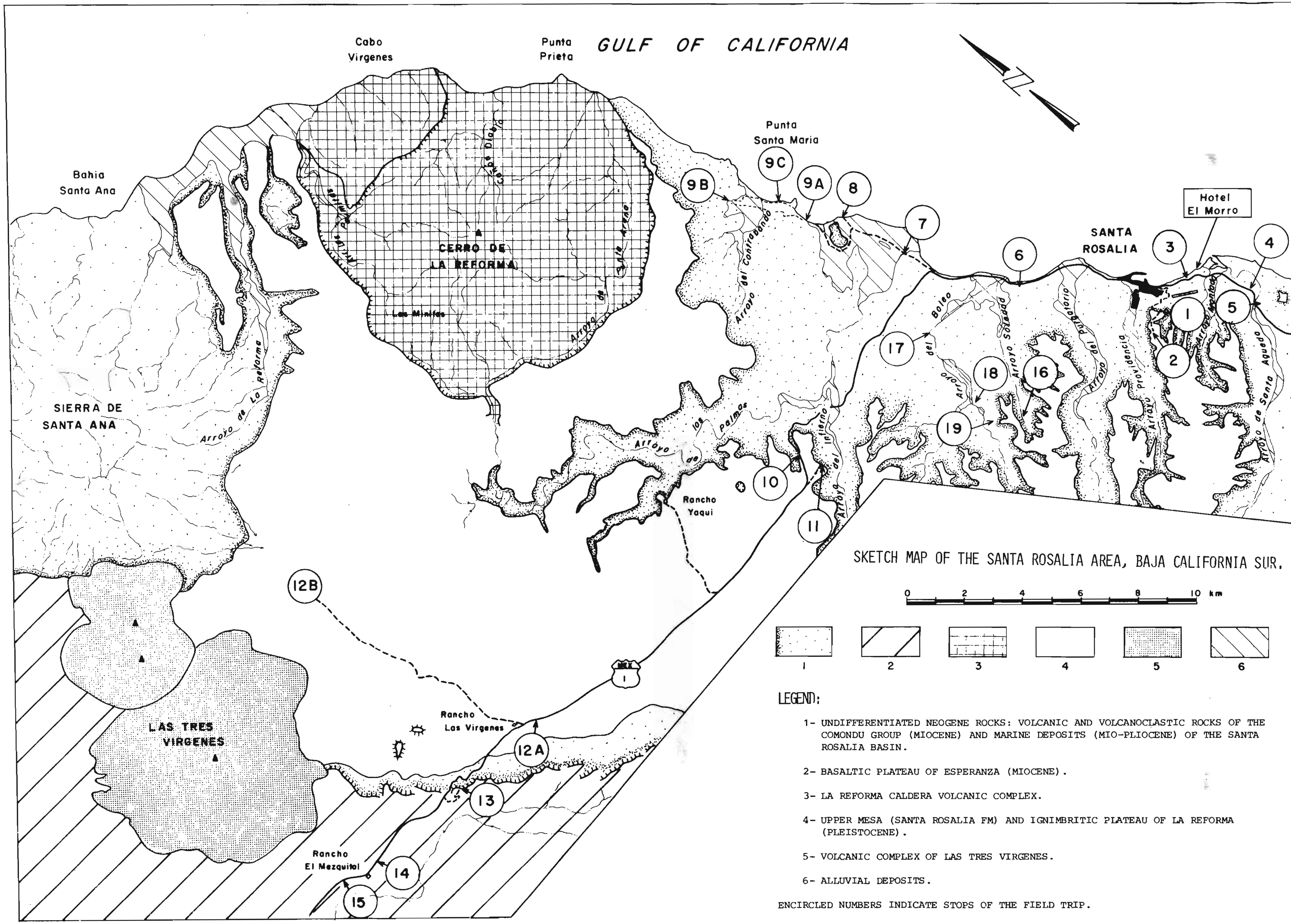
  The main cone is built on the edge of a high escarpment cut in the Esperanza basaltic plateau and volcanoclastic andesites (Miocene Comondú Group).

- In the Santa Rosalía Basin: late Neogene marine embayment uplifted during the Quaternary and limited to the W by the Sierra Santa Lucía (Comondú Group).

  Dissected upper mesa (Sta. Rosalía Formation and old abrasion marine terrace).

  Mio (?)- Pliocene marine deposits exposed in the arroyo cuts.

  Peaks of Comondú rocks rise through the Late Neogene



SKETCH MAP OF THE SANTA ROSALIA AREA, BAJA CALIFORNIA SUR.

LEGEND:

1- UNDIFFERENTIATED NEOGENE ROCKS: VOLCANIC AND VOLCANOCLASTIC ROCKS OF THE COMONDU GROUP (MIOCENE) AND MARINE DEPOSITS (MIO-PLIOCENE) OF THE SANTA ROSALIA BASIN.

2- BASALTIC PLATEAU OF ESPERANZA (MIOCENE).

3- LA REFORMA CALDERA VOLCANIC COMPLEX.

4- UPPER MESA (SANTA ROSALIA FM) AND IGNIMBRITIC PLATEAU OF LA REFORMA (PLEISTOCENE).

5- VOLCANIC COMPLEX OF LAS TRES VIRGENES.

6- ALLUVIAL DEPOSITS.

ENCIRCLED NUMBERS INDICATE STOPS OF THE FIELD TRIP.

			sedimentary series (paleoreliefs), and along the coast S of town.
			Series of marine terraces particularly well-developed between Arroyos del Purgatorio and Santa Agueda.
13:00 h.			Landing at Sta. Rosalía airstrip (+ 100 m marine terrace).
			Lunch.
	00.0 Km.		Aboard vehicles.
			Depart toward the upper mesa. Take dirt road at the northern extremity of airstrip. Small outcrops of Infierno Fm in roadcut.
	0.6		Leave right road to cemetery , and turn off for cobbled road uphill.
			Overlook on Santa Rosalía, in left hair-pin bend. Coarse talus deposits and conglomeratic facies of Infierno Fm.
STOP 1	1.4		Top of the grade. Immediately before reaching the upper mesa, roadcut showing fossiliferous littoral deposit assigned to the Santa Rosalía Fm. Highest marine terrace of the area (elevation + 190 m): see section J in Ortlieb, this volume.
			The road heads W. Small scarp before reaching stop 2.
STOP 2	2.0		Estación de microondas built in a small graben limited by two NW-SE normal faults. Obvious vertical offset of about 3 m. The northeastern fault appear as a calchified gap of about 0,50 m wide. This represents the most recent faulting activity in the Basin of Santa Rosalía.
			View of the Arroyo Providencia. On other side of the canyon: pink tuffaceous Boleo Fm, yellowish sandy and conglomeratic Gloria Fm, greyish sandy and conglomeratic Infierno Fm.
			Turn back
	4.0		Airstrip.
			If times permit, visit of + 132 m marine terrace above southern extremity of airstrip, and of + 86 m marine terrace (with very fossiliferous deposit) below the soccer field, E of the airstrip. (See section J, Ortlieb, this volume).

Descent to Highway 1.

5.0 Km — Right turn on Highway 1, towards S.

Roadcuts in Boleo Fm and Pleistocene marine deposits.

5.4 — Boleo Fm overlying Comondú Group. Numerous faults on E roadcut; flat abrasion marine surface covered with well- rounded cobbles.

STOP 3 — 6.2 — Dirt road to E. Pleistocene marine surface (+ 25 m) with successive ridges. Lower terrace at + 10 m, in sea-cliff.

Return to Highway.

6.5 — Hotel El Morro. Pleistocene fossiliferous conglomeratic marine deposit overlying Comondú Group in road cut in front of the hotel.

7.1 — Descent to Arroyo Montado.

To the W view of tilted blocks of Boleo Fm and Gloria Fm on the eastern compartment of the major Santa Agueda Fault (See Plate 1, Colletta and Angelier, this volume).

7.6 — Arroyo Santa Agueda. The southeastern bank at the mouth of Arroyo Santa Agueda presents a conspicuous abrasion terrace (+ 10 m) cut in volcanoclastic rocks of the Comondú Group.

STOP 4 — 10.0 — Brown calcareous crust, rich in Fe and Mn oxides, from the base of the Boleo Fm. This unit locally fossiliferous, which unconformably overlies the Comondú Group, has been interpreted as the first marine deposit of the Santa Rosalía Basin.

At the top of the southern bank of Arroyo Santa Agueda, low angle disconformity between Infierno and Gloria Fm. The upper surface corresponds to the Santa Rosalía Fm (morphostratigraphic unit) and is offset by a NW-SE normal fault.

Highway 1 crosses Arroyo Santa Agueda.

STOP 5 — 10.5 — Exposures of the base of Boleo Fm.

- Talus breccia on Comondú rocks.
- Calcareous crust
- Gypsum beds overlain by tuffaceous sandstones.

The Santa Agueda fault can be observed in the northern bank of the arroyo: contact between Infierno Fm and Comondú Group (vertical displacement probably superior to 200 m).

If times permits climb up hill to reach the remnant of the upper mesa. Panorama to the N : 5 well-defined marine terraces (see sections J and K, Ortlieb, this volume). Note the general flat surface cut by the sea during Santa Rosalía time. In the background: the three peaks of the Las Tres Vírgenes and associated cones; to the N: the La Reforma Caldera.

The upper mesa (Sta. Rosalía Fm ?) is cut by a 4 m high scarp; this scarp is the superficial evidence of a WNW-ESE normal fault that cuts underlying sandy deposits of the Gloria Fm. Slickensides observed in Gloria Fm indicate pure dip slip movement.

Turn back toward Sta. Rosalía.

	16.2 Km	Santa Rosalía airport turnoff.
		Gloria Fm in roadcuts.
	17.0	Km 0 of Highway 1, at the intersection with Santa Rosalía main street (old mine train monument).
	17.3	Smelter of the copper company (Compañía Minera de Santa Rosalía).
	17.9	Refuse dumps of the earlier "Compagnie du Boleo". Along the shore small ore trains.
	19.6	Marine and fluviatile terrace on Gloria Fm.
	19.7	Cross the Arroyo Purgatorio.
STOP 6	21.8	Loma del Tirabuzon (Corkscrew Hill) fossiliferous locality in Gloria Fm : shark fauna (see Applegate and Espinoza, this volume).
		Turn back to Hotel El Morro.
	28.9	Hotel El Morro.

DAY TWO (March 29)

		Highway 1 towards N.
	0.0 Km	Km 0, Santa Rosalía.

	5.3 Km	Cross Arroyo del Boleo. Outcrops of Gloria Fm.
	7.6	Leave Highway 1 and bear right just before the grade at sign: "No deje piedras en el Pavimento" (aviso a los Geólgos). Cliffs of greenish silty Gloria Fm capped with Pleistocene marine deposits, along the dirt road.
STOP 7	9.2	Arroyo Infierno. Abundant tension gashes filled with gypsum crystals in Gloria Fm. Statistical microtectonic analysis reveals two directions of extension: E-W and WNW-ESE (see: Colletta and Angelier, this volume).
	10.3	To the NW, view of two Pleistocene basaltic volcanoes.
	10.5	Fork, take dirt road heading N.
STOP 8	11.3	Reach coastline. General view of La Reforma. Succession of 6 marine terraces, in staircase disposition, at Punta Santa María (Section I, see: Ortlieb, this volume).
	12.1	Turn back to fork.
	13.6	Facing sandy Gloria Fm overlapped by Pleistocene basaltic flows. Turn seaward, to the NE.
STOP 9 A	14.8	Hike to the Arroyo del Contrabando (don't forget to bring water).

Approx. walking time:

0:00	Follow trail along the beach toward N.
	Climb up hill just before reaching Punta Santa María cliffs.
0:15	Top of grade. Calichified rounded cobbles of the + 40 m marine terrace. Take left at fork.
0:20	Descent in canyon; Gloria Fm overlapped by Pliocene volcanic flows.
0:30	Climbing up on the other bank of canyon. Top of the grade (*in situ* marine fossils, + 40 m terrace).
0:45	General view of the northern cliffs in the Arroyo Contrabando; descent in a small arroyo.
1:00 h	Arroyo del Contrabando. Head N, and cross the arroyo bed.

STOP 9 B		1:30 h	Base of main cliff. Pliocene volcanic sequence overlying Gloria Fm: pumicitic tuffs, sills, lopolites and lava flows. Marine shells associated to pumicitic tuffs.
		1:45	Follow arroyo to its mouth.
		2:00	Reach the beach and follow it to the south.
STOP 9 C		2:15	Paleo-valley in Gloria Fm filled with pumicitic tuffs, and volcanoclastics. Arroyo-cutting in the latter deposits.
		2:30	Exposures of basaltic flows in the sea-cliff.
		2:40	Climb up steep grade and reach the lowest marine terrace of Punta Santa María.
		3:00	Back to the vehicles. Lunch.
	20.4 Km		Back to Highway 1: head W, up the grade. Roadcuts in Gloria Fm to the SE; in the background observe a paleorelief of Comondú rocks.
	22.3		View of the two volcanic cones on the SE edge of the La Reforma volcanic complex.
	23.8		Massive gypsum of the Boleo Fm.
	24.9		Pink tuff overlying gypsum layers (Boleo Fm).
	26.1		Descent in Arroyo del Infierno. Yellowish sandy Gloria Fm. Well- exposed subvertical fault plane in roadcut to the left.
	26.9		Arroyo del Infierno
	27.5		Numerous gypsum tension gashes in microconglomerates and greyish sands of the Gloria Fm. They indicate an E-W extension.
STOP 10	29.6		"Cuesta del Infierno". Ignimbritic flow of the La Reforma Caldera, covering the Pleistocene Santa Rosalía Fm and the Pliocene Infierno and Gloria Fm.

The complete volcanic sequence consists in (from bottom to top):

- Thick pumicitic layers and light coloured and thinly layered ashes that result of plinian- type eruption,

- A scoriaceous basaltic bed,

- Ignimbritic flows (20 m thick).

A close association of basalts and acid products appears in the magmatism of the Reforma caldera.

The Santa Rosalía marine Fm is conglomeratic and fossiliferous. This is the highest outcrop of Pleistocene marine deposits of the Sta. Rosalía Basin. It is attributed to Early Pleistocene (Wilson, 1948) and maybe to the late Early Pleistocene, around 1 M.y. (Ortlieb, this volume).

In the Gloria Fm two families of tensions gashes were found: the older one shows E-W extension, and the other corresponds to an WNW-ESE extension, probably related to the present extensional regime in the Gulf of California.

	30.01 Km	Top of grade. Estación de Microondas.
	30.8	In major right bend of Highway, turn off to the E. Take the very bad old transpeninsular road.
STOP 11	31.7	Panorama of NW part of Santa Rosalía Basin and southern flank of La Reforma.

To the N, ignimbritic sheet overlying the conglomeratic Sta. Rosalía and Infierno Fm. Below, sandy Gloria Fm. and conglomeratic Boleo Fm. Observe normal fault in the latter formations. In the background the Cerro de la Reforma, and outer slope of the caldera covered with Pleistocene basalts.

To the NE, confluent of Arroyos Las Palmas and Infierno, and in the background, brownish massive beds of gypsum (Boleo Fm).

To the E, by clear weather, Isla Tortuga is visible.

To the SE, ignimbrites capping the Santa Rosalía Fm (upper mesa).

	32.6	Back to Highway 1.

Flat surface of the ignimbritic plateau, with isolated peaks of Comondû basement rocks.

STOP 12 A	45.0	View of the SE flank of the las Tres Virgenes volcano (see: Fig. 3 Sawlan, this volume).

	45.9 Km	Rancho las Tres Virgenes. If time permits turn off to the ranch; follow dirt road for about 12 Km, heading N. After second cattle shack, arroyo cut (stop 12B) showing Pleistocene basalt overlain by ignimbritic flows from La Reforma complex and las Tres Virgenes older sequence.
	47.0	Highway begins to climb up major scarp. Thick volcanoclastic and andesitic sequence of the Sierra Sta. Lucía Fm (Comondú Group).
	49.2	Several faults in roadcuts. Association of pure normal faults, oblique faults and tension gashes that indicate ENE - WSW extension.
	50.2	Top of grade.
	50.4	Turn off to the "Estación de Microondas".
STOP 13	51.6	Estación de Microondas. Panorama of La Reforma and las Tres Virgenes (See geological map, Demant this volume).
	52.8	Back to Highway 1.
	54.1	Pleistocene pumice in roadcuts, and on the slopes of reliefs.
STOP 14	56.2	Most recent basaltic lava flows, 200 m N of Highway.
STOP 15	57.8	Highway crosses basaltic lava flows.
		"This lava contains plagioclase microlites, small olivines, clino-pyroxenes, and numerous magnetite grains...(it) has no obvious relationship with the Tres Virgenes dacitic magma chamber, but represents a small batch of basic magma rising from a deeper zone" (Demant, this volume).
		Way back to Santa Rosalía.
	100.3	Back to Motel El Morro.

DAY THREE (March 30)

	Highway 1 to the north.
00.0	Km 0, Santa Rosalía.

	5.3 Km	Leave Highway 1 to take dirt road entering the arroyos Boleo and La Soledad.
	5.5	Fork: bear left to go upstream in the arroyo La Soledad. Arroyo cut in Gloria Fm ; deposits dipping about 5° to the NNE.
	6.0	To the north, on the left, peak El Morrito; yellowish sands capped by brown calcarenites, all attributed to Gloria Fm. Nannofauna collected at the base and on the flanks of the peak indicates an Early Pliocene age (NN12 Zone).
	6.4	Pink clayey tuff of the Boleo Fm overlain by yellowish strata of Gloria Fm.
	6.8	Dark brown ore beds rich in Mn and Cu. Mineralization is of hydrothermal origin and occurred during a NE-SW to E-W extensive stage contemporaneous with Boleo deposits. Normal faults led hydrothermal solutions to the surface.
	8.4	Conglomerates of the Boleo Fm.
	9.1	Normal faults cutting Boleo and Gloria Fm. Small outcrop on the left showing distinct density of faulting in Boleo Fm and in Gloria Fm.
	9.7	Contact Gloria Fm / Boleo Fm : yellowish conglomerate and sandstones of the Gloria Fm lying over pink clayey tuff of the Boleo Fm in slight unconformity.
	10.0	Boulders of Gloria Fm coquina can be observed along the road. On the south side of the road residues of ore beds with copper mineralization.
	10.2	Mine gallery.
		Leave 2 dirt roads on the left and follow the road that crosses the arroyo and climb on the northern bank.
STOP 16	10.5	Association of reverse faults and strike slip faults induced by a N-S compressive stress. Strike slip faults strike 155 to 170 and are mainly dextral. The strike slip faulting stage occurred between Boleo and Gloria deposition.

Observe the pink-red volcanoclastic layer that constitutes a key horizon called "Cinta Colorada" (Wilson, 1948).

Turn and go back to the mouth of the arroyo.

	15.5 Km	Back to the fork at the arroyo Boleo entrance. Turn left to go upstream in the arroyo Boleo.
	17.00	Gypsum of the Boleo Fm.
	17.7	Gypsum quarry on the left.
STOP 17	18.6	Huge crystal of gypsum in a "synclinal faulted zone". Gypsum strata are gently bent: each anticline is separated by a recrystallized fault zone whithout true syncline. Directions of folds are parallel to the main faults of the region and are probably more related to underlying faulted blocks than to a compressive event.
	18.7	Mouth of the "Cañada de la Gloria".
	19.7	Opening of the gypsum cañon; valley get wider in the clayey tuff of the Boleo Fm. On the southern bank, the brown ore beds are slightly offset by small reverse faults according to a N-S compressive stress. This minor reverse faulting is probably related to strike slip events that occurred at the limit between Boleo and Gloria time.
	21.2	In the background to the south, angular discomformity between Boleo and Gloria Fm.
	21.8	Fork: bear left and cross a small cañon cut in volcanic rocks of the Comondú Group.
STOP 18	22.2	Paleorelief of Comondú rocks covered by mineralized fossiliferous limestone and tuffs of the Boleo Fm. On the slope of the structure, conjugated normal faults in Boleo deposits have been tilted showing that the present dip of the stratas does not only result of depositional processes and that the pre-Boleo paleotopography was somewhat milder.
	22.3	Leave dirt road on the left.
	22.4	Leave other dirt road on the left.

STOP 19	22.7 Km	Multistriated fault plane in Boleo and Comondú Fm. Leave vehicles and climb up the thalweg to the south. At about 5 mn hiking, reach obvious slickenside showing two sets of striation (a fainter third set can locally be observed) that indicate two successive movements on the same fault plane. The older (syn-Boleo) slickenslides indicate a dip slip displacement while the younger (Post-Boleo) ones indicate oblique right slip with important lateral component.
		View of the antiform- paleorelief to the NE.
	37.2	Turn and go back to the Santa Rosalía airstrip.
13:00 h		Lunch.
14:30		Take off. Servicios Aéreos flight.
15:30		Guaymas airport.
18:00		Arrive Valle Grande Hotel in Hermosillo.

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THE GEOLOGY AND SELACHIAN PALEONTOLOGY OF LOMA DEL TIRABUZON (CORKSCREW HILL), SANTA ROSALIA, B.C.S.

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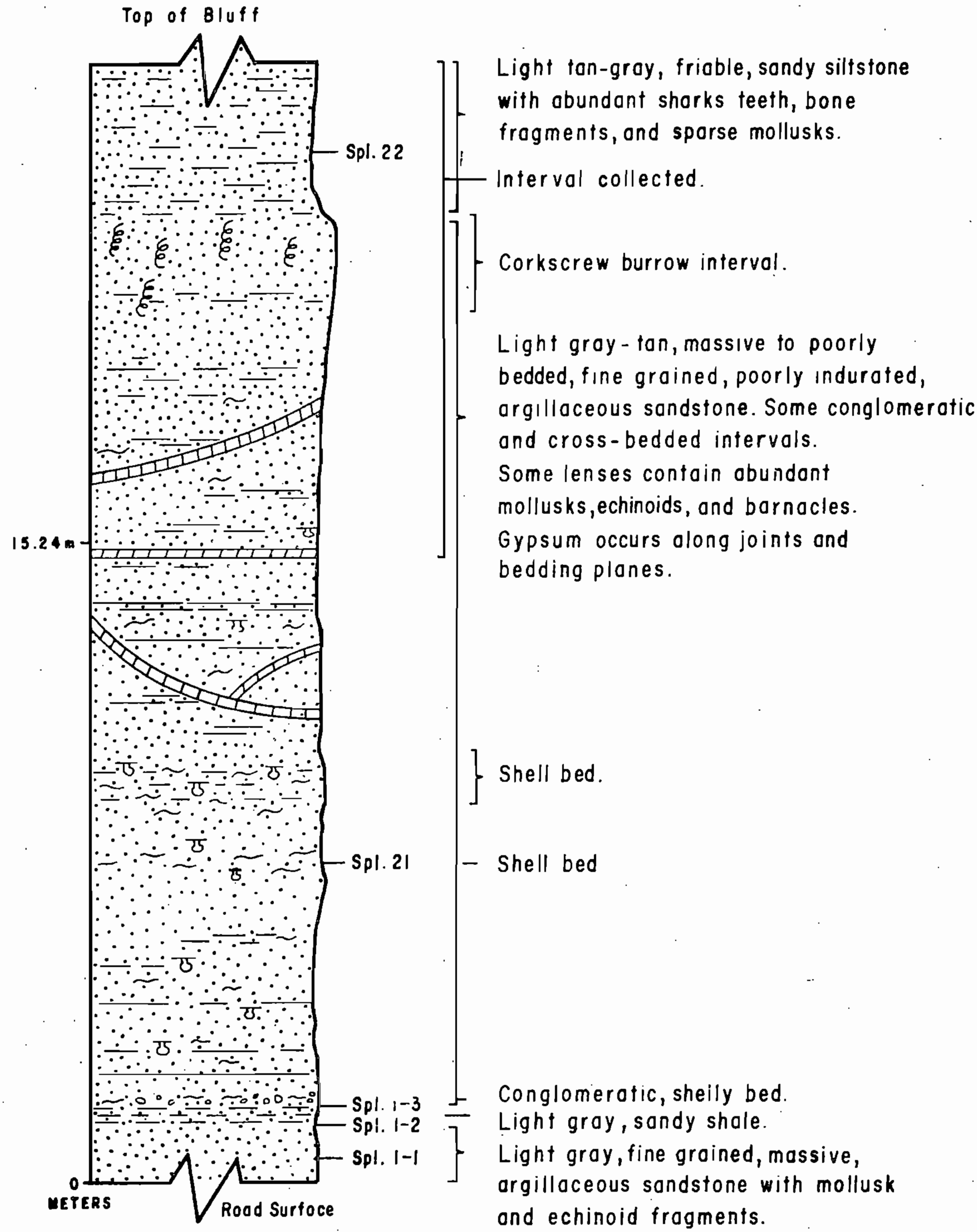
The rich fossiliferous beds that exist at Loma del Tirabuzon have been discussed by Applegate, (1978). The locality is 5 km north of the town of Santa Rosalia. On the east the locality is bounded by sea cliffs that are on the west side of the road. The area covers about 1.5 hectares, where approximately 50 meters of section are exposed. The lower 30 meters form the bluffs at the side of the road, (Figure 1). The top 3 meters of these cliffs contain shark's teeth. Below the shark's tooth layer occurs the corkscrew-like burrows which give the locality it name. These burrows reach a length of one or two meters. Below the ichnofossils are shell beds and layers rich in echinoderm spines. The base of the formation is not exposed at this locality. The sediments consist of greyish tan silts and sands with interfingering conglomerates.

The lower beds including the shark's tooth layer are part of Wilson's, Gloria Formation, (1955). Since the name Gloria was preoccupied, we suggest that the formation be called the Cañada de la Gloria Formation, because the original name Gloria was taken from the Canyon known as the Cañada de la Gloria.

The fossil fauna consists of: Foraminifera, ostracods, bryozoans, gastropods, pelecypods, echinoderm plates and spines, crab claws, as well as the corkscrew-like burrows, bony


Top of Bluff
Spl. 22
15.24m
Spl. 21
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METERS
Road Surface
Light tan-gray, friable, sandy siltstone with abundant sharks teeth, bone fragments, and sparse mollusks.
Interval collected.
Corkscrew burrow interval.
Light gray-tan, massive to poorly bedded, fine grained, poorly indurated, argillaceous sandstone. Some conglomeratic and cross-bedded intervals.
Some lenses contain abundant mollusks, echinoids, and barnacles.
Gypsum occurs along joints and bedding planes.
Shell bed.
Shell bed
Conglomeratic, shelly bed.
Light gray, sandy shale.
Light gray, fine grained, massive, argillaceous sandstone with mollusk and echinoid fragments.

fish teeth, head plates, vertebrae and spines, shark and ray teeth, vertebrae and dermal denticles, turtle bones and scutes, whale and dolphin ear bones and teeth and other mammal bone which is poorly preserved.

Only the shark fauna and one new species of gastropod has been discribed from this locality. A revised and expanded list of the sharks is as follows:

1. Hexanchus cf. griseus;
   Common off of the Califonia Coast but not known from the Gulf of California.
2. Notorhynchus sp.; The teeth are close to the living Notorhynchus cepedianus recently reported from the Gulf of California (Applegate 1979).
3. Heterodontus sp.;2 or 3 living species exist in the Gulf of California.
4. Squalus sp. Known from the west side of Baja but not from the Gulf of California.
5. Odontaspis ferox; Known from southern Baja near la Paz.
6. Eugomphodus acutissima;Extinct, a related species living in the Western Pacific and North Atlantic.
7. Isurus benedeni;Extinct, known from the middle Oligocene to the lower Pliocene of Europe.
8. Isurus oxyrinchus;Living in the Gulf of California.
9. Carcharodon megalodon; extinct.
10. Carcharodon sulcidens; extinct.
11. Carcharodon carcharias; living in the Gulf of California.
12. Alopias pelagicus; Known from San Blas,Mexico Most likely living in the Gulf of California.
13. Cetorhinus sp.;Living Cetorhinus maximus known in the Gulf

of California today from a single record.

14. *Mustelus* sp.;Over 5 species living in the Gulf of California at our locality known by only two teeth.

15. *Galeorhinus galeus*?;Common on Pacific side of Baja rare in the Gulf of California.

16. *Galeocerdo rosaliaensis*; Extinct, probable ancestor of *Galeocerdo cuvier* which lives in the Gulf of California today.

17. *Hemipristis serra*; Extinct, a living related single species is confined to the Indian Ocean.

18. *Rhizoprionodon longurio*; Common at our locality and common in the Gulf of California today.

19. *Prionace glauca*; Rare as a fossil at our locality but living south of La Paz in the Cape area.

20. *Carcharhinus albimarginatus*?; Living in the Gulf of California, fossil teeth may represent a different species.

21. *Carcharhinus altimus*; Living in the Gulf of California.

22. *Carcharhinus brachyurus*; Living in the Gulf of California.

23. *Carcharhinus falciformis*; Living in the Gulf of California, a common fossil at our locality.

24. *Carcharhinus galapagoensis*; living in the Gulf of California.

25. *Carcharhinus leucas*; Living in the Gulf of California, a common fossil.

26. *Carcharhinus limbatus*?; Living in the Gulf of California, rare as fossil.

27. *Carcharhinus obscurus*; Living in the Gulf of California, a common fossil.

28. *Carcharhinus porosus*; Living in the Gulf of California,

a rare fossil at our locality.

29. Carcharhinus velox; Living in the Gulf of California.

30. Sphyrna lewini; Living in the Gulf of California today where it is very common.

31. Sphyrna media; Living in the Gulf of California.

32. Sphyrna mokarran; Living in the Gulf of California.

33. Sphyrna tiburo vespertina; Living in the Gulf of California.

34. Sphyrna zygaena; Living in the Gulf of California.

The lack of a recent species in a fossil fauna only represents negative evidence, yet it is of interest to analyze the recent pacific species which do not exist in this locality in relationship to their known habitats. The Loma del Tirabuzon lacks a number of deep water sharks known in the pacific waters off of Mexico, such as: Echinorhinus cookei, Alopias superciliosus, Apristurus brunneus, Apristurus kampae, Cephalurus cephalus, Galeus piperatus, and Parmaturus xaniurus. In the Tirabuzon fauna we do have sharks known to live in fairly deep water today: Hexanchus cf. griseus, Notorhynchus sp. and Odontaspis ferox. All of these are known by only a few teeth. The open sea pelagic sharks that have not been found are: Carcharhinus maou, Alopias vulpinus and and Rhincodon typus, on the other hand open ocean sharks such as: Prionace glauca, Carcharhinus falciformis, Sphyrna mokarran and Isurus oxyrinchus do occur. Two sharks that are found in extremely shallow water are also absent Negaprion fronto and Ginglymostoma cirratum. Rocky substrate forms such as: Triakis semifasciata, Cephalosyllium ventriosum and one or two species of Heterodontus are not known. It is interesting that we have only two Mustelus teeth, a genus with 5 species living many of them are quite common in the Gulf of California. Perhaps the most surprising thing is the total lack of Squatina, a shark known from moderate depths.

From the above and the known distribution of living sharks that occur in our fauna we could expect a depth from 20 to 200 meters. The shallow depths being favored. The surface conditions must have been that of an open ocean, 2 or 3 km from the shore.

Various works have placed the age of the Cañada de la Gloria Formation, from Lower Pliocene to Upper Pliocene. Applegate, (1978), suggested a Middle Pliocene age. Recent work in progress at the Geological Institute on the Pliocene of Baja California has produced no evidence to change this determination.

Along the Pacific Coast, Lower Pliocene shark faunas are poorly known. The Pliocene of Simi Valley, California, USA, appears to be of this age. Here we find two species of *Isurus*. *Isurus hastalis* and *I. plana*. These species are common in Middle and Upper Miocene sediments, evidently these did not extend into the Middle Pliocene. North of San Felipe, Baja California Norte, in Pliocene beds above the Miocene diatomites we have one shark's tooth that seems to be intermediate between the Miocene *Galeocerdo aduncus* and the Middle and Upper Pliocene *Galeocerdo rosaliaensis*, which at least suggests the possibility of a Lower Pliocene age for these Imperial Formation beds.

The fauna at Rancho Algodones, Baja California Sur, is Upper Pliocene in age although sharks teeth are abundant the species appear limited. *Isurus benedeni* is absent as is *Eugomphodus acutissima*. All three species of *Carcharodon* are still present as is *Hemipristis serra* and *Galeocerdo rosaliaensis.*

Since the discovery of the fossils at Loma del Tirabuzon numerous amateur collectors have visited this area. Today it is almost impossible to picture the wealth of exposed teeth that occurred there. We hope that this locality will ultimately become a national monument so at least the corkscrew burrows will be preserved.

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FAULTING EVOLUTION OF THE SANTA ROSALIA BASIN, BAJA CALIFORNIA SUR, MEXICO

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RESUMEN

Se realizaron más de 600 medidas en fallas localizadas en la cuenca neógena de Sta. Rosalía. Estas medidas permitieron determinar la orientación de los esfuerzos principales $\sigma 1, \sigma 2, \sigma 3$. Los resultados muestran la existencia de un episodio de fallamiento lateral dextral el cual separa dos episodios de fallamiento normal extensivo. El primero de los episodios extensivos fué mucho mas intenso: produjo fallas de orientación general NNW-SSE que influenciaron las deformaciones posteriores y que resaltan actualmente como patrón principal. La existencia de desplazamientos laterales sugiere que la parte oriental de la Península de Baja California se comportó como una zona transformante extensional desde el Mioceno Superior-Plioceno Inferior.

INTRODUCTION

Over 600 faults planes and tension gashes were measured in the Neogene formations of the Santa Rosalía area. Measurements were performed at several distinct localities, each of them including 10 to 100 readings. For each faulted locality, the orientation of the 3 principal tectonic stresses. $\sigma 1$, $\sigma 2$, $\sigma 3$, were then computed with a statistical method analysis elaborated by Angelier (Angelier and Mechler, 1977; Angelier and Goguel, 1979; Angelier and Manoussis, 1980). The results are coherent and lead us to propose a tectonic history of the Santa Rosalía Basin. (These results are presented in a larger paper, by Angelier and others, in press).(1)

GEOLOGIC SETTING

The oldest rocks of the area are quartz monzonites of Cretaceous age that crop out in the Arroyo de Las Palmas and in the central part of the Reforma caldera (Wilson, 1948; Schmidt 1975). This substratum is covered by thick volcanic and volcanoclastic series defined by Heim (1922) as the Comondu Formation. Overlying this formation disconformably are marine sediments, the deposition of which-

(1) Preliminary reports of this work were previously presented (Chorowicz and others 1980; Colletta and others 1980).

was periodically interrupted by tectonic movements and limited emersions. The sedimentary sequence was subdivided by Wilson (1948) into four formations, each of them slightly unconformable on the earlier one. The following sequence, can be observed (from bottom to top):

- the Boleo Formation: essentially conglomeratic with interbedded tuffaceous clayey sandstone and grading locally into thick gypsum facies (average thickness 100 m);
- the Gloria Formation: yellowish marine clayey sandstone and coarse conglomerates (average thickness 60 m);
- the Infierno Formation; conglomeratic and sandy with tuffaceous layers (average thickness 55 m);
- the Santa Rosalía Formation: marine and continental conglomerates (average thickness 10 m);

In the northern part of the basin, the whole sedimentary sequence is overlaped by ignimbritic flows from the Reforma complex (Demant and Ortlieb, 1979; Demant, this book).

Along the Gulf coast several marine terraces are well exposed (Ortlieb 1979; Demant and Ortlieb, 1979; Ortlieb, this book ; Colletta and others, in prep.).

CHRONOSTRATIGRAPHY OF THE SANTA ROSALIA BASIN

Wilson (1948) proposed a chronostratigraphy based on marine faunal determinations. The three formations (Boleo, Gloria, Infierno) were thought to be, respectively, of Lower, Middle, and Upper Pliocene age, and an Early Pleistocene age was attributed to the Santa Rosalía Formation. Yet recent nannoplanktonic dating of the Gloria Formation is somewhat inconsistent with this chronology. A few samples collected in the lower and middle part of the Gloria sequence (BC 49, 50, 51, 52, 58, 59, see Plate 1 for location) carry nannofauna of Early Pliocene age probably the NN12 zone (determination C. Muller). Although this age is based on only a few samples and should be confirmed by further studies, we consider it reliable. Consequently we proposed a new chronostratigraphic interpretation:

- Comondu Formation (in the area of Santa Rosalía): no older than the Middle Miocene (?)
- Boleo Formation: Upper Miocene (?)
- Gloria Formation: Lower to Middle Pliocene
- Infierno Formation: Upper Pliocene (?)
- Santa Rosalía Formation : Pleistocene

Up to now, no direct evidence of the older age we suggest for the Boleo Formation has been found. Nevertheless we can argue that Miocene marine deposits are documented at various localities of the Gulf Province (Gómez , 1971; Andersen, 1969; Gastil and Krummenacher, 1977, Minch, 1979) and that, the very poor marine fauna reported by Wilson did not firmly date the Boleo Formation as Lower Pliocene.

As for the age of the Comondu Formation, K/Ar dates (Mc Fall, 1968; Gastil and others, 1975; Gastil and others, 1979) show that it could be bracketed between 21.6 and 6.6. My. In the San Ignacio area (about 70 km west of Santa Rosalía) the Comondú Formation grades in a marine facies (the San Ignacio Formation) that was dated by Gastil and others (1979) at II My K/Ar on tuffs.

Thus, the older ages we suggested for the Comondu and Boleo Formation appear quite consistent with the general chronological data in Central Baja California.

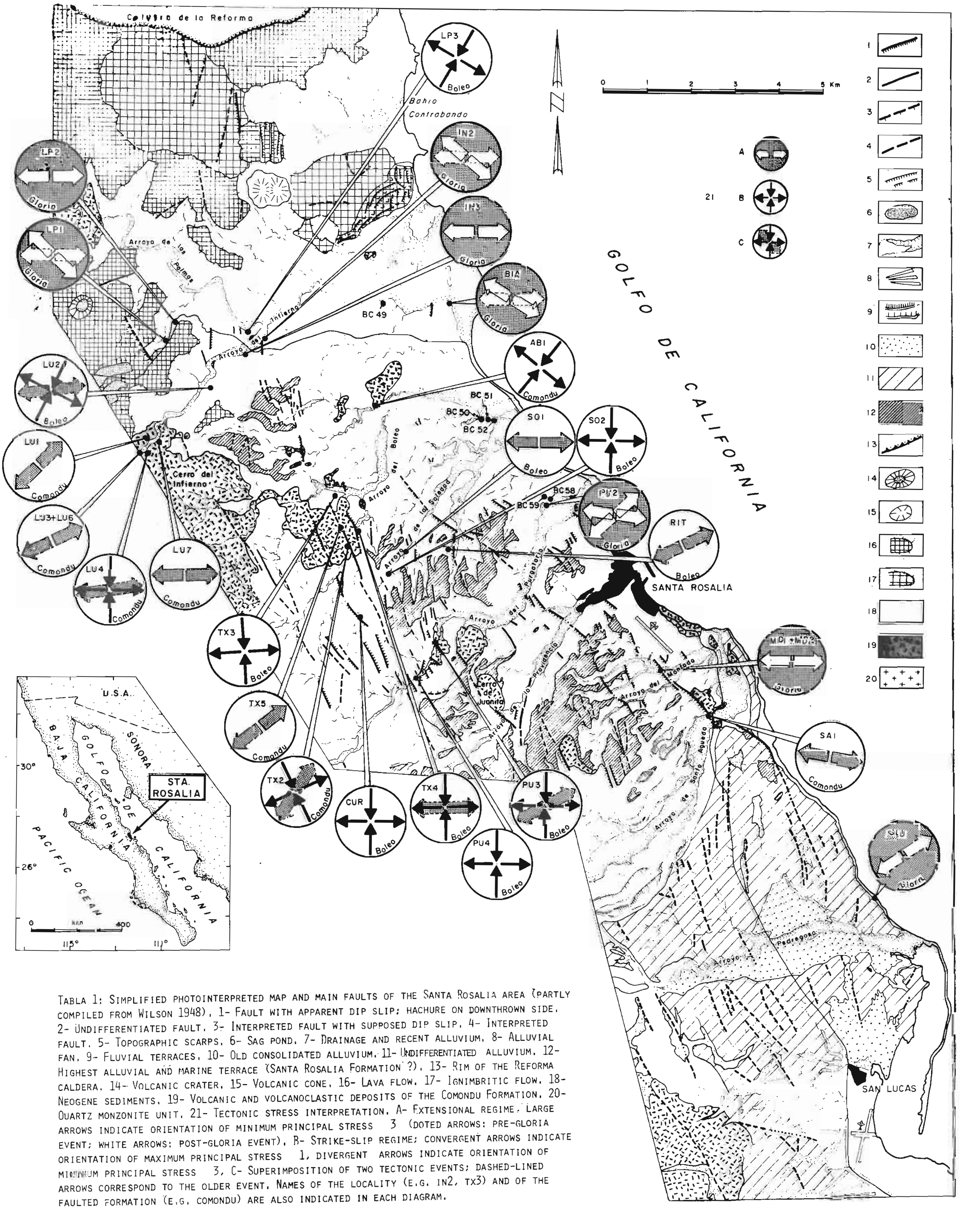

Tabla 1: Simplified photointerpreted map and main faults of the Santa Rosalia area (partly compiled from Wilson 1948). 1- Fault with apparent dip slip; hachure on downthrown side. 2- Undifferentiated fault. 3- Interpreted fault with supposed dip slip. 4- Interpreted fault. 5- Topographic scarps. 6- Sag pond. 7- Drainage and recent alluvium. 8- Alluvial fan. 9- Fluvial terraces. 10- Old consolidated alluvium. 11- Undifferentiated alluvium. 12- Highest alluvial and marine terrace (Santa Rosalia Formation ?). 13- Rim of the Reforma caldera. 14- Volcanic crater. 15- Volcanic cone. 16- Lava flow. 17- Ignimbritic flow. 18- Neogene sediments. 19- Volcanic and volcanoclastic deposits of the Comondu Formation. 20- Quartz monzonite unit. 21- Tectonic stress interpretation. A- Extensional regime. Large arrows indicate orientation of minimum principal stress 3 (doted arrows: pre-Gloria event; white arrows: post-Gloria event). B- Strike-slip regime; convergent arrows indicate orientation of maximum principal stress 1, divergent arrows indicate orientation of minimum principal stress 3, C- Superimposition of two tectonic events; dashed-lined arrows correspond to the older event. Names of the locality (e.g. IN2, TX3) and of the faulted formation (e.g. Comondu) are also indicated in each diagram.

FAULTING PATTERN

As shown on Fig. 1 A, in the Santa Rosalía Basin, the faults have two predominant trends: one N-S (175) and the other NNW-SSE (160 to 155). Statistical analysis of all the measured brittle structures, including tension gashes, indicates a general N-S attitude and a lack of E-W trends; 75% of the strikes are included between 155 and 190. West-dipping fault planes are more numerous that east-dipping ones. This assymetry which appears in Fig. 1 B, results from the high number of antithetical secondary faults induced by a few main gulfward synthetical faults.

About 90% of the faults planes have a dip over 45°(Fig.2C) while pitches of the slickenlines are widely distributed between 0 to 90°(Fig. 1 D). This attitude corresponds to a general high angle faulting with all kind of movements from pure strike-slip to pure dip-slip.

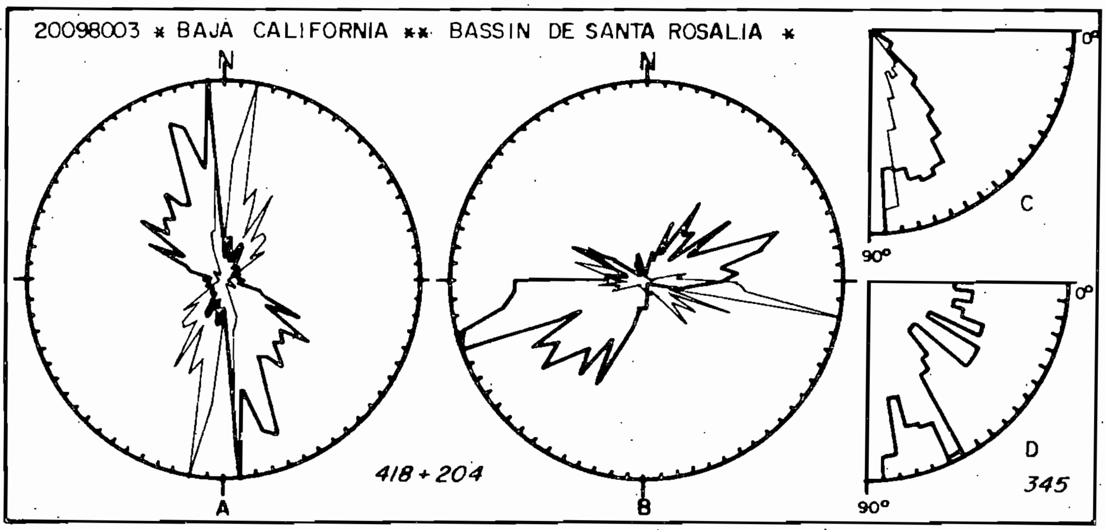

Fig. 1: Rose diagrams based on 418 fault planes (bold lines) 345 of which carry slickenslides, and on 204 tension gashes (thin lines) A- Strikes of planes. B- Dipping directions. C-Dips. D-Pitches of slickenslides.

Only very few true reverse faults, with pitch over 45°and reverse displacement, are observed (Fig. 2). Displacements are mainly right-normal-slips; in detail two populations of faults are predominant: (1) pure right-slip faults and (2) oblique-slip faults with pitches of about 60°(Fig. 2).

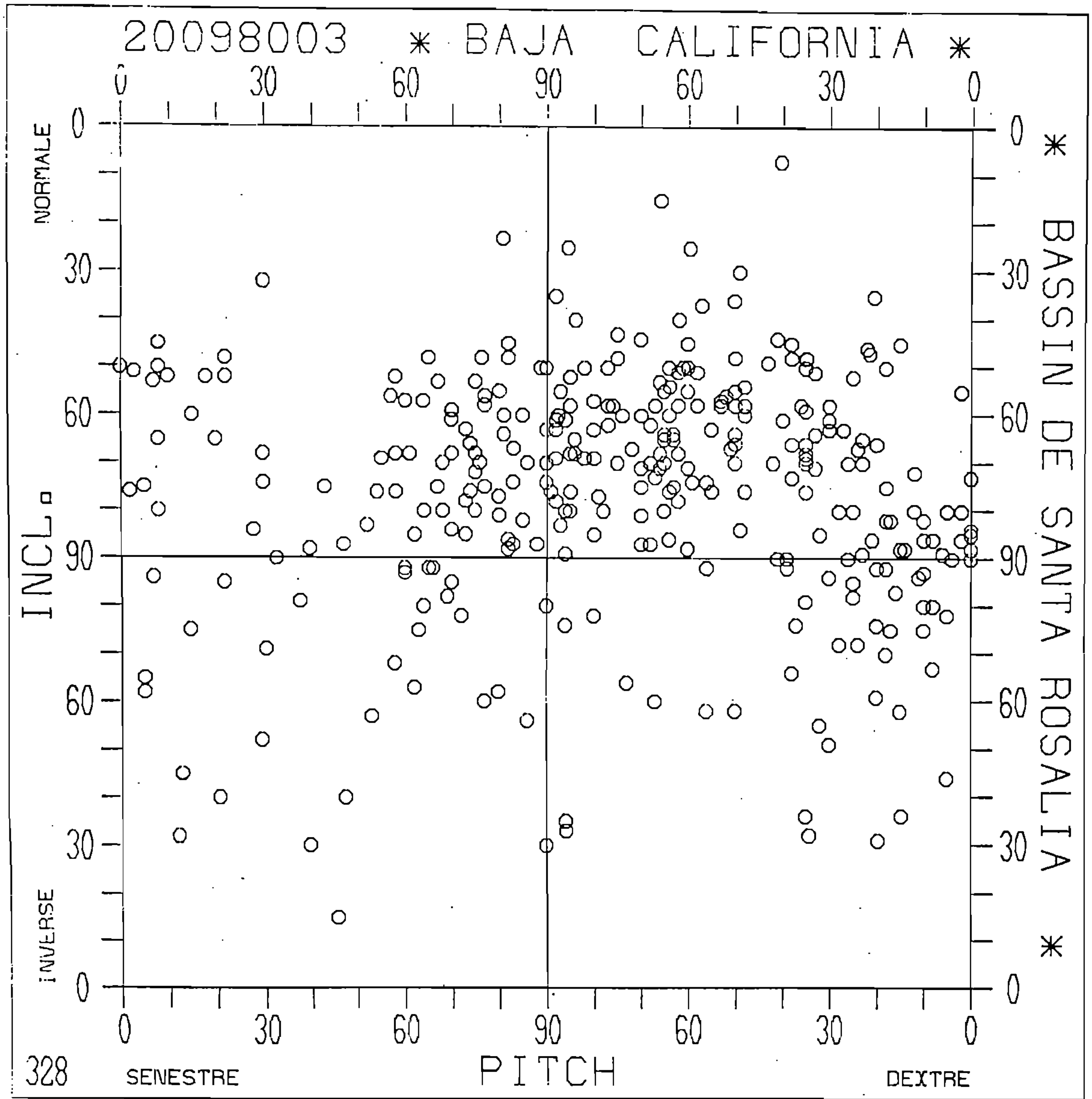

Fig. 2 : Plot of slickenslides pitches versus dips for 345 fault planes in the Santa Rosalía area. Observe the two predominant groups of pure strike-slips (pitch= **90°**) and oblique slip faults with pitches of about 60°.

FAULTING EVENTS

The whole structural pattern is not the result of a single event. The faulting complexity increases with the age of the formations and indicates several superimposed tectonic stages. Three main successive faulting events are evident.

The extensive post-Comondu, pre Gloria event

The oldest tectonic regime registered in the Santa Rosalía Basin, is an extensional one: it postdate the Comondu volcanics, goes on through Boleo time and predates the Gloria time. A slight rotation of stresses might have occurred during this event and the $\sigma 3$ extensive principal stress does not appear uniformely oriented in the whole area; statistical study indicates a $\sigma 3$ ranging from NE-SW to E-W and the two major fault trends (NNW-SSE and NS) probably result of this extensive event. Although no major change in the tectonic regime is evidenced, two generations of faults were definitely recognized during this extensive event: one pre-Boleo and the other contempraneous to the Boelo deposits.

The first generation (pre-Boleo) is well represented by numerous antithetical normal faults in the Comondu Formation particularly in the Arroyo del Infierno. Sets of conjugate normal faults are locally eastward tilted 10 to 30° (Fig.3). Both structures, faults and tilted strata were buried by the Boleo deposits. The tilting is thought to immediately postdate the faulting event and to predate the marine deposits . The paleotopography described in the Comondu volcanics by Wilson (1948) resulted probably from this first faulting stage.

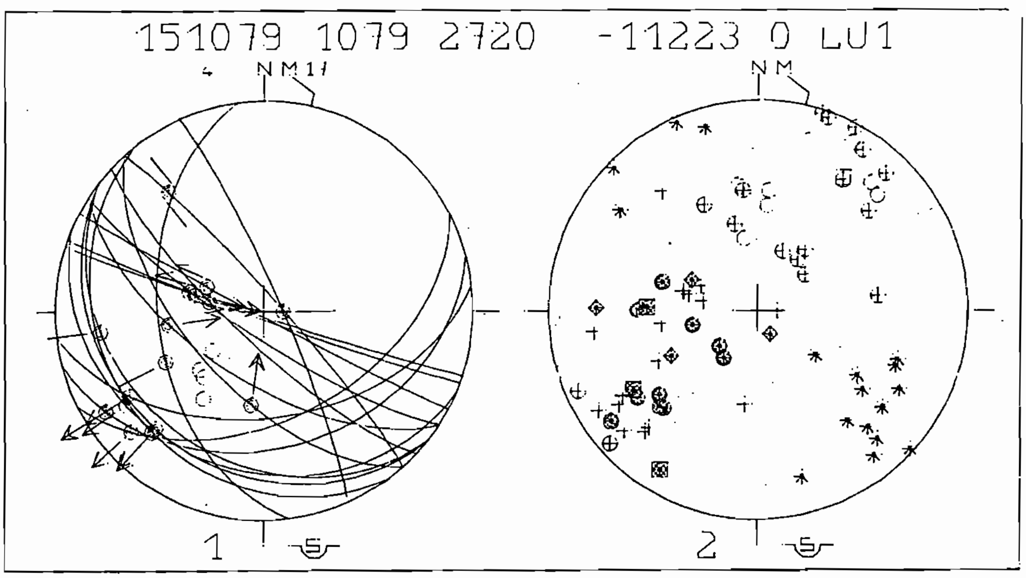

Fig 3: Example of tilted normal faults in the Arroyo del Infierno (Mina Lucifer). Schmidt net, lower hemisphere . A- Fault planes with slickenslides, small open circles are poles of strata. B-axes related to each fault plane (⊕ , poles of fault planes; + , slickenslides; ⊛, ○ , *, axes related to individual faults mecanisms). Observe that sub-vertical faults and reverse faults will get a west dipping normal attitude after rotating strata to an horizontal position.

The second generation (during the Boleo deposition) is more subdued but can be demonstrated by various features. In the Boleo Formation, normal faults due to a NNW-SSE extension are truncated by strike-slip and reverse faults of a younger tectonic event (L U2). Several striated fault-planes show two generations of slickenslides; the first one indicates a normal faulting related to a NNW-SSE extension and the second one indicates strike-slip displacement belonging to the younger tectonic events (LU 2, TX 4, PU 3). Moreover , in the higher part of the Arroyo del Purgatorio and of the Arroyo del Boleo, several fault gaps which are filled with conglomerate indicate extensive tectonic movements contemporaneous with the Boleo deposits. Other evidences of these synsedimentary movements are a low angle unconformity and an intraformational conglomerate in the gypsum of the Arroyo del Infierno. Volcanic activity recorded by a layer of lapillis and cinders, called the Cinta Colorada, is doubtless related with these extensive tectonics. On the other hand, the ore deposits are thought to be of hydrothermal origin and also to be definitely related to the faulting (Wilson 1948). Ore beds are confined to the Boleo Formation and were offset by later tectonic events. Therefore the mineralization probably arose during this second faulting stage.

The post-Boleo-pre-Gloria strike-slip faulting event

At various localities, strike-slip movements are evidenced by horizontal - slickenslides. Right- lateral trends are more frequent but numerous left lateral faults were found, particularly in the Arroyo del Purgatorio. However, right or left trends are in agreement with a compressional principal stress (σ 1) roughly oriented N-S as deduced from the statistical study (Plate 1). A few small reverse faults related to this stress field can be observed in the Arroyo del Boleo. Fault planes of the first extensive stage were reactivated as shown by the superimposition of strike-slip slickenslides on earlier dip-slip slickenslides (PU 3, TX 4).

The amount of lateral offset cannot be precisely known but we think that no large strike-slip displacement occured along any single major fault in the Santa Rosalía area. Yet, the general plot of lateral slip versus transversal (extensional) slip (Fig.4) indicate a high number of lateral offsets. All the measurements showing strike-slip stress field (σ 1 and σ 3 horizontal) were performed in Comondu or Boleo Formation and no strike-slip system appears in the younger Gloria Formation. Therefore, we conclude that this tectonic event probably occured at the boundary between the Boleo Formation and the Gloria Formation.

The post-Gloria extensive event

Gloria, Infierno and Santa Rosalía deposits are cut by important normal faults. Large faulted outcrops of the last two marine formations (Infierno and Santa Rosalía)are scarce and useful measurements could only be performed in the Gloria Formation. Post-Gloria brittle structures consist essentially of normal or oblique faults and gypsum tension gashes.

Veins of gypsum are sometimes very numerous and give good statistical results in computing the extensional stress σ 3. Stress diagrams indicate two main extensional trends (BIA; LP2; IN2): one E- W and the other WNW-ESE. Detailed analyses of the attitude of gypsum cystals permits the establishment of the chronology of the two extensive stages, at least in the LPI locality.

First the E-W extension produced N-S veins with gypsum crystals perpendicular to the edges of the veins.

Then a WNW-ESE extension that reactived older tension gashes, produced new oblique gypsum crystals and new NNE-SSW veins.

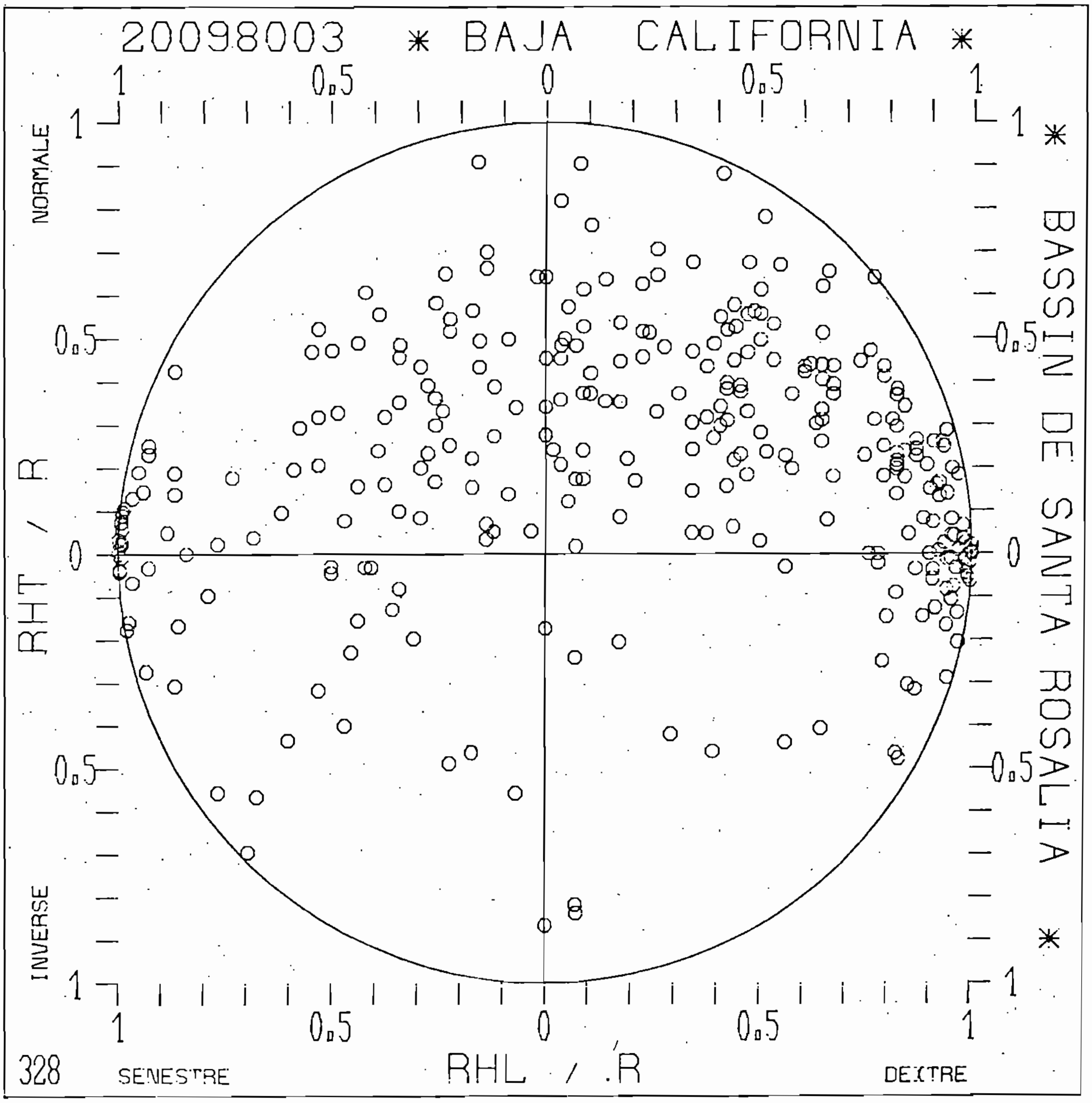

Fig. 4: Plot of the ratio RHL/R (RHL: horizontal -lateral component of the net slip, R: net slip) versus the ratio RHT/R (RHT: horizontal-transverse component of the net slip). Each quadrant of circle corresponds to reverse, normal, sinistral or dextral motion. Note the predominance of lateral movements, RHT/ R= 0 and RHL/R= 1.

During these last two extensive events the earlier pre-Boleo NNW-SSE trends were reactived and major faults of post-Gloria age were directly inherited from older zones of weakenss. Therefore the general faulting trend appears unchanged. At the same time, the Gloria strata experienced an important eastward tilting in the southeastern part of the basin.

The timing of the two ultimate extensions could not be precisely established but it is obvious that tectonic movements went on during Pleistocene time.

Faults scarps which cut the conglomerates of the highest Pleistocene marine terrace(Santa Rosalía Formation ?) can be observed at the "Estación de microondas" of Santa Rosalía, and on the southern bank of the Arroyo de Santa Agueda,near its mouth.

HISTORY OF FAULTING

On the basis of the above mentioned chronostratigraphy, we can attempt to propose a timing of the faulting events. The tectonic history of the Santa Rosalía Basin may be subdivided in six successive stages:

1 . At the end of the Middle Miocene, about 10 My ago (?),occurred an important extension oriented NE-SW to EW associated to an eastward tilting. This first stage produced the major faults of the region that trend principally NNW-SSE.

2 . During the Upper Miocene, extensional processes went on concomitantly to the deposition of the Boleo Formation and to a volcanic and hydrothermal activity.

3 . At the boundary between Miocene and Pliocene, about 6 My ago, a main change in the tectonic regime appeared: strike slip movements occured in reponse to a N-S compressional principal stress($\sigma 1$). The earlier NNW-SSE normal faults were reactivated in right strike-slips.

4 . After Gloria time, at about 4 to 2 My (?), a new E-W extensional regime took place. Extension was milder than in pre-Pliocene events and only reactivated earlier faults while a first generation of gypsum veins occurred.

5 . More recently (not definitely dated), extensional stress changed to a WNW-ESE orientation. As a result of this change, a new set of tension gashes appeared and reactivation of the older structures went on.

6 . During the Quaternary, the Santa Rosalía area has experienced the most important uplift registered on the western coast of the Gulf. This exceptional - uplift is the result of two interrelated phenomena: (1) the regional rising of the Baja California block related to the opening of the Gulf and (2) the local resurgent doming related to the magmatic evolution of the Reforma caldera (Ortlieb, this book; Demant, this book).

CONCLUSIONS

In the Santa Rosalía area, detailed analysis of faulting demonstrates the existence , at about 6 My., of a strike-slip episode included in a dominant extensive regime. Other evidences of lateral movements during Pliocene and Pleistocene time were observed at several localities of the western Gulf coast (Mc Fall, 1968; Minch and James, 1979; and unpublished data).This strongly suggests that the Península, in its eastern part at least, has worked as a complex transform extensional zone since Late Miocene-Early Pliocene time.

During later events (Upper Pliocene ?), the clockwise rotation of the extensional stress from E-W to WNW-ESE is probably related to the spreading of the main basins in the Gulf of California.

ACKNOWLEDGMENTS

This work was supported by the "Instituto de Geología, U. N.A.M." and the "ATP Geodynamique" of the "Centre National de la Recherche Scientifique, (C.N.R.S.)". Field measurements were partly performed by J. CHOROWICS and L. ORTLIEB. Determination of nannofauna was done by Carla MULLER. Mathematical treatment was supported by the "Centre National de la Recherche Scientifique (A.T.P. I.P.O.D.) and the Centre National pour l" Exploitation des Oceans (C.N.E.X.O.)".

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SEQUENCES OF PLEISTOCENE MARINE TERRACES IN THE SANTA ROSALIA AREA, BAJA CALIFORNIA SUR, MEXICO

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ABSTRACT

The coastal area near Santa Rosalía and on the eastern flank of the La Reforma volcanic complex, in eastcentral Baja California, presents an exceptional sequence of Pleistocene marine terraces. These remnants of past high stands of sea-level have been studied along 11 traverses roughly perpendicular to the coastline. The shorelines interpreted to correspond to distinct interglacial sea-level are regularly distributed at elevations varying from about + 9 m to + 190 m above mean sea level. A number of nine main shorelines were identified. Since no radiometric dates are yet available, a tentative chronostratigraphy of these features has been inferred from the V28-238 deep-sea core paleoclimatic curve; according to these correlations nine "interglacial" isotopic stages would be represented: one in early Late Pleistocene, six in Middle Pleistocene, and two in late Early Pleistocene. The Santa Rosalía Formation previously attributed to the base of the Pleistocene is thought to be a late Early Pleistocene (about 1 M. y.) interglacial marine deposit. The vertical motions in the whole coastal area have probably been constant during the Quaternary although uplift rates are interpreted to have changed from a near value of 240 mm/ka to approximately 130 mm/ka, at about 350 000 years B.P.

RESUMEN

La costa cerca de Santa Rosalía y de la ladera oriental del complejo volcánico de La Reforma, en el noreste de Baja California Sur, presenta una secuencia excepcional de terrazas marinas pleistocénicas. Se han estudiado estas huellas de antiguos niveles del mar por medio de 11 secciones perpendiculares a la costa. Las antiguas líneas de costa, que son interpretadas como correspondientes a distintos períodos interglaciales, se encuentran en forma escalonada, estando la más baja a + 9 m aproximadamente, y la mas elevada + 190 m sobre el nivel del mar.

Se identificaron en total nueve líneas de costas principales. Puesto que no existen todavía dataciones radiométricas de las terrazas, se intenta establecer una cronoestratigrafía de éstas a partir de la curva paleoclimática del núcleo V28-238; según estas correlaciones, nueve estadíos isotópicos "interglaciales" serían representados: uno al principio del Pleistoceno Tardío, seis en el Pleistoceno Medio, y dos al final del Pleistoceno Temprano. La Formación Santa Rosalía, anteriormente atribuída a la base del Pleistoceno, bien podría ser un depósito marino interglacial de fines del Pleistoceno Temprano (cerca de 1 M.a). Los movimientos verticales en el conjunto de la zona costera han sido probablemente continuos durante el Cuaternario aunque parece que hace cerca de 350 000 años las tazas de levantamiento cambiaron de aproximadamente 240 mm/ 1000 años, a 130 mm/ 1000 años.

INTRODUCTION

The fluctuations of sea-level related to Pleistocene climatic variations have sometimes been registered and preserved from erosion as series of wave-cut benches, or of coral reefs, or as a succession of depositional features. In eastern Baja California the remnants of past high stands of sea level mainly consist of wave-cut platforms covered by thin littoral deposits. In Baja California peninsula, the region of Santa Rosalía (Fig.1) is known for its elevated Quaternary deposits (Wilson,1948). The coast north and south of Santa Rosalía and the eastern flank of La Reforma volcanic complex prove to exhibit some of the most complete sets of staircase terraces in the Gulf of California area. These series of marine terraces which were only recently (1978-80) surveyed are briefly described here. Lateral and vertical correlations of the distinct shorelines are proposed in an attempt to decipher the amplitude and evolution of the Quaternary vertical movements of this region.

THE SANTA ROSALIA FORMATION

The Santa Rosalía Formation, described and named by Wilson (1948), is the most extended, and possibly the earliest, Quaternary marine unit in the region of Santa Rosalía. This formation crops out on top of the mesas to the W and to the NW of the town of Santa Rosalía. In the NW part of the Santa Rosalía Basin, the formation is overlapped by an ignimbritic sheet. These volcanics were formerly called "Tres Vírgenes volcanics" (Wilson, 1948; Wilson and Rocha Moreno, 1955; Schmidt, 1975), from the name of the Tres Vírgenes volcano (Fig.1) but are related to the volcanic history of La Reforma caldera (Demant and Ortlieb, 1979; Demant, this book). The Santa Rosalía Formation generally overlies unconformably the Infierno Formation. The latter formation was thought to be Late Pliocene (Wilson, 1948), but large scale regional correlations, particularly with the San Diego and Borrego Formations from southern California, suggest that it actually might be, at least partly, of Early Pleistocene age (Colletta and others, in preparation). Consequently the Santa Rosalía Formation would be late Early Pleistocene.

The Santa Rosalía Formation is a marine conglomerate with a sandy matrix. It contains a marine fauna indicating a nearshore or littoral environment. The fossil shells are notably better preserved than those of the underlying Pliocene (?) marine series. Lists of this fauna were published by Wilson (1948) and Ortlieb and Malpica (1978). The thickness of the fossiliferous deposits is commonly 1-3 meters. The marine beds are reported to grade laterally (?) and vertically to coarse terrestial sediments (Wilson, 1948; Wilson and Rocha Moreno, 1955). In the present work, the Santa Rosalía Formation is referred to the marine facies only.

The lithology, the thickness and the faunal content of this sedimentary unit, as well as the location of its outcrops, indicate that the Santa Rosalía Formation is a result of a relatively short transgressive event, as are the Pleistocene interglacial stages . As a matter of fact, the Santa Rosalía Formation is very different, in many aspects, from the three underlying sedimentary formations (Boleo, Gloria and Infierno) of this basin; it would be perhaps better characterized as a morphostratigraphic unit rather than as a formation.

Except for two limited outcrops near the mouth of Arroyo Santa Agueda, Wilson (1948) did not identify the Santa Rosalía Formation along the present coastal area. Nevertheless fossiliferous marine conglomerates, such as those outcropping at about + 200 m, immediately W of the airstrip of Santa Rosalía, can be assigned to this formation (Fig. 2). The lithology and the state of preservation of the fossils in this locality are similar to those of the Santa Rosalía Formation type-

Figure 1.- Localization sketch-map of the Santa Rosalía- La Reforma area, in Baja California Sur.

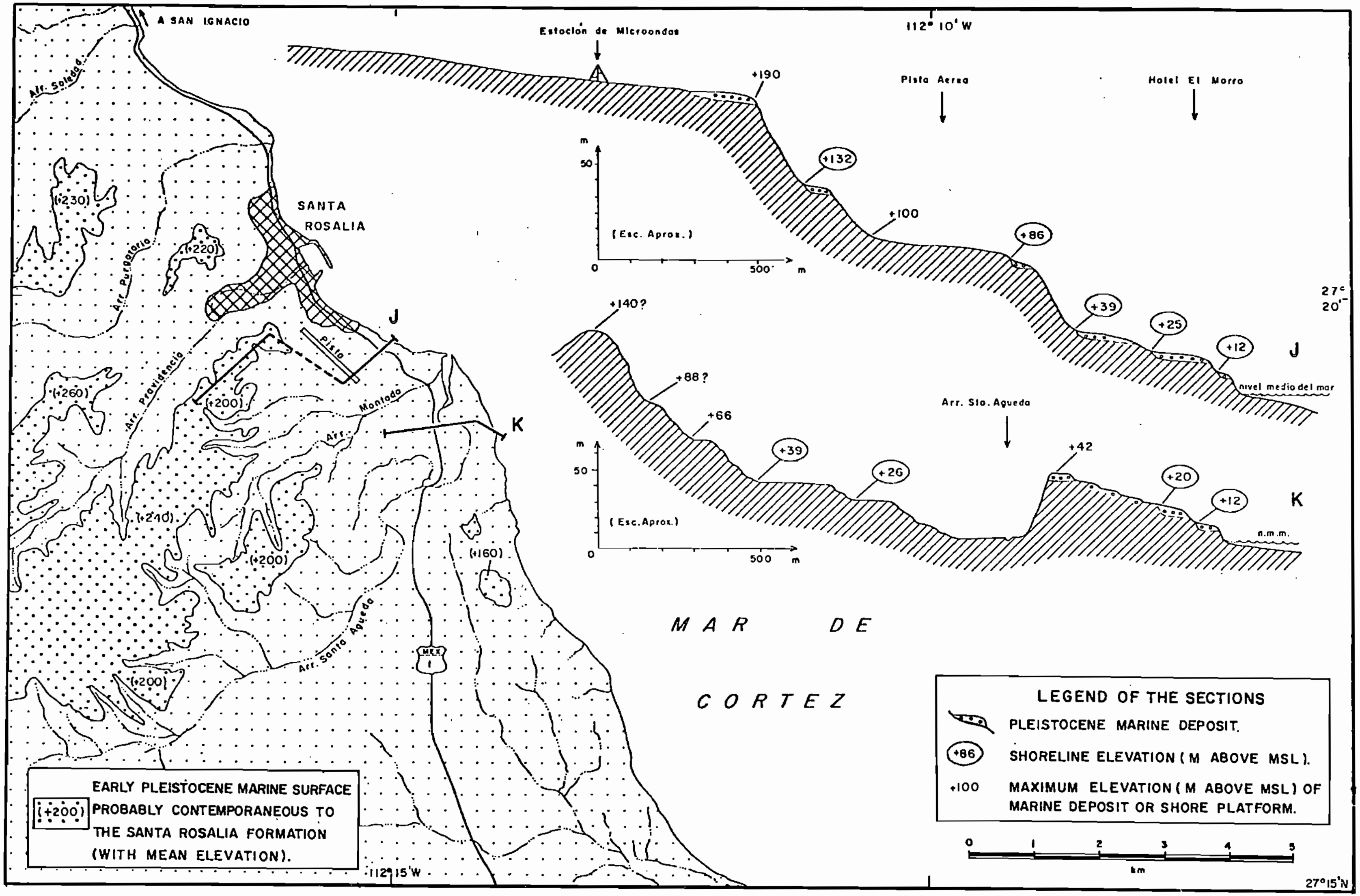

Figure 2.- Cross-sections J and K in Santa Rosalía area: localization and elevations of the Pleistocene shorelines identified south of the town.

localities of the NW part of the basin.

The upper surface of the mesas which dominate the coastal area of the basin is relatively flat and evenly inclined toward the SE; this surface was originally horizontal and has been formed by marine abrasion penecontemporaneously with the Santa Rosalía Formation. It has been affected by a few trending NNW-SSE, notably in the area of Santa Rosalía- Santa Agueda (Colletta and others, in preparation; Colletta and Angelier, this book; Angelier and others, in press).

RECONNAISSANCE STUDY OF THE MARINE TERRACES

The Santa Rosalía coast

Although the Santa Rosalía Formation was studied, and mapped, by Wilson (1948) and Wilson and Rocha Moreno (1955), these authors did not pay much attention to the marine terraces that fringe the littoral areas immediately N and S of the town. Only two of these conspicuous features were noted by Wilson and Rocha Moreno (1955). The highest marine terrace reported by them is between + 100 and + 80 m and corresponds to the wide and subhorizontal surface used for the airstrip, while the second one, between + 40 and + 20 m, constitutes the "Mesas" Francia and Mexico (respectively N and S of the Arroyo Providencia mouth) on which is built part of the town of Santa Rosalía. In a reconnaissance study of the low-lying marine terraces along the Gulf of California, Ortlieb (1978a) and Ortlieb and Malpica (1978) distinguished two terraces at Santa Rosalía, at + 8 -12 m* and at about + 20 m. Recently more complete series of marine terraces have been studied at the southern exit of the town (Ortlieb, 1979a, 1980; Colletta and others, in preparation).

Two cross-sections of the coastal area are presented here (Fig.2). Section J is perpendicular to the shore, starting near the Hotel El Morro, crosses the airstrip (Aeropuerto) and ends on the mesa near the microwave relay station (Estación de Microondas). Section K starts from the coastline, 1,5 km SE of the mouth of Arroyo Santa Agueda, heads NW and then W and terminates on top of the interfluve between Arroyo Montado and Arroyo Santa Agueda (Fig.2). A total number of 9 distinct marine terraces is inferred from these sections (see below).

The marine terraces are identified by their morphology and the presence of typical Quaternary littoral deposits. The width of the platforms varies between a few meters to several hundred meters. The backshore angle, at the foot of the paleo-sea cliff, is not always clearly marked in the topography. The deposits associated with former high stands of sea level are either well preserved (up to 2 or 3 meters of fossiliferous sands and conglomerates) or simply consist of a lag of rounded pebbles including scattered marine shells fragments. The oldest, and highest, littoral deposits are frequently calichified, as a result of meteoric water circulation and mobilization of fossil carbonates. S of Santa Rosalía, the marine terraces have been cut in Miocene and Pliocene rocks. The most elevated ones were carved in the fine-grained Gloria and Infierno Formations, and the lowest ones in the Boleo Formation, or in the volcanics of the Comondú Group.

This study is mainly concerned with the elevations of the distinct Pleistocene shorelines which were registered along the coast. The measurements have been performed with a precision aneroid altimeter, and the results were corrected for the variations of temperature and atmospheric pressure. When possible the shoreline elevations were measured at the backshore angle of the marine terraces. In most cases the maximum altitude reached by the paleo-sea level for each

* All the elevations reported in this work are relative to the present Mean Sea Level (MSL).

terrace could be determined either morphologically, or by interpreting the depth of deposition of the sublittoral, or littoral, sediments when preserved. When the terraces were poorly defined in the field, measurements were performed but these results are regarded as much less significant than the other ones. It must be emphasized that sound lateral and vertical correlations require that measured elevations always correspond to a common datum, which should be the highest level reached by the sea during the formation of the terraces (that is during the maximum stand of the respective interglacial periods).

The lowest and most recent paleo-coastline observed of Santa Rosalía, in both sections J and K, is at + 12 m, and the highest one is at + 190 + 200 m (section J, Fig. 2). The elevations of the 6 intermediate shorelines are found at + 20, + 25, + 39, + 66, + 86 and + 132 m (Fig.2). The two broadest Pleistocene marine platforms are the upper mesa (at about + 200 m), and the surface on which the airstrip is located (+100 m). The lateral correlation between terraces from sections J and I is treated together with that of the terraces found on the eastern flank of La Reforma complex.

The coast of La Reforma

The presence of marine terraces and benches on the coast E of the La Reforma volcanic complex was only briefly mentioned by Bowden (1973), Wright and others (1973), Schmidt (1975) and Schmidt and others (1977). In a preliminary survey, Ortlieb (1978 a) and Ortlieb and Malpica (1978) noted marine terraces at about + 10, + 20, + 50 and + 70 m in the areas of Caleta Santa María and Punta Contrabando, on the SE flank of La Reforma (See location Fig. 3). In 1978-79 additonal field work was done on the coast of La Reforma, and more specifically, along nine cross- sections perpendicular to the coastline. Results of this study have already been reported (Ortlieb, 1979a, 1979b,1980b; Demant and Ortlieb, 1979) but have not been published in full yet.

The La Reforma terraces differ from those studied just S of Santa Rosalía. The former ones generally lack fossiliferous deposits and can be described as true abrasion platforms cut in hard Plio-Pleistocene volcanic rocks. Fossil shells and beachworn organic debris are rarely found, except in some low-lying terraces, but the terraces are easily identified by unconsolidated layers of well-rounded cobbles or pebbles.

The nine sections studied on the flanks of La Reforma, about 2-3 km apart, are presented in Fig. 3. They show from 3 to 8 successive shorelines. The northernmost section (A), at Rancho La Reforma, exhibits three well-defined shorelines, between + 17 and + 70 m and another one more subdued at + 29 m. Immediately NW of Cabo Vírgenes is a spectacular set of staircase terraces, each wave-cut platform being terminated shoreward by the sea-cliff formed during a following transgressive cycle. As the terraces in the area of Cabo Vírgenes have an unusual lateral extension (3km), two sections were studied: sections B to the NW and C to the SE. Six definite shorelines were found between + 28 m and + 167 m in section B, while in section C, five definite shorelines and three indefinite ones were identified, between + 26 and + 154 m (Fig. 3). In the following section toward the S (D), at Cañon Diablo, the lowest shoreline is at + 12 m and the highest one at about + 185 m. Between Punta Prieta and Punta Contrabando, four sections (E, F, G, and H) have been surveyed; they show three to six distinct shorelines at elevations varying from + 9 to + 169 m (Fig. 3). The last section (I), at Santa María, is located at the boundary between the Santa Rosalía Basin and the La Reforma volcanic complex. Since it constitutes an important link between the two areas, it is fortunate that this section presents five definite shorelines (and two more poorly determined paleo-coastlines) at elevations ranging between + 12 and about + 166 m.

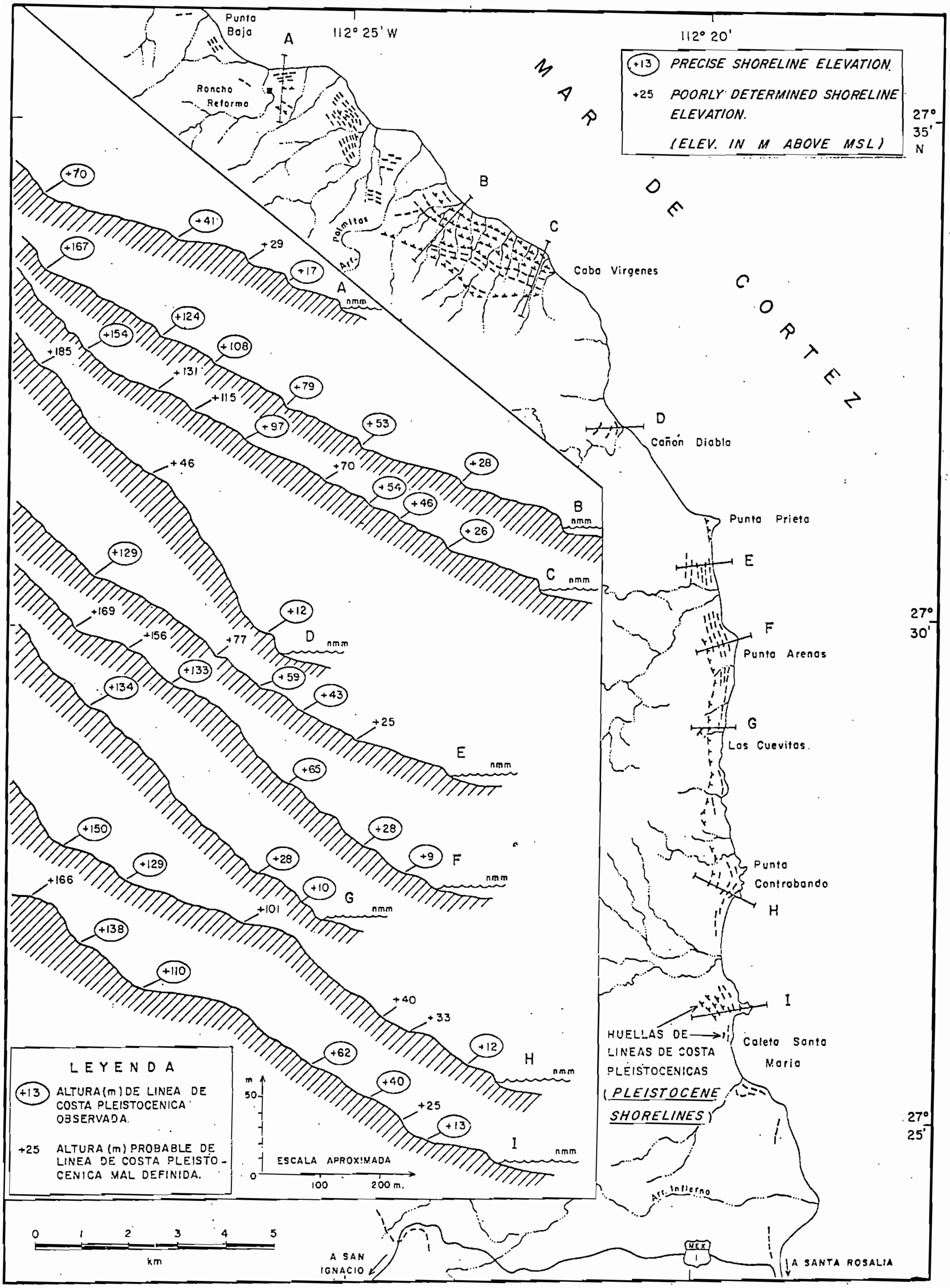

Figure 3.- Cross-sections A to I on the coast of la Reforma: localization and elevations of the observed Pleistocene shorelines.

LATERAL CORRELATIONS AND CHRONOSTRATIGRAPHY OF THE TERRACES

Each marine terrace forming part of a series, is interpreted as a remnant of a high stand of sea- level. These high stands are correlated with the warmer interglacial periods of the Pleistocene. According to deep-sea core data (oxygen isotope ratios, planktonic micropaleontology, ice-rafted debris, $CaCO_3$ ratios, etc.) about a dozen glacial/interglacial cycles occured during the second half of the Pleistocene. Each cycle lasted between 80 000 and 100 000 years. The V28-238 deep-sea core isotopic curve (Shackleton and Opdyke, 1973) has been considered to provide a reliable chronostratigraphy, notably because it seems that the sedimentation rates have been constant (Fig.4). Thus it is worth trying to interpret the chronostratigraphic significance of the series of terraces observed in the area through this paleoclimatic and chronological framework.

At this moment, no radiometric dates which could help in the age determination of the shorelines are yet available. Fossil shells from terrace deposits in Santa Rosalía area have been submitted for U/Th dating, and several volcanic rocks, stratigraphically related to marine terraces features and deposits, are in process of K/Ar dating. Furthermore several samples of fossil material are being analyzed by the amino-acid racemization method. At present the only reported U/Th dates of marine terraces in the Gulf of California were obtained on the Sonoran coast, about 150 km NE of Santa Rosalía; these ages (80 000 - 120 000 years B.P.) concerned Sangamonian (last interglacial) deposits cropping out at less than + 6 m (Bernat and others, 1980). On the Pacific coast of southern Baja California, more Sangamonian fossil material, at a similar elevation, provided an average Uranium-series age of 116 500 years B.P. (Omura and others,1979).

In this work, the Late Pleistocene is meant to cover the period 130 000 - 10 000 years B.P., and the Middle Pleistocene the period 700 000 - 130 000 years B.P. (Butzer,1974). The age of the Pliocene/Pleistocene boundary, which has been discussed for so many years,is supposed to be 1,8 million years.

Rather than attempt to interpret directly the chronology of the marine terraces in each studied section, it seems wiser to examine, first, how do the shoreline remnants correlated from one section to the other.

Lateral correlations of the sections

The results of the altimetric measurements performed along the 11 sections of the Santa Rosalía- La Reforma area are indicated in Table 1. These data include the uncertainties in the measurements as well as for the definition of the shorelines in the field. The presentation of the values in Table 1 recapitulates the lateral correlations proposed for the distinct sections. Because the marine terraces have a restricted lateral extent, only a few of them can be directly correlated in the field. Photo-interpretation and, most of all, geometric considerations on the sequences of shoreline elevations had to be used.

In sections J and K, near Santa Rosalía, four shorelines at + 12 m, + 25 or 26 m, + 39, and + 88 or 86 m, can be easily correlated. Two more shorelines, found in section K, at + 20 m and about + 66 m, seem to have no equivalent in section J. In section J, three high well-marked terraces are observed, at + 100, + 132, 1n3 + 190 m. The latter one corresponding to the upper mesa of the Santa Rosalía Basin is tentatively correlated with the Santa Rosalía Formation (see above). To sum up, the area S of Santa Rosalía shows a total of nine distinct shorelines.

SANTA ROSALIA AREA		LA REFORMA COAST								
Santa Agueda (K)	Santa Rosalia (J)	Santa Maria (I)	Punta Contrabando (H)	Cuevitas (G)	Punta Arena (F)	Punta Prieta (E)	Cañon Diablo (D)	Cabo Virgenes S (C)	Cabo Virgenes N (B)	Rancho Reforma (A)
	190^{+10}_{-5}				169^{+2}_{-7}		185^{+7}_{-7}			
		166^{+8}_{-6}	$\underline{150}^{+2}_{-2}$		156^{+4}_{-4}					
	$\underline{132}^{+5}_{-5}$	$\underline{138}^{+2}_{-5}$	$\underline{129}^{+2}_{-4}$	$\underline{134}^{+2}_{-2}$	$\underline{133}^{+2}_{-2}$	$\underline{129}^{+11}_{-4}$		$\underline{154}^{+2}_{-2}$	$\underline{167}^{+2}_{-4}$	
	100^{+6}_{-6}	$\underline{110}^{+2}_{-7}$	$\underline{101}^{+3}_{-7}$				116^{+2}_{-13}	131^{+19}_{-2}		
88^{+7}_{-5}	$\underline{86}^{+6}_{-5}$					77^{+2}_{-9}		115^{+10}_{-10}	$\underline{124}^{+2}_{-3}$	
66^{+6}_{-6}		$\underline{62}^{+2}_{-6}$			$\underline{65}^{+2}_{-2}$	$\underline{59}^{+2}_{-2}$		$\underline{97}^{+2}_{-7}$	$\underline{108}^{+2}_{-5}$	
$\underline{39}^{+5}_{-5}$	$\underline{39}^{+3}_{-5}$	$\underline{40}^{+4}_{-2}$	$\underline{40}^{+2}_{-9}$			$\underline{43}^{+2}_{-2}$		70^{+6}_{-6}	$\underline{79}^{+2}_{-5}$	$\underline{70}^{+2}_{-2}$
$\underline{26}^{+4}_{-4}$	$\underline{25}^{+5}_{-2}$	25^{+7}_{-7}	33^{+2}_{-8}	$\underline{28}^{+2}_{-2}$	$\underline{28}^{+2}_{-8}$	25^{+4}_{-5}		$\underline{54}^{+2}_{-5}$	$\underline{53}^{+2}_{-5}$	$\underline{41}^{+2}_{-2}$
$\underline{20}^{+5}_{-5}$								$\underline{46}^{+2}_{-6}$		29^{+2}_{-6}
$\underline{12}^{+5}_{-3}$	$\underline{12}^{+2}_{-3}$	$\underline{13}^{+2}_{-5}$	$\underline{12}^{+2}_{-2}$	$\underline{10}^{+2}_{-4}$	$\underline{9}^{+2}_{-2}$		$\underline{12}^{+2}_{-2}$	$\underline{26}^{+2}_{-6}$	$\underline{28}^{+2}_{-4}$	$\underline{17}^{+6}_{-2}$

Table 1 Measured elevations (m above present MSL) of shorelines observed along 11 sections across the coastal area of La Reforma and the Santa Rosalia Basin (Localization in figs. 2 and 3). The accuracy of the measures of elevation mainly depends on the precision with which paleo-sea levels could be determined in the field (the most reliable data are indicated here by underlined values); the distinct ranges stated take account of the indefiniteness of the maximum elevation reached by paleo-sea levels, in each case. The horizontal lines show the suggested lateral correlation (see text).

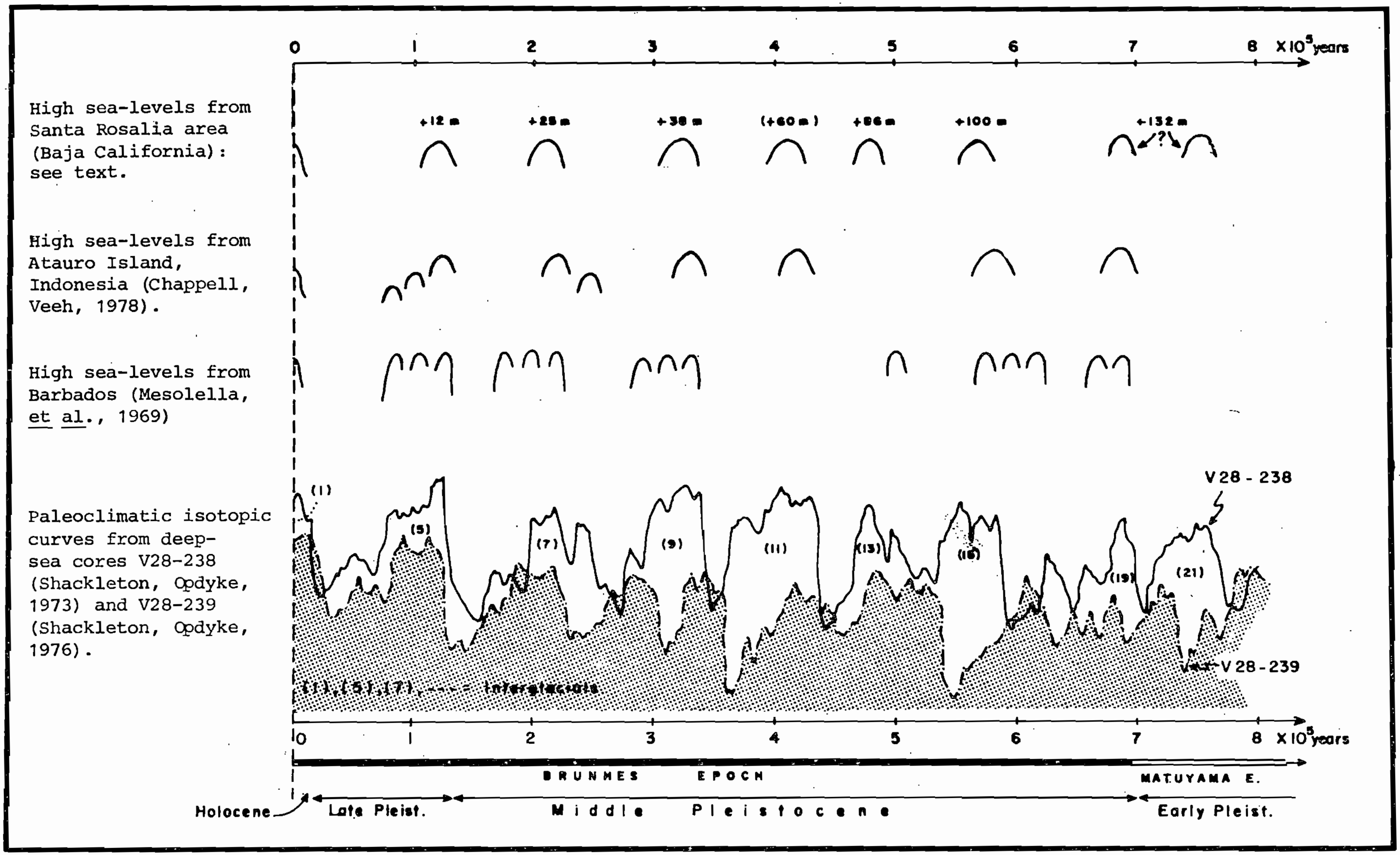

Figure 4.- Speculative correlation between the series of marine terraces from Santa Rosalía (Section J), from Atauro Island and from Barbados, and chronostratigraphic interpretation of these shorelines based on the V28-238 and V28-239 isotopic curves (the most reliable paleoclimatic scale is supposed to be provided by the V28-238 deep-sea core). According to this correlation, the lowest emerged terrace in Santa Rosalía area would be early Late Pleistocene, and the next five or six more elevated shorelines (between +25 and + 132 m) would be Middle Pleistocene.

Between sections J and I, respectively at Santa Rosalía and Santa María, the lateral correlation of the three lowest shorelines is easy to make, since their respective elevations are practically the same (+ 12 and + 13 m; + 25 m; + 39 and + 40 m). The shorelines found at + 110, and + 138 m, at Santa María are interpreted to correspond to those at + 100, and + 132 m, in the Santa Rosalía section, and thus would suggest a slightly more rapid uplift in the former area. The shorelines observed at + 62 and at about + 166 m, in the Santa María section, apparently have no lateral equivalent in the Santa Rosalía section; similarly the + 190 and + 86 m littoral deposits of section J are thought to have no equivalents in sections I. So, on the basis of the proposed correlations between sections I, J and K, there would be a total number of 10 shorelines

Section D, E, F, G, and H are more poorly documented than the preceding ones, and therefore correlation of the scattered shorelines data is rather more hazardous. However, two series of values are noteworthy: a higher series at + 129 m (section E), + 133 m (F), + 134 m (G) and + 129 m (H) and a lower series at + 12 m (D), + 9 m (F), + 10 m (G) and + 12 m (H). The former series is tentatively correlated with the + 138 m (I) or + 132 m (J) shorelines, and the latter with the + 13 m (I) or + 12 m (J, K) shoreline, both previously described in the southernmost sections.

Between sections C and B, at Cabo Vírgenes, most of the marine terraces can be followed in the field and on air-photographs. So the shorelines correlation is in this case better substantiated, even if the exact elevation of maximum stands of sea-level was sometimes difficult to determine (particularly in section C). The backshore angle of the lowest terrace was found at + 26 m (C) or + 28 m (B), and no other remnant of sea-level stand could be observed, in either section, between the present (Holocene) coastline and this elevation. The base of the next following paleo-sea cliff is at + 54 m (C) or + 53 m (B). A small littoral scarp is observed at + 46 m, in section C, but this shoreline progressively disappears to the NW and is thus interpreted as a remnant of a short stand of sea-level that occurred during the regressive phase of the last but one glacial/interglacial cycle. The next following more elevated shorelines are found systematically at higher elevations in section B with respect to section C: + 79 m (instead of + 70 m), + 180 m (+ 97 m), + 124 m (+ 115 m), and + 167 m (+ 154 m). The lateral equivalent of the + 131 m shoreline of section C was not identified in section B. If the + 46 m shoreline of section C is excluded, a total number of 7 shorelines were thus counted in the area of Cabo Vírgenes. Because of the regular spacing of the steplike terraces it is supposed that the coast at Cabo Vírgenes (sections C and B) recorded the last 7 high stands of sea-level, probably corresponding to the last 7 interglacials.

The lateral correlation between sections B and C, and the other sections to the S, depends on the interpretation made for the + 26 (C) or + 28 m (B) shoreline. If the elevations alone are taken into account, it would seem consistent to correlate the + 25 or + 26 m shoreline of sections I, J, and K with the + 26 m shoreline of sections B and C; nevertheless field data show that the latter is the lowest and youngest shoreline while the former is an older one. Consequently the same youngest paleo-shoreline is thought to be presently registered at about + 12 m in almost all the southernmost sections and at about + 27 m at Cabo Vírgenes. The correlation of the more elevated shorelines, between sections B and C on one hand, and sections D to K on the other hand, is made according to this pairing of the lowest terraces.

In the northernmost section (A), where only four shorelines were identified, it seems that uplift rates have been intermediary between those of the Cabo Vírgenes and those of the more southern localities. The lowest observed shoreline is situated at + 17 m . The next higher shoreline was poorly determined in the field, and for that reason might be the lateral equivalent of the faint + 46 m shoreline of section C (and possibly, of the + 20 m shoreline of section K). The two highest definite shorelines are thought to correspond to the + 53 m and + 79 m shorelines of section B.

In conclusion, in the whole area, ten successive shorelines have been identified. One of these shorelines is probably due to a short stillstand during a regressive phase, and the nine others are interpreted as remnants of interglacial high stands of sea-level. The three youngest terraces and the seventh in elevation are generally better preserved than the other ones. Along the coast S of Cabo Vírgenes the shorelines suffered very little local deformations. At Cabo Vírgenes the vertical spacing of the shorelines is as regular as in the other sections but the height difference between successive shorelines is approximately double as compared to what it is in the more southern sections. To be able to compare uplift rates in this coastal area, it is necessary to interpret the chronology of the shorelines.

Chronostratigraphic and paleoclimatic interpretation

According to the V28-238 chronostratigraphy (Shackleton and Opdyke, 1973) the Late Pleistocene was characterized by 4 isotopic stages, and the Middle Pleistocene by 14. Each isotopic stage is considered to correspond to a half glacial/interglacial cycle (except, probably, for stages 2 and 3). So there were probably 8 interglacial high stands of sea-level during the period 700 000- 10 000 years B. P. On the V28-238 paleoclimatic curve, the early Late Pleistocene isotopic stage 5, and the Middle Pleistocene isotopic stages 7, 9, 11, 13 and 15 are well-marked and somewhat better defined than the earlier ones (stages 17, 19, 21 and 23) (Fig.4). The number of glacial/interglacial cycles of the Early Pleistocene is not yet firmly established but is probably low, the Early Pleistocene being often referred to as the "preglacial Pleistocene".

The total number of shorelines found in the Santa Rosalía-La Reforma area compares well with the number of interglacials as interpreted from the V28-238 chronostratigraphy, and with the number of successive marine terraces described in other parts of the world (e.g. Stearns, 1935; Colquhoun, 1965; Broecker and others, 1968; Ward and others, 1971; Bloom and others, 1974; Chappell and Veeh, 1978; Bender and others, 1979).

The lowest and most recent shoreline, which is generally well-defined, is at about + 12 m in the studied area. It is interpreted as early Late Pleistocene, as are the numerous remnants of a low terrace found all along the coasts of the Gulf of California (Ortlieb, 1978a; 1978b; 1979a; 1979b; Ortlieb and Malpica, 1979). It is noteworthy that this lowest terrace is at a significantly higher elevation than in any other locality of the Gulf, except probably at the northermost extremity of the gulf (Ortlieb, 1978b; 1980a). As noted above, the coast at Cabo Vírgenes exhibits its lowest shoreline, and thus probably Late Pleistocene in age, at an elevation much higher than to the E and the S of La Reforma. In fact, the + 28 m shoreline observed at Cabo Vírgenes is thought to be the most elevated remnant of the last interglacial sea-level from the whole Gulf of California. There is no general agreement as to whether the Late Pleistocene maximum stand(s) of sea level was (were) one- or threefold, and in the latter case what were the amplitudes of the fluctuations (Hollin, 1965 and 1980; Steinen and others, 1973; Bloom and others, 1974; Stearns, 1976). In the Gulf of California area no positive field evidence of more than one Late Pleistocene high stand of sea-level has been found, up to now.

The lack of any conspicuous subsequent paleoshoreline below the + 28 m elevation might be a further indication that, if the sea-level rose again after the + 28m stand, it did not reach an elevation comparable to the " maximum interglacial level".

In most of the studied sections a similar difference in height is found between the present mean sea level and the first (lowest) paleo-shoreline, as between the first and the second paleo-shoreline, and also as between the second and the third ones. These height differences are about 10-15 meters, except at Cabo Vírgenes where they are about 27 meters. Assuming that the last Quaternary climatic variations have been cyclic, that the interglacial high stands of sea-level have been eustatically equivalent, and that a relatively regular uplift took place in the area, the constant height difference observed along each section leads to consider that the last and lowest terrace is Late Pleistocene (isotopic stage 5), and that the next two higher terraces probably correspond to the isotopic stages 7 and 9 of the V28-238 chronostratigraphy (Fig.4). The approximate ages of the two sea-level maxima, as deduced from the V28-238 curve (Figs. 4 and 5) are 220 000 and 320 000 years B. P. In the case of the highest shorelines, height differences are more variable than between the youngest ones. Besides, the successive older shorelines have not always been registered (or identified), and so the study of the height difference ratios, between all the sections, is more difficult. A chronostratigraphic interpretation of the series of terraces must take into account the missing shorelines, and so rely on the lateral correlation framework (Table 1).

Three sections are better documented than the others, and moreover are distributed along the whole studied area: Santa Rosalía (J), Santa María (I) and Cabo Vírgenes (B); at Cabo Vírgenes, section B was preferred to section C because its shorelines are more definite in the field, and thus the elevation data more reliable. The chronostratigraphic interpretation of the series of terraces from the Santa Rosalía-La Reforma area are based on these three sections.

Section J, when compared to section K and I seems to be lacking a shoreline at about + 60 m, and another one at about + 160 m. The best correlation fit between the shorelines data of section J and the V28-238 chronostratigraphy is indicated in Fig. 4. This correlation results in assignating each shoreline to an "interglacial" isotopic stage (5 to 15). Because of the relatively large vertical spacing of the + 100 m and + 132 m shorelines, and because of the shortness of the peak 17 in the V28-238 isotopic curve, it is inferred that the high sea-level corresponding to that interglacial did not reach the full "interglacial eustatic level". The time correlation of the + 132 m shoreline with either (or both?) isotopic stages 19 or (and?) 21 (Fig. 4) is speculative . According to the preceeding correlations, and assuming that the uplift rate has been approximately the same, both the probably missing shoreline at about + 160 m, and the + 190 m fossiliferous deposit, may be assigned to the late Early Pleistocene. The age of the + 190 m deposit, being interpreted to belong to the Santa Rosalía Formation, may then be estimated to be about 1 000 000 years B.P. To sum up, the shorelines at + 12 m, + 25 m, + 39 m, + 86 m, + 100 m and + 132, observed in section J are interpreted to correspond respectively to the V28- 238 isotopic stages 5, 7, 9, 13, 15, 19 and (or) 21, while the most elevated shoreline (at + 190 m) is thought to be late Early Pleistocene.

From the tentative chronology suggested for the sequence of shorelines in section (Fig.4), and the lateral correlation proposed in Table 1, possible ages of the shorelines of sections B and I (Fig. 5) are deduced. In section I, the + 62 m, + 110 m, + 138 m and + 166 m shorelines are respectively correlated with the V28- 238 isotopic stages 11, 15, 19 and 21. In section B, the + 108 m, +124 m, and + 167 m shorelines are thought to correspond to stages 11,13 and 19.A

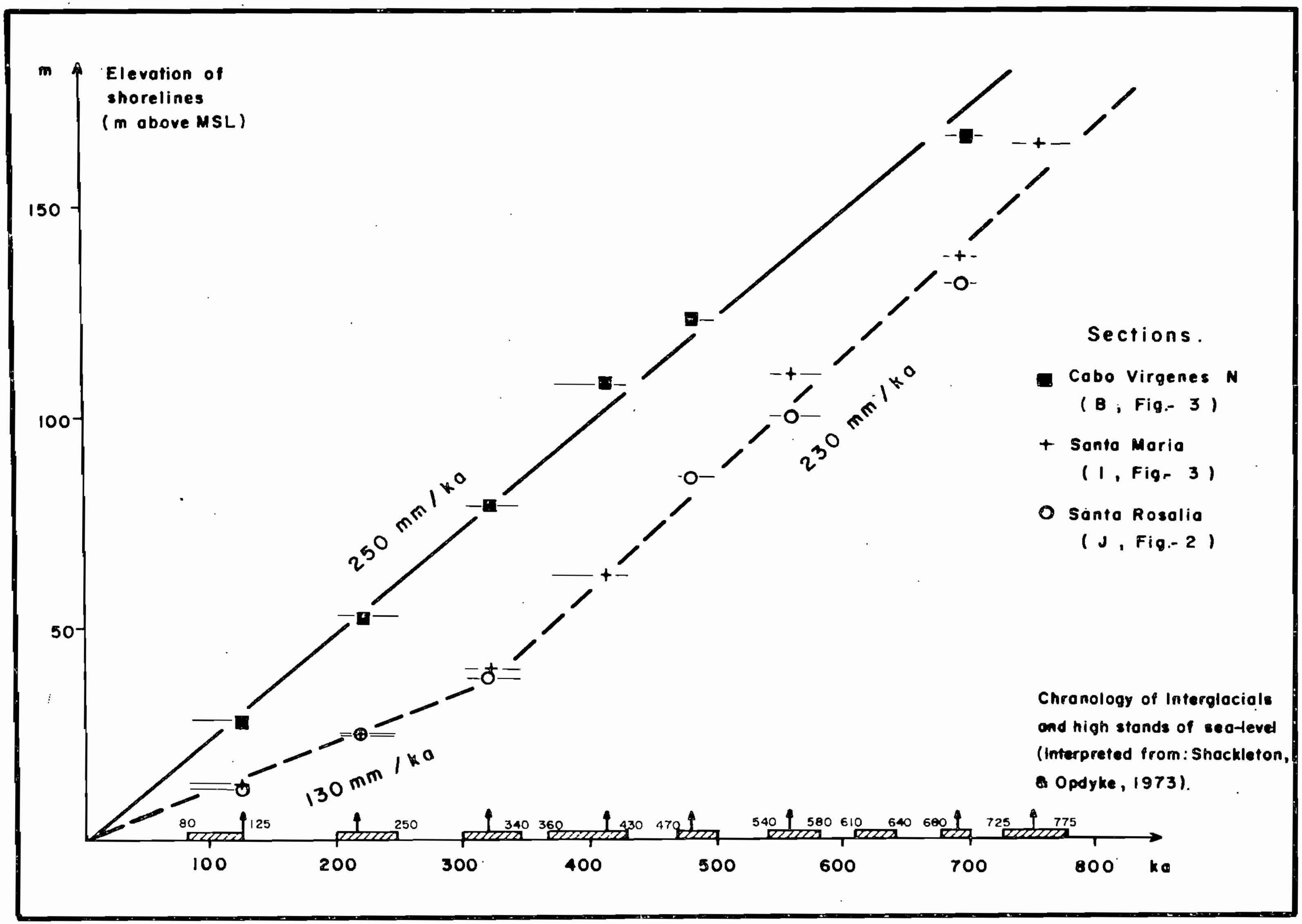

Figure 5.- Tentative elevation-age plot of shorelines from sections B, I and J. Vertical arrows on the time scale correspond to the peak of each "interglacial" stage deduced from the V28-238 isotopic curve (see Fig. 4); hatched boxes and thin horizontal lines figure the duration of the isotopic stages. The plot supports a fair correlation of the successive shorelines with most of the Middle- Late Pleistocene high stands of sea-level. Suggested uplift rates are indicated along the distinct correlation curves.

plot of shorelines elevations versus maximum interglacial ages based on the V28-238 chronostratigraphy (Fig. 5) shows a reasonably good correlative relationship in each section (B, I and J). This plot illustrates that the proposed correlations (both vertical and lateral) suggest different uplift rates between section B on one hand, and sections I and J on the other. The elevation-age plot of the shorelines of section B determines a straight line indicative of a constant uplift rate of 250 mm/ka, and the correlation curve of sections I and J is composed of two straight segments suggesting uplift rates of 230 and 130 mm/ka. Thus the Cabo Vírgenes area would have been submitted to a constant vertical motion since Early Pleistocene time, while the more southern coastal area probably has been uplifted, at a similar rate, during the Early Pleistocene and the first 1/2 of the Middle Pleistocene, and afterwards at almost half this rate (130 mm/ka). The break in the elevation-age correlative curve is situated between the isotopic stages 9 and 11, that is probably around 350 000 years B.P.

CONCLUSION

If many shorelines were registered in the coastal area of the Santa Rosalía Basin and La Reforma, it has been because vertical movements occurred during the major part of the Pleistocene. The relatively regular vertical spacing of marine terraces strongly suggests that these movements have been continuous. According to the proposed chronostratigraphic correlation of the distinct shorelines in the 11 studied sections, it is inferred that the whole coastal area has been uplifted, since about 1 000 000 (?) years B. P. until about 350 000 years B.P., at a rate averaging 240 mm/ka. After 350 000 years B. P., only one locality (Cabo Vírgenes) has continued to be uplifted at this rate, while the rest of the coastal area has been suffering reduced (rate about 130 mm/ka) but continuous vertical movements.

Marine terraces have not been found inland, except for the Santa Rosalía Formation. This formation is closely associated with a morphologic surface (the upper mesas) which evenly slopes down from more than + 300 m, in the NW of the basin (at "Cuesta del Infierno", km 17 of Highway 1), to less than + 200 m at the mouth of Arroyo Santa Agueda (see Fig. 2).

This tilting is related to the volcano-tectonic history of the La Reforma caldera. Since deposits of the Santa Rosalía Formation predate the principal ignimbritic eruption of La Reforma, this unit was most probably tilted during the last stages of the intumescence phase (Demant and Ortlieb, 1979; Demant, this book). This phenomenon accounts for at least part of the inclination of the upper mesas, but cannot be alleged to explain the series of uplifted shorelines observed on the coast.

The whole coastal area, including the La Reforma eastern flank and the surroundings of Santa Rosalía, has been uplifted at a uniform rate, in such a way that no gradient in the vertical motions could be detected. Evidence was provided that Cerro La Reforma, inside the caldera, has been strongly uplifted during the Quaternary; this uplift which might have reached 1 000 m in a million years, has been related to block-faulting and "resurgent doming" (Demant, this book). The mean uplift rate, of the order of 1000 mm/k.a., suggested for the Cerro La Reforma, is several times superior to the rates interpreted from the marine terrace data. Notwithstanding those discrepancies, a regional component of this "resurgent doming" is probably involved in the uplift of the studied coastal area.

Finally, part of the Quaternary vertical motions in the Santa Rosalía-La Reforma area is thought to be related to a regional upheaval of east central Baja California (Ortlieb, 1980b). Since Pleistocene shorelines are found at up to + 50 to + 100 m elevations, in distinct localities along the coast between Santa Rosalía and Loreto, it is clear that tectonic forces, either local or regional, have been active in the second half of the Quaternary. A global comparison of the tectonic behavior on both sides of the Gulf of California shows that the eastern coast of Baja California has been generally uplifted, including during Late Pleistocene time.

More studies on the sequences of marine terraces, and particularly geochronological results, presently underway, are still needed to substantiate the tentative lateral correlations and the chronostratigraphy of the Pleistocene shorelines.

ACKNOWLEDGMENTS

This study has been realized through a cooperative program between the Instituto de Geología , Universidad Nacional Autónoma de México and the Office de la Recherche Scientifique et Technique Outre-Mer. The author benefited by the facilities of the Estación Regional del Noroeste, Inst. Geol., U.N.A.M.. Part of the fieldwork has been done with A. Demant, B. Colletta, J. Angelier, J. Chorowicz and C. Hillaire-Marcel.

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PLIO-QUATERNARY VOLCANISM OF THE SANTA ROSALIA AREA, BAJA CALIFORNIA, MEXICO

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INTRODUCTION

The Santa Rosalía area, located near the 27°30' N parallel on the western coast of the Gulf of California, has been known since the end of the last century for its ore deposits. A new copper mineral, the boleite, was described from this locality (Fuchs, 1886). The Boleo copper veins are interbedded in a thick Pliocene marine sequence (Wilson, 1948). Such marine sediments are more common along the Pacific coast (Darton, 1921; Heim, 1915 and 1922; Mina, 1956 and 1957) than in the eastern part of the peninsula.

From the volcanological point of view, two Plio-Quaternary structures are of particular interest: (1) the Sierra La Reforma caldera (Demant and Ortlieb, 1979), clearly recognizable on the ERTS-LANDSAT documents, and (2) the southernmost cone of the Tres Vírgenes Group (Mooser and Reyes, 1961), the only historically active volcano in Baja California (Ives, 1962). This volcanism is part of an Upper Miocene-Plio-Quaternary magmatic sequence well represented all along the peninsula (Gastil et al, 1975 and 1979).

Considering the general geology of Baja California, the Santa Rosalía area represents a key zone between the Cretaceous batholitic belt intrusive in a volcano-sedimentary sequence, the Alisitos Formation (Gastil et al, 1975), to the north, and the Middle Miocene (McFall, 1968; Gastil et al, 1979) volcanic and sedimentary rocks (Comondú Formation) of the Sierra La Giganta, to the south.

The oldest rocks found in the Santa Rosalía region are quartz monzonites (Wilson, 1948) dated by Schmidt (1975) 91, 2$\pm$2, 1 m.y. Resting on the Cretaceous basement are the Santa Lucía volcanic rocks (Fig. 1), northern limit of the Comondú Formation. They constitute a typical calcalkaline sequence, from basalt to dacite, with some pyroclastic tuffs and breccias (Demant, 1975). In Pliocene time, this irregular paleotopography was invaded by a marine gulf extending as far as 10 Km west of the present coastline. The littoral sedimentation is rather complex and was first studied in detail in the mining district (Wilson, 1948; Wilson and Rocha, 1955). The post-Pliocene volcanism is referred by Wilson (1948) and Schmidt (1975) as Tres Vírgenes Volcanics, but I will not use this designation since these products came from two different volcanic centers; the Reforma caldera and the Tres Vírgenes volcano.

THE TRES VIRGENES VOLCANO

The name Tres Vírgenes designate a group of three volcanoes lying in a NE-SW direction (Mooser and Reyes, 1961), but only one of them, the southernmost, was active during the late Quaternary. This youngest cone is built on a Plio-

Quaternary basaltic plateau overlying Tertiary continental sediments and pyroclastic tuffs of the Comondú formation. The first lavas are relatively viscous and dacitic in composition. Some of these flows, to the north, show well marked "levées" and ridges. At the end of this late Quaternary episode, the volcanic cone reached 2,000 m high.

The historic activity of the Tres Vírgenes volcano is clearly owing to the existence of 18th century manuscripts written by the Jesuit missionaries present at this time in Baja California and according to Ives (1962) an eruption occurred in 1746. Although there was no observation of this eruption, it is possible to reconstruct the succession of the volcanic events by field observations.

The eruption started with a major explosive phase responsible for the important pumice deposits that cover a wide area around the volcano. These pumices do not represent a plinian type eruption, as defined by Lirer et al . (1973) from the last eruption of the Vesuvius, but more likely a succession of gas blasts, a kind of mechanism that happens in strato-volcanoes in their mature stage. The Pumice ce beds 10 to 20 cm thick, alternate with fine ash falls which correspond to drops in gas pressure during the eruption. As a result of the explosive activity, a crater, 1 Km in diameter, was formed on the upper part of the Tres Vírgenes cone and big fractures notched their slopes. A dacitic lava was then pourred out from a fissure on the southern flank, near the base of the volcano, forming a short (1.5 Km) but thick (≃ 100 m) flow, a small dacitic plug was filling up the vent.

Near the SW limit of the summit crater, a small cinder cone built up and the black ashy material it generated covers the top and the slopes of the volcano, - clearly demonstrating a change in the nature of the magma. The lavas, emitted trough a NE-SW fracture, flowed down the flank and formed two malpais at the south-western and south-eastern base of the cone. These are basaltic in composition and have a typical block-lava morphology. The three small viscous dacitic flows (Fig. 1) observed south of the Tres Vírgenes Volcano are also recent, as deduced from their sparse bush cover and their morphology.

The other products emitted by the Tres Vírgenes Volcano are not related to the dacitic ones, but could be due to fissural eruption. Yet, considering the close relations in time and space of these two magmas, the question might be raised as to whether the basalitc lava is responsible of the triggering of the pumicitic eruption, as was considered in many similar events (Sparks, et al, 1977; Self and Williams, 1979).

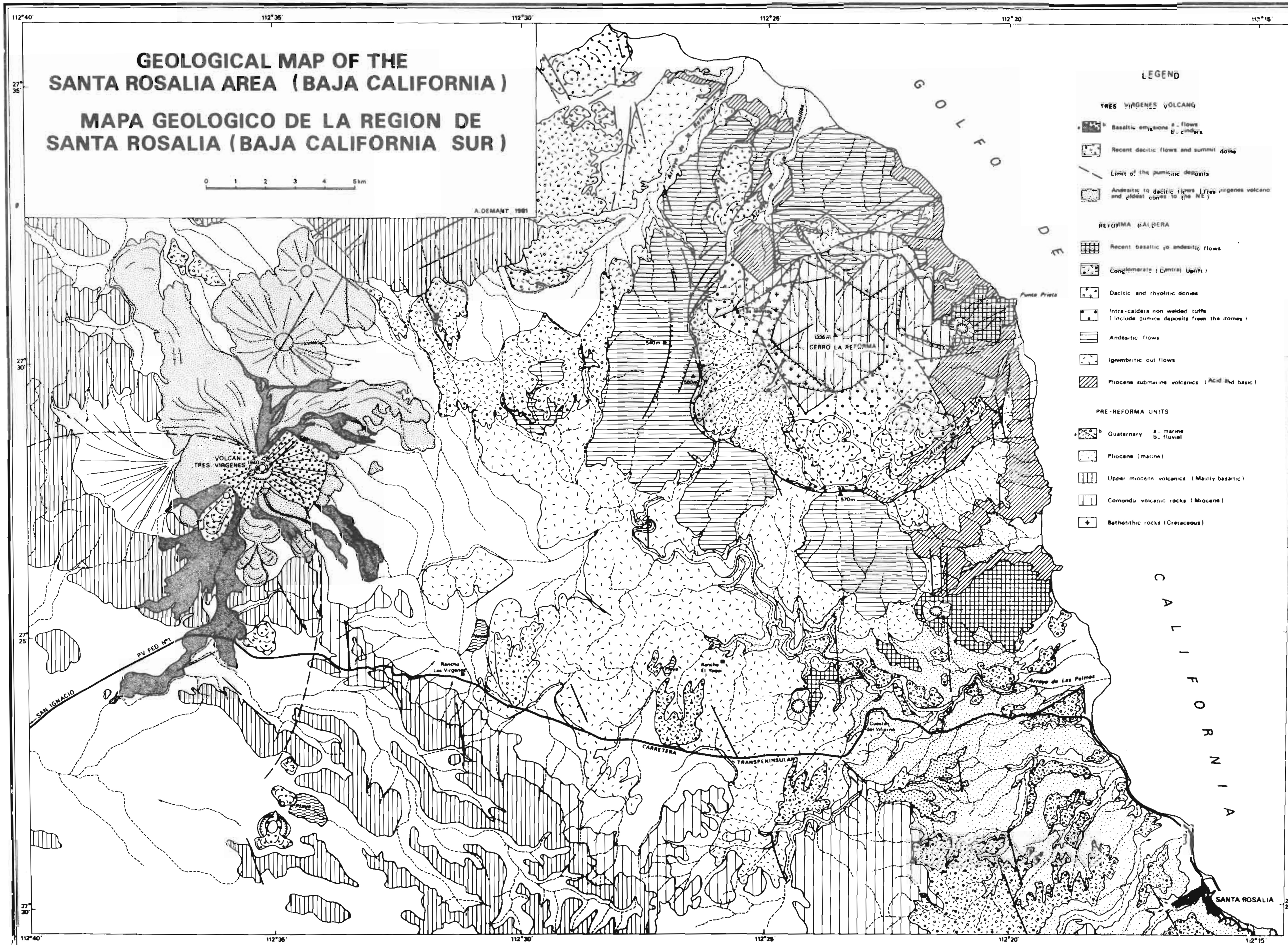
THE SIERRA LA REFORMA VOLCANICS

This wide volcanic structure located 20 km NW from Santa Rosalía presents most of the elements typical of a caldera i.e.: (1) ignimbrite deposits, (2) a central collapse (10 km in diameter) and (3) viscous domes located near the margin of the caldera. The only particular phenomenon that can explain the morphology of the Reforma Caldera, is the large uplift of the central block. Nevertheless, Schmidt (1975) and Schmidt et al, (1977) assert that in spite of its circular outline, the Sierra La Reforma is not a caldera, but a complex system of tectonics blocks, the vertical movements involved being related to the Gulf of California rift system.

Two different periods can be distinguished in the evolution of the Sierra La Reforma: (1) a Pliocene sequence, mainly submarine, and (2) a Quaternary activity responsible for the present morphology.

1.- The Pre-Reforma Pliocene volcanic sequence

It is rather difficult to reconstitute the Pliocene volcanic centers as the older rocks only outcrop in the big cañon cutting the more recent products (Fig.1),



GEOLOGICAL MAP OF THE
SANTA ROSALIA AREA (BAJA CALIFORNIA)
MAPA GEOLOGICO DE LA REGION DE
SANTA ROSALIA (BAJA CALIFORNIA SUR)
0 1 2 3 4 5 km
A. DEMANT, 1981
LEGEND
TRES VIRGENES VOLCANO
Basaltic emissions a_ flows b_ cinders
Recent dacitic flows and summit dome
Limit of the pumicitic deposits
Andesitic to dacitic flows (Tres virgenes volcano and oldest cones to the NE)
REFORMA CALDERA
Recent basaltic to andesitic flows
Conglomerate (Central Uplift)
Dacitic and rhyolitic domes
Intra-caldera non welded tuffs (Include pumice deposits from the domes)
Andesitic flows
Ignimbritic out flows
Pliocene submarine volcanics (Acid and basic)
PRE-REFORMA UNITS
Quaternary a_ marine b_ fluvial
Pliocene (marine)
Upper miocene volcanics (Mainly basaltic)
Comondu volcanic rocks (Miocene)
Batholithic rocks (Cretaceous)
GOLFO DE CALIFORNIA
VOLCAN TRES VIRGENES
CERRO LA REFORMA
Punta Prieta
Arroyo de Las Palmas
Rancho Las Virgenes
Rancho El Yaqui
Cuesta del Infierno
CARRETERA TRANSPENINSULAR
SAN IGNACIO
PV FED Nº1
SANTA ROSALIA
112°40'
112°35'
112°30'
112°25'
112°20'
112°15'
27° 35'
27° 30'
27° 25'
27° 20'

and are included in the marine Pliocene sequence. Pliocene sediments are found up to the center of the caldera, in Las Minitas locality for example, and are mostly yellowish sands and clays, very similar in aspect with the middle Pliocene Gloria Formation defined in the Santa Rosalía area (Wilson and Rocha, 1955). The volcanic activity in the Sierra La Reforma region probably started some 3 m.y. ago.

The first Pliocene volcanic units are pumicitic flows found in the Tertiary sediments. Examples of acid products erupted in a submarine surrounding are rare and in this respect Sierra La Reforma is an interesting area. The pumicitic lava fragments are rounded, enclosed in the yellow Pliocene sands, and they often resemble the pillow structures produced by submarine basaltic eruption. Such pumice flow can be well observed near the coast-line, on the southern rim of the Arroyo del Contrabando, south of the Cerro La Reforma, and also near the Rancho La Reforma, to the north (Fig.1). So they are not localized events, but part of an important acide eruptive sequence developed near to the gulf coast. Very thick (100-150 m) layers of ash pumice falls deposited in the sea, as demonstrated by the included pecten shells, are also present and are conspicous in the southeastern part of Cerro La Reforma, cut by deep cañons. Pumice flow and pumice falls result from plinian-like explosive activity, and lava flow are relatively scarce. Nevertheless in the Arroyo de Punta Arenas, a small obsidian mass can be seen intruding the Pliocene sediments. The brecciated surface of the lava underline a rapid cooling due to the contact with water saturated material. Another outcrop of acid lava is located on the northern rim of the Caño del Diablo, near the shoreline.

The next volcanic unit in the sequence is also submarine, but predominantly basic in composition. It forms a complex system of dykes, sills and lopolites intrusives in the Pliocene sediments as well as in the ash and pumice falls. Prismation is always well developed. The explosive nature of the contact between magma and water explains the formation of brownish palagonitic tuffs, visible for example in the Arroyo de Punta Arenas. Lava flows are sometimes present, as in the northern rim of the Arroyo de La Reforma, where a 30 m thick aphyric lava unit appears among the Pliocene sediments. Pillow structures were formed in the upper part of the flow, while vertical prismation are ubiquitous in the lower part. Schmidt (1975) describes in the Sierra La Reforma granodioritic stocks. One of them, located in the Las Minitas region (Fig.1) was dated 1.34 $\pm$ 0.50 m.y., galene deposits and native sulfur are associated with this "Plutonic event". Two other intrusives, the Cañon del Diablo and the Borrego stocks were distinguished by the same author in the north-eastern part of the Reforma caldera. The exact stratigraphic position of these rocks is not very clear on Schmidt's map.

They outcrop in an area near the gulf coast where numerous basic Pliocene lavas are visible, and in Pliocene sediments (eg. at Las Minitas) and may be considered as part of the pre-Reforma basic intrusive sequence. This interpretation is also supported by the close relationship between the plutonic stocks and the lava flows (Schmidt, 1975).

In the northern rim of Arroyo de la Reforma (Fig. 1), the submarine lavas are overlain, without angular disconformity, by aerial flows; the emersion of this zone was thus progressive. The latter sequence, named Aro volcanics by Schmidt (1975), was dated by the K/Ar method in 1.09 $\pm$ 0.12 m. y. The Aro volcanics are clearly related with the disappearance, in the Pleistocene time, of the Santa Rosalía-La Reforma marine gulf. This sequence outcrops essentially in the eastern and north-eastern part of the Sierra La Reforma ; a black glassy lava of intermediate composition, with elongated feldspar crystals, is a very common facies.

The pre-Reforma volcanism is thus represented by important acid explosive phases followed by numerous intrusions and associated lava flows of more basic composition that were emplaced under water. These volcanic products are not associated with a well defined vent, but the close geographic relation with the more recent Reforma lavas is probably not fortuitous. This sequence ends with aerial eruptions in the Middle Quaternary indicating that the Reforma caldera is very recent, and certainly less than 1 m. y. old.

2.- The Reforma caldera

The caldera forming eruptions are grey colored welded tuffs extending throughout the southern and western regional of Cerro La Reforma, covering an area of at least 100 km^2. In some places, a vitrophyric zone (Smith, 1960a ; 1960 b) can be observed in the lower part of this 10 to more than 50 m thick unit. The ignimbrite plateau is not horizontal, but radially inclined from the center of the structure, and corresponds with the present Cerro La Reforma . The altitude of the ignimbrite deposit varies from 590 m, near the limit of the caldera, to 400 m, 10 km farther south. Such a regular slope ($\simeq$ 2%) is not the mark of an original topography, but the result of a regional uplift related to the development of the magmatic chamber, named intumescence stage by Smith and Bailey (1968).

In the upper part of the Cuesta del Infierno, 15 km WNW of Santa Rosalía, the ignimbrite unit covers a fossils rich marine conglomerate of the Santa Rosalía Formation (Wilson, 1948), situated at + 290 m. This deposit represents the highest Quaternary marine terrace in the Gulf of California (Ortlieb, 1977) and serves to indicate the amplitude of recent vertical movements in this region. In this same locality the first products issued from the Reforma caldera, pumice falls capped by white ash falls can be also observed; this 10 m thick unit is the result of a plinian-type eruption. The close association of plinian and ignimbritic deposits is well explain by the dynamic of these eruptions. As was pointed out by Wilson and Sparks (1979), the mechanisms of both explosions are rather similar, but gas rich eruptions give rise to plinian clouds climbing high in the atmosphere, whereas in the ignimbritic eruptions, the gas and magma mixture is denser and thus spreads horizontally. Between the ash and pumice deposits of the Cuesta del Infierno and the ignimbritic unit, basaltic scoriae are present. Thus basaltic magmas are closely associated with acid products in building up the Reforma caldera. This is also demonstrated by the large basaltic flows, 2 to 10 m thick, that cover the southern and western part of the ignimbritic plateau. In the western part of the Reforma caldera, the volcanic units have filled up a paleo-valley, and are recovered by talus deposits of the Middle Quaternary epoch. The volume of the acid pyroclastic deposits can be estimated in $\simeq$ 5 km^3, while the basaltic one is widely inferior ($\simeq$ 0,5 km^3) due to the thinness of the lava flows.

As a result of the rapid emptying of the magma chamber, a caldera structure, 10 km in diameter and 100 m deep, was formed. A system of concentric fractures cuts the ignimbrites and the basaltic lavas. The structure of the central part is rather complex, as it was affected by later vertical movements and volcanic events. Yellow non-welded tuffs are widespread in this region; they overlie volcanic rocks of the Comondú Formation and the Pliocene sediments. As these tuffs were deposited in an aerial surrounding, they cannot be considered as equivalent to the eastern pre-caldera ash and pumice falls, but are probably related with the Reforma ignimbritic eruptions.

Three rhyolitic domes-coulées, very recent judging from their morphology (since the crests and other flow structures are well preserved) are located near - the southeastern rim of the caldera. Obsidian is very common on the front and -

margins of the flows.Ash and pumice fall deposits cover all the adjacent area and demonstrate the explosive character of the first stage development of these domes. Another lava dome is present on the north-western flank of the caldera, but is cut by the fracture of the Arroyo de Las Palmitas. The eruption of acid magma in caldera structures generally occurs after central subsidence and the resurgent doming phenomenon (Smith and Bailey, 1968), result of the hydrostatic re-equilibration of the collapsed mass, as seen in the classical example of Valles Caldera, New Mexico (Smith et al, 1970).

The most outstanding morphological feature of the Reforma caldera is the tremendous uplift of the Cero La Reforma. This block of Miocene Comondú lavas is the highest point of the area (1,350 m) and it rises more than 800 m over the caldera rim. Yellow tuffs are preserved in some places on its top. The Cerro de La Reforma is limited by faults,and thus corresponds to a tectonic block uplifted by a piston-like movement. This vertical thrust was not uniform, but more pronounced in the south-western part. This difference explains the general tilt toward the northeast of the Cerro La Reforma block and the outcropping of Cretaceous quartz monzonite in the southwestern side of the mountain. The rapid uplift ($\simeq$ 1,000 m in 1 m.y.) has induced an important erosion and the formation of a wide detritical fan that fills up the southwestern part of the collapsed center (Fig.1) and conceals the topographical steep slopes of the caldera in this region. Some volcanic eruptions occurred during the uplift, as demonstrated by the presence of three pyroclastic units interbedded with the conglomerate named Palmas Terrestrial Conglomerate by Schimdt (1975). This author considers the detrital formation as Pliocene in age but it was in fact formed during the Middle Quaternary, after the development of the domes.

Such vertical movement was interpreted in the La Primavera caldera located near Guadalajara, Mexico, as renewed insurgence of magma that may carry the development of a second eruptive cycle (Mahood,1980). In that case, the uplift ($\simeq$ 500 m) would concern the entire center of the caldera, so that the original collapsed zone would be completely concealed and replaced by a convex morphology. In the Reforma caldera, however the vertical movement is rather distinctive. Only - part of the central zone, the Cerro La Reforma, probably located upon the magma chamber, was strongly uplifted, but as a consequence of this rise, blocks of Comondú rocks were also tilted in the western, southern and eastern margins (Fig.1). The northern flank of the caldera also moved upwards, thus the Arroyo de Las Palmillas flows ... to the north, and not alongside the edge of the caldera as the Arroyo de Punta Arenas does in the south-eastern region (Fig.1). Other evidences of the uplift of the northern part are the higher altitudes of the caldera rim (700 m) and of the marine terraces of Cabo Vírgenes (Ortlieb, this book). So, the Arroyo de Las Palmillas does not underline the edge of the caldera, but rather the limit of a more recent local tectonic movement. The important uplift of the Cerro La Reforma has the same volcanic significance than the intumescence stage, and would indicate the strong probability of a new ignimbritic eruption. In any case, the very recent age of the Reforma caldera does not allow to consider this structure as extinguished.

The most recent volcanic eruptions in the Reforma region are basaltic. They built up three scoria cones and associated lava flows: the Palmas and Punta Santa María cones, on the southern and south-eastern flanks of the caldera, and the Punta Prieta volcano to the north-east (Fig.1), which is the youngest. Different lava - flows were emitted from this cone, and the last one covers a marine terrace of Middle Pliocene age (Ortlieb, 1979). These basaltic eruptions, located along N-S to NNW-SSE fractures, are not the result of a new period of activity of the caldera, but indicate that the interference of important volumes of such a basic material with the rhyolites in the magma chamber is probable. Such a mechanism is generally considered as the cause of a rejuvenated stage in acid systems.

So as shown by field work, Sierra La Reforma is really a caldera structure, whose formation started in the Late Quaternary ($\simeq$ 1 m.y.). After a regional vertical uprise related to the intumescence stage ignimbritic eruptions occur immediately followed by basaltic emissions.

As a consequence of the partial emptying of the magma chamber a circular zone collpase forms a caldera. Following the hydrostatic re-equilibration of this central part, acid lavas erupt near the caldera rim, building up four domes. The outstanding characteristic of this caldera is yet the important uplift of the Cerro La Reforma block which also moved up the adjacent areas.

Only few K/Ar data are available (Schmidt, 1975; Schmidt et al, 1977) and they concern only the pre-caldera volcanics. These ages date the drying up of the marine gulf in $\simeq$ 1 m.y. Age determinations on the Quaternary lavas are in progress, and it wouldbe particularly interesting to correlate the marine terraces corresponding to the first regional rise (intumescence stage), and the last piston-like uplift of Cerro La Reforma which are the cause of the staircase wave-cut terraces well preserved on the eastern side of the caldera (Ortlieb, this volume).

PETROGRAPHY AND CHEMISTRY OF THE LAVAS

1.- Volcanic rocks from Tres Vírgenes volcano

The lavas emitted by the Tres Vírgenes volcano are porphyric and they have a rather constant mineralogy. Plagioclase phenocrysts are more than 1 cm long ; clino-pyroxene + orthopyroxene + hornblende are the ferro-magnesian minerals. The glassy matrix contains few feldespars and pyroxene microlites. In one of the viscous lava flow located on the southern flank of the cone, biotite, quartz and olivine are also present. This last mineral is rimmed by ortho-pyroxene. Such a complex association is probably the sign of the mixing of the dacitic magma filling the chamber with an uprising basaltic lava. The pumice deposits surrounding the volcano, and the more recent dacitic flow located on the southern foot of the - cone have the same mineralogy and are certainly connected with the Tres Vírgenes magma chamber. Three samples were analyzed (Table 1). All are dacitic in composition and show a weak evolution from 63 to 66% of silica. Considering their mineralogy and chemistry these rocks are typically calc-alkaline dacites.

The 1746 black lava is on the contrary very different as its chemical compositon is basaltic (Table 1). This rock is aphyric and only a few small olivine - phenocrysts with quenched morphology can be observed. The brown glassy matrix contains plagioclase microlites, small olivines, clino- pyroxenes, and numerous magnetite grains. Chemically this basalt (52% of silica) has a relatively high alumina content, calcium and alkali values are high also and it has also a definite calc-alkaline character. It contains 4.5% of normative olivine in the C.I.P.W. norm, but no nepheline. This basaltic lava has no obvious relationship with the Tres Vírgenes dacitic magma chamber, but represents a small batch of basic magma rising from a deeper zone.

2.- The Reforma volcanic rocks

The succession of volcanic events is complex in the Sierra La Reforma, but as a result of the volcanological study, two sequences can be distinguished: the pre-caldera sequence, and the Reforma volcanics.

2.1.- The pre-caldera sequence

The pumicitic rocks, conspicuous near the Gulf coast, contain only a few -

phenocrysts of plagioclase and greenish clinopyroxene. Magnetite, apatite, and zircon are accesory minerals, and the groundmass is glassy. A small acid lava pile outcropping in the eastern region has the same mineralogical composition,but the pumice flows interbedded in the Pliocene sediments are completely aphyric. A fragment samples in the center of a "pumicitic pillow" was analyzed, giving a rhyolitic composition (Table 2), but more detailed chemical studies on the pumice falls deposits are difficult because of their contact with sea water.

The structure of the submarine basic Pliocene lavas is rather variable as the cooling conditions change according to the size of these intrusions. In the palagonitic tuffs, the basaltic fragments have a glassy quenched structure while in the thick lava flows a finelly crystallized groundmass is observed. The porphyric intrusives stocks described by Schmidt (1975) represent in fact the largest Pliocene emissions, and this explains their microcrystalline structure, the similar petrography and the close connection with the lava flows. Olivine is not common in these rocks though relics of peridot are in some case observed included in pyroxene crystals. Plagioclase is the most abundant mineral, and is associated with orthopyroxene, clinopyroxene and small magnetite grains. Calcite is very frequent, probably as a result of the contact with Pliocene sediments. In the intrusive stocks (Schmidt, 1975), hornblende and biotite are present but generally in the groundmass. These lavas are mostly andesites, and true basalts are rare. In the two analyzed samples (Table 2) the amounts of Al_2O_3 are low and those of FeT relatively high but the chemical diagrams show a well defined calk-alkaline character.

Among the Quaternary Aro volcanics, a plagioclase rich dacitic facies is frequent. The plagioclase crystals present large glassy inclusions. Clinopyroxene, orthopyroxene and magnetite are the others phenocrysts. The matrix is glassy and contains small feldspar microlites . The chemical analyses (Table 2) confirms the silica-rich nature of these lavas. The three basic Pliocene samples show a regular evolution of the different oxydes and their mineralogical association are similar. These rocks are probably the products of a common parent magma.

2.2.- The Reforma volcanics

The ignimbrites covering the flanks of the Reforma caldera are typically aphyric. The more common minerals are euhedral plagioclases and greenish clinopyroxenes, but some fayalite crystals can also be observed. The pumices from the Cuesta del Infierno pumice falls deposits have exactly the same mineralogy; they are beyond doubt part of the caldera forming eruptions. The peralkaline character of these rocks is indicated by the presence of acmite in the C.I.P.W. norm (Table2). Using the nomenclature of MacDonald (1974), the FeO^T and Al_2O_3 values classify these rocks as comendites.

On the flanks of the caldera, the ignimbrite units have thereafter been covered by more basic flows. These lavas contain a plagioclase + clinopyroxene + orthopyroxene phenocrysts association. The same minerals are present as fine microlites in a brown glassy matrix. The analyzed rock (Table 2) has an andesitic composition, very similar to one of the Pliocene lava.

Two samples of the post-caldera domes were studied with more detail. One of them (1083) has a mineralogical association similar to that of the ignimbrite but the fayalite crystals are completely transformed. The chemical composition is almost identical, though no acmite is formed in the C.I.P.W norm. The other lava (1094) has higher Al_2O_3 and CaO contents, and has a calc-alkaline character.

The last volcanic eruption in the Reforma region is the Punta Prieta scoria cone and its associated flows. These lavas are porphyric and they contain numerous-brown amphiboles which have totally reacted to form a fine grained magnetite-rich pseudomporh . Clinopyroxene is also abundant and olivine is present in the center of some pyroxene clusters. Plagioclase phenocrysts are not common, but the groundmass contains numerous fine feldspars, and pyroxene microlites, magnetite grains, brown glass and tridymite. This lava is an alkali-rich, low-silica andesite (Table 2).

From this mineralogical and chemical study of the Reforma and Tres Vírgenes volcanics, some results can be emphasized.

(1) There is no difference between the pre-caldera Pliocene rocks and the Quaternary Reforma sequence. The chemistry of the lavas is rather similar, and a bi-modal distribution of andesites and rhyolites is observed in both cases. The close geographic relation of the Pliocene products with the Reforma caldera, and the absence of such an activity in the Santa Rosalía area also demonstrate that the Pliocene events represent the first stage of the caldera development.

(2) The La Reforma ignimbritic products have a comenditic affinity, but this peralkaline character is not observed in the dome lavas or in the Pliocene pumicitic eruptions. In fact, a loss of alkalies as a result of hydrothermal alteration or hydration of the glass is frequent in this type of rocks and leads to a lowering and a loss of the agpaitic character (Araña et al, 1974). Yet one of the rhyolitic lava domes has a well-defined calc-alkaline tendency.

(3) In fact, the great majority of the Plio-quaternary Reforma and Tres Vírgenes volcanic rocks show a calc-alkaline affinity. No tholeiitic lavas were found in the Santa Rosalía area. Schmidt (1975) and Schmidt et al, (1977) have pointed out an important change in the Reforma products from Pliocene calcl-alkaline rocks to Quaternary tholeiitic products, but in fact none of their chemical analysis exhibit a tholeiitic tendency. On the contrary, the latest basaltic eruptions from the Tres Vírgenes volcano and from the Punta Prieta cone show a middly alkaline character according to the diagram of Schwarzer and Rogers (1974).

(4) The close association of basic magmas with the dacitic products of the Tres Vírgenes volcano or with the rhyolitic ignimbrites of the Reforma caldera implies the intervention of phenomena triggering an acide explosive eruption and magma mixing is probable.

(5) Comenditic rocks normally occur in oceanic islands or continental zones of marked tensional tectonics, as oceanic islands near crests (Baker, 1974) or continental rifts like the Afar depression (Barberi et al, 1974). The La Reforma comendites are related with such a tensional tectonic, as they lie in the margin of the Gulf of California rift system, but they are also closely associated, as are the comendites of Sardinia (Araña et al, 1974) or those from La Primavera in the Trans-Mexican volcanic belt(Mahood,1977 ; Demant 1978 and 1981), with a calc-alkaline sequence. In fact the volcanism of the Santa Rosalía area has to be considered within the more general framework of the magmatism related with the evolution of the Gulf of California.

DISCUSSION: TECTONICS AND MAGMATISM IN THE GULF OF CALIFORNIA AREA

About 30 m.y. ago, the East Pacific Rise reached the continental plate of North America; the Farallon plate subduction stopped and right lateral motion took place along the north-western coast of Mexico (Atwater,1970). South of La Paz, oceanic crust appeared between 6 and 3.5 m.y. as a result of the jump of the East Pacific Rise to its present position (Mammerickx, 1979). Before Pliocene time the Gulf of California was most probably an extensional zone (Karig and Jensky, 1972; Chorowicz et al, 1980), and may be considered as a continental rift in an early stage of its history.

The 10 m.y. old basalts lying upon the Comondú Formation (Gastil et al, 1979) seem to be related to this continental opening. Studies provided evidence that the Gulf of California is now a region of lithospheric plate separation (Moore, 1973); spreading zones were recognized in several basins, and tholeiitic basalts were cored in the Guaymas Basin. Isla Tortuga, east of Santa Rosalía is a recently formed island with such a tholeiitic affinity (Batiza,1978). Yet, on the peninsular block, tholeiitic rocks are not present, and a complex association of calc-alkaline rocks, on the Gulf side, and alkaline rocks near the Pacific side was recognized by Gastil et al,(1979). The calc-alkaline magmatism is not related with a subduction zone, and is probably atypical. Until now, no satisfactory explanation of this sequence has been provided.

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	1106	1076	58	1078
SiO_2	65.42	64.09	62.74	52.02
TiO_2	0.73	0.73	0.90	1.48
Al_2O_3	15.07	14.35	16.07	17.77
Fe_2O_3	1.73	1.05	2.01	2.77
FeO	2.42	1.84	2.49	4.45
MnO	0.07	0.07	0.07	0.12
MgO	2.36	1.54	1.96	5.26
CaO	4.36	4.12	4.45	9.83
Na_2O	4.36	4.82	4.92	4.39
K_2O	2.50	2.34	2.06	0.78
P_2O_5	0.17	0.04	0.23	0.39
H_2O+	0.44	4.54	1.00	0.10
H_2O-	0.09	0.20	0.12	0.04
Total	99.72	99.73	99.02	99.40
	C. I. P. W. Norms			
Q	18.60	18.46	14.78	-
Or	14.79	14.57	12.18	4.61
Ab	36.85	42.89	41.58	37.10
An	14.13	11.14	15.65	26.44
Di	5.21	8.14	4.07	15.98
Hy	5.34	1.65	4.51	3.01
Ol	-	-	-	4.42
Mt	2.51	1.60	2.91	4.01
Ilm	1.39	1.46	1.71	2.81
Ap	0.40	0.10	0.54	0.92

1106: viscous dacitic flow, eastern flank of the cone
27°27'00" N 112°34'00" W

1076: pumice fall deposits from the Tres Virgenes
27°24'30" N 112°34'45" W

58: small recent dacitic flow, southern foot of the cone
27°24'50" N 112°35'15" W

1078: 1746 basaltic flow
27°24'40" N 112°36'30" W

Table 1: Chemical analysis, CIPW norms, petrography and localization of Tres Virgenes volcanics.

	749	1985	1098	1082	1074	1079	1083	1094	1104
SiO_2	72.29	56.36	58.63	66.50	70.80	59.69	70.99	65.69	55.56
TiO_2	0.20	2.16	1.25	0.90	0.55	1.42	0.32	0.49	1.33
Al_2O_3	12.78	14.97	15.61	14.65	11.75	15.06	12.42	13.57	15.97
Fe_2O_3	0.26	1.27	2.53	1.34	2.35	2.20	0.67	1.78	2.96
FeO	1.12	8.22	4.87	2.90	0.97	5.07	2.10	1.07	3.81
MnO	0.01	0.13	0.12	0.07	0.10	0.12	0.01	0.06	0.12
MgO	0.08	4.66	3.74	0.99	0.17	3.30	0.07	0.51	4.26
CaO	0.54	5.37	6.45	1.94	0.90	5.66	0.57	1.91	7.32
Na_2O	3.77	3.99	4.18	5.47	4.95	4.64	4.90	4.22	4.55
K_2O	4.65	1.36	1.72	2.82	3.82	1.78	3.72	2.90	1.92
P_2O_5	0.01	0.55	0.33	0.19	0.04	0.39	0.01	0.02	0.41
H_2O+	3.97	0.14	0.68	1.59	2.98	0.75	3.08	6.18	0.94
H_2O-	0.30	0.07	0.03	0.10	0.18	0.06	0.15	0.99	0.12
Total	99.98	99.25	100.14	99.46	99.56	100.14	99.01	99.39	99.27
				C.I.P.W. norms					
Q	32.02	7.00	9.35	17.79	27.90	9.74	27.28	27.41	3.14
Qr	28.74	8.04	10.17	16.68	23.44	10.52	22.97	18.60	11.35
Ab	33.29	33.72	35.32	46.23	40.53	39.21	43.23	38.67	38.45
An	2.74	18.89	18.71	7.06	-	14.97	0.92	10.15	17.44
Ac	-	-	-	-	2.53	-	-	-	-
Dl	-	3.74	9.19	1.21	-	8.82	1.75	-	13.09
Hy	1.80	20.50	9.88	4.73	-	9.29	2.17	1.38	6.99
Wo	-	-	-	-	1.32	-	-	-	-
Mt	0.39	1.84	3.66	1.94	1.93	3.19	1.01	2.41	4.29
Hem	-	-	-	-	0.23	-	-	0.27	-
Ilm	0.40	4.10	2.37	1.71	1.08	2.69	0.63	1.01	2.52
Ap	0.02	1.30	0.78	0.45	0.10	0.92	0.02	0.05	0.97

749: pumicitic flow in Pliocene sediments, southern rim of Arroyo de Punta Prieta 27°26'30" N 112°19'45" W

1085: thick lava flows in Pliocene sediments, northern rim of Arroyo de las Palmillas 27°34'30" N 112°26'15" W

1098: Pliocene lava flow, unnamed arroyo north of Cañon del Diablo 27°32'00" N 112°21'30" W

1082: aerial dacitic lava of the Aro sequence, north of Las Minitas 27°32'00" N 112°25'15" W

1074: ignimbritic vitrophyric level, Cuesta del Infierno 27°23'30" N 112°22'45" W

1079: basic lava flow overlying the ignimbrites, southern flank of the caldera 27°27'30" N 112°25'00" W

1083: rhyolitic dome, north-western rim of the caldera 27°27'30" N 112°25'30" W

1094: rhyolitic dome inside the caldera, southern region 27°29'45" N 112°24'30" W

1104: recent lava flow from the Punta Prieta cone 27°31'00" N 112°20'00" W

Table 2: Chemical analysis, Cipw norms, Petrography and localization of La Reforma volcanics samples.

LATE CENOZOIC VOLCANISM IN THE TRES VIRGENES AREA

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ABSTRACT

Four periods of late Cenozoic volcanism are represented by the volcanic rocks in the Tres Virgenes area, northern Baja California Sur. Neogene volcanism consists of calc-alkalic andesite that is succeeded by tholeiitic basaltic rocks. Pleistocene bimodal, basaltic-rhyolitic volcanism predates the Tres Virgenes calc-alkalic, basalt through dacite suite. At La Virgene volcano, the principal vent of the Tres Virgenes rocks, two major sequences of basalt through dacite testify to the two-stage evolution of this volcano. The Tres Virgenes vents are aligned north-south and parallel the extensional, Aguajito fault zone which may be a product of northwest-southeast right-lateral shear couple.

RESUMEN

Cuatro epochas de volcanismo del Cenozoico último son representados por las rocas volcánicas en la área de las Tres Virgenes en el parte más norte de Baja California Sur. Volcanismo del Neogeno se compone de andesita calc-alcalina y el más jóven basalto tholeiitico. Volcanismo basaltico-riolítico de dos modas del Pleistoceno antecede basalto a dacita calc-alcalina de las Tres Vîrgenes. Al volcán La Virgene, la abertura principal de làs rocas Tres Virgenes, dos sucesiónes de basalto a dacita testifica al evolution de esta volcán en dos series. Las aberturas de las Tres Virgenes compone una linea del norte al sur y siguen paralelo a la zona de faltas extensional de Aguajito que pueden ser un producto de esfuerza derecha-lateral en una dirección noroeste-sudeste.

INTRODUCTION

Tres Virgenes rocks compose two stratovolcanoes, La Virgene and La Soufre, and satellite vents that crop out in a north-south linear array west of las Vîrgenes valley (Fig. 1). This Tres Virgenes volcanism is Pleistocene and/or Holocene in age, and it was preceded by three magmatic episodes since Miocene time (Fig. 2). Oldest to youngest, these 3 episodes are represented by: (1) the early Miocene Andesite of the Sierra Santa Lucia; (2) the (?) mid to late Miocene Basalt of Esperanza; and (3) the Pleistocene La Reforma ignimbrites and basalt.

The Tres Virgenes area discussed herein is approximately 20-25 km wide and approximately 40 km in length (north-south). The eastern margin of this area is the La Reforma volcanic complex to the north and the village of Santa Agueda to the south (Fig. 1). The Boleo basin and La Reforma are thus not included.

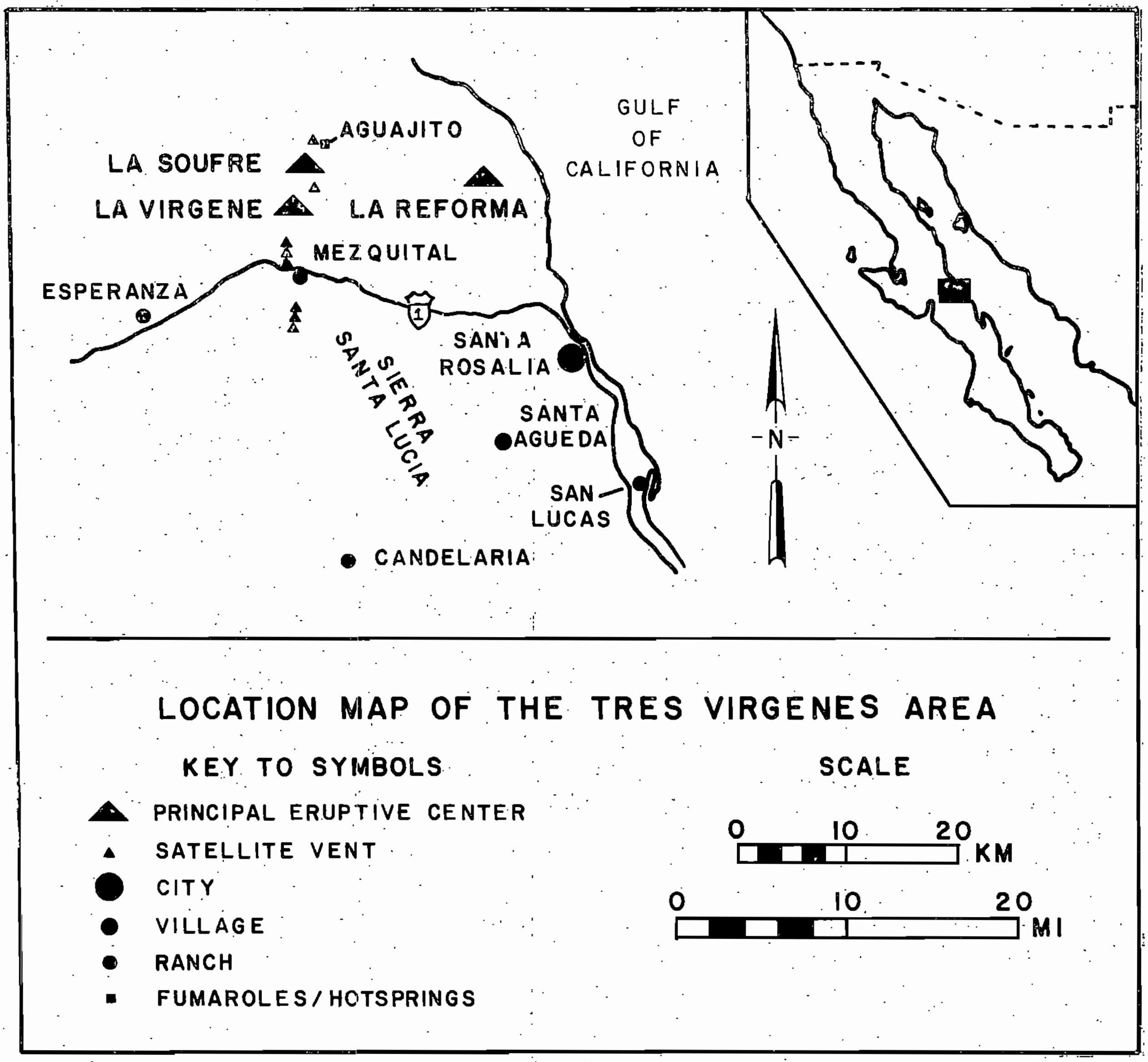


Figure 1. Location map. Rectangle in inset sketch map of Baja California represents the area of the location map. The area between La Soufre, La Reforma and highway 1 is Las Virgenes Valley.

PRE-TRES VIRGENES ROCKS

Granitic rocks of Cretaceous age crop out in the area between highway 1 and La Reforma and they probably form a plutonic basement in the Tres Virgenes area. Overlying these granitic rocks is a late Cenozoic volcanic cover that includes the Andesite of the Sierra Santa Lucia, the Basalt of Esperanza, and the La Reforma volcanic rocks.

The Andesite of the Sierra Santa Lucia is exposed mostly south of highway 1 (Fig. 1). This unit comprises gently-dipping (10^o or less) andesite, and mudflows and minor associated fluvial and eolian sediments that increase in abundance to the west. Hornblende is the characteristic phenocryst of the andesite. X-ray fluorescence analyses of 13 samples show that the volcanic rocks of this unit are calc-alkaline with respect to variations in FeO*/MgO vs SiO_2 (Miyashiro, 1974), have a limited range in silica of 57-64% SiO_2, and have $K_2O \approx 1.3$ at 60% SiO_2 (Table 1). An early Miocene age is assigned on the presumption that this unit correlates with the 22-17 m.y. hornblende andesite of Gastil and others (1979).

The ?mid to ?late Miocene Basalt of Esperanza crops out mostly north of highway 1 and west of the Tres Virgenes volcanoes in the Tres Virgenes area (Fig. 1). It consists of mesa-forming basalt flows that apparently issued from nearby, monogenetic cones. The lava flows tend to be laterally extensive in contrast to the localized, intercoalescing flows of the Andesite of the Sierra Santa Lucia. The contact between these two Miocene volcanic units is observed only in an area south of La Virgene volcano where the Basalt of Esperanza disconformably overlies the Andesite of the Sierra Santa Lucia (Figs. 3A,B; 4A,B). Petrographic studies indicate the most common rock type is basaltic andesite rather than true basalt. Typically, the rocks lack olivine, and the common phenocryst assemblage is Plag + Opx + Cpx + Fe-Ti oxides. A single chemical analysis indicates that K_2O is very low and total iron is markedly higher than in the Sierra Santa Lucia and Tres Virgenes rocks (Table 1). The chemistry is tentatively characterized as tholeiitic. It is similar to an analysis of basalt from near San Ignacio, a town about 30 km west of Esperanza, that was dated by Gastil and others (1979) at 11.1 ± 0.8 m.y.

The youngest of the pre-Tres Virgenes rocks are Pleistocene (Wilson, 1949) rhyolite ignimbrite (ash-flow tuff) and basalt that erupted from the La Reforma complex and perpherial vents, respectively (Fig. 2). La Reforma tuffs consist of two ignimbrite sheets exposed mostly north of highway 1 (Fig. 1) and east of the Tres Virgenes (Fig. 3A,B). In addition, remnants of intracanyon flows of the older ash-flow crop out in arroyo Santa Agueda, 4-8 km southwest of Santa Agueda, and in arroyos west of the Tres Virgenes. This ash-flow spread across las Virgenes valley, and in one instance, surmounted a ridge with a minimum height of 100 m., and flowed down the east-west canyon 0.8 km south of Mezquital, nearly reaching Esperanza. The lower tuff is characteristically partially welded, with large pumice lumps or fiamme (to 40 cm) common. Pumice airfall, locally overlain by cross-bedded surge deposits, is present beneath the lower tuff along highway 1 at Infierno grade (see locality description for 79BMS16B, Table 1). Fayalite, ferroaugite, anorthoclase and Fe-Ti oxides are the characteristic phenocrysts in the lower ignimbrite. Chemically, the rock is a comendite (Table 1)

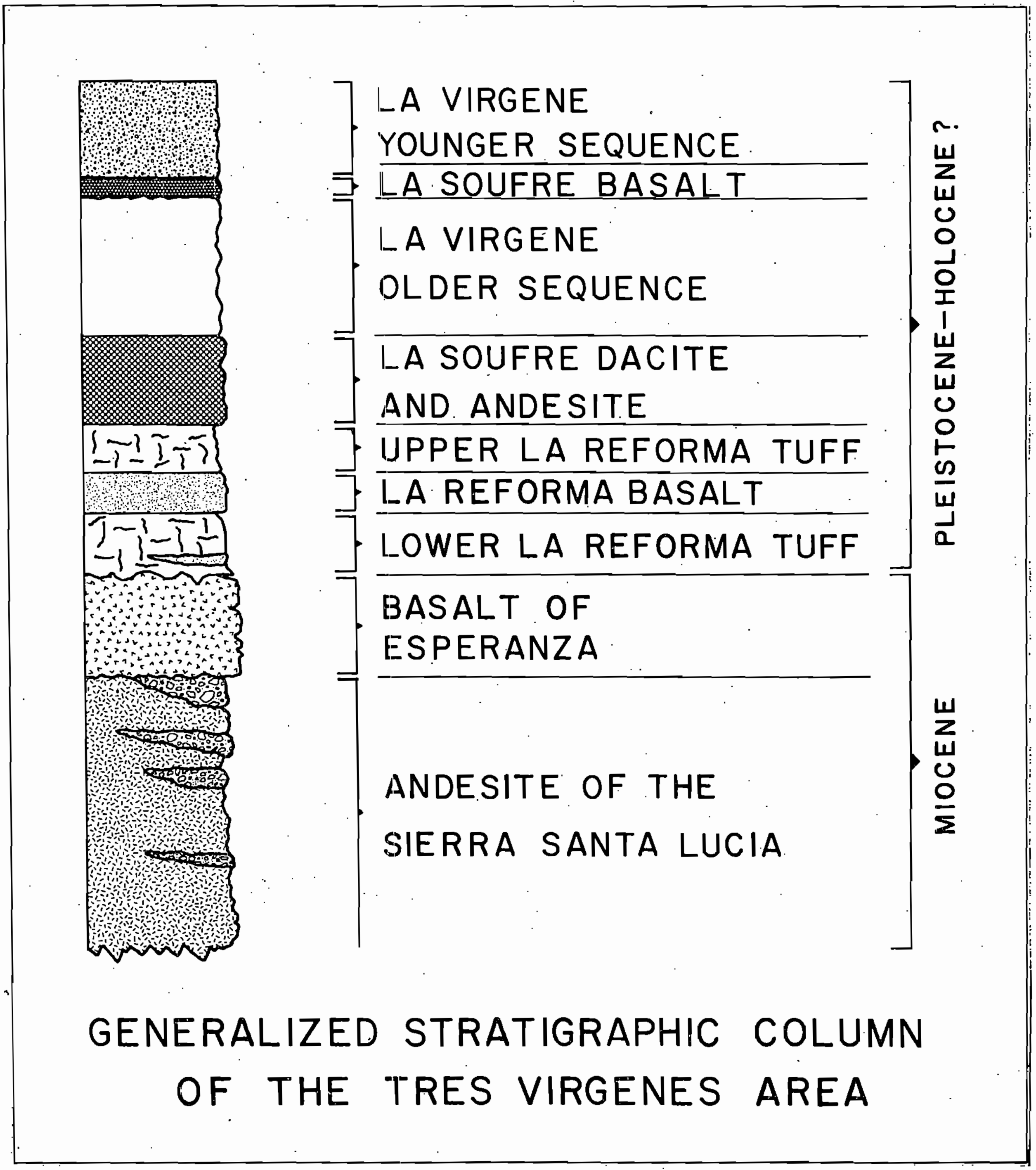


Figure 2. Composite stratigraphic column. Thicknesses of units shown here are schematic only and are not to scale.

TABLE 1. Representative Major Element Analyses of Volcanic Rocks in the Tres Virgenes Area

Sample No.	79BMS67	79BMS93	79BMS16B	79BMS103	79BMS88	79BMS104
Major elements (wt. %) (anhydrous)						
SiO_2	58.95	54.33	74.33	52.20	59.35	65.85
TiO_2	0.76	1.43	0.23	1.32	1.02	0.74
Al_2O_3	18.17	15.20	12.29	17.50	17.09	16.02
Fe_2O_3 [a]	2.27	2.93	1.75	2.82	2.54	2.25
FeO*	3.46	7.12	0.91	4.30	3.53	1.94
MnO	0.10	0.14	0.06	0.12	0.11	0.08
MgO	3.63	6.33	0.35	6.11	3.86	1.66
CaO	6.62	8.96	0.70	10.01	6.70	4.10
Na_2O	4.38	3.31	5.39	4.58	4.40	5.17
K_2O	1.48	0.15	3.96	0.72	1.21	1.99
P_2O_5	0.19	0.11	0.03	0.32	0.20	0.19
L.O.I.[b]	0.98	0.0	n.d.	0.02	0.61	0.90

Sample descriptions and localities:

79BMS67 - Andesite of the Sierra Santa Lucia; olivine and hornblende-bearing two pyroxene andesite from base of lava flow in ridge outcrop on southeast side of arroyo Santa Agueda, approximately 4km southwest of Santa Agueda, 1.7km northeast of Rancho El Bule (elevation: 440m).

79BMS93 - Basalt of Esperanza; hypersthene basaltic andesite from outcrop at intersection of spur from highway 1 and the old highway (dirt), 1.1km north of highway 1, 2.5km east of Esperanza.

79BMS16B - Lower La Reforma tuff; fayalite ferroaugite rhyolitic ignimbrite (devitrified) from roadcut along highway 1 at the crest of Infierno grade, 0.2km east of the Almejas microondas station.

79BMS103 - La Virgene basalt of younger sequence; basalt from roadcut along highway 1, 0.7km west of Mezquital.

79BMS88 - La Virgene andesite of younger sequence; olivine - two pyroxene andesite from outcrop of the elongate lava flow southeast of La Virgene adjacent to the base of the cone.

79BMS104 - Satellite vent dacite; two pyroxene - hornblende dacite from outcrop of coulee 100m north of Mezquital.

[a] Fe_2O_3 was calculated according to the method of Irvine and Baragar (1971)
[b] L.O.I. = loss on ignition produced by fusion of sample.

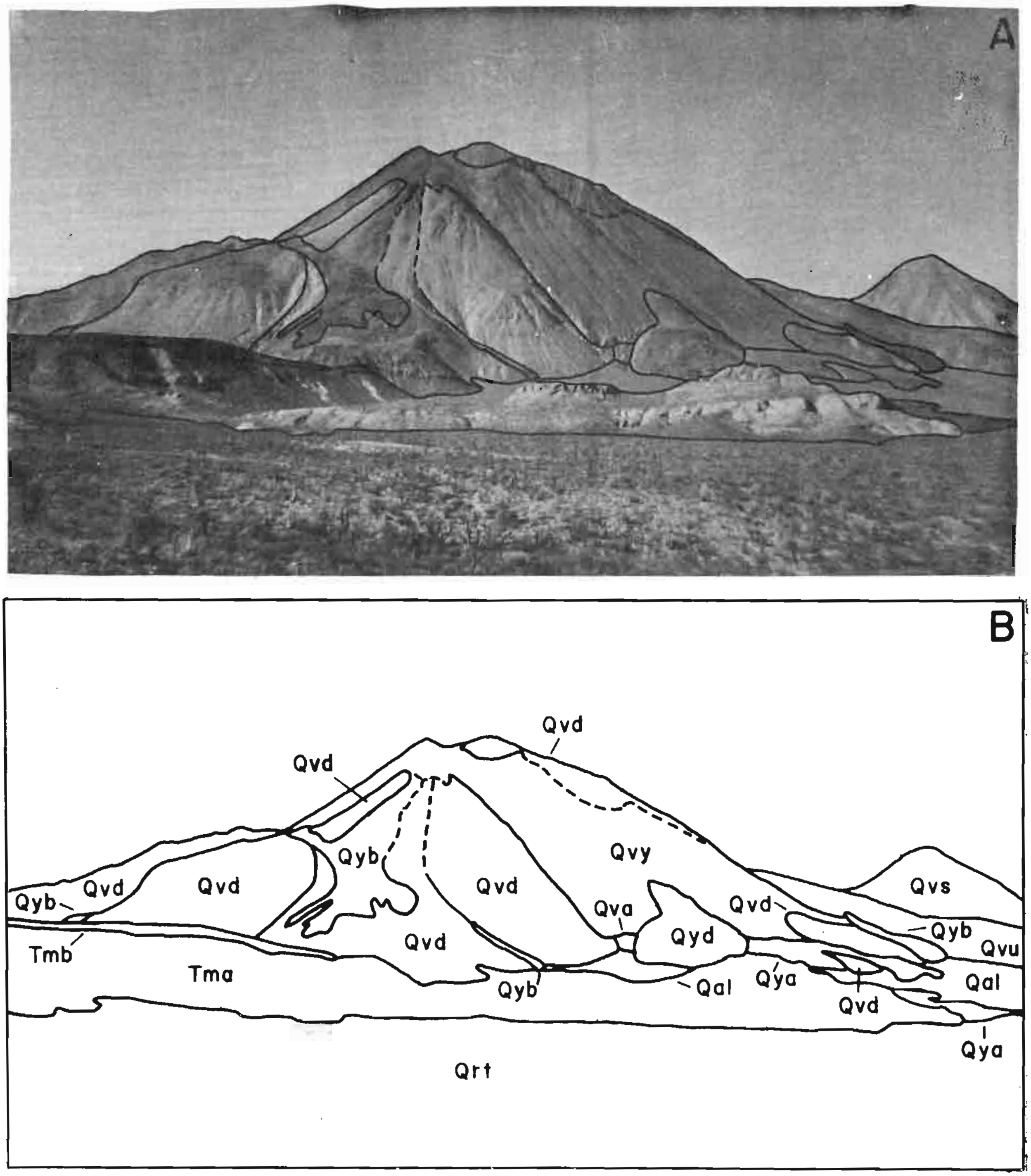


Figure 3A, B. View of the southeast flanks of La Virgene volcano (center) and La Soufre volcano (right) from highway 1 near Rancho Las Virgenes. Units are as in Figure 5 with the following exceptions. Tmv of Figure 5 is differentiated into Tma - Andesite of the Sierra Santa Lucia and Tmb - Basalt of Esperanza. Qvy is differentiated into Qyb - La Virgene younger sequence basalt, Qya - La Virgene younger sequence andesite, and Qyd - La Virgene younger sequence dacite. An additional symbol is Qvu - undifferentiated La Virgene volcanic rocks.

(McDonald, 1974).

The upper tuff is separated from the lower by basalt flows that erupted from peripheral vents, one of which is located in the eastern portion of the mapped area. In contrast to the lower tuff, it is poorly welded throughout and contains generally smaller (1-4 cm) pumice lumps. The phenocryst assemblage of the upper tuff, hypersthene, plagioclase and Fe-Ti oxides, is also quite distinct from that of the lower tuff.

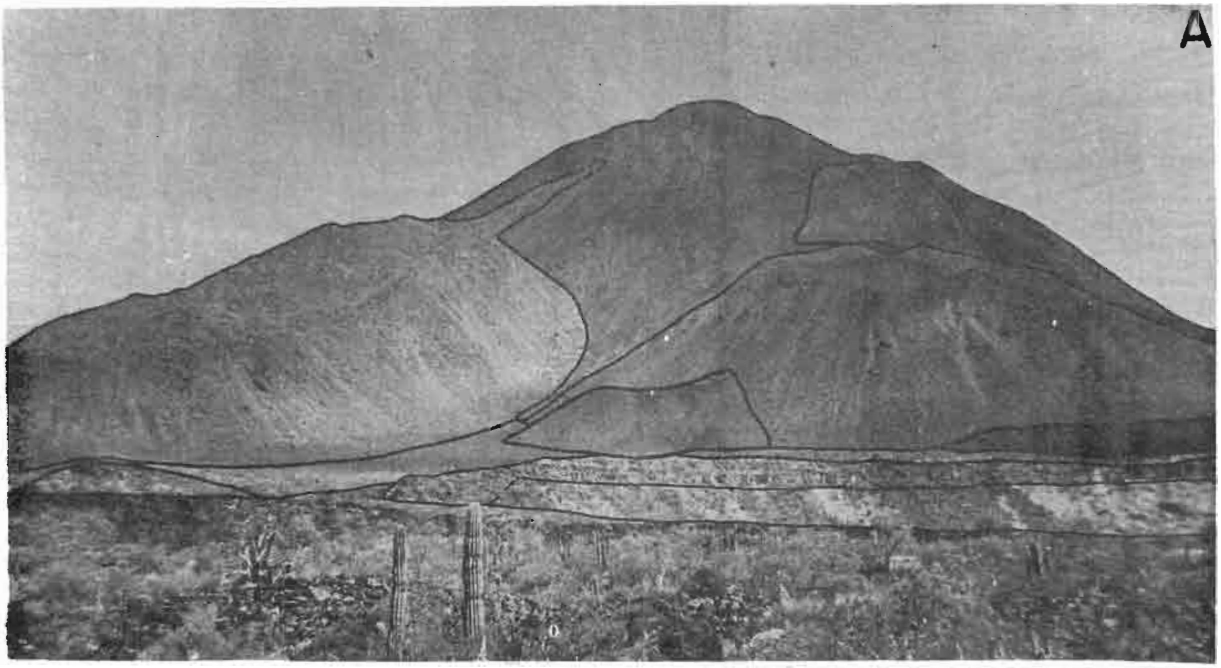
TRES VIRGENES ROCKS

Nearly the entire volume of the Tres Virgenes rocks was erupted from the four principal vents shown in Figure 5. Two occur in the summit area of La Virgene, one coincides with the peak of La Soufre, and the fourth lies to the northeast of La Virgene. The northern La Virgene vent comprises dissected feeder dikes within hydrothermally-altered pyroclastic deposits. The southern La Virgene vent is a crater that marks the vent for the youngest La Virgene rocks. Although La Soufre peak was not visited, the position of the La Soufre vent is inferred from the attitudes of the fragmental deposits that dip radially away from the summit. The third "virgin", the northernmost peak of the Tres Virgenes, is not a composite cone as are La Virgene and La Soufre. It is instead a thick accumulation of dacite apparently erupted as flows from La Soufre volcano. The northeast vent (Fig. 5), the most productive of the satellite vents, extruded andesite flows that were accompanied by little, if any, pyroclastic activity. The eruptions from the north-south array of satellite vents were volumetrically minor, and with the exception of the southernmost vent, which produced basaltic andesite, all formed either dacite coulees or domes.

Eruptions at La Virgene volcano occurred in two stages represented by basalt through dacite sequences. The locus of activity of the first cycle was the northern La Virgene vent. Basalts of this older stage are exposed in two distal flows northwest and northeast of La Virgene (Fig. 5). Older cycle andesites compose much of the northwest flank though they are distributed around all sides of the volcano. The thick dacite coulees on the south side of La Virgene (Fig. 4A,B) are the ultimate products of the first cycle of activity. The present height of the cone was achieved early in the history of La Virgene, before extrusion of the older dacites, on the basis that older andesites can be traced nearly to the older vent. In addition, a thick, dacitic, pumice airfall, distributed in a lobe southwest of La Virgene, was deposited as a product of a violent eruption that postdated the older andesites but predated some of the dacite flows of the older sequence.

The extrusion of La Soufre basalt (Fig. 5), which contains cumulate gabbroic inclusions, initiated the second cycle of activity. This eruption was followed almost immediately by extrusion of basaltic flows at La Virgene that overlie La Soufre basalt and that drape over the earlier-formed dacite coulees (Figs. 3A,B; 4A,B). The limits of the youngest andesite and dacite are outlined in Figure 4A,B.

Thin section examination of the La Virgene rocks shows that phenocryst phases vary regularly with rock type. Typical assemblages, in decreasing



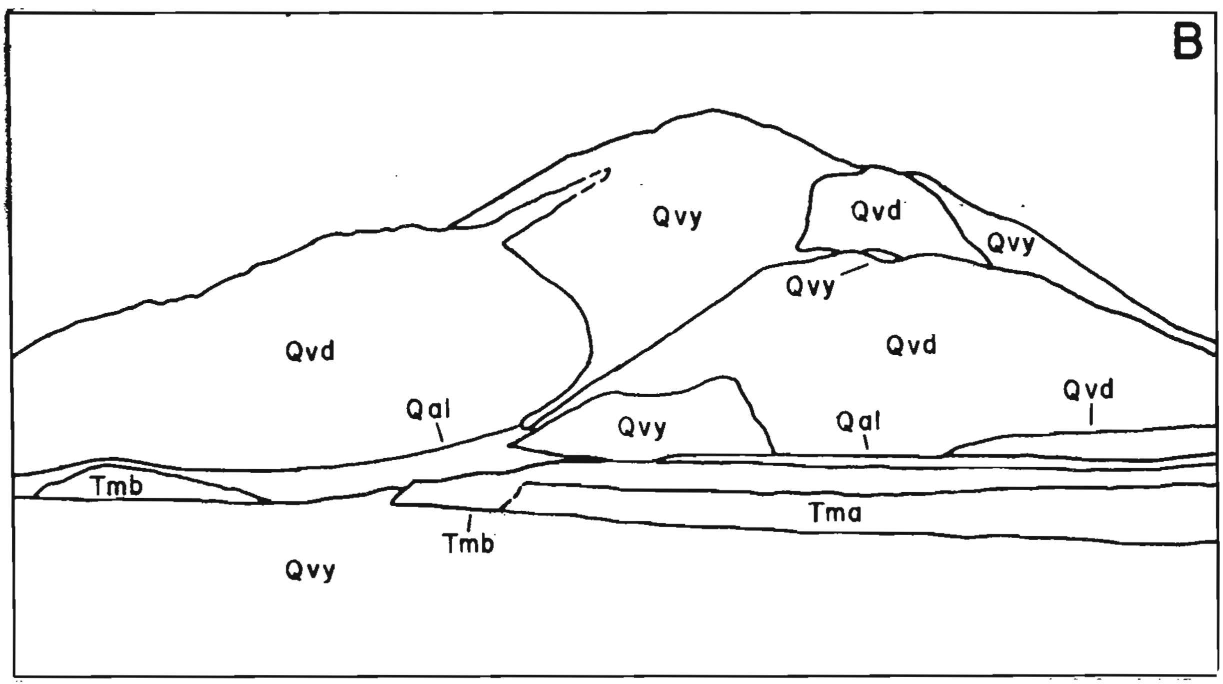
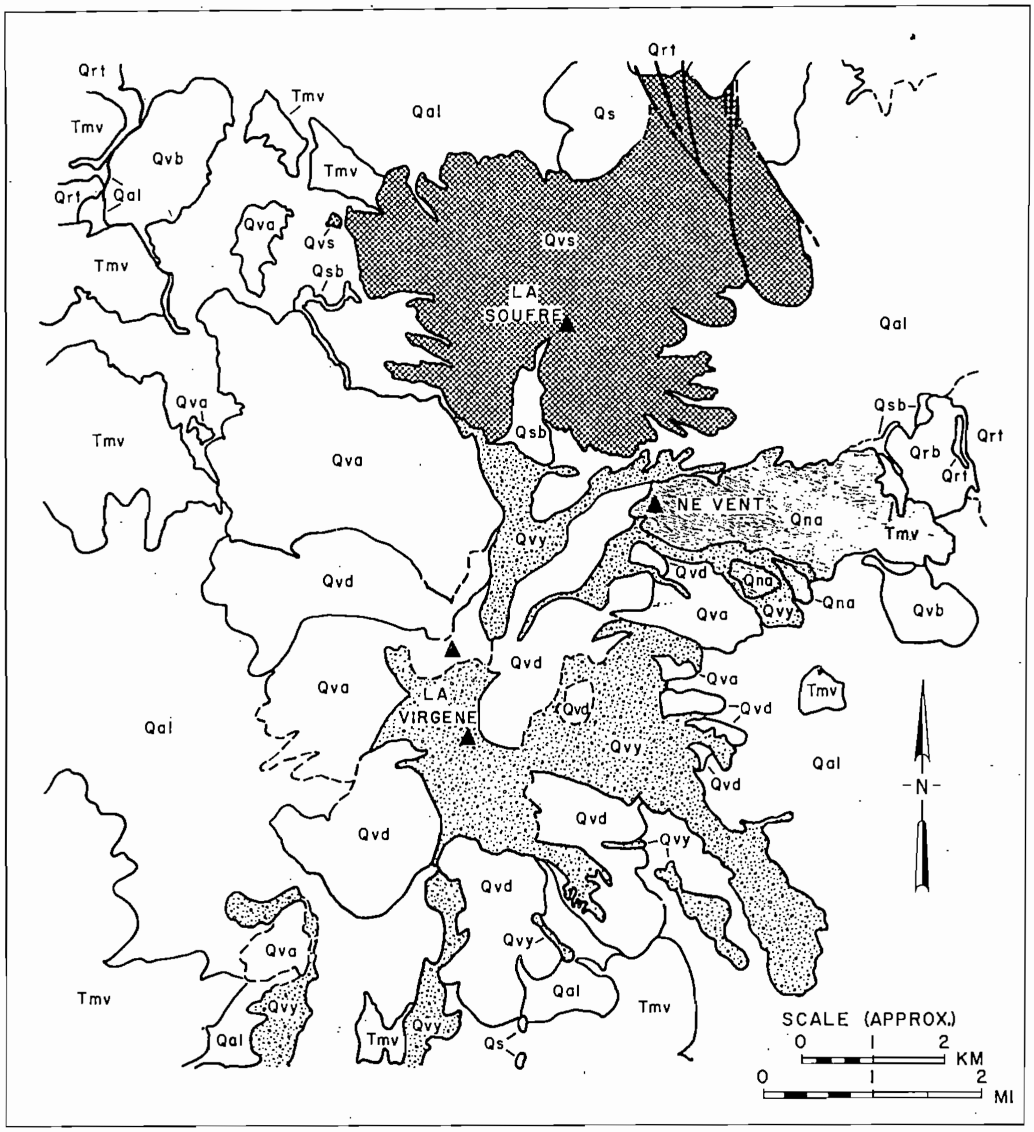


Figure 4A, B. View of the south flank of La Virgene volcano from highway 1 approximately 3km west of Mezquital. Units are the same as in Figure 5 with the following exception. Tmv of Figure 5 is differentiated into Tma - Andesite of the Sierra Santa Lucia and Tmb - Basalt of Esperanza. Qal also includes primary and reworked pumice airfall deposits.



GENERALIZED GEOLOGIC MAP OF LA VIRGENE AND LA SOUFRE VOLCANOES

GEOLOGY BY MICHAEL G. SAWLAN

EXPLANATION

Qs	SATELLITE VENT FLOWS AND DOMES (UNDIFF.)	Qvd	OLDER SEQUENCE LA VIRGENE DACITE	Qrb / Qrt	LA REFORMA BASALT AND LA REFORMA TUFF
Qna	NORTHEAST VENT ANDESITE	Qva	OLDER SEQUENCE LA VIRGENE ANDESITE	Tmv	BASALT OF ESPERANZA AND ANDESITE OF THE SIERRA STA. LUCIA (UNDIF.)
Qvy	YOUNGER SEQUENCE LA VIRGENE FLOWS (UNDIFFERENTIATED)	Qvb	OLDER SEQUENCE LA VIRGENE BASALT	Qal	ALLUVIUM
Qsb	LA SOUFRE BASALT	Qvs	LA SOUFRE DACITE AND ANDESITE		

Figure 5. Geologic map prepared using a 1:50,000 CETENAL air photo enlarged 2x for a base map. Solid triangles denote main vents.

order of abundances of phases, are: basalt, Ol + Cpx + Plag; basaltic andesite, Plag + Cpx + Opx + Ol; andesite, Plag + Opx + Cpx + Hb $\pm$ Qtz; and dacite, Plag + Hb + Opx + Cpx $\pm$ Bt $\pm$ Qtz. Eight samples analyzed from La Virgene volcano are calc-alkaline on the basis of FeO*/MgO vs SiO_2 variations. SiO_2 ranges from 52-68%, and K_2O is about 1.3 at 60% SiO_2. Analyses of the La Virgene andesite and the Miocene Andesite of the Sierra Santa Lucia are virtually identical (Table 1).

STRUCTURAL SETTING OF THE TRES VIRGENES AREA

The trends of faults and folds within the area mapped suggest that these features may be a product of a northwest-southeast directed, right lateral shear couple. The Tres Virgenes vents are aligned in a north-south array along the western margin of the Aguajito fault zone. This zone is defined as the 1-2 km wide north-trending, multiple horst and graben sets that occur from Aguajito in the north to 6-8 km east of Mezquital. Vertical displacements are small, approximately 1-10 m. Axes of the folds within fault blocks trend at large angles to the northwest.

RECENT ACTIVITY OF TRES VIRGENES VOLCANOES

The Tres Virgenes volcanoes were cited as historically active in 1746 and 1857 (Wilson, 1949, 1955; Mooser and Lagos, 1961). The reported activity in 1746 is based on a Spanish missionary's labelling of the Tres Virgenes as "volcanoes of fire" on his sketch map of the region bordering the Gulf of California (Ives, 1962). Mooser and Lagos (1961) presented unreferenced reports of "clouds of smoke and vapor" that apparently were observed in 1857, but they doubted that an eruption had occurred. Inspection of the present La Virgene crater, clearly the source of the youngest La Virgene lavas, showed it to be in a state of degradation, partially infilled with colluvium and lacking recent pyroclastic debris. This author's qualitative appraisal of the crater suggests that there has not been magmatic activity in the past several hundred years although small phreatic eruptions cannot be ruled out.

ACKNOWLEDGEMENTS

Many thanks are due to Michael McGroder and Richard Slack whose cooperation as field assistants during long, hot Baja days greatly helped the program. This research was supported by National Science Foundation Grant EAR77-09006 awarded to K. L. and M. Cameron, University of California at Santa Cruz.

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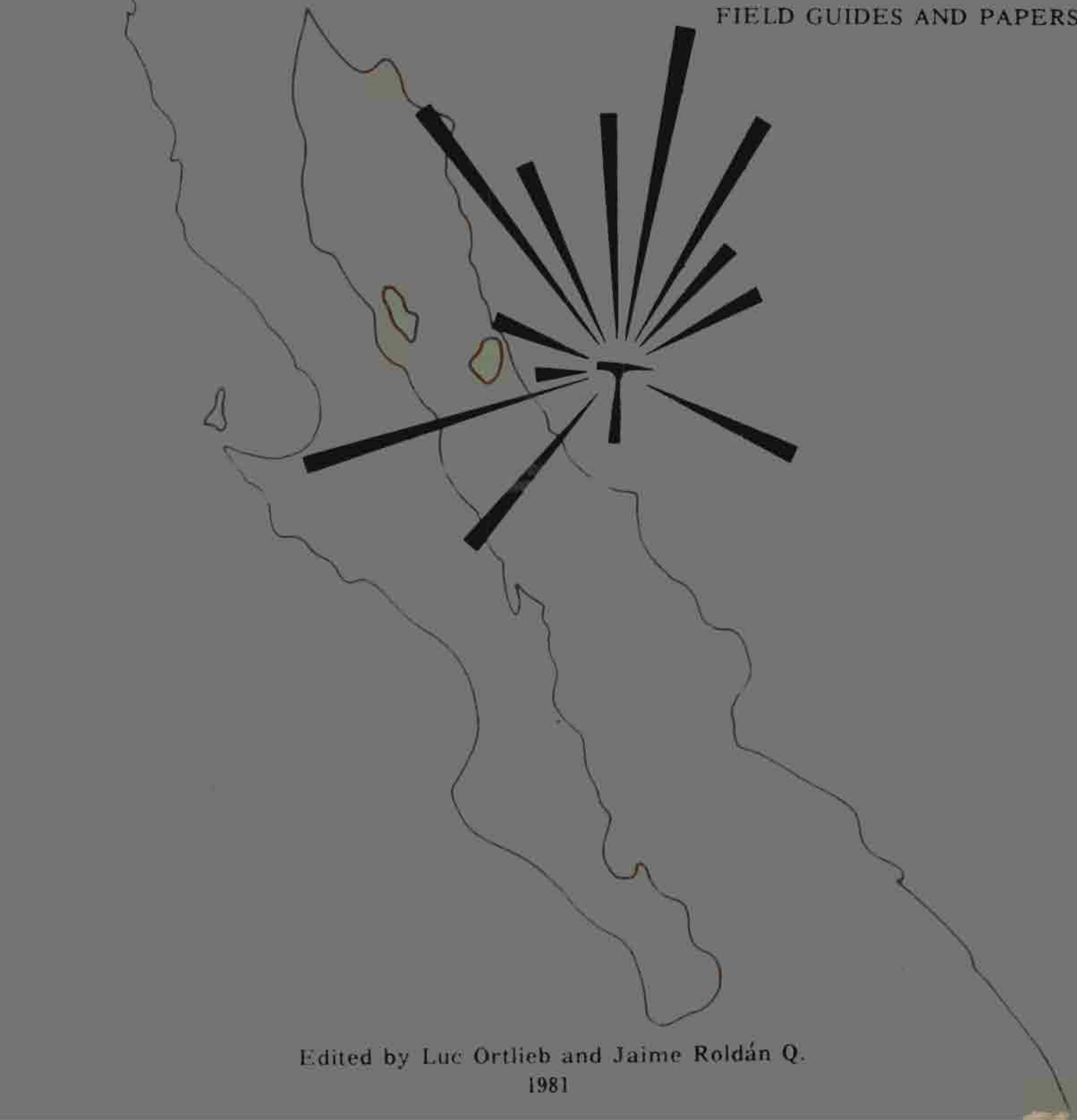
Geology of Northwestern Mexico and Southern Arizona

FIELD GUIDES AND PAPERS



Edited by Luc Ortlieb and Jaime Roldán Q.

1981

GEOLOGY OF NORTHWESTERN MEXICO AND SOUTHERN ARIZONA

DESCRIPTION OF FIELD TRIPS PREPARED FOR
THE GEOLOGICAL SOCIETY OF AMERICA,
CORDILLERAN SECTION 1981 ANNUAL MEETING,
HELD IN HERMOSILLO, SONORA, MEXICO, MARCH 21-30,
AND SPONSORED BY THE INSTITUTO DE GEOLOGIA U.N.A.M.
IN COOPERATION WITH THE UNIVERSIDAD DE SONORA.

Geología del noroeste de México y del sur de Arizona

Descripción de excursiones preparadas para la reunión anual de 1981 de la Geological Society of America, Cordilleran Section, efectuada en Hermosillo, Sonora, México, del 21 al 30 de marzo, y organizada por el Instituto de Geología, U.N.A.M., en cooperación con la Universidad de Sonora.

EDITED BY

LUC ORTLIEB AND JAIME ROLDAN Q.

ESTACION REGIONAL DEL NOROESTE
INSTITUTO DE GEOLOGIA, U.N.A.M.
HERMOSILLO, SONORA, MEXICO.

1981

Published by / Publicado por:

Instituto de Geología, U.N.A.M.
Circuito Exterior
Ciudad Universitaria
México 20, D. F., México.