THE GEOLOGICAL EVOLUTION OF THE PARAGUAYAN CHACO

by

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ABSTRACT

The main objective of this study is to reconstruct the geologic evolution of the Paraguayan Chaco. The Paraguayan Chaco occupies an area of approximately 240 thousand km^2, and is part of a string of modern foreland basins to the east of the Andean Belt. Only 38 wells, mostly shallow stratigraphic tests, were drilled. Over 5,000 kilometers of seismic reflection lines were interpreted.

Three main geologic events were observed in the Paraguayan Chaco: (1) Deposition of a Paleozoic sedimentary section in a relatively stable platform with a predominantly eastern source area; (2) rifting of this Paleozoic section during the Cretaceous to form the Pirizal Subbasin; and (3) deposition of continental and marine sediments in a foreland basin setting. The Paleozoic section penetrated is mostly marine, and ranges from Lower Ordovician to Upper Permian. It contains a Devonian to Carboniferous westward regressing sequence of marine, transitional and continental facies. The main structural features consist of subbasins, arches, and subvertical faults. Paleozoic tectonic events occurred during the Devonian, Carboniferous (Late?) and possibly Late Ordovician to Early Silurian. Later events include the Early Cretaceous rifting of the Pirizal Subbasin and an Eocene event. Thick Paleozoic marine shales generated oil and gas. High temperature gradients are associated with arches, resulting in gas prone settings. Areas distant from the arches have lower temperature gradients and should produce oil.

The sedimentary fill of the Pirizal rift basin is mostly of continental origin, with sea incursions during the Late Cretaceous (Maastrichtian)-Paleocene and Miocene. Two stages were identified in the evolution of the Pirizal Subbasin: (1) Rifting of the Paleozoic sequence, and the accumulation of continental sediments in an asymmetric graben bordered by normal down to the basin faults; and (2) a sag phase with sediments overlapping the graben borders. The subsidence of the basin flanks during the sag phase resulted in a symmetrical distribution of the sedimentary section of this phase. The Late Cretaceous-Paleocene marine sediments have good source potential and generated hydrocarbons. This study relates the Paraguayan Chaco with the better known Bolivian and Argentinian Subandean Belts and adjacent regions of both countries.

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CHAPTER I

INTRODUCTION

The Paraguayan Chaco constitutes the western part of the country of Paraguay and comprises approximately 260 thousand square kilometers, or sixty percent of the total area of the country. Only thirty eight exploratory wells and five shallow stratigraphic wells have been drilled since 1947 --mostly by U.S. companies searching for hydrocarbons in intermittent efforts. Although extensive coring was conducted in the first nine wells drilled by Union Oil (1947-1949) and Pure Oil (1958-1959), samples were no longer available at the time of this study. Subsequent exploration efforts did not result in the extensive recovery of long cored sections. Therefore, material at hand for this project was mainly of indirect nature, such as geophysical and sample logs, seismic sections, and various internal reports.

Published material on the Paraguayan Chaco is virtually non-existent. Interpretations and conclusions on the Paraguayan Chaco in this study are based on the unpublished information obtained for this study, unless otherwise specified. References to the neighboring countries are from published material. Four subbasins are located in the Paraguayan Chaco: Carandaity, Curupaity, Pirizal (Pirity or Lomas de Olmedo) and Pilar. The sedimentary sequences of the Carandaity and Curupaity subbasins in almost their entirety consist of Paleozoic sediments, while the sedimentary package of the Pirizal Subbasin consists mostly of sediments of Late Cretaceous to present age. The study of the stratigraphy of the Paraguayan Chaco will thus be divided into a Paleozoic section and the Mesozoic-Cenozoic stratigraphy of the Pirizal Subbasin in order to facilitate the understanding of the geologic evolution of the area.

Objectives

The objectives of this dissertation project are:

1. The integration of all the available data on the Paraguayan Chaco.

2. Interpretation of the data to reconstruct the geologic evolution of the Paraguayan Chaco.

Location

The Paraguayan Chaco is located in the country of Paraguay and extends approximately from 19 to 25° S and from 57 to 63° W (Fig. 1). Its limits are to the north and west, the Republic of Bolivia; to the south, the Pilcomayo River separating it from Argentina; and to the east, the Paraguay River separating it from Brazil and Eastern Paraguay.

Methods of Study

The methods of study applied in this project were to a large degree dictated by the types of information available. Direct data was very scarce, save for some well cuttings from a few wells and some short segments of cores from the Don Quixote-1 well.

Good palynological data was obtained from the Carandaity Subbasin, which enabled the characterization of depositional environments and determination of ages with confidence. In some areas only geophysical logs and sample descriptions were available. Seismic sections of good quality from the Pirizal Subbasin were helpful in determining the areal extent of sedimentary packages, and gave insight into the structures and tectonic character of that area. Cuttings from selected intervals of the Don Quixote-1 well were subjected to x-ray diffraction analysis to identify the types of clays present. Figure 1 shows the location of wells in Paraguay, and Table 1 shows the locations of wells drilled in Paraguay.

Main Geotectonic Units of South America

The Chaco Basin belongs to a string of modern foreland basins east of the Andean Belt that extend from the Pampas in central Argentina to the Llanos in eastern Venezuela (Fig. 2). These basins are located between the Andean Belt and the Central Brazilian and Guiana shields.

Main Structural Units of Paraguay

Figure 3 shows the main structural features of Paraguay. The Apa High, an extension of the Central Brazilian Shield, and the Asunción High, both crop out in Eastern Paraguay. These are crystalline basement and lower Paleozoic outcrops separated by the deep (>3,000 meters) San Pedro Trough (Banks and Robinson, 1988). These two highs separate the intracratonic Paraná Basin to the east from the foreland Chaco Basin to the west.

Four subbasins are present in the Chaco: Carandaity, Pirity (Pirizal or Lomas de Olmedo), Curupaity and Pilar. Santa Fe Energy Resources is presently engaged in a geophysical exploration program in the Pilar Subbasin (William A. Schaefer, 1991, oral communication). No data from the Pilar Subbasin was available for the present study.

The subbasins are separated by the Central Chaco High and the arches of Cerro León (Izozog, as it is known in Bolivia), Boquerón (Michicola in Argentina) and Hayes (Quirquincho in Argentina).

Geologic Events

Three major geologic events occurred in the Paraguayan Chaco:

1. Deposition of clastic Paleozoic (Lower Ordovician to Lower Pennsylvanian, and in some areas to Upper Permian-Lower Triassic) sediments in marine to continental environments in a continental platform setting.

2. Rifting of the Paleozoic section in the Pirizal Subbasin during the Early Cretaceous with deposition of a thick, predominantly continental, fill.

3. Deposition of continental and marine sediments in a foreland basin setting from Eocene to present.

Data on the Paleozoic sediments is concentrated in the Carandaity Subbasin; some in the Curupaity Subbasin, and very little is widely scattered in the remaining areas. Because there are only very few and scattered outcrops in the Paraguayan Chaco, early exploration efforts were conducted based on the knowledge of the Andean region sequences and terminology. Where facies changes from marine to coastal and continental environments were encountered towards the east in Paraguay, these Andean region sequences were not repeated exactly. Consequently, where fossils were lacking, incorrect assumptions based on lithologic character commonly were made.

Figure 4 shows the tectonic character of the Subandean region extending eastward into the Chaco area. The Subandean zone is characterized by thrust faulting with decreasing intensity eastward. These compressional forces are greatly diminished in the Chaco area, where only subvertical faults with some possible lateral movement are found.

Table 1

HYDROCARBON EXPLORATION WELLS OF PARAGUAY

Operator	Well	Area	Year	Meters	Feet	Location .	
Union Oil Co.	Santa Rosa-1	Carandaity	1947	2,309.4	7,577	21 45S	61 41W
	Pirizal D-1	Pirity	1948	3,148.9	10,331	23 03	60 38
	Picuiba B-1	Carandaity	1949	2,290.9	7,516	20 40	61 56
	La Paz D-1	Boquerón Arch	1949	2,210.4	7,252	21 53	60 58
	Orihuela B-1	Hayes Arch	1949	2,047.3	6,715	23 24	58 40
Pure Oil Co.	Madrejón-1	C. Chaco High	1958	1,728.1	5,668	20 28S	59 29W
	Lagerenza-1	Carandaity	1959	2,889.5	9,480	20 00	61 00
	Mendoza-1	Carandaity	1959	3,242.7	10,639	20 12	61 42
	López-1	C. Chaco High	1959	1,730.9	5,679	21 46	59 58
Placid Oil Co.	Mendoza-1	Carandaity	1967	792.1	2,598	20 07 30S	61 45 20W
	Mendoza-2	"	"	1,246.6	4,090	20 02 20	61 52 10
	Mendoza-3	"	"	693.4	2,275	20 03 10	61 53 30
Pennzoil & Victory Oil Holdings	Alicia-1	Carandaity	1971	1,305.4	4,283	20 57 02S	61 48 57W
	Brigida-1	"	"	1,512.7	4,963	21 18 50	61 50 22
	Christina-1	"	"	643.1	2,110	21 26 54	61 53 26
	Dorotea-1	"	"	853.4	2,800	21 17 01	62 08 54
	Emilia-1	"	"	1,022.0	3,353	21 06 34	62 07 14
	Federica-1	"	"	800.0	2,624	21 34 56	62 11 30
	Gabriela-1	"	"	1,015.6	3,332	21 46 34	62 00 02
	Hortensia-1	"	"	765.2	2,510	21 30 29	61 39 27
	Isabel-1	"	"	944.9	3,100	21 01 14	61 27 40
	Julia-1	"	"	1,280.1	4,200	20 36 05	61 37 03
	Katerina-1	"	"	1,139.6	3,739	20 44 30	61 33 50
	Luciana-1	"	"	819.3	2,688	20 10 40	61 43 10
	Marta-1	"	"	827.5	2,715	20 16 31	61 40 27
	Nola-1	"	"	760.1	2,493	20 07 49	61 47 13
	Don Quixote-1	"	"	2,894.4	9,496	21 37 47	61 56 43
	Olga-1	"	"	1,171.3	3,843	21 25 13	61 52 41
REPSA & Compañía Petr. del Chaco	Palo Santo-1	Pirity	74-75	3,765.2	12,350	23 10 20S	60 46 08W
ESSO, AMINOIL, REPSA, CPC	Berta-1	Pirity	1976	4,792.4	15,723	22 32 47S	61 00 58W
Chaco Exploration	Parapití-1	Carandaity	1977	2,834.2	9,296	21 00 00S	61 00 00W
	Parapití-2	"	"	2,350.9	7,711	21 34 00	62 00 00
Texaco & Marathon Petroleum Co.	Cerro León-1	C. León Arch	1977	1,970.1	6,462	19 49 00S	60 56 45W
	Toro-1	Curupaity	1978	3,417.7	11,210	58 57 00	20 07 58
	Gato-1	"	"	1,646.3	5,400	20 03 03	58 52 03

Table 1 Continued

Operator	Well	Area	Year	Meters	Feet	Location .	
Compañía Petr. del Chaco	Anita-1	Pirity	1978	4,127.9	13,543	22 53 24S	61 30 18W
	Gloria-1	”	1979	4,015.1	13,173	22 56 55	60 38 04
Occidental	Carmen-1	Pirity	85-86	4,511.0	14,800	23 04 29S	61 28 43W
	Tte. Acosta-1	”	1987	4,268.0	14,003	22 44 55	60 25 15
	Nazaret-1	”	87-88	4,025.0	13,205	22 39 16	59 51 37
Pecten	Asunción-1	Paraná Basin	1982	3,223.0	10,574	24 04 13S	56 27 12W
	Asunción-2	”	1983	2,926.0	9,600	23 41 48	56 35 02
Texaco	Mallorquín-1	”	1990	2,990.4	9,811	25 28 47.6S	55 16 40W

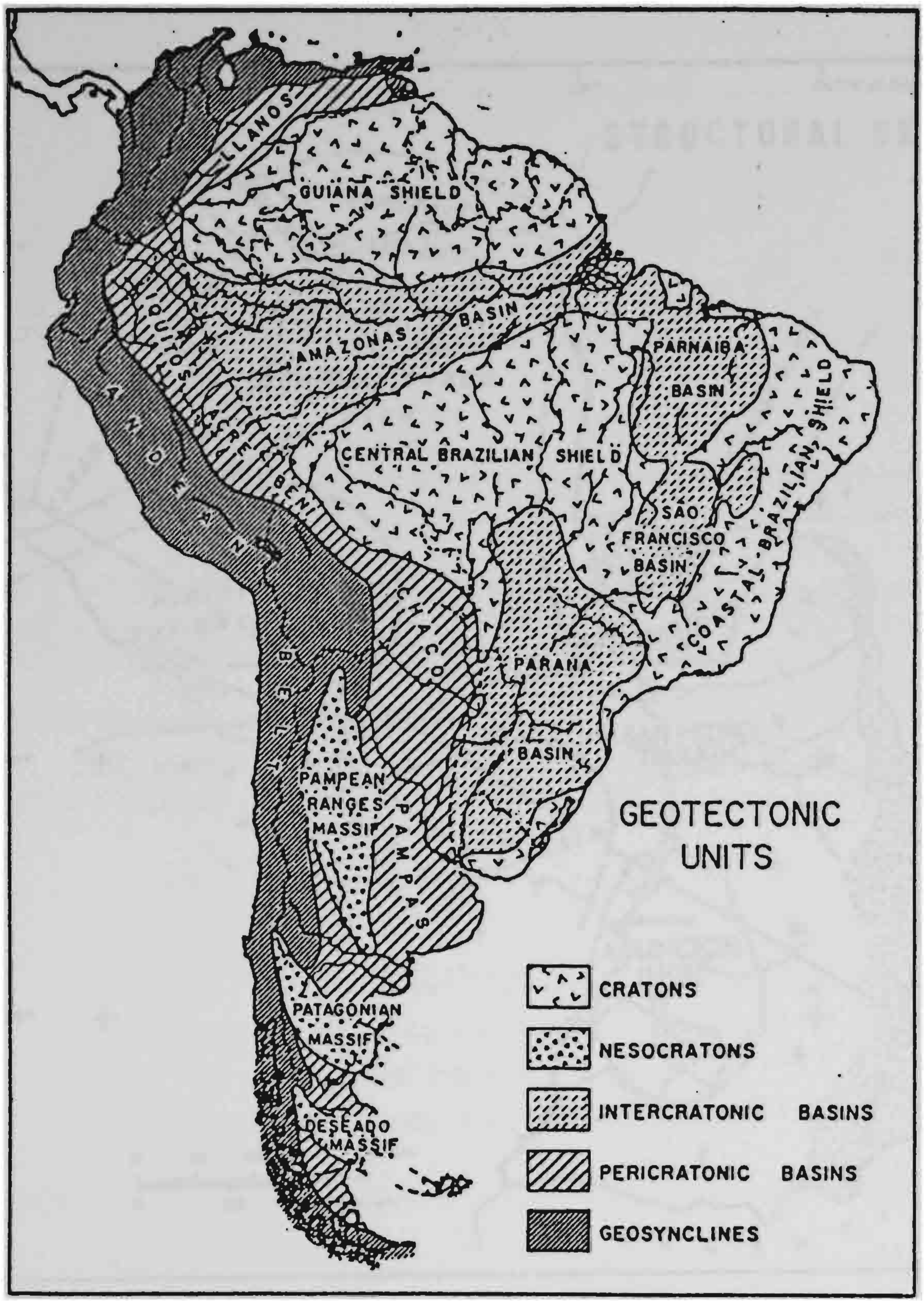


Fig. 2. Geotectonic units of South America (Harrington, 1962).

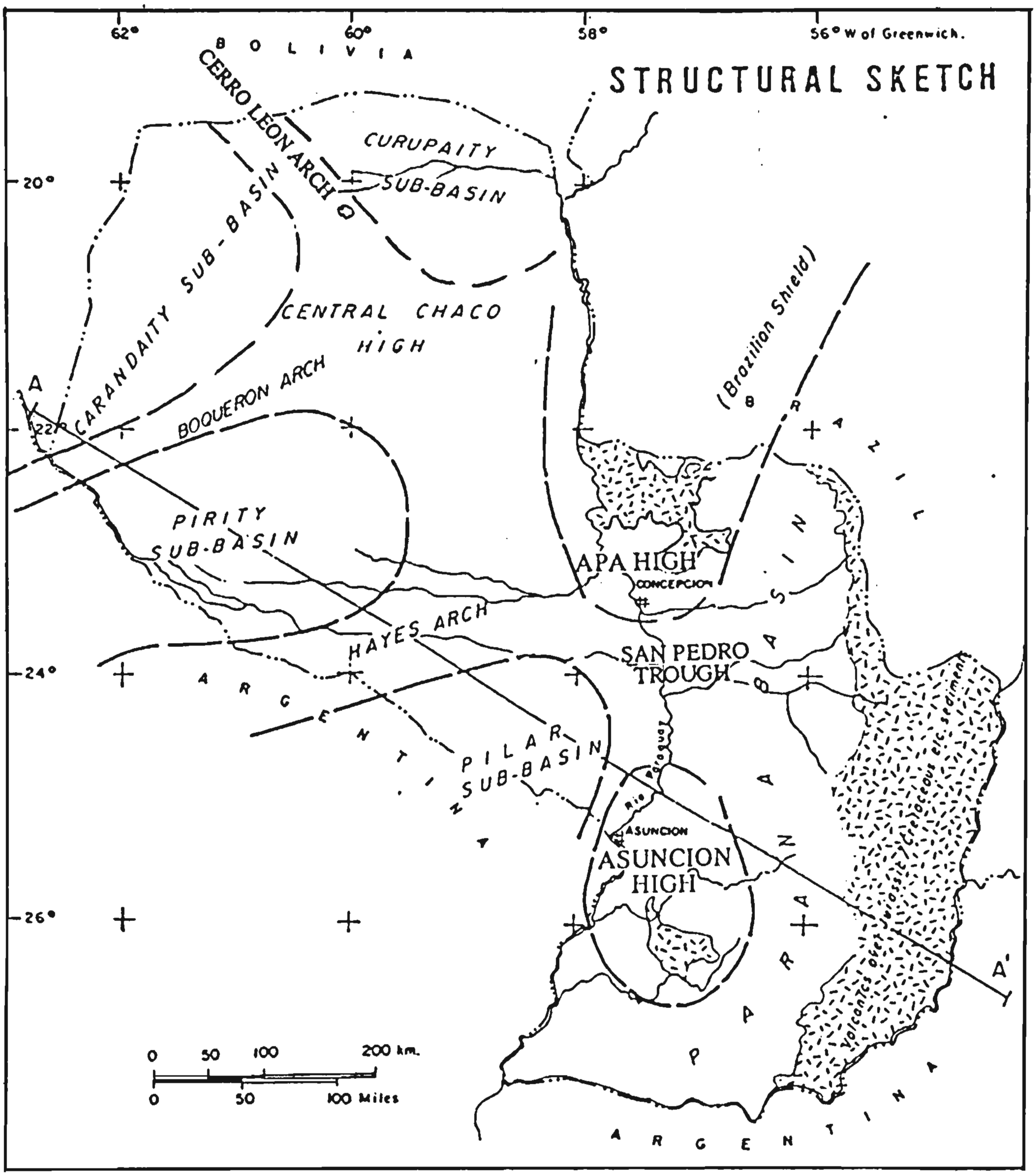


Fig. 3. Structural units of Paraguay (Modified from Banks and Robinson, 1988).

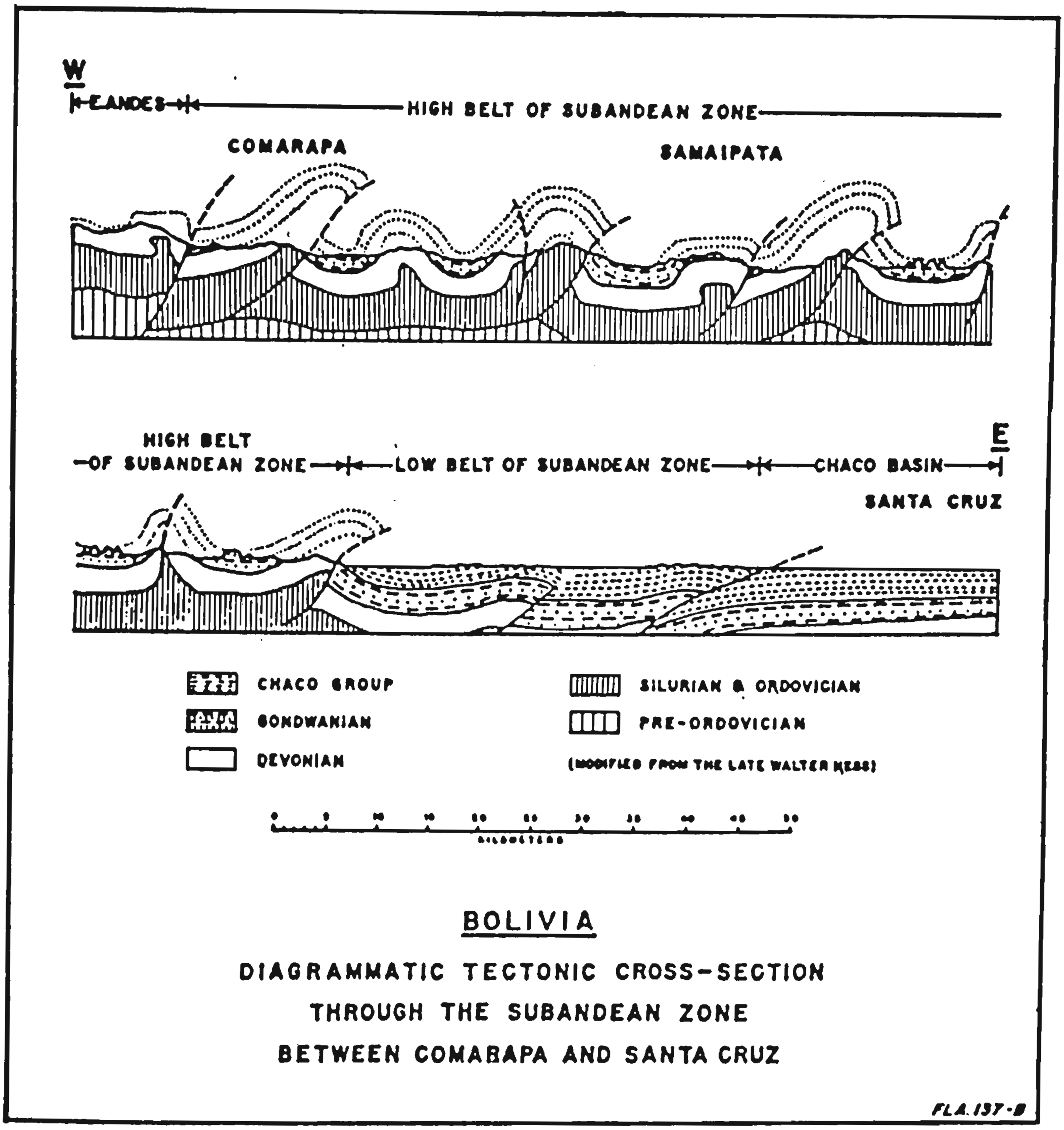


Fig. 4. Diagrammatic tectonic cross section through the Subandean Belt and parts of the Chaco between Comarapa and Santa Cruz, Bolivia (Lamb and Truitt, 1963).

CHAPTER II

PALEOZOIC STRATIGRAPHY

Crucial to the understanding of the Paleozoic history of the Paraguayan Chaco are the Subandean Belt of Bolivia to the west, and to a lesser degree, the area of Roboré-Santiago de Chiquitos (Serranías de Santiago y San José) to the north, in easternmost Bolivia (Fig. 5). This is because, as determined in this study, the Paraguayan Chaco shares similar environments of deposition with these areas. In addition, the bulk of the information in the form of outcrop and well data originated in Bolivia, and consequently, so did the nomenclature and formational units known for the area. The area immediately to the south in Argentina has not contributed as much to the understanding of the Paraguayan Chaco in terms of nomenclature, because units there are still identified on the basis of lithologic character and stratigraphic position rather than on more reliable paleontologic and palynological determinations. Also, the Early Cretaceous rifting that formed the Pirity Subbasin resulted in the erosion and collapse of substantial Paleozoic sedimentary packages. Thus, thick sections of Paleozoic sediments either are missing or collapsed as blocks at the base of the thick Cretaceous-Quaternary sedimentary fill of the Pirity Subbasin.

A brief description of the lithologic units found and defined in Bolivia, in the western part of the Subandean Belt, will be made. Also, their Paraguayan equivalents --which may not always reflect the same lithologies due to changes in depositional environments-- will be described.

The sedimentary section penetrated in the Paraguayan Chaco ranges from Lower Ordovician to Lower Pennsylvanian and Upper Permian to Lower Triassic. In the

Subandean Belt of Bolivia, shaly and sandy sequences from Ordovician to Tertiary are present (Oblitas et al., 1972).

Important lithologic differences are found between the pre-Devonian sequences in Paraguay and those in the Subandean Belt to the west of the study area. The section found in the central portion of the Southern Subandean Belt of Bolivia in the Serranía Sararendá (Sararendá Hills), on the Parapetí River, in the well CAM-20 (Fig.6) is similar to the sequence found in the Carandaity and Curupaity subbasins of Paraguay (Fig. 7).

The area of the Roboré Basin or Serranías Chiquitanas (Chiquitos Hills or Serranías Santiago y San José) in easternmost Bolivia is of relatively less importance to the study of the Paraguayan Chaco than the Subandean Belt, because of its different facies characteristics. Therefore, only a brief mention of the geology of this area will be made here. The Roboré Basin contains a poorly dated stratigraphic sequence (Fig. 8). Only some sections of the Precambrian, Silurian and Devonian sequences are paleontologically dated. The Cambrian sequence was dated from algae in the area of Ladario in Brazil (Ahlfeld, 1972). The Silurian and Devonian sequences were dated macropaleontologically by López-Paulsen et al. (1982; Fig. 9 of this study).

The areas around the Apa and Asunción Highs (Fig. 3) have been elevated topographic features --it is not known whether they were exposed or not-- probably since Early or Middle Paleozoic (Ordovician or Silurian) times, and have constituted a source area for sediments of the Chaco and Paraná basins. Large pebble to boulder conglomerates of Silurian age, in areas around Lake Ypacaraí in Eastern Paraguay, indicate the high topographic relief of the Asunción High.

The Chaco area is located west of the Brazilian Shield. Sediments derived from this shield were deposited in the Chaco in a relatively undisturbed continental to marine shelf environment dipping gently towards the west. Reconstruction of pole migration during the Paleozoic (Caputo and Crowell, 1985, Van der Voo, 1988, and Veevers and Powell, 1987) indicate high to polar latitudes for the study area, and help to relate the lithologies found with likely climatic conditions.

Only three wells (Don Quixote-1, Parapití-1 and La Paz-1) were deep enough to reach Lower Paleozoic sediments. The Parapití-1 well penetrated sediments of Early Ordovician age, and Don Quixote-1 well penetrated sediments of Middle Ordovician age. Sediments of the La Paz-1 well are assigned to the Ordovician based on lithology.

Cambrian

The presence of the Cambrian can not be excluded in the Chaco because of its presence in the Andean region and its possible existence in Eastern Paraguay and the Chaco-Pampean Plains in the Formosa Province of Argentina (Russo et al., 1980). The Itapucumí carbonates and clastics that crop out in Eastern Paraguay and along the western margin of the Paraguay River in the Chaco (Fig. 10; Pennzoil, 1968) are assigned to the Cambrian based on lithology and stratigraphic position.

Ordovician

The descriptions of the Subandean formations of Bolivia given in this study are based on Oblitas et al. (1972) unless specified otherwise, and correspond to the western part adjacent to the Eastern Cordillera (Fig. 5). The Subandean Belt in Bolivia has a band of outcrops extending from southern Peru to northern Argentina. The oldest sediments observed in the Subandean Belt correspond to Ordovician outcrops along the border with the Eastern Cordillera. The base of these Ordovician sediments is not known (Oblitas et al., 1972). These Ordovician outcrops have been divided into three formations. The Enadere and Tarene formations occur in the Northern Subandean Belt, and the San Benito Formation in the Southern Subandean Belt (Fig. 5). Figure 11 shows a stratigraphic correlation chart between the Paraguayan Chaco and the adjacent areas in Bolivia and Argentina.

The Enadere Formation is the oldest formation of the whole section outcropping in the Northern Subandean Belt. This unit consists in its lower outcropping section of gray and greenish gray silts with intercalated black shales containing Lingula fragments. The upper outcropping section is composed of shaly sands and fine grained quartzarenites of gray to whitish gray color, in stratified layers of up to 80 centimeters, with abundant Cruziana furcifera D'Orbigny and common occurrence of Skolithos, which would indicate shallow marine environments. The section below the outcrops is not known. The upper contact with the Tarene Formation is concordant, and defined by a lithologic change.

The overlying Tarene Formation is a monotonous succession of hard, gray and whitish sandstones. These rocks are fine- to medium-grained, well sorted, clean and thinly stratified, but with some layers of up to 6 meters thick. The upper contact is described by Oblitas et al. (1972) as "pseudo-concordant" with Devonian shales.

The San Benito Formation, of the Central and Southern Subandean Belt is the equivalent of the Enadere and Tarene formations of the Northern Subandean Belt. It is also composed of fine grained, massive compact and hard whitish gray quartzites and sandstones. The occurrence of Cruziana D'Orbigny is common and fossil dating assigns it a Late Ordovician (Caradocian) age (Oblitas et al., 1972). The base of this formation is unknown in the Subandean region. The top is marked by a sharp lithologic change to tillites of the Silurian Cancañiri Formation.

In the Paraguayan Chaco, the Ordovician sequence has so far been identified only in the Carandaity Subbasin. Palynological analysis from the Parapití-1 (Gilbert Boyd, 1988, oral communication) and Don Quixote-1 (Urban, 1972) wells indicate the presence of Lower to Upper Ordovician strata (Figs. 12 and 13). The Don Quixote-1 well penetrated 155 meters (510 feet) of sediments of Middle Ordovician age at total depth (Urban, 1972). The Parapití-1, well located farther east from Don Quixote-1 well, has the Upper Ordovician section missing (Gilbert Boyd, 1988, oral communication). Because only scant paleontological information was obtained from the upper section of the Parapití-1 well, and no seismic data of this area was available for this study, it is not known whether the section is missing at this locality because of erosion or absence of deposition.

The Ordovician dark marine shales range from Middle to Upper Ordovician in the western part of the Paraguayan Chaco in the Don Quixote-1 well. In the eastern part of the Carandaity Subbasin (Parapití-1 well), the shales range from Lower to Middle Ordovician. The shales are overlain by marine silts and shales of Late Ordovician age in the Don Quixote-1 well and of Middle Ordovician age in the Parapití-1 well. The Ordovician shales are black to very dark gray, firm, silty and siliceous in parts, in part fissile, pyritic, very micaceous, interbedded with sand. The interbedded sand is white to medium gray, silty and micaceous in part, very fine-to fine-grained, predominantly friable and sometimes firmly cemented by silica; with occasional stringers of anhydrite, occasionally slightly calcareous (Pennzoil, 1972b). The lower contact of the Ordovician shales was not reached in Paraguay, and the upper contact appears to be transitional to the Middle and Upper Ordovician silts and shales. This shale sequence is herein informally referred to as the Don Quixote Formation (Figs. 7 and 12), in reference to the well from which the first age determination --through palynology-- was made.

The sediments overlying the dark shales consist of fine to coarse grained gray silt, firm to hard and micaceous. The silts are intercalated with shales of medium gray color, firm, micaceous, fissile to silty in parts (Pennzoil, 1972b). This section is herein informally referred to as the Siracuas Formation. The name is derived from the town of Siracuas located on the Transchaco road between the town of Mariscal Estigarribia and the Bolivian border. Both its lower contact with the Don Quixote Formation and its upper contact with the Silurian section appear to be transitional (Fig. 12).

The Lower and Middle Ordovician sediments represent a transgressive period in the whole region as indicated by its shaly nature. During the later part of the Late Ordovician through the Silurian and Early Devonian (lower part of the Emsian) deposition of an intercalation of siltstones, sandstones and shales took place (Figs. 7, 12 and 13). The Don Quixote-1 well penetrated 566 feet (172 meters) of Middle Ordovician, and 1,168 feet (356 meters) of Upper Ordovician sediments. The total thickness of Ordovician sediments should therefore be in excess of 528 meters (1,734 feet) in this well. The Parapití-1 well penetrated 1,296 feet (395 meters) of Ordovician sediments, of which 296 feet (90 meters) are Lower Ordovician and 1,000 feet (305 meters) are Middle Ordovician shales. Assemblages of chitinozoans and acritarchs are abundant and render a clear Ordovician age in the Parapití-1 well (Gilbert Boyd, 1988, oral communication). The Ordovician --and probably Cambrian, if it is found in the Chaco-- represents a shelf environment in the study area (Fig. 14 and 15) as indicated by palynology and regional geology.

The Ordovician shale section was not penetrated in the Bolivian Subandean Belt nor in the Bolivian Chaco. The more distal facies of the Ordovician sediments in Paraguay, as opposed to the Subandean Belt, indicate that the deepest part of the Ordovician sea between the Subandean Belt and the Brazilian Shield was located in the western Paraguayan Chaco. The Asunción-1 well, in the San Pedro Trough in Eastern Paraguay, penetrated paleontologically dated (Asunción-1 final composite log, Pecten, 1981) Middle to Upper Ordovician sandstones from approximately 2,780 to 3,011 meters (9,120 to 9,878 feet). The remaining 212 meters (689 feet) of sandstones to the final depth of 3,223 meters (10,574 feet) of this well did not yield any age determination. It is possible that a section of the lower 212 meters in this well could be of Early Ordovician age.

Silurian

The Silurian System is widely distributed throughout Bolivia as well as in the Chaco and Eastern Paraguay. Data from the Paraguayan Chaco discussed in this section indicate that the sequences found in Bolivia and Paraguay are lithologically very different.

Two formations occur in the Subandean Belt of Bolivia. These are the Cancañiri (Koeberlin, 1979, in Rodrigo et al., 1974) Formation (Zapla --Schlagintweit, 1943 in Rodrigo et al., 1974-- Formation) and the Kirusillas Formation (Ahlfeld and Branisa, 1960, in Branisa et al., 1972). Both crop out in the central and southern sections of the Subandean Belt, and the Kirusillas Formation is also found in subsurface in the Southern Subandean Belt. None of the lithologies found in these two formations in Bolivia extends into the Paraguayan Chaco because of facies changes.

The Silurian period is marked by the migration of the pole from NE to SW through South America, and this paleomagnetic data is reflected in the tilloids of the Cancañiri Formation in Bolivia. The term tilloid is used here in the sense of Harland et al. (1966, p. 251, in AGI Glossary of Geology, 1987) applied "as a nongenetic term for a rock resembling tillite in appearance, but whose origin is in doubt or unknown." According to Oblitas et al. (1972), the Cancañiri (Zapla) Formation unconformably overlies the Ordovician San Benito Formation, and is concordant with the superjacent Kirusillas Formation. The Cancañiri Formation is composed of greenish tilloid deposits with clasts of granite and quartz up to 8 centimeters in diameter. The upper section of the tilloids contains clasts of vein quartz, quartzite and white granite, some of which are faceted and striated. Intercalated with these sediments are medium to thick beds of medium- to fine-grained, compact and hard, gray, whitish and greenish quartzarenites. The thickness of the Cancañiri Formation reaches 40 to 70 meters where it crops out in the Western Subandean Belt. The age, as determined by palynology, is Early Silurian (Wenlockian, Oblitas et al., 1972) and possibly older. In Argentina, the Zapla Formation is of Ashgillian-Llandoverian (Late Ordovician-Early Silurian) age (Monaldi and Bosso, 1986).

According to Oblitas et al. (1972), the Kirusillas Formation consists almost totally of a monotonous succession of black shales with a "high organic content" and rare interbeds of fine-grained gray micaceous sandstones. Its upper contact in the western Subandean Belt is determined only through palynology, because of the identical nature of the Lower Devonian shales that overlie it in this area. The Formation reaches a thickness of 300 to 450 meters (984 to 1,476 feet). The age, as determined by macrofossils and palynology, is Early to Late Silurian (Llandoverian to Ludlovian; Berry and Boucot, 1972; Crowell et al, 1980).

The Silurian section in the Paraguayan Chaco is characterized by sandstones with interbeds of siltstones and shales deposited in a marine environment as indicated by palynological studies (Urban, 1972). The Silurian period was characterized by a continuation of the regression of the coastline that started during the Late Ordovician, as indicated by the presence of sandstones throughout the study area. The sandstones are white to very light gray, sucrosic in appearance, very fine grained, slightly silty, subrounded to rounded, occasionally micaceous, and friable to firmly cemented by silica or locally by carbonates. Certain intervals in the Don Quixote-1 well, for example 2,327 to 2,346 meters (7,636 to 7,700 feet) have macrofossils, particularly crinoid stems replaced by pyrite (Pennzoil internal report, 1972a). Samples 2,338 to 2,347 meters (7,670 to 7,700 feet) contain up to 25 % pyrite. The shaly interbeds of the Silurian section are similar to the Ordovician shales in Paraguay. This Silurian sandstone interval is herein informally referred to as the Nueva Asunción Formation (Fig. 7). The name is derived from the town of Nueva Asunción near the Bolivian border on the Transchaco road. The exact Silurian epoch and age of the Nueva Asunción Formation are not known. The upper contact with the Santa Rosa Formation appears to be conformable. The Don Quixote-1 well penetrated a total of 135 meters (442 feet) of Silurian sediments (Fig. 12; Urban, 1972), whereas the Parapití-1 well penetrated a total thickness of 335 meters (1,100 feet; Fig. 13 of this study; Gilbert Boyd, 1988 oral communication).

The same sequence of intercalated sandstones, siltstones and shales, which in the Parapití-1 well extends from Middle Ordovician to Lower Devonian and in the Don Quixote-1 well from Upper Ordovician to Lower Devonian, appears to be distributed throughout the Chaco area and could extend into the Paraná Basin in Eastern Paraguay. Wells López-1 and Orihuela-1 (Fig. 13) exhibit the same lithologies found in the Nueva Asunción Formation in the Don Quixote-1 well although no fossils have been reported so far. The same is true for wells Pure Madrejón-1 and Pure Lagerenza-1 (Fig. 16). In this last well, palynological samples down to approximately 2,316 meters (7,600 feet) yielded an Early Devonian age; below this depth, fossils are carbonized and not identifiable (Urban, 1972).

Paleogeographically, the Paraguayan Chaco continued to be a marine shelf during the Silurian (Fig. 17). The lack of the thick Silurian shales of the Kirusillas Formation of the Subandean Belt of Bolivia and Argentina, and the apparent concordant upper and lower contacts in Paraguay, suggest that the deeper parts of the Silurian sea migrated westward.

The Asunción High was probably exposed during the Early Silurian, as indicated by the Paraguarí Conglomerate of Eastern Paraguay, described by Harrington (1950, 1956 and 1972), and by the conglomerates assigned to the Zapla Formation tillites in the Piranė well, near the town of Formosa, in the Formosa Province of Argentina (Russo et al., 1980; Fig. 1 of this study). The outcropping Paraguarí conglomerate is up to 40 to 50 meters thick, and has interbeds of arkosic sandstones. Clasts of vein quartz, quartzite and chert are 1 to 30 centimeters in diameter. Some small rhyolite clasts also occur. It unconformably overlies Precambrian granites and rhyolites and grades into overlying sandstones. Harrington (1972) considers the conglomerate of probable fluvial origin based on pebble orientation and by the steep angles of the fore-set beds of the intercalated cross laminated sandstones. The age is early Llandoverian because it underlies sediments containing a graptolite fauna of early Llandoverian (Early Silurian; Harrington, 1950) age.

Whether some tectonic adjustment was already occurring in the area during the Silurian is not known. No Silurian or Ordovician sediments are known in the Apa High. This area could have been exposed subaerially at this time, or eroded at a later time (Late

Paleozoic?). The Asunción-1 and 2 wells, in the San Pedro Trough of Eastern Paraguay, penetrated 731 and 768 meters (2,398 and 2,520 feet), respectively, of sandstones and some marine shales (Vargas Peña shales) of Silurian age. The San Pedro Trough must have been subsiding in order to accommodate this thick Silurian sequence.

Devonian

Introduction

The Devonian Period as a whole is characterized by a generally transgressive sea in South America, and is reflected in widely distributed shales. However, in certain areas, stages within the Devonian Period also represent rises and falls of sea level. Figure 18 shows a worldwide sea level curve for the Devonian Period. Figure 19 shows the extent of the Devonian transgression in South America based on data mainly from Brazil. The original figure has been modified for the shoreline in the Chaco and Eastern Paraguay based on the wells in the study area and on the two Pecten wells Asunción-1 and Asunción-2 in Eastern Paraguay. Palynological data in Brazil is abundant and clearly indicate the transgression of the sea communicating all the intracratonic basins progressively from the Paraná to the São Francisco, Parnaíba, and into the Amazon Basin, with a possible connection with the Andean Basin and also the Chaco Basin through northern Bolivia and through the Chiquitos area in southeastern Bolivia.

Devonian of the Bolivian Southern Subandean Belt

The Devonian formations in the Southern Subandean Belt of Bolivia are identified by their lithologic character and age. The alternations of sandy and shaly sediments, each one corresponding to a Devonian stage, are probably due to the proximity of this area to a western source area which would correspond to the northwestern extension into Bolivia of the Pampean Ranges of northwestern Argentina (Fig. 19).

The top of the Devonian in the Subandean Belt is marked by an angular unconformity. Stages range up to the Frasnian, and the Fammenian is absent in Bolivia. The lower contact with the Silurian Kirusillas Formation shales is concordant (Oblitas et al, 1972).

According to Oblitas et al. (1972), the Bolivian Devonian section is well known. It represents a complete marine section, with abundance of macro- and microfossils and palynomorphs. These fossil assemblages permit correlations of the Devonian sequences of the Subandean Belt with those of the Altiplano (Bolivian Plateau), Eastern Cordillera, Chaco-Beni plains and neighboring northwestern Argentina. The thick marine Devonian sediments constitute source rocks of Bolivian hydrocarbon accumulations.

A description of all Devonian formations in Bolivia --always according to Oblitas et al. (1972)-- will be made here to help understand the regional character of the Devonian System. Regionally, the Devonian system starts with the Santa Rosa Formation, which has a Gedinnian age in Bolivia (Oblitas et al., 1972) and Emsian age in northwestern Argentina (Garrasino and Cerdan, 1982).

The Santa Rosa Formation (Ahlfeld and Branisa, 1960) in the Subandean Belt consists of a predominantly sandy sequence with individual units up to 150 meters (492 feet) thick. The sandstones are whitish, well sorted, subangular and medium- to fine-grained. These rocks are cemented by silica and have porosities ranging from 8 to 20 % (Oblitas et al., 1972). These crossbedded to parallel beds are intercalated with black micaceous shales containing organic matter and whitish gray siltstones. The formation thickness varies between 250 to 300 meters (820 to 984 feet). Its age, as determined by macrofossils and palynomorphs, is Gedinnian. The basal contact with shales of the Silurian Kirusillas Formation is transitional and concordant. Its upper contact is identified by a lithologic change (Oblitas et al., 1972).

According to López Pugliessi and Suárez-Soruco (1982), the sandy character and grain size of the Santa Rosa Formation strongly indicate a coastal or very shallow environment. The presence of feldspars indicates proximity to the source area. The sandy content increases westward towards the Alto de Santa Victoria (Santa Victoria High) towards the Argentinian border (Fig. 19). Another environmental indicator in Bolivia is the Scaphiocoelia and Proboscidina fauna of intertidal brachiopods, which occurs at the top of the Santa Rosa Formation. Also, the type of crossbedding, color of sediments, worm tracks, the frequency and abundance of primitive vascular plants are interpreted by the aforementioned authors as indicative of a supratidal environment.

The Icla Formation (Steinmann, in López Pugliessi and Suárez-Soruco, 1982) in the Western Subandean Belt of Bolivia is a shaly unit composed of black, micaceous, greasy feeling shales with high organic content. It also contains rhythmic intercalations of thin siltstone beds of whitish gray to dark gray color, and intercalated sandstone beds. The upper and lower contacts are concordant. Whereas the lower contact is sharp, the upper one is transitional to the Huamampampa Formation. Guide macrofossils and palynomorphs indicate a Siegenian age (Oblitas et al., 1972).

According to López Pugliessi and Suárez-Soruco (1982), initial deposits of the Icla Formation contain intertidal sediments and faunas containing Proboscidina and Scaphiocoelia. It is succeeded upward by shallow and medium depth subtidal sediments and faunas containing Australospirifer and Notiochonetes, and then to deep environments containing Metaplasia and Austranoplia. The upper section of the Icla Formation becomes more sandy towards the Santa Victoria High, and it becomes difficult to separate it from the overlying Huamampampa Formation.

The Huamampampa Formation (Steinmann, in López Pugliessi and Suárez-Soruco, 1982) consists of intercalating shaly and sandy sediments. The sandy intervals are medium to thick and consist of whitish gray, fine grained, siliceous and micaceous sediments. These intervals are important reservoir rocks in the Southern Subandean Belt. The Formation thickness ranges from 200 to 400 meters (656 to 984 feet). It is of Emsian age as determined by macrofossils and palynomorphs (Oblitas et al., 1972). Its upper contact with the Los Monos Formation is transitional and concordant (Oblitas et al., 1972).

According to López Pugliessi and Suárez-Soruco (1982), the Huamampampa Formation represents a coastal facies. This is indicated by sediments and lower intertidal faunas containing Tropidoleptus, Derbyina and Pustulatia as well as plant remains. The intercalation of subtidal communities reflect fluctuations of the shoreline.

The Los Monos Formation (Mather, 1922, in López Pugliessi and Suárez-Soruco, 1982) is widely distributed in central South America (Fig. 11). It consists of thick black purplish shales, very micaceous, greasy feeling, with organic content. These shaly units are intercalated with dark and light gray sandstones which are reservoirs in the Southern Subandean Belt. The Los Monos Formation is Eifelian in age in Bolivia and is up to 1,000 meters thick in the Southern Subandean Belt (Oblitas et al., 1972).

The Iquiri Formation in the Subandean Belt (Figs. 6 and 11) is coarser than the Los Monos Formation. It consists of an intercalation of sandy and shaly units, with predominance of the sandy units. These sandy units are rather thick in places, and consist of whitish gray and greenish, medium- to fine-grained sandstones, micaceous and siliceous sandstones, which are reservoir rocks in the Southern Subandean Belt. The formation thickness ranges from 400 to 700 meters (1,312 to 2,296 feet). Its lower contact is transitional with the Los Monos Formation, and the upper contact is marked by a regional unconformity at the base of the Carboniferous in Bolivia. Macrofaunal and palynological data assign it a Givetian-Frasnian age (Oblitas et al., 1972).

Devonian of the Paraguayan Chaco

In the Paraguayan Chaco, the alternation of sandy and shaly formations of the Bolivian Subandean Belt does not occur, and a very thick and monotonous shaly section characterizes most of the Devonian System, indicating a relatively deeper environment, less susceptible to variations in clastic input. There is palynological evidence that the Devonian sediments in Paraguay begin in the Early Devonian (Gedinnian; Lammons, 1977). In the deeper parts of the Carandaity Subbasin, the Devonian passes transitionally into the Lower Mississippian (Tournaisian) and on into the Lower Pennsylvanian.

The lithologic distinction between the Santa Rosa, Icla and Huamampampa formations of the western part of the Southern Subandean Belt of Bolivia does not exist in Paraguay. The sequence is similar to the one found in the eastern part of the Southern Subandean Belt of Bolivia in the Serranía Sararendá and in northwestern Argentina (Figs. 6 and 7). That is, the Santa Rosa Formation ranging from Gedinnian to Emsian (Early Devonian) is overlain by the shaly Los Monos Formation.

The lithologic unit of intercalated sandstones, siltstones and shales is widespread throughout the Chaco, and its identification in some wells is based on lithology in the absence of palynological data. In the Carandaity Subbasin, this unit was dated palynologically in the well Don Quixote-1 as Upper Ordovician to Lower Devonian (Urban, 1972), and in the Parapití-1 well (Boyd, 1988, oral communication) as Upper Ordovician to Lower Devonian. This section can be found at relatively great depth in the eastern portion of the Chaco in wells La Paz-1, Palo Santo-1, López-1, Orihuela-1 and Toro-1 (Figs. 1, 12, 13 and 16).

In the López-1 well, palynological determinations by Urban (in Gayer, 1972) indicate a Devonian age for the marine sands underlying the Los Monos shales, although no stage level identification was available for the present study (Fig. 13). The presence of this unit, especially quartzites and sandstones, had previously served as an indicator of possible Silurian age, always following the Andean region sequences.

The top of this unit has a palynological age of Emsian in the Don Quixote-1 well (Fig. 7), which seemingly would correlate with the Huamampampa Formation of the western part of the Bolivian Subandean Belt. The depositional environment is "possibly continental" (Urban, 1972), but the lithology has a gray color. The next 27 meters (90 feet) downwards are barren of palynomorphs, and are underlain by marine Silurian sandstones with intercalations of silts and shales (Urban, 1972). Some age determinations for the Parapití-2 well were made by Lobo (1989) from very small amounts of samples (3 grams as opposed to about 30 grams needed for confident palynological age determinations). He reported leiospheres and some fragments of *Schizocystia* sp. and determined for the interval 2,149 to 2,164 meters (7,050 to 7,100 feet) a possibly Siegenian age (Fig. 12). This age correlates with the Icla Formation of the western part of the Southern Subandean Belt of Bolivia.

The Palo Santo-1 well in the Pirizal Subbasin (Fig. 1) reached an Early Devonian marine sandstone. The palynological report by Millioud (1975) indicates strongly carbonized marine microorganisms i.e. acritarchs and chitinozoans with rare spores. A precise age determination was not possible because of the poor preservation of palynomorphs. However, the association of *Neoveryhachium carminae* and *Baltisphaeridium* cf. *denticulatissium* with the spore *Emphanisporites* sp. was interpreted in the report as suggesting an Early Devonian age. Chitinozoans with forms similar to *Angochitina comosa* and *Angochitina toyetae* also were interpreted as supporting an Early Devonian age.

In the López-1 well, this Lower Devonian marine sandstone is white to gray and has an unconformable contact at the top with Devonian continental redbeds (Figs. 12 and 13). Urban (in Gayer, 1972) interpreted the 695 meters (2,279 feet) section from 3,400 feet to total depth at 5,679 feet (1,036 to 1,731 meters) as being of Devonian age according to palynology. According to wireline core and well cutting descriptions by Pure Oil geologist Harris (1959), this section is composed of "red to brick red, sometimes blue green to green, frequently sandy shales or clay shale, and red to grayish brown, sometimes clear or gray, very fine to very coarse grained sandstone down to 5,342 feet (1,628 meters), at which point some angular fragments of reddish and gray quartzite were present in the sample." Cores from 5,342 to 5,353 feet (1,628 to 1,631 meters) revealed "tan and tan to red, fine grained weathered and dense quartzite." From 5,358 to 5,450 feet (1,633 to 1,661 meters): "white to light gray fine to medium grained quartzite, with a small amount of red micaceous hematitic clay." From 5,450 to 5,665 feet (1,661 to 1,727 meters): "Dark gray to light gray, very fine to fine grained shaly micaceous quartzite and dark gray, hard siliceous and soft, very micaceous shale with some hard dolomitic shale and dark brown, dense, shaly dolomite." From 5,665 to 5,679 feet (1,727 to 1,731 meters): "Light gray, fine grained, clean to slightly shaly, slightly dolomitic quartzite with dark gray to very micaceous shale. Some of the quartzite has intergranular light gray micaceous shale and appears friable in the drill cuttings."

The upper contact of this white to gray marine unit was described by Harris (1959) as consisting of a weathered quartzite containing large angular clasts of gray to white quartzite together with reddish quartzite clasts. One of these white quartzite clasts had an 8 inch (20 centimeters) diameter as observed in a drilled core. This contact represents an unconformity within the Devonian sequence. Immediately above the Santa Rosa Formation in this well, occurs a continental redbed section that was previously ascribed to the Mesozoic-Tertiary because it is a redbed, and the Devonian was always associated with the presence of gray to black shales. Palynological information obtained by Urban (in Gayer, 1972) identified the redbed section from at least 3,400 feet (1,036 meters) down to total depth of the López-1 well, including the white to yellowish quartzites intercalated with sandstones, siltstones and shales as definitely Devonian, but no better age resolution was mentioned.

Short segments of cores of the lower section of the Santa Rosa Formation from depths of 7,168.8 to 7,229 feet (2,185 to 2,203.4 meters) from the Don Quixote-1 well were available for this study. This section consists of intercalated dark black shales (Figs. 20

and 21), dark gray siltstones and fine sands (Figs. 22, 23, 24 and 25). The shales normally contain very fine laminae of dark gray silt and fine sand (Figs. 26 and 27). The fine sandstones and siltstones locally have a clay matrix (Fig. 23). The clay minerals in the section consist of chlorite, illite and kaolinite, as determined by x-ray diffraction analysis (See chapter VI). The sand- and silt-sized grains consist mostly of quartz and some plagioclase and orthoclase (Fig. 25). The fine sandstones and siltstones have no porosity due to extensive quartz, plagioclase, and orthoclase syntaxial overgrowths, which resulted in sutured boundaries between overgrowths (Figs. 25 and 27).

In the Curupaity Subbasin, the Toro-1 well penetrated the Santa Rosa Formation. Well cuttings reveal a light gray to white, clean, fine grained quartzarenite, intensely cemented by silica. The well terminated in a very dense quartzite. A 200-point count of a thin section of cuttings from 11,200 feet (3,414 meters) reveal a metaquartzarenite with 95% quartz, 4% orthoclase and 1% plagioclase, with no porosity (Figs. 28, 29 and 30).

Texaco geologists (1975) produced a composite stratigraphic column of the southwestern flank of the Cerro León outcrop. The basal section consists of 100 meters of homogeneous light gray quartzite with thin streaks of hematitic quartzite along bedding planes, very well bedded, with beds of 0.5 to 3 meters thick. Some beds have well developed cross bedding. Abundant fossil casts, including fragments of corals and crinoids were reported in the uppermost beds. Overlying the quartzites, in apparently gradational manner, are 25 meters of light gray micaceous sandstones, bedded in 10- to 30-centimeters-thick units containing fossil casts. These sandstones are apparently missing in some areas, and an erosional unconformity was inferred. Overlying the gray sandstones are 25 meters of pink to brick red quartzose sandstones, fine to medium grained, with "subrounded to subangular, fairly well sorted grains with little silty matrix. Very friable, very porous, well bedded 50 cm thick beds" (Texaco Paraguay, 1975).

According to Harrington (1946), Union Oil geologist Morán collected a few fossils from the northern flank of Cerro León from a "float" consisting of blocks of hard siltstones and "dirty" sandstones. Harrington (1946) identified one of these fossils as Leptocoelia flabellites, which he considers an Eodevonian marker (Cassel, 1957).

A 200-point count of a thin section of cuttings of the Cerro León-1 well at 6,460 feet (1,69 meters) revealed a meta-arkose with 75% quartz, 22 % orthoclase, and 3% plagioclase (Figs. 31, 32 and 33). The rock was subjected to recrystallization (Fig. 33). No porosity was observed, as in the samples of Toro-1 and Don Quixote-1. The feldspar content suggests greater proximity to a source area than the samples from Toro-1 and Don Quixote-1.

A total of 2,615 kilometers of seismic reflection lines covering the Curupaity Subbasin, the Cerro León Arch and the southwestern part of the Carandaity Subbasin were interpreted in this study in order to determine the areal distribution of formations and the general structure of the area (Fig. 34). Figure 35 shows the distribution of the Santa Rosa Formation in the Curupaity and Carandaity subbasins and Cerro León Arch as interpreted from seismic sections.

Figures 12 and 13 show the distribution of the Santa Rosa Formation throughout the study area in cross sections. Figures 36 and 37 show the likely paleogeography of the Chaco during the Gedinnian, Siegenian and Emsian.

Wells Lagerenza-1 and Cerro León-1 (Fig. 1) are located in the area of the Cerro León or Izozog Arch (Fig. 3). Only a thin sequence of Quaternary sediments 710 feet (216 meters) in Lagerenza-1, and about 50 feet (15 meters) in Cerro León-1 overlies the Devonian sequence. Palynological analysis for Texaco by Lammons (1977) of the Cerro León-1 well down to a depth of 5,850 feet (1,783 meters) indicates a Gedinnian age for the interval 5,400 to 5,850 feet (1,646 to 1,783 meters): "Fair assemblages yielding the terrestrial spores Leonispora cf. L. argovejae Cramer, 1975, and Amocosporites cf. A.

subornatur Cramer, 1975 as well as fragments of the chitinozoan Ancyrochitina support an Early Devonian (Gedinnian) age for this interval. The size distribution curves are corroborative." The lithology of this interval is shaly and would therefore correspond to the homogeneous black shale of the Los Monos Formation. A sandy lithology characterizes the lower section of the well, suggesting a transition to the underlying sandy character of the Santa Rosa Formation.

The lithology of most of the Devonian sequences in Paraguay, from the later part of the Emsian, is represented by a homogeneous section of dark gray to black, shallow marine shales which extend to the Frasnian in the Carandaity and Curupaity Subbasin (Fig. 7). This shale sequence contrasts with the marked change in lithology observed in the western part of the Southern Subandean Belt of Bolivia in well ING-1; and is similar to the central section of the Bolivian Subandean Belt in the Parapetí River area in well CAM-20 (Fig. 6). This thick Devonian shale sequence is known as the Los Monos Formation as it occurs in the eastern part of the Subandean Belt and Chaco of Bolivia and Argentina (Fernández Garrasino, 1981; Fig. 11 of this report). It is the age equivalent of the Icla, Huamampampa and Los Monos formations of the western part of the Subandean Belt of both countries (Fig. 11). The Devonian shales are medium to dark gray to black, firm, micaceous to very micaceous, fissile in part, with interbeds of siltstone. These intercalated siltstones are light gray, fine to medium grained and very micaceous.

The general structure of the Devonian section can be interpreted from Figures 38 and 39. Figure 38 is an aeromagnetic map of the Carandaity Subbasin area showing the basement features. The Cerro León Arch can be clearly observed in the northernmost section, as well as some high points around the Don Quixote-1 and Emilia-1 areas. Figure 39 shows a structure map of a seismic stratigraphic level (D-5) corresponding to the Middle Devonian (Givetian) as interpreted by Pennzoil (1972). This map is based on poor quality (2-fold stack) seismic lines. According to Pennzoil (1972), the fault patterns shown in this map are highly interpretative and resolution of their attitude and position could only be obtained with higher quality seismic data. The Pennzoil seismic lines from the Carandaity Subbasin were available for this study. However, only 5 reprocessed seismic lines with a total of 350 kilometers (Fig. 34) were interpreted herein because of the poor resolution of the non-reprocessed lines.

The top of the Devonian sequence in the Carandaity Subbasin shows a transitional regressive sequence from marine to marine-deltaic, lagoonal to continental facies, as determined by palynology (Urban, 1972) and lithology. This section has thicknesses from approximately 244 meters (800 feet) in Hortensia-1, to 701 meters (2,300 feet) at Picuiba-1 (Fig. 14), and it corresponds to the Iquiri Formation (Fig. 18).

Figure 40 shows a schematic cross section of the relatively deep wells of the study area. Relatively deep angular unconformities affect the Paleozoic sedimentary package. The central areas of the Carandaity Subbasin show a transitional contact between the Los Monos and Iquiri and the Carboniferous Tupambi formations, while in the surrounding areas, including the Curupaity Subbasin, the Los Monos Formation is affected by deep unconformities clearly observed in seismic sections. Figure 41 shows a structure map of the top of the Los Monos shales in the Chaco. This surface is erosional throughout the Chaco, except in the area contained approximately within the 800 meter contour line of the Carandaity Subbasin.

The thickest Devonian section drilled in the Chaco was penetrated by the Pure Mendoza-1 well with over 8,339 feet (2,542 meters), of which 8,200 feet (2,500 meters) correspond to the Los Monos marine shales and 139 feet (42 meters) to the upper part of the Santa Rosa Formation. However, the thickest Devonian section, as determined by seismic reflection means, is found in the Curupaity Subbasin with over 3,600 meters (11,811 feet). Figure 42 shows an isopach map of the Los Monos Formation in the Curupaity Subbasin and Cerro León Arch area.

The easternmost occurrence of Devonian black shales outside the Curupaity Subbasin was penetrated by the La Paz-1 well (Fig. 41). Approximately 100 meters (300 feet) occur between 4,600 feet (1,402 meters) and 4,900 feet (1,493 meters) in this well (Fig. 12). The top of this interval is erosional and is associated with the uplifting and rifting process that formed the Pirity Subbasin during the Early Cretaceous. This location was an elevated area during the Cretaceous, but was covered by the Lumbrera Formation during the Tertiary (Figs. 12 and 40).

The thickest Lower Devonian (Emsian) shales are found in the Santa Rosa-1 well (Fig. 12). Harrington (1946) did the paleontological identification of cores from 3,055 to 6,717 feet (931 to 2,047 meters), and assigned the whole dark shale section to the Early Devonian. From his report:

> A total of 19 forms (1 crinoid, 1 doubtful Trilobite?, 2 Tentaculites and 15 Brachiopods) have been determined in the collection of core-samples from the Santa Rosa Nr. 1 drill-hole.... 14 forms were sufficiently well preserved to warrant specific determinations (2 Tentaculites and 12 Brachiopods).
>
> The uniformity of the Eodevonian fauna throughout the great thickness of 3652 feet, can only be explained by a protracted period of marine sedimentation under practically unchanged environmental conditions and comparatively rapid sinking of the sedimentary trough which proceeded pari passu with the accumulation. The sediments are obviously of shallow water facies containing a normal 'shelly fauna' and even some doubtful plant remains.

There is a relatively large difference in thickness in the Lower Devonian sediments of the Santa Rosa-1 and Don Quixote-1 wells. The Santa Rosa-1 area would represent a more rapidly subsiding area, accompanied by a steady and larger supply of sediments in pace with the sinking, thus maintaining the same environment throughout the thickness.

According to core descriptions of the Santa Rosa-1 well (Pennzoil, 1968), the upper section, from 3,035 to 3,025 feet (925 to 922 meters), consists of dark gray shales interbedded with red, yellow, lavender, brown and green shales. The gray shales disappear above this level. This interbedding would indicate a transitional environment into a continental one belonging to the Lower Devonian (Figs 12 and 37). Further above, the interval 2,995 to 2,985 feet (913 to 910 meters) has a conglomerate containing firmly lithified sandstone and shaly pebbles, and light and dark colored angular siliceous pebbles; with layers of pebbly greenish sand, and red, yellow and purple clay levels. This conglomerate is interpreted here as representing an unconformity marking the top of the Devonian section and the base of the Tertiary Lumbrera Formation (Fig. 12).

The Middle Devonian represents an expansion of the seas as indicated by the shales of the Los Monos Formation as they occur in the western part of the Southern Subandean Belt. It is difficult to speculate how far east into Paraguay the Middle Devonian coastline extended, because of the deep erosion that affected the Devonian sequence towards the center of the Chaco in the Central Chaco High area (Figs. 12, 13 and 16).

Prior to the use of palynology in the area by Urban in the 1970's for the Pennzoil exploration efforts, the Devonian had been identified by the first occurrence of the gray to dark black marine shales, and the upper transitional sandstones were ascribed to the Permocarboniferous based on the lithologic sequences found in Bolivia. These upper sandstones were clearly placed in the Devonian by Urban. The gradational upper contact of the Devonian marine shales is of early Late Devonian (Frasnian) age. Figures 43 and 44 show the likely paleogeography of the Chaco during the Middle Devonian (Eifelian and Givetian). Figures 45 to 50 show several cross sections in the Carandaity Subbasin showing the correlation of environments and ages in the upper part of the Devonian and its transition into Lower Mississippian and Lower Pennsylvanian deposits. The upward (and westward) transition from a marine to lagoon to marine deltaic to continental environments can be observed. The marine deltaic complex is of Late Devonian to Early Mississippian (Frasnian to Fammenian to Tournaisian) age, and probably ranges into the Early Pennsylvanian. Early Mississippian (Tournaisian) to Early Pennsylvanian palynomorphs were found in lagoonal sediments in the Dorotea-1 well (Urban, 1972). Figure 51 shows the Frasnian-Fammenian paleogeography, as interpreted herein. Fammenian palynomorphs were found in the Brigida-1 well at a depth of 2,200 to 2,260 feet (670 to 689 meters). This sample is in the overlying continental redbed facies and was questioned by Urban (1972) as being possibly reworked.

Carboniferous

In the Carandaity Subbasin, the section extending from the base of the continental clastics and redbeds to the Quaternary unconformity is very poor in fossils. Only scattered samples extending into the lower section of the redbeds provided fossils of mostly Tournaisian and some of Early Pennsylvanian age (Urban, 1972). The stratigraphy of the remainder of the section to the Quaternary boundary has not been established because of lack of fossils. The section of Early Mississippian age, extending into the redbeds, would be the equivalent of the Tupambi Formation in Bolivia (Figs. 6, 7 and 11). The Early Pennsylvanian ages would indicate the presence of the continental Tarija Formation in the Carandaity Subbasin. Figures 52 and 53 show the paleogeography of the Chaco during the Tournaisian and Early Pennsylvanian.

In the Curupaity Subbasin, the Toro-1 and Gato-1 wells penetrated a section of shales interbedded with fine sands and silts ascribed to the (Upper?) Carboniferous by Lobo (1989). The section in Toro-1 extends from 1,400 to 5,300 feet (427 to 1,615 meters). The upper and lower contacts are erosional as observed in seismic sections. The Carboniferous-Devonian unconformity is noted by an erosional surface well defined by its seismic response (Fig. 54) and by the palynological study by Lobo (1989). Seismic correlations by Phillips Petroleum between the Bolivian and Paraguayan sections of the Curupaity Subbasin suggest this Carboniferous section to be the Tupambi Formation (Carlos Bustamante, 1991, oral communication). Figure 55 shows the distribution of the Carboniferous section in the Curupaity Subbasin.

Permo-Triassic

Late Permian to Early Triassic sediments occur in the Curupaity Subbasin. A preliminary palyriological report of the Toro-1 well by Lammons (1978) indicates that palynomorphs of the interval 490 to 1,320 feet (149 to 402 meters) are "typical of the continental, Late Permian-Early Triassic (Seithian) (sic) phase of the Gondwanan sequence." The microfloral assemblages include Guttalapollenites hannonicus, Polipodiisporites mutabilis, Carisaccites alutas, Laevigatosporites callosus, Paravittatina (Weylandites) lucifer and a fair representation of taeniate disaccate pollen.

This section consists of loose sand and claystones. The sand is loose, fine to medium grained, quartzose, clear to milky to orange, transparent, well to moderately sorted, subrounded to rounded, with good porosity. The claystones are varicolored to reddish brown and gray, soft, in parts silty and sandy with fine grains of quartz. Its upper and lower contacts are erosional (Fig. 16). The lower contact is with the Carboniferous sequence, while the section above the Triassic unit contains only reworked samples of the palynomorphs mentioned above. This section is herein named the Toro Formation in reference to the well in which its age determination --through palynology-- was made. It is difficult to ascertain the areal extension of this unit in the Curupaity Subbasin because of the relatively poor definition in seismic sections.

Quaternary

The Tertiary-Quaternary section was deposited on an erosional unconformity that transects most of the Paleozoic section in the Paraguayan Chaco (Fig. 40) According to Urban (1972), Quaternary sediments overlie Upper Devonian lagoonal sediments in the Christina-1 well (Figs. 46 and 47). The Quaternary section in the Carandaity Subbasin belongs to the Chaco Formation, and its thickest section 1,185 feet (361 meters) was found in well Brigida-1.

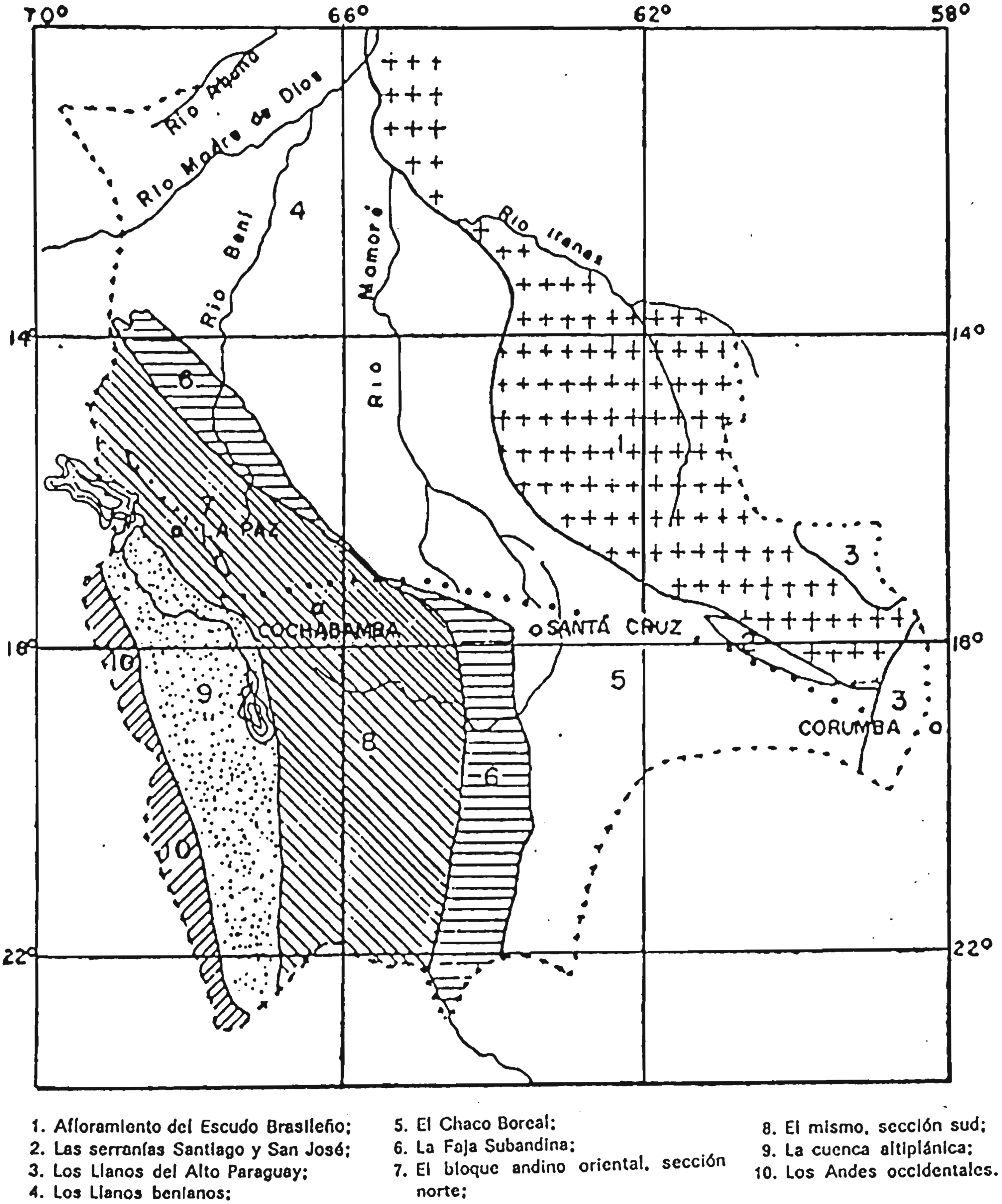


Fig. 5. Morphostructural units of Bolivia (Ahlfeld, 1972).

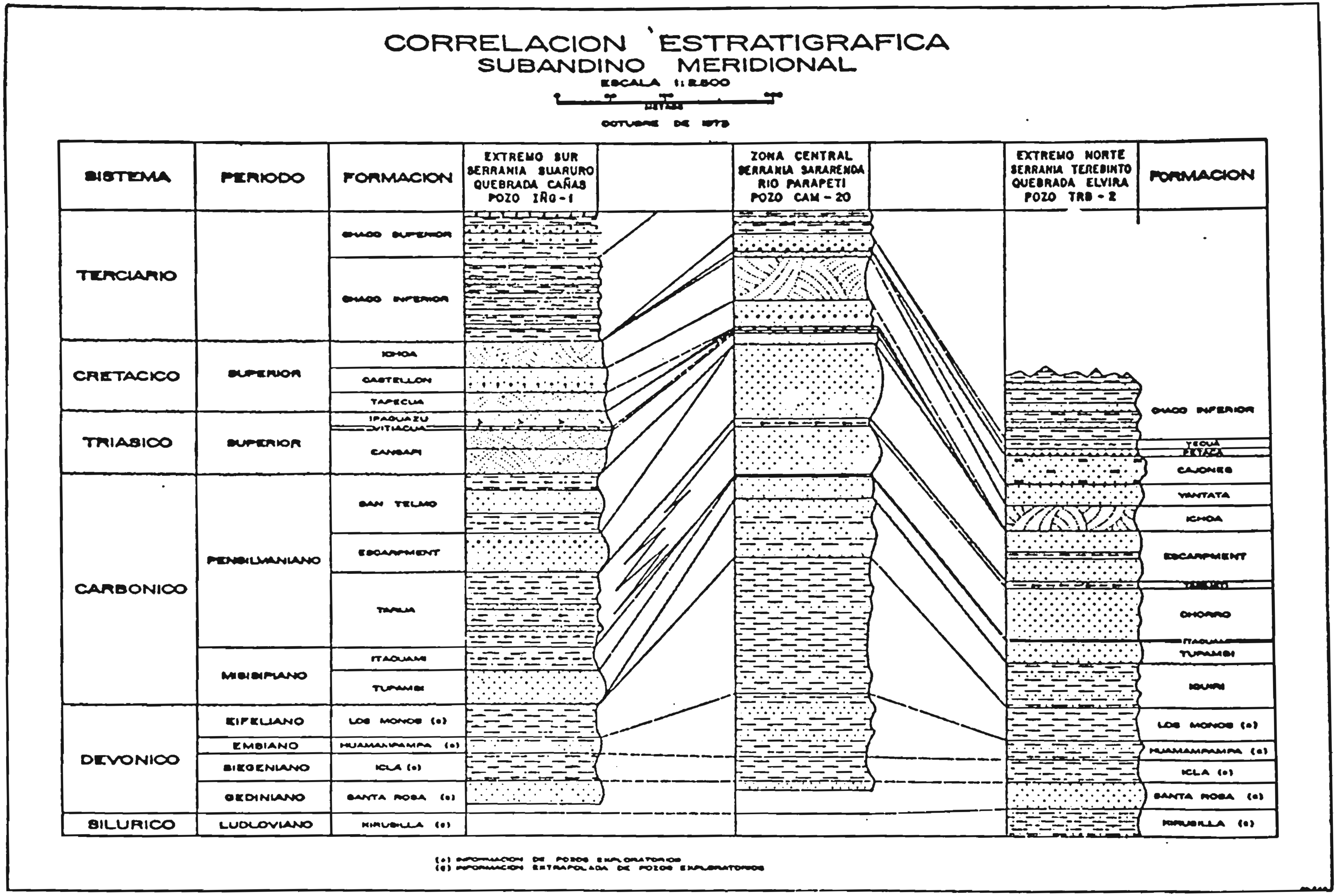


Fig. 6. Stratigraphic correlation of the southern, central and northern sections of the Southern Subandean Belt of Bolivia (Oblitas and others, 1972).

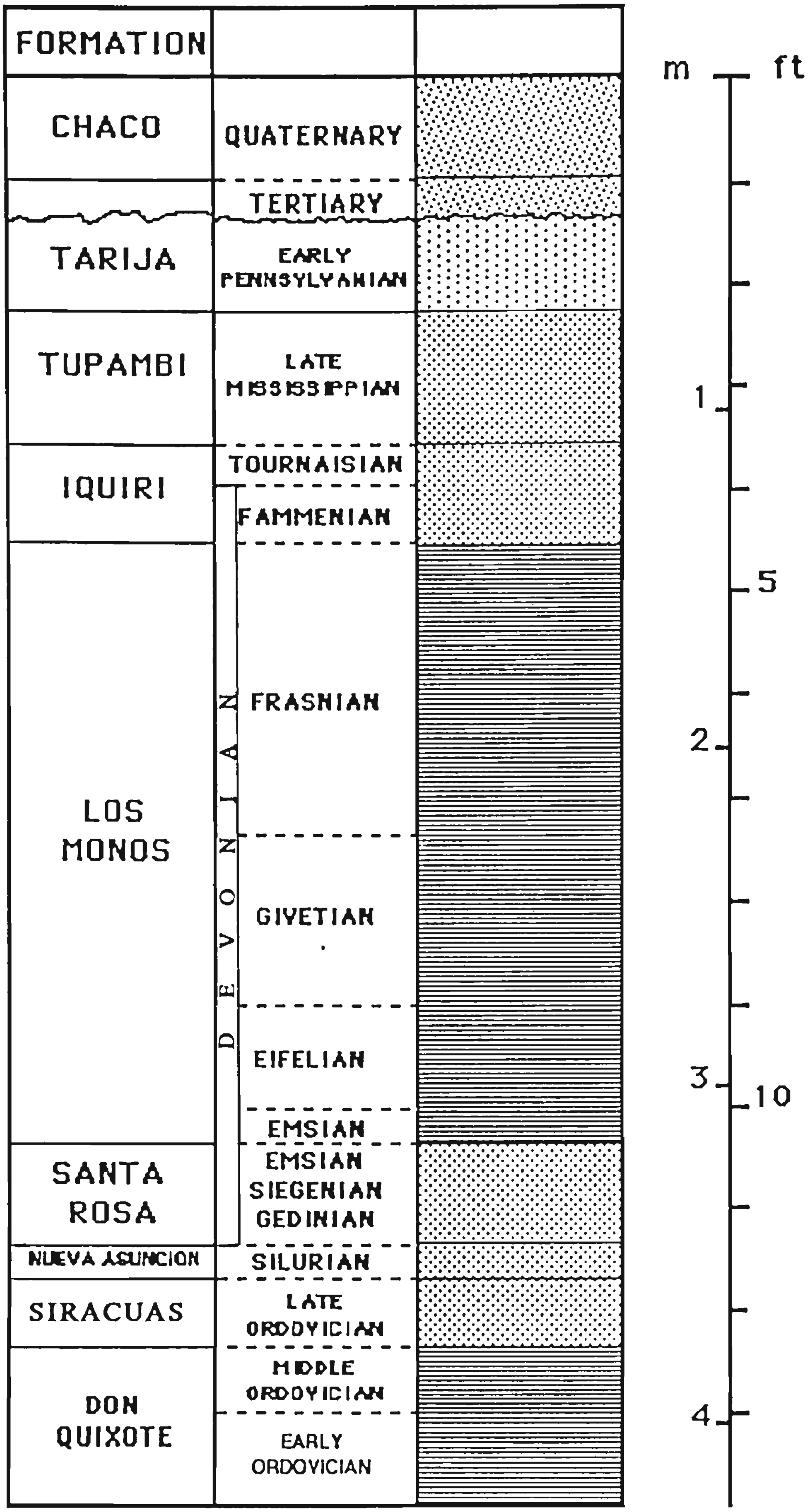


Fig. 7. Stratigraphic chart of the Carandaity Subbasin.

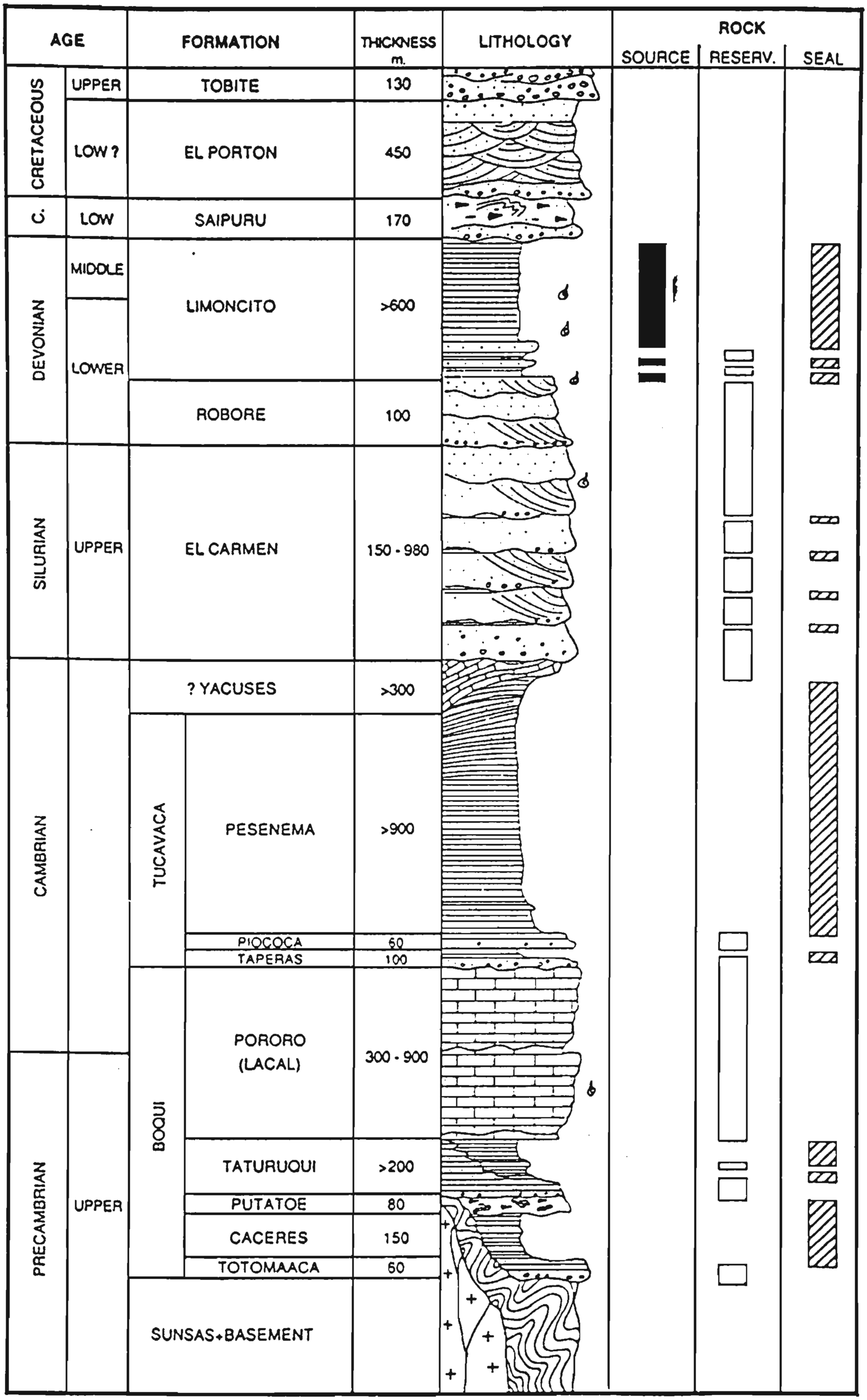


Fig. 8. Generalized stratigraphic column of the Roboré Basin of Bolivia according to the Bolivian national oil company YPFB. (Livieres, 1991; oral communication).

STRATIGRAPHIC SYNTHESIS

SAN JOSE-SANTIAGO HILLS					ANDEAN CORDILLERA Acc.to M. Suarez R.	
SISTEM	GROUP	FORMATION	ZONE	STAGE	FORMATION	ZONE
DEVONIAN	SANTIAGO	LIMONCITO		EMSIANO	ICLA	
			Scaphiocoelia boliviensis			Scaphiocoelia boliviensis
		ROBORE	Proboscidina abastoflorum		SANTA ROSA (=Vila Vila)	Proboscidina abastoflorum
				SIEGENIANO GEDINIANO		
SILURIAN		EL CARMEN	Clarkeia Antisiensis	LUDLOVIANO	TARABUCO (=Catavi)	Clarkeia Antisiensis
			Phragmolites Suaresi		KIRUSILLA (=UNCIA)	Phragmolites Suaresi
				?		
					ZAPLA	

Fig. 9. Correlation chart of Middle Paleozoic between San José-Santiago Hills and the Andean Cordillera (López-Paulsen and others, 1982).

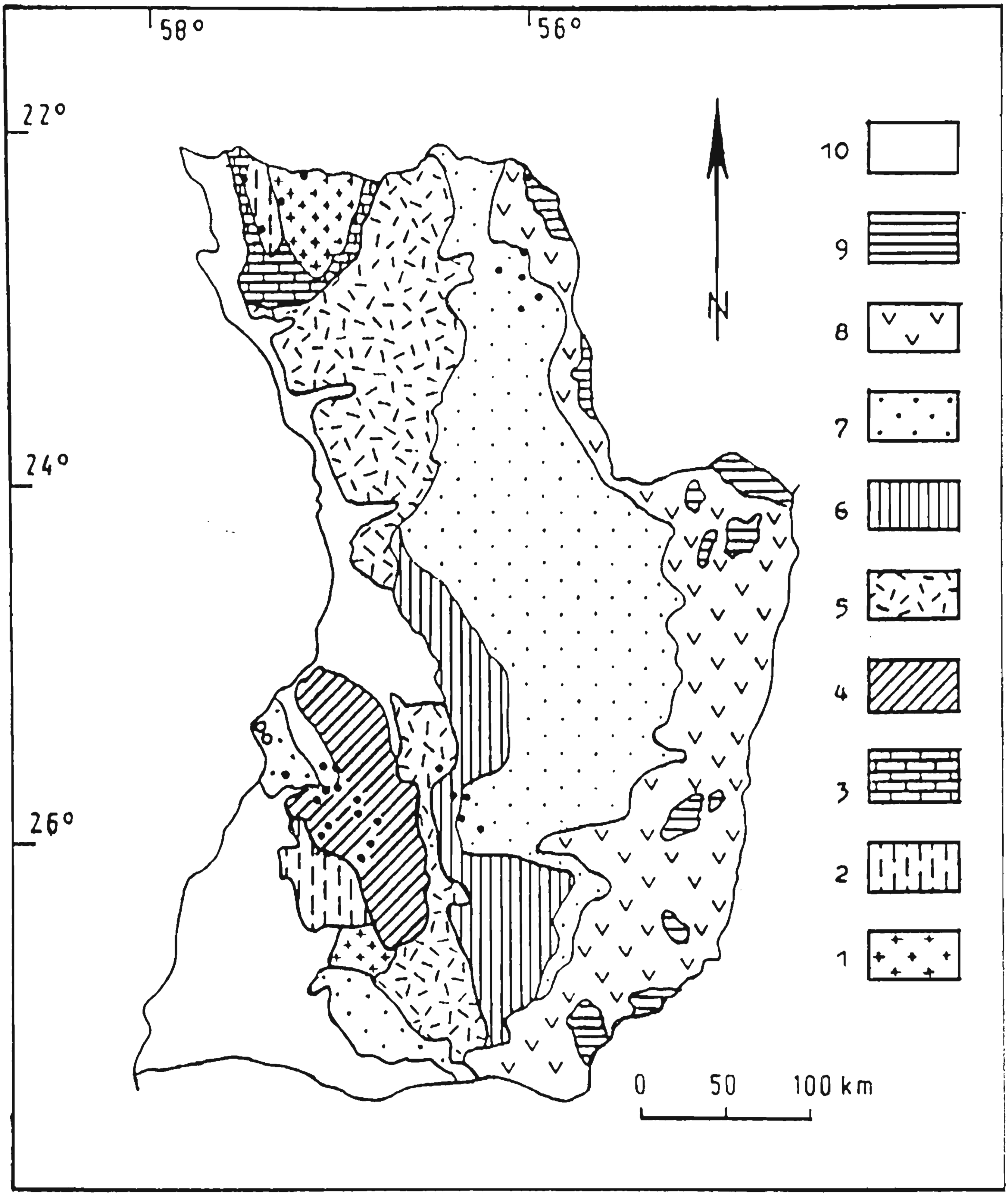


Fig. 10. Geological map of Eastern Paraguay. 1) Precambrian: crystalline; 2) Precambrian-Eocambrian: intrusives, extrusives and metasediments; 3) Eocambrian: carbonates (Itapucumí Group); 4) Silurian: clastic marine sediments (Caacupé and Itacurubí Groups); 5) Lower Permocarboniferous: fluvio-glacial sediments (Aquidabán Group); 6) Upper Permocarboniferous: fluvio-marine sediments (Independencia Formation); 7) Triassic-Jurassic: fluvio-eolian sediments (Misiones Formation); 8) Jurassic-Cretaceous: basaltic flows (Alto Paraná Formation); 9) Tertiary: continental sediments; 10) Quaternary: aluvial sediments. Jurassic intrusives (•), Tertiary intrusives (o). In Livieres (1987).

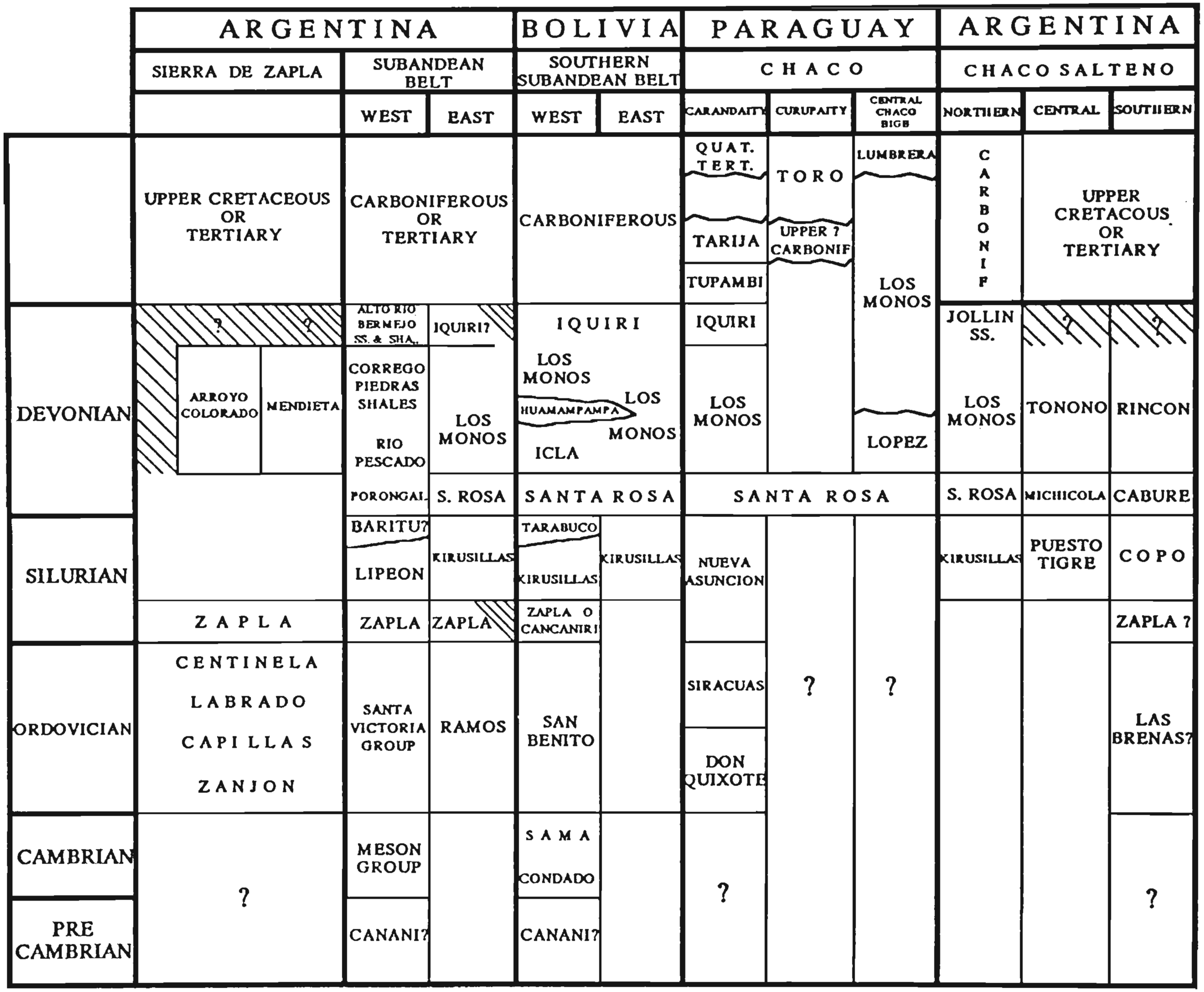


Fig. 11. Paleozoic correlation chart of northwestern Argentina and the Southern Subandean Belt of Bolivia (Fernández Garrasino and Cerdán, 1981), modified to include the Paraguayan Chaco.

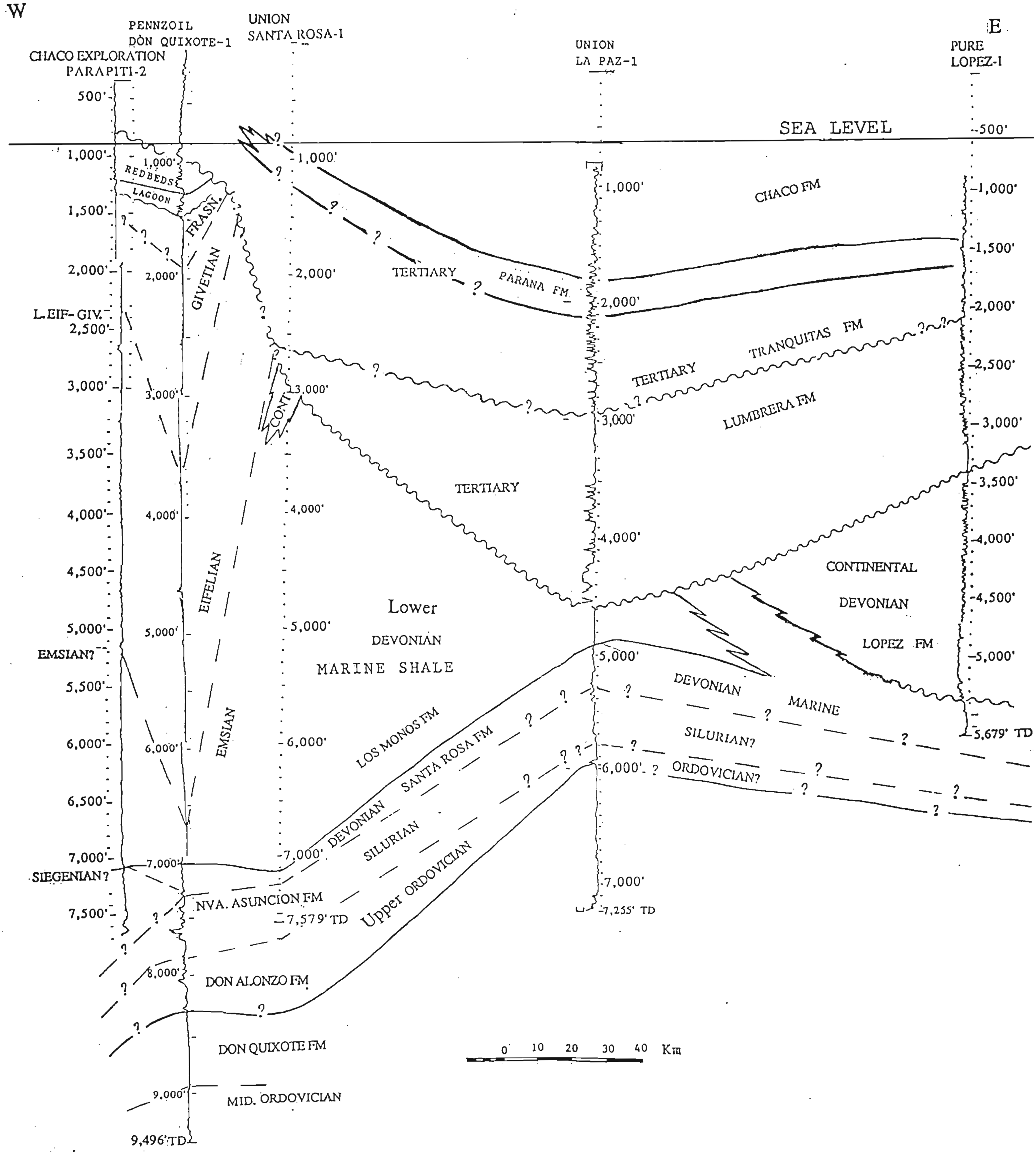


Fig. 12. East-West cross section from the Central Chaco High area to the Carandaity Subbasin between wells López, La Paz, Santa Rosa, Don Quixote and Parapití-2. See Fig. 1 for location of cross section. Spontaneous potential logs.

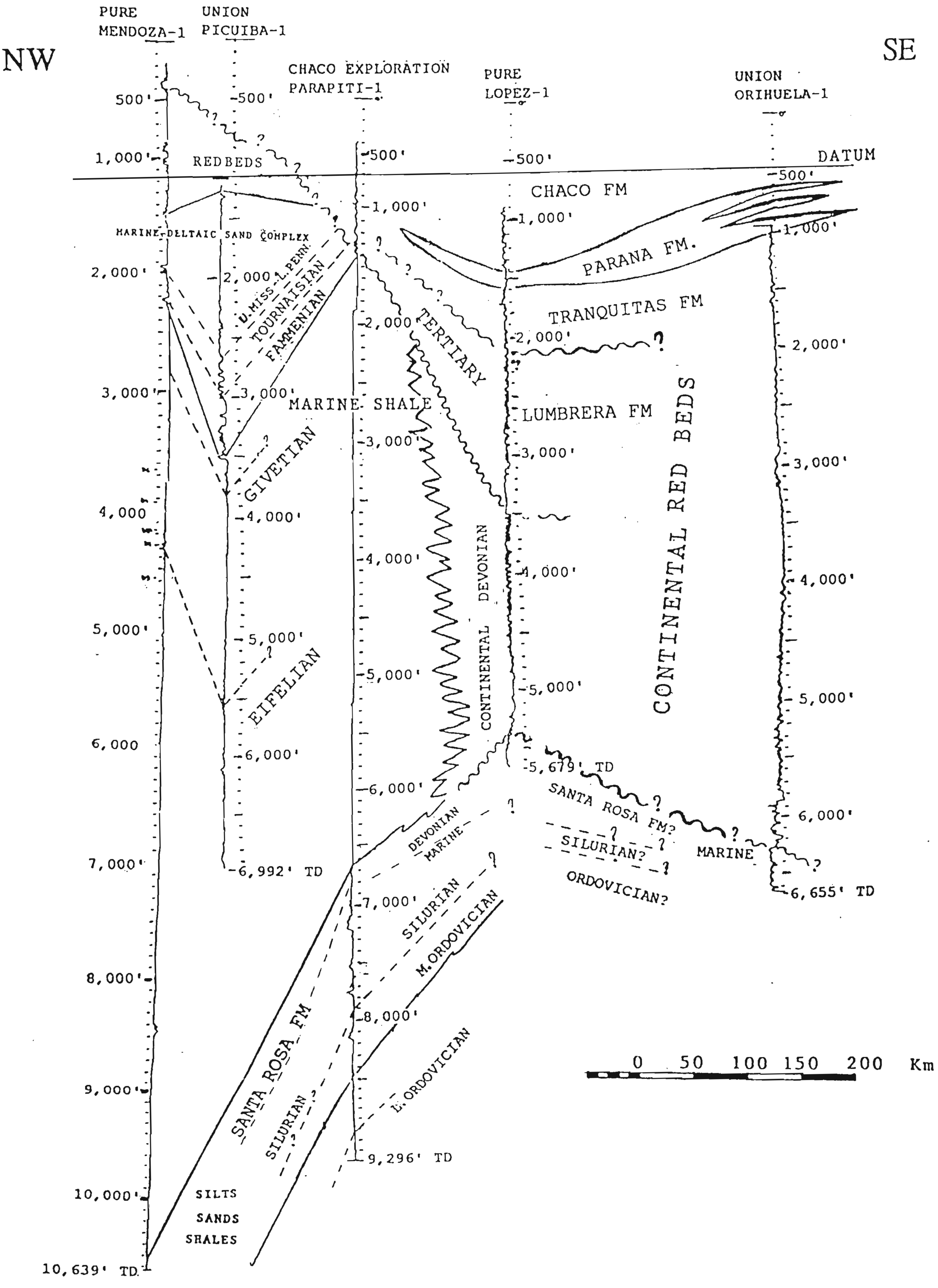


Fig. 13. Southeast-Northwest cross section between wells Orihuela, López, Parapití-1, Picuiba and Pure Mendoza-1. See Fig. 1 for location of cross section. Spontaneous potential logs.

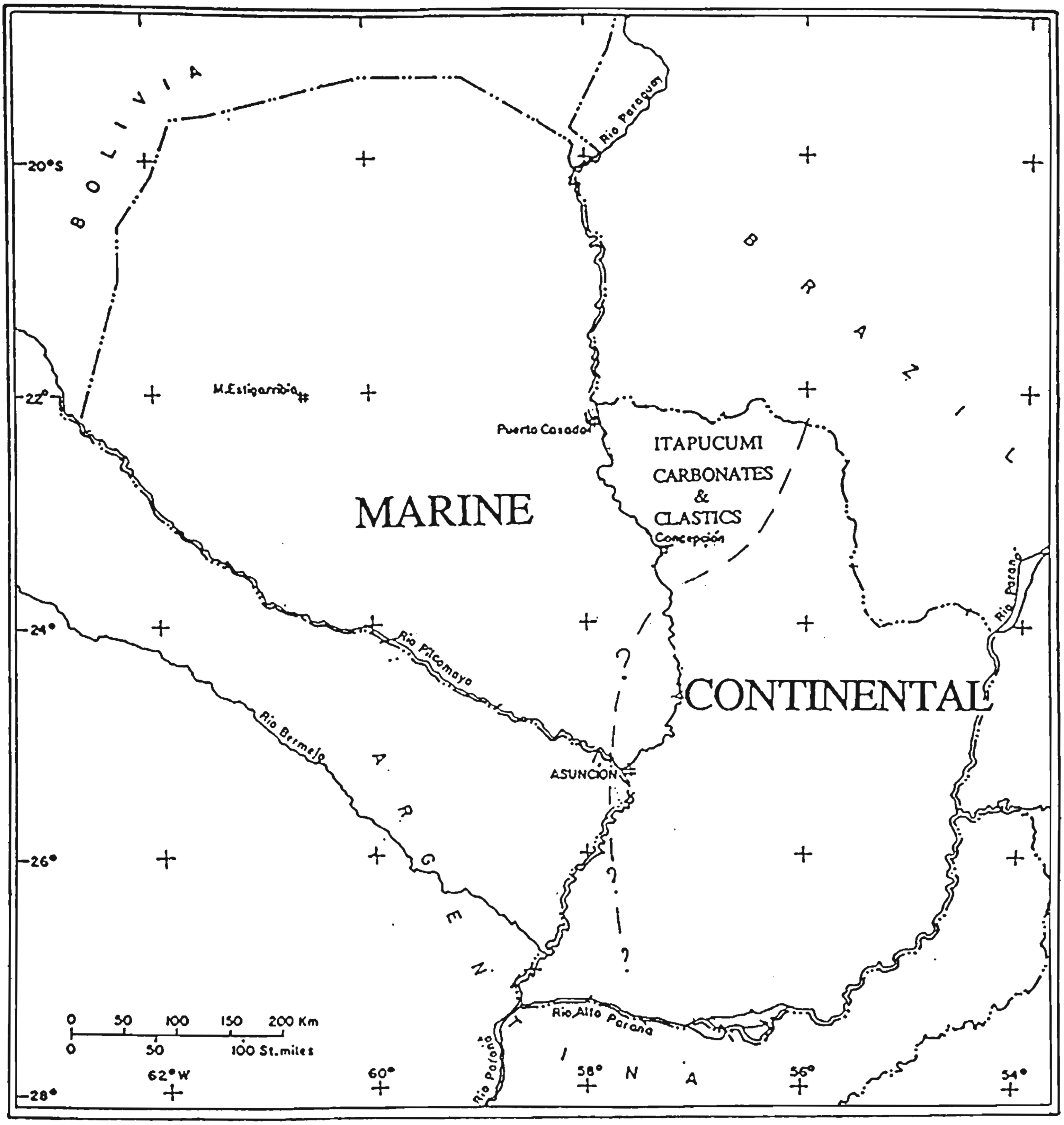


Fig. 14. Cambrian paleogeography of the Paraguayan Chaco.

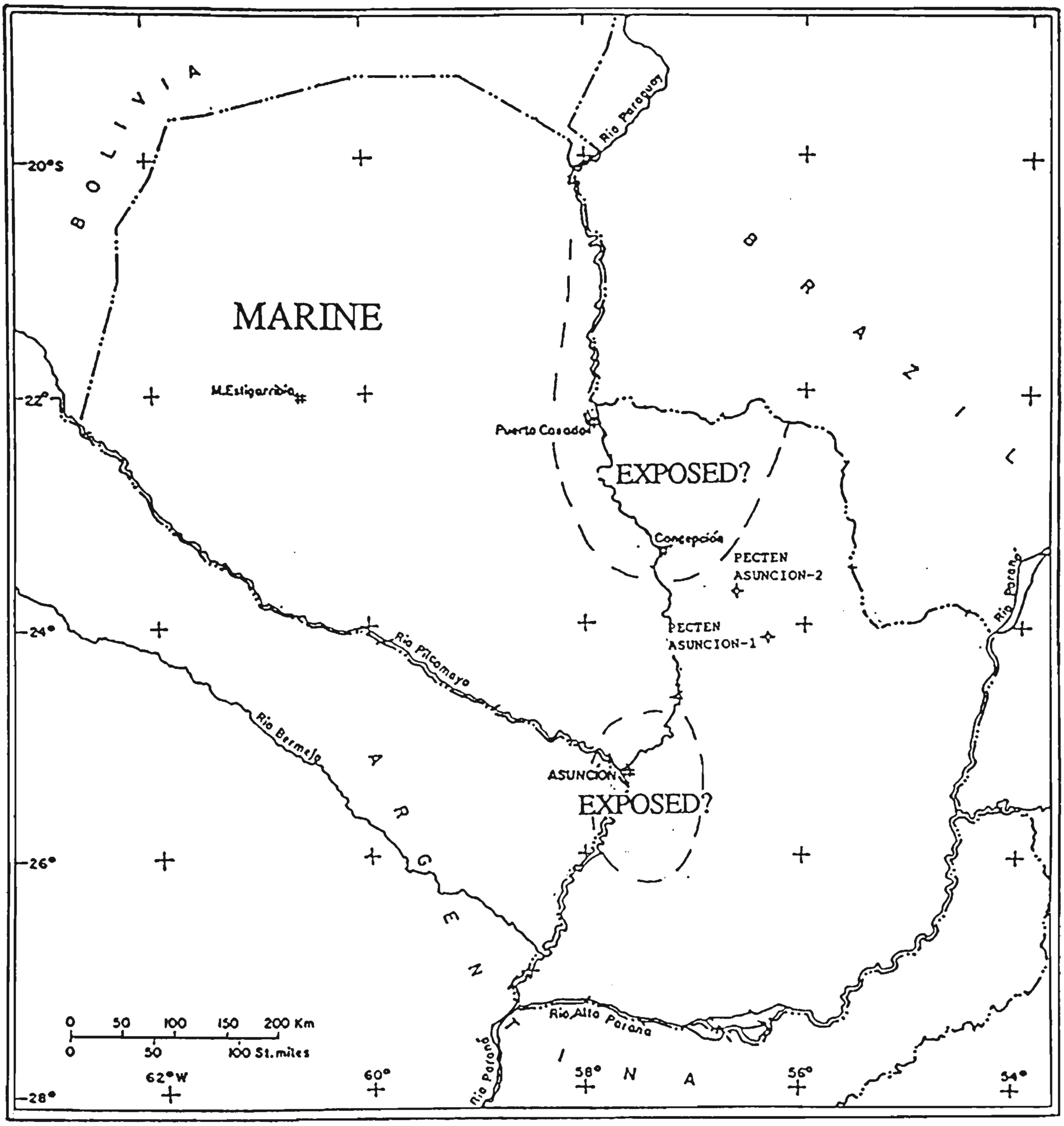


Fig. 15. Ordovician paleogeography of the Paraguayan Chaco.

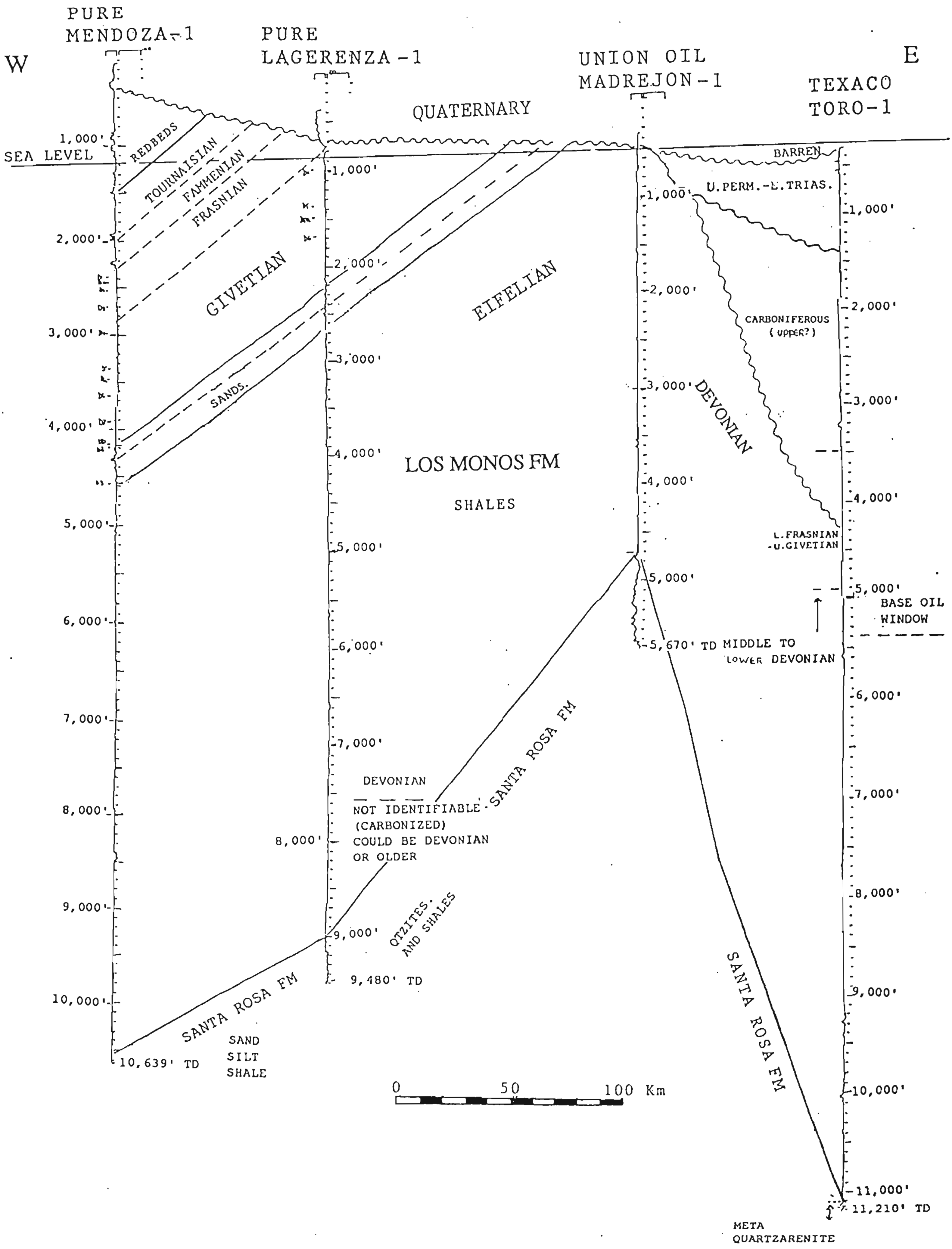


Fig. 16. East-West cross section from the Curupaity to the Carandaity Subbasin between wells Toro, Madrejón, Lagerenza and Pure Mendoza-1. See Fig. 1 for location of cross section. Spontaneous potential logs.

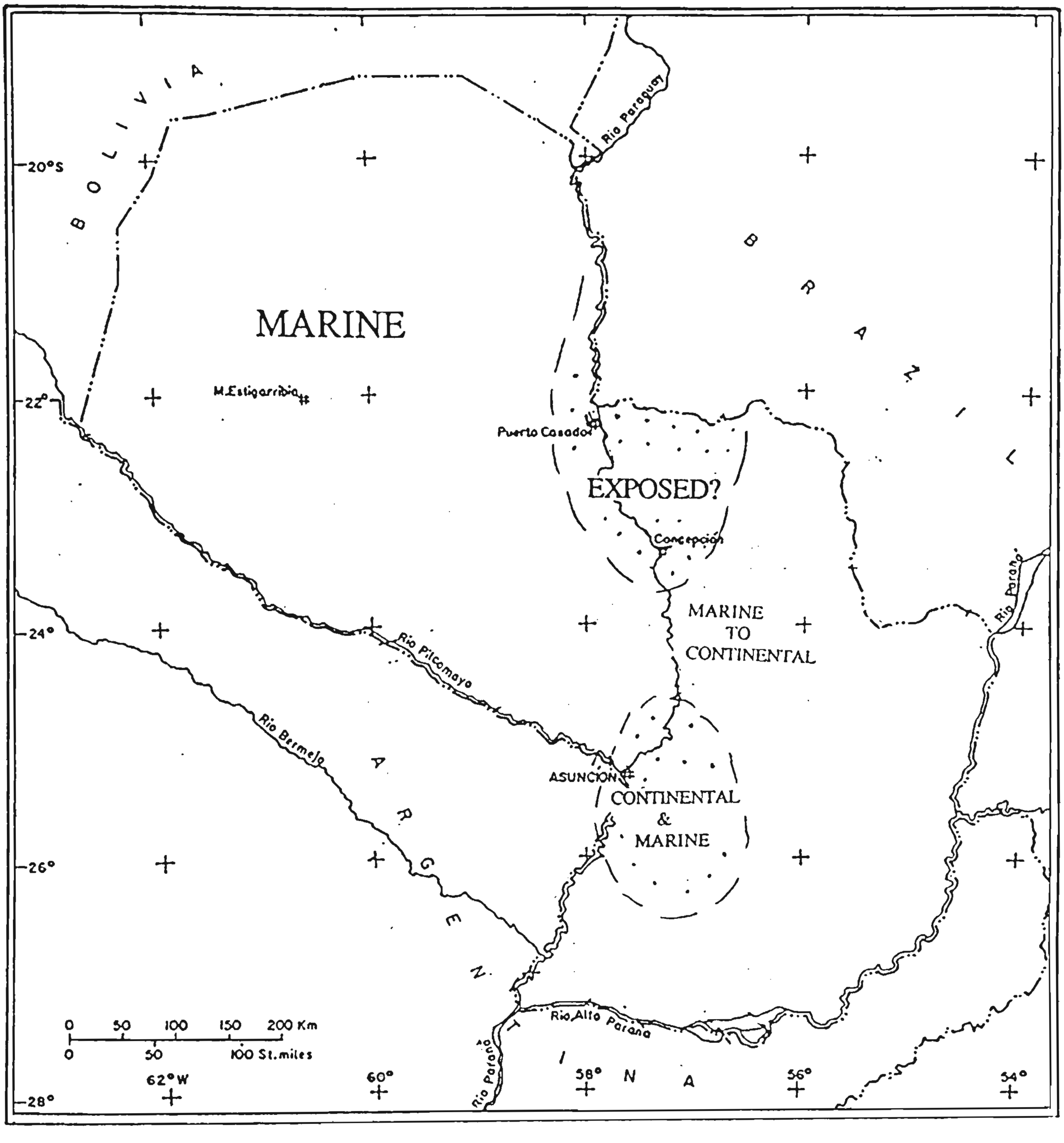
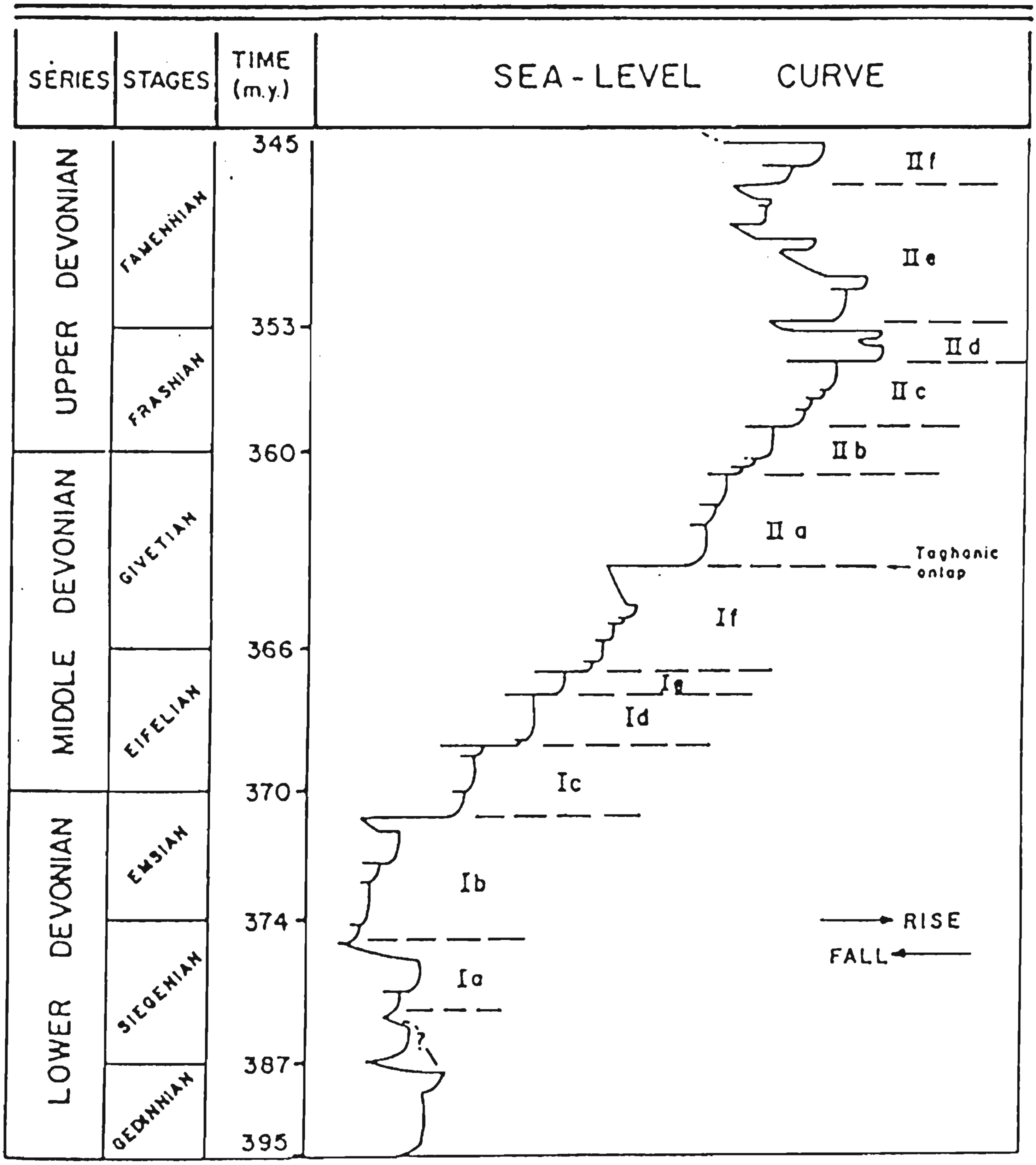


Fig. 17. Silurian paleogeography of the Paraguayan Chaco.



(Modified from Johnson et al., 1985, and including data from Dennison, 1985 – Geol.Soc.Am. Bull. 96: 1595-1597.)

Fig. 18. Sea level fluctuation curve for the Devonian Period (Melo, 1988).

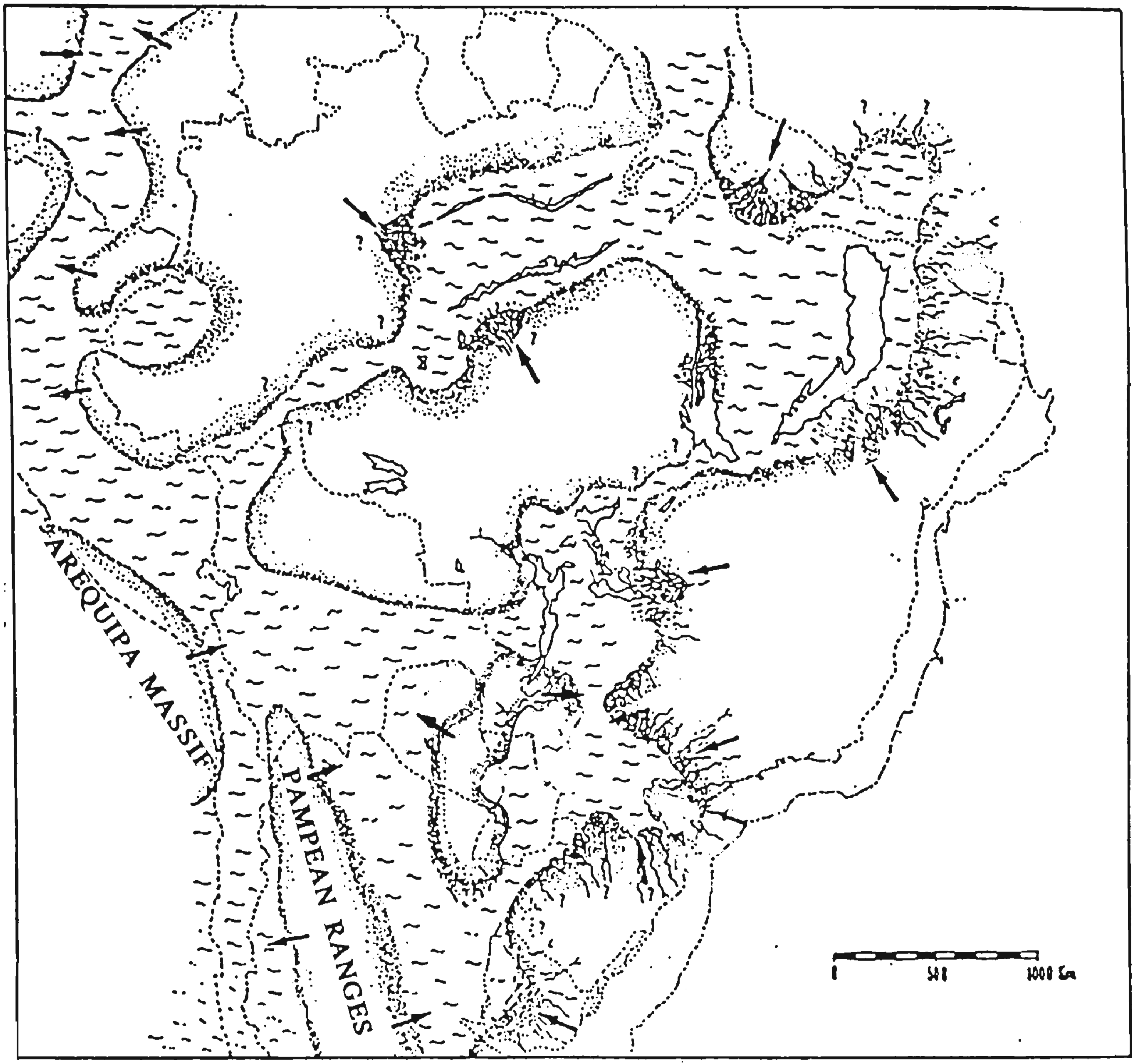


Fig. 19. Late Emsian/Eifelian paleogeography. Arrows indicate source areas. Modified for Paraguay from Melo, 1988.

Fig. 20. Core photograph of a black shale of the lower section of the Santa Rosa Formation in the Carandaity Subbasin, Don Quixote-1 well, 7,210 feet (2,197.6 meters).

Fig. 21. Photomicrograph of a black shale of the Santa Rosa Formation. Note sharp contact of two layers of shales. Don Quixote-1 well, 7,210 feet (2,197.6 meters). Bar at right represents 1 mm.


DON QUIXOTE-1
CENTIMETERS
10
7210'

Fig. 22. Core photograph of a silty sandstone of the Santa Rosa Formation. Don Quixote-1 well, 7,188.5 feet (2,191 meters).

Fig. 23. Photomicrograph of a silty sandstone of the Santa Rosa Formation. Bar at right represents 1 mm. Don Quixote-1 well, 7,188.5 feet (2,191 meters).


DON QUIXOTE-1
CENTIMETERS
10
7188.5'


1 mm

Fig. 24. Core photograph of laminated fine sand to siltstone and black shale of the Santa Rosa Formation. Don Quixote-1 well, 7,227.5 feet (2,203 meters).

Fig. 25. Photomicrograph of fine sand to siltstone of the Santa Rosa Formation. Note quartz overgrowths resulting in sutured boundaries between grains, which is responsible for the absence of porosity in the sandy and silty sections of the Santa Rosa Formation. Also note alteration of plagioclase. Don Quixote-1 well, 7,227.5 feet (2,203 meters).


DON QUIXOTE-1
CENTIMETERS
10
7227.5'

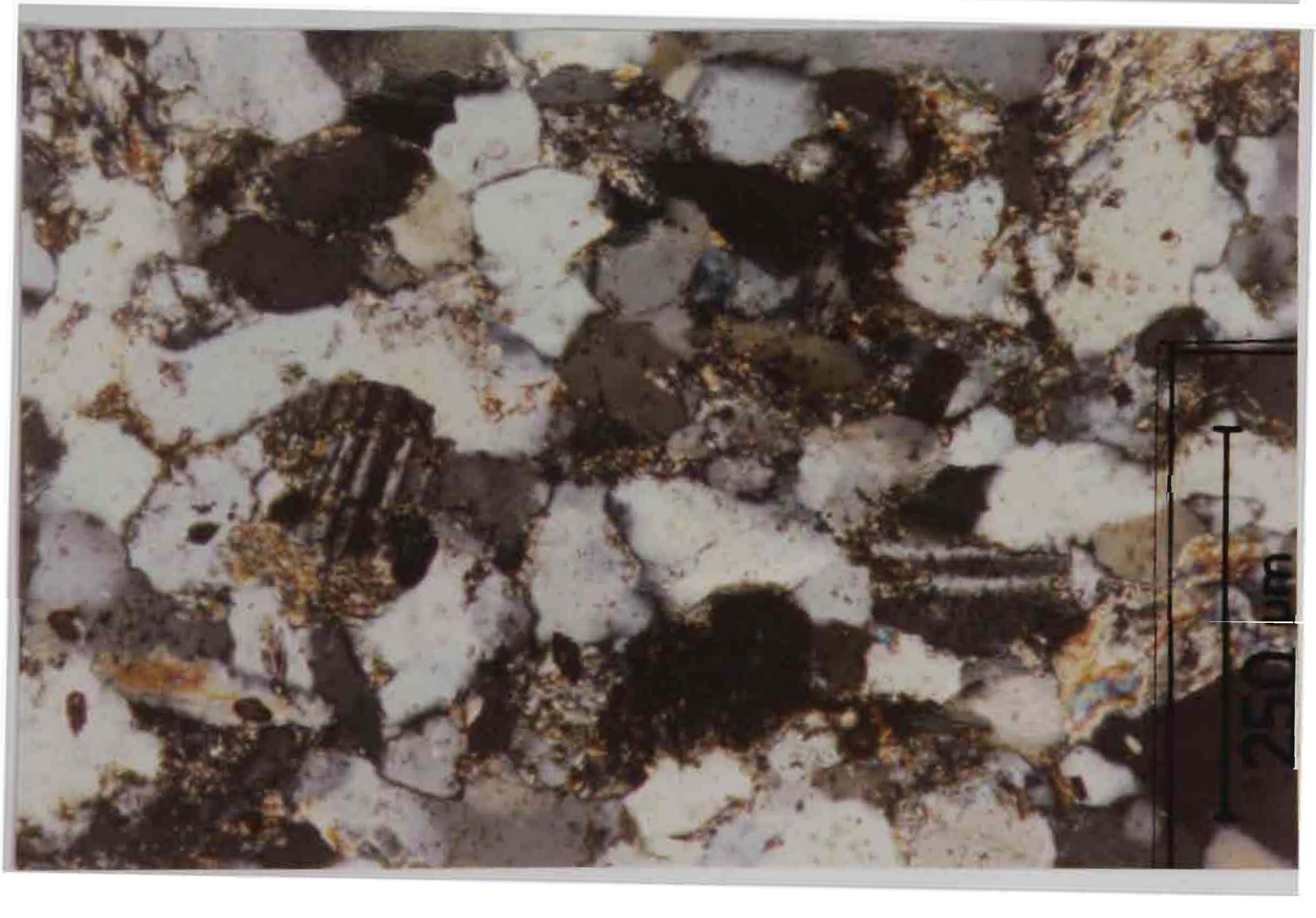

250 µm

Fig. 26. Core photograph of laminated silt to fine sand and shale of the Santa Rosa Formation. Don Quixote-1 well, 7,222.5 feet (2,201.4 meters).

Fig. 27. Photomicrograph of laminated silt to fine sand and shale of the Santa Rosa Formation. Note absence of porosity due to sutured boundaries between grains in silt and sandlaminae. Bar at right represents 1 mm. Don Quixote-1 well, 7,222.5 feet (2,201.4 meters).


DON QUIXOTE-1
CENTIMETERS
10
7222.5'

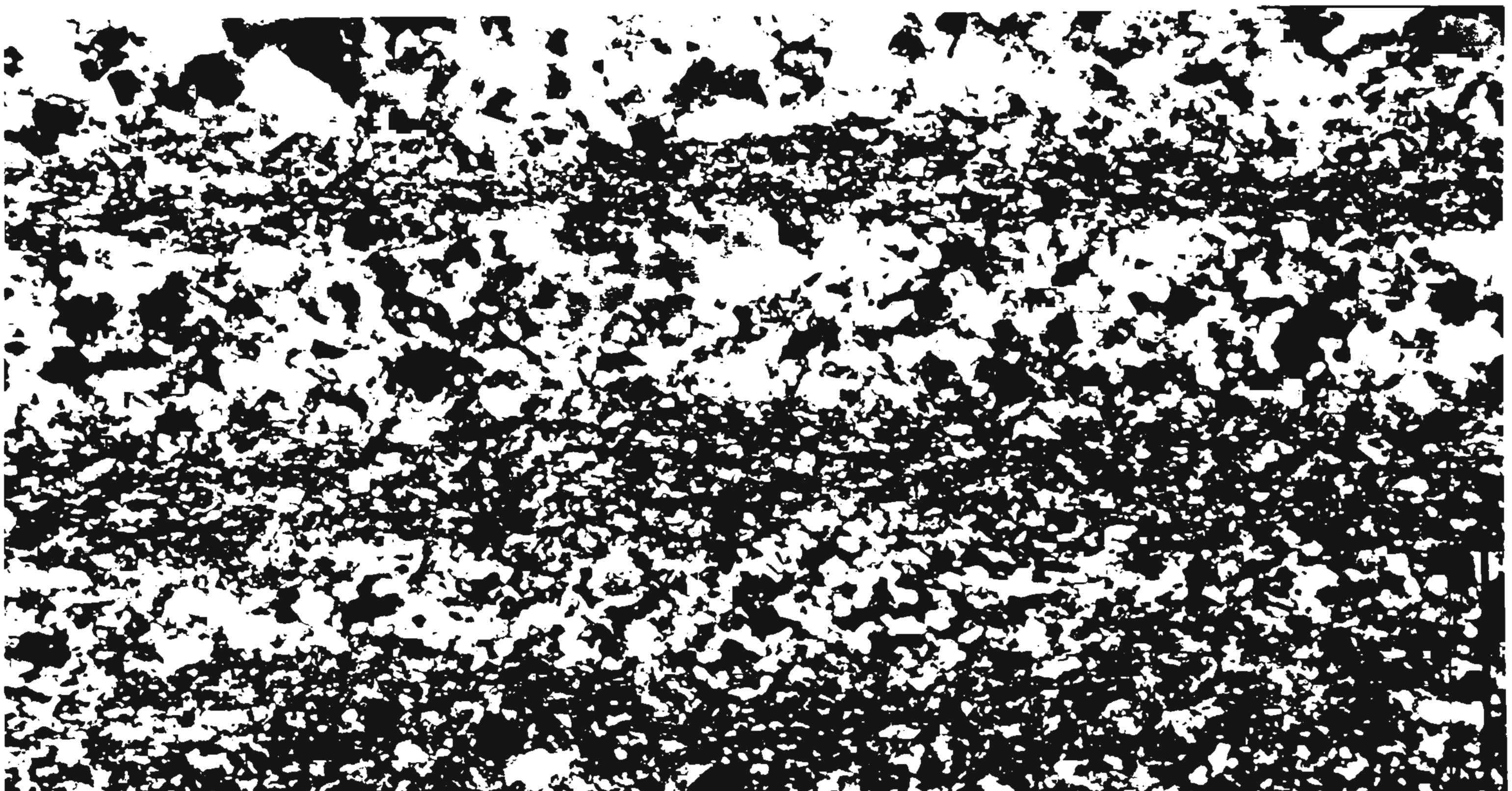
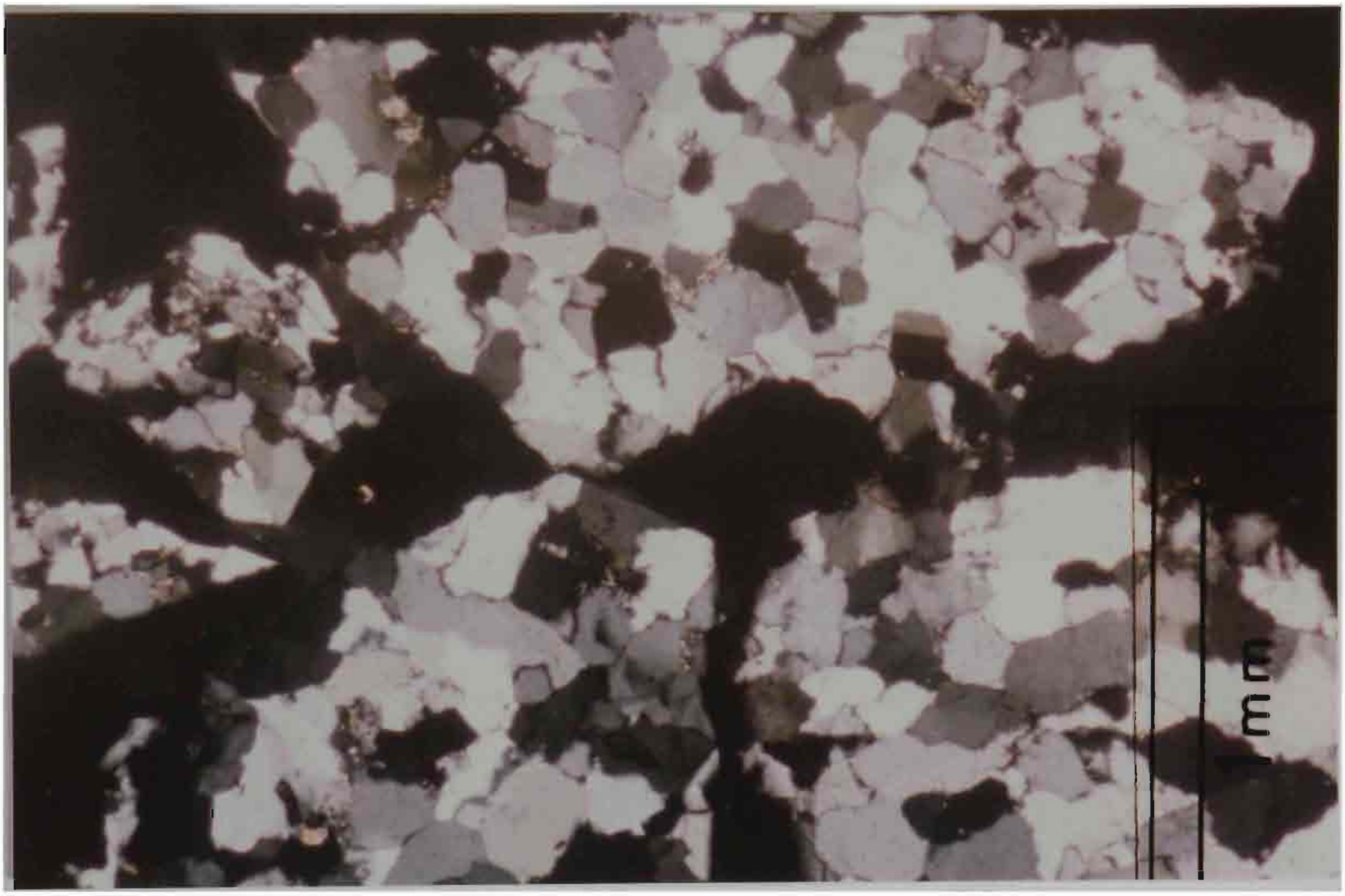


Fig. 28. Photomicrograph of cuttings of a metaquartzarenite from the Santa Rosa Formation in the Curupaity Subbasin. Toro-1, 11,200 feet (3,414 meters).

Fig. 29. Photomicrograph of a well cutting showing recrystallization of the metaquartzarenite of the Santa Rosa Formation. Toro-1, 11,200 feet (3,414 meters).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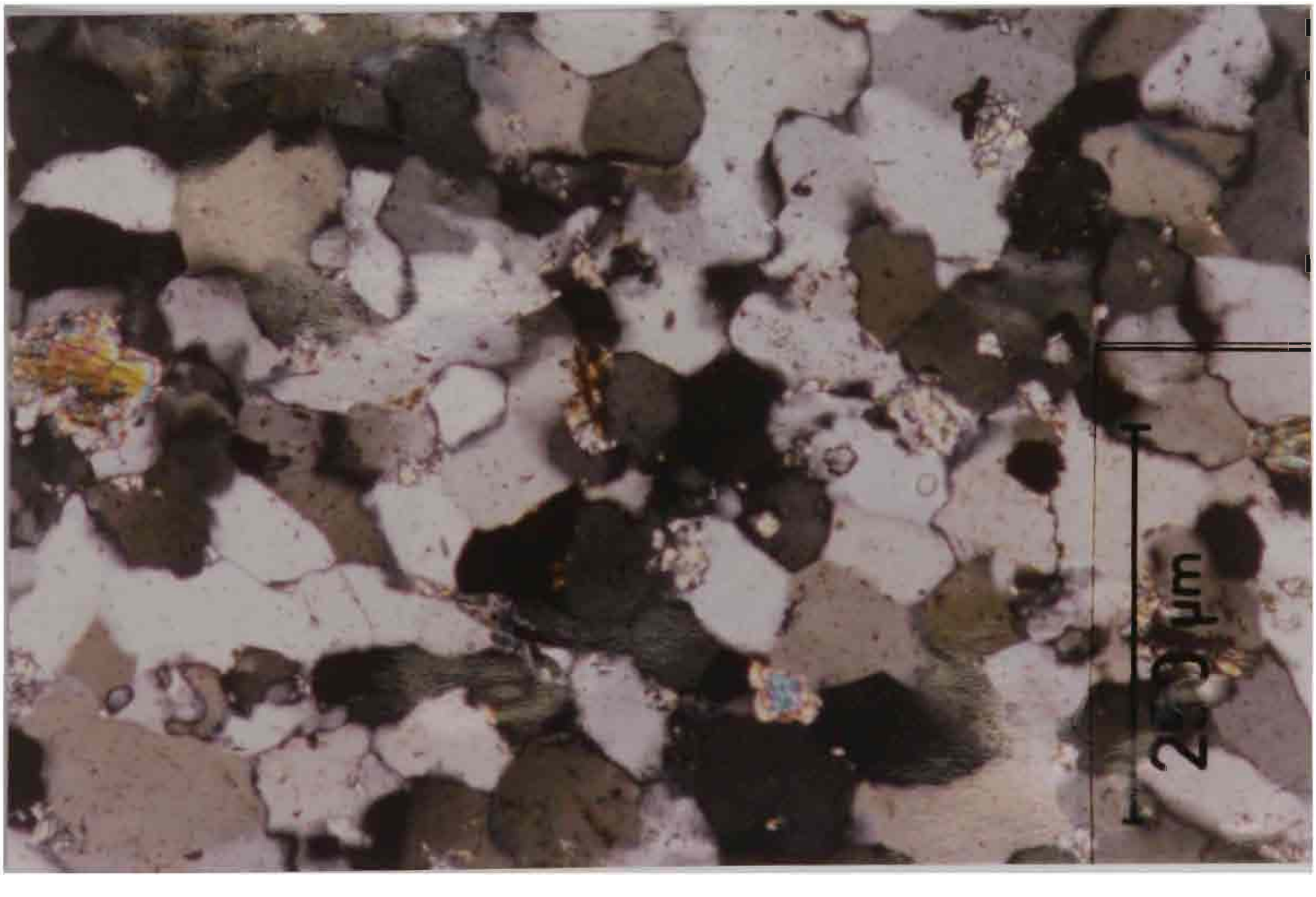
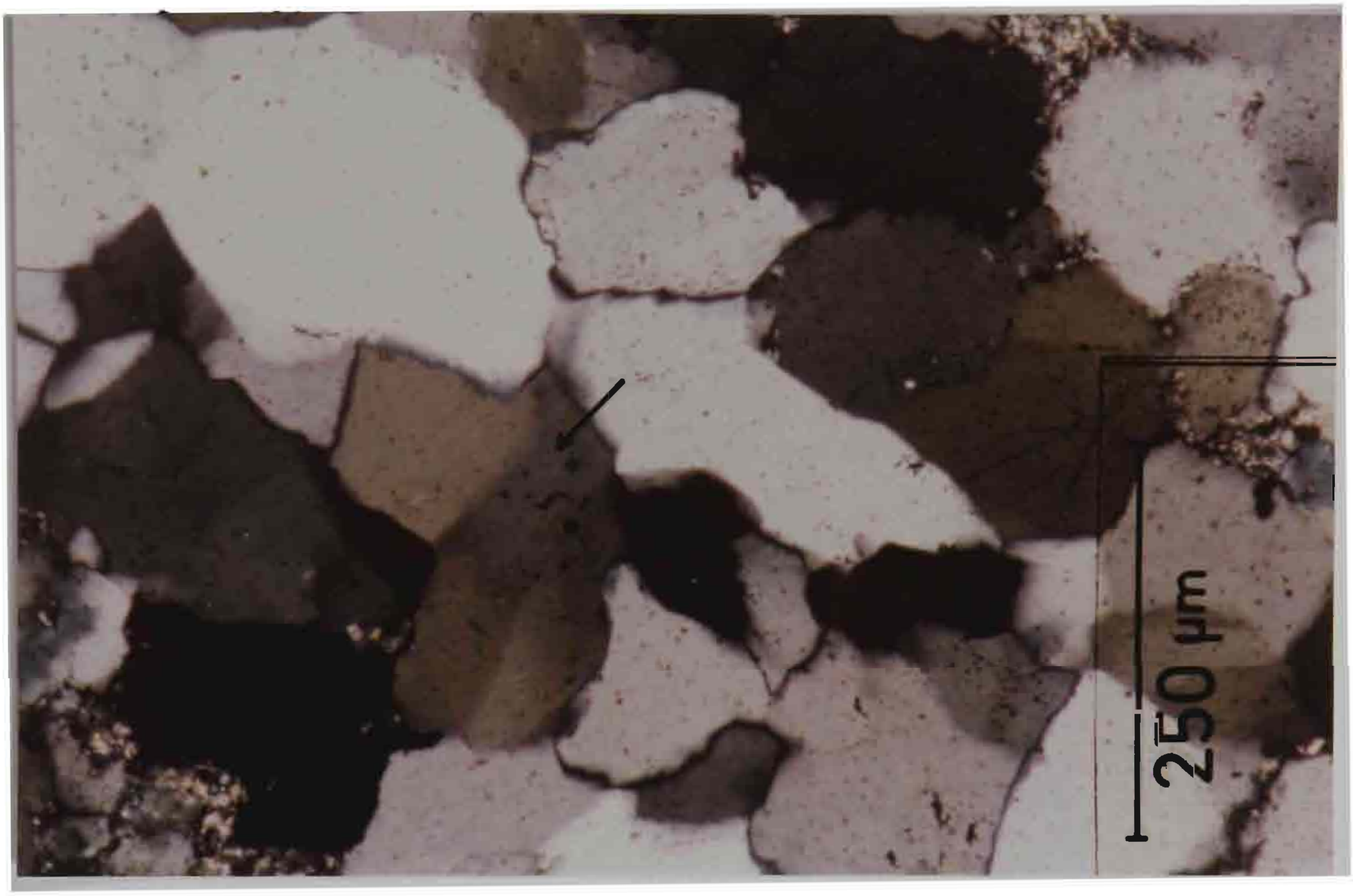

250 µm

Fig. 30. Photomicrograph of a well cutting showing a metaquartzarenite of the Santa Rosa Formation. Note undulose extinction (arrow). Toro-1 well, 11,200 feet (3,414 meters).

Fig. 31. Photomicrograph of cuttings of a meta-arkose of the Santa Rosa Formation in the Cerro León Arch. Note alteration of feldspars (arrows). Cerro León-1 well, 6,460 feet (1,969 meters).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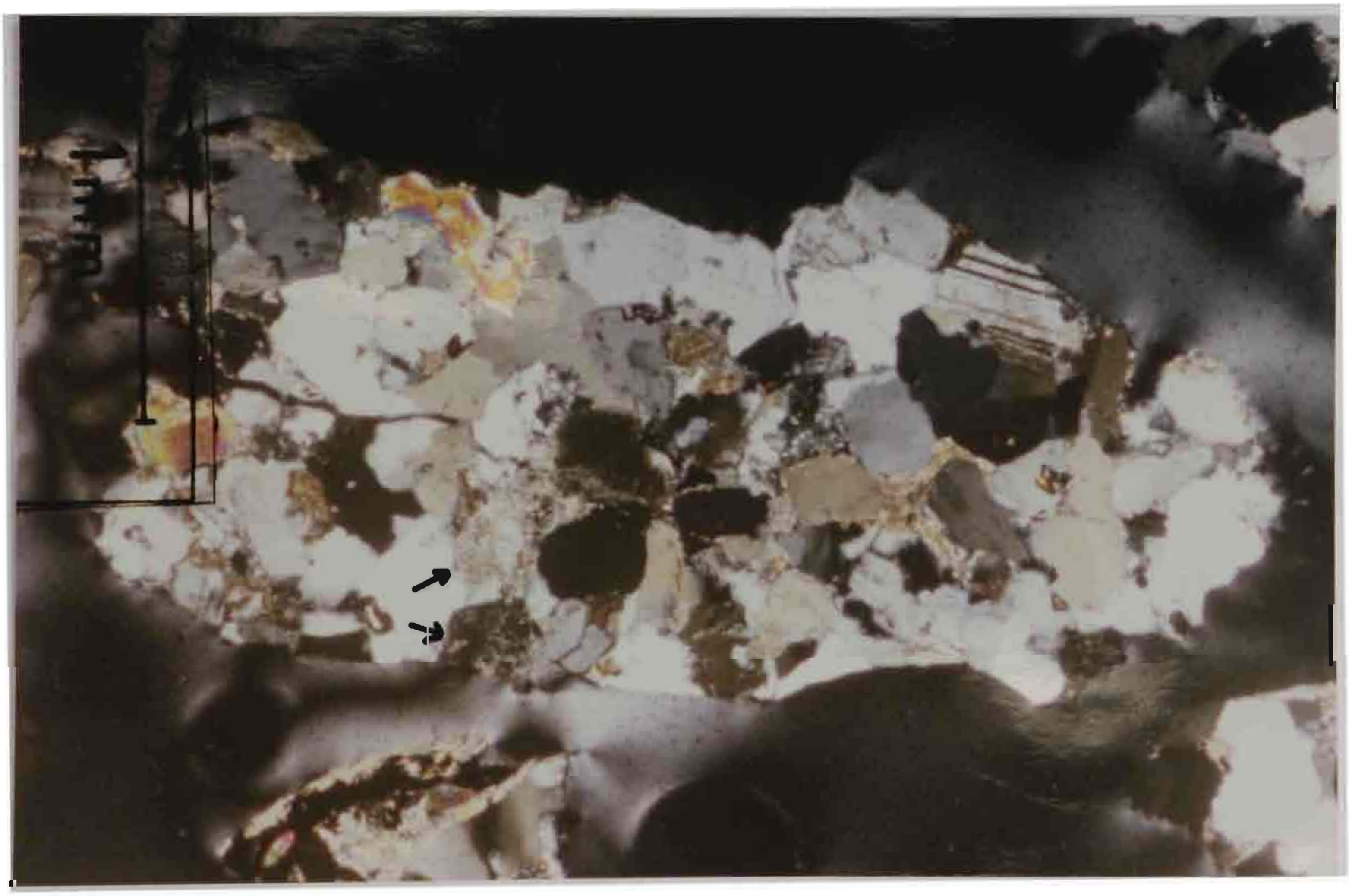
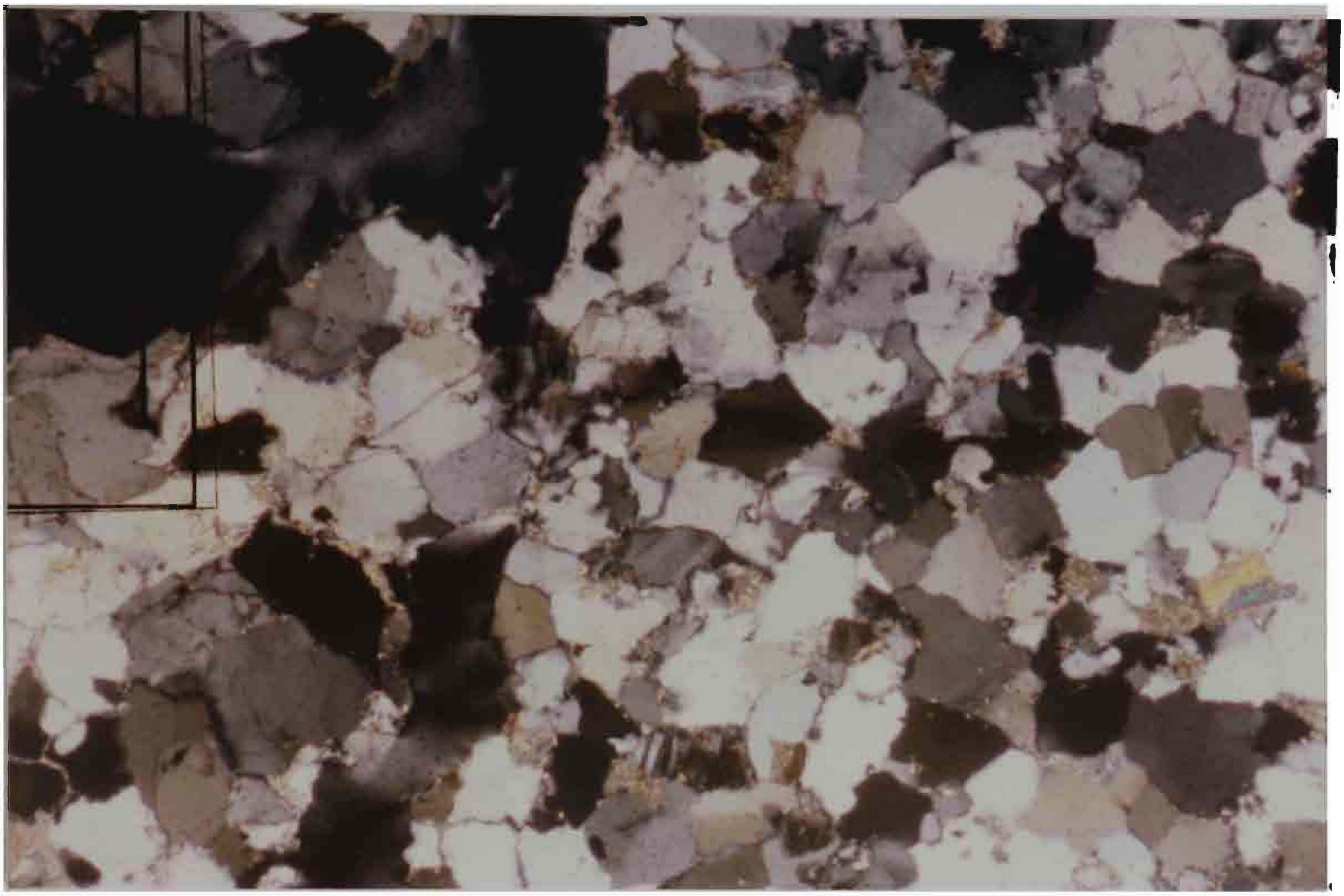
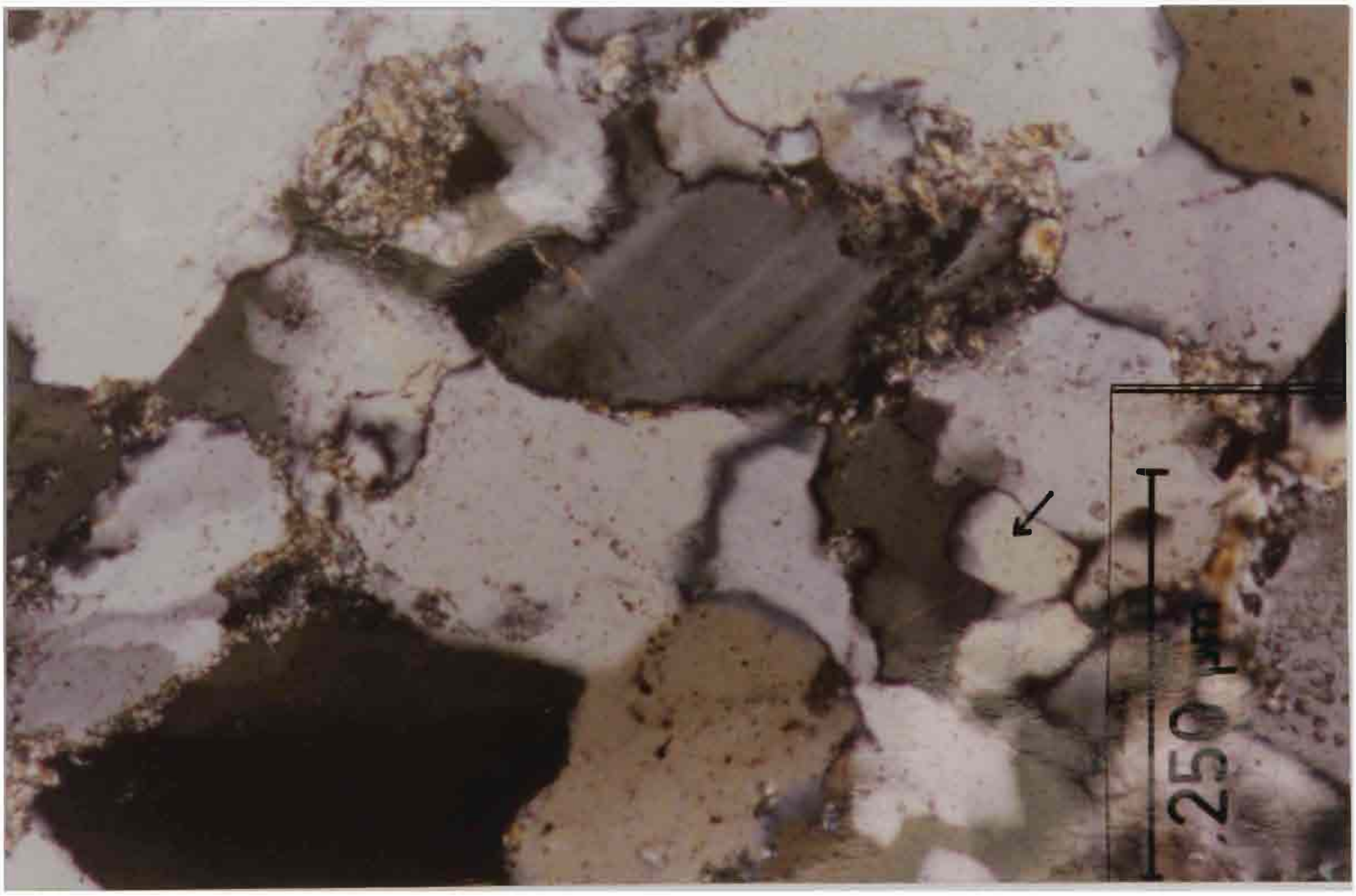

1 mm

Fig. 32. Photomicrograph of a cutting showing a meta-arkose of the Santa Rosa Formation. Note total absence of porosity. Cerro León-1 well, 6,460 feet (1,969 meters).

Fig. 33. Close up of the meta-arkose of Fig. 31. Note recrystallization of quartz grains (arrow). Cerro León-1 well, 6,460 feet (1,969 meters).

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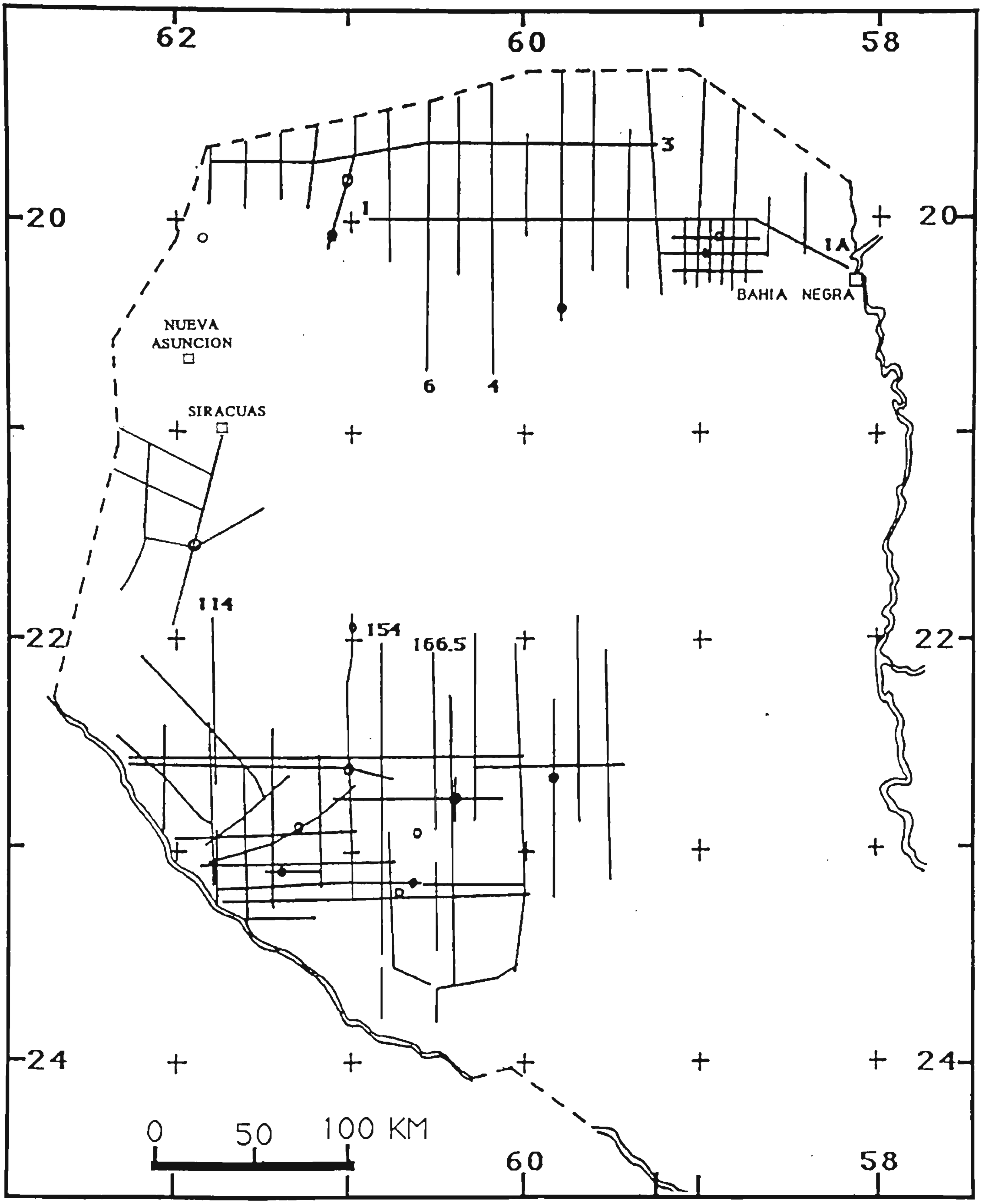


Fig. 34. Base map of over 5,000 kilometers of seismic reflection lines interpreted in this study.

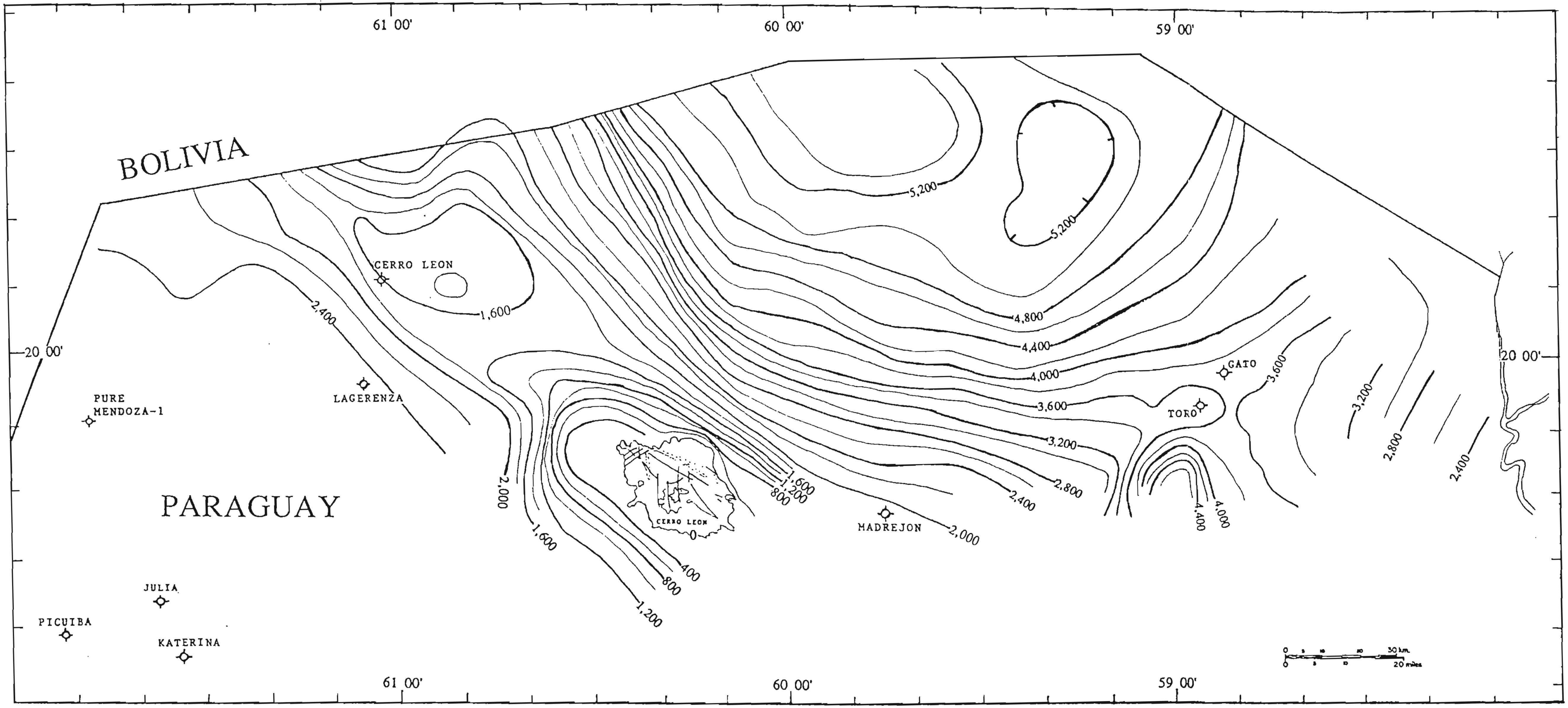


Fig. 35. Structure map of the top of the Lower Devonian Santa Rosa Formation in the Curupaity Subbasin and Cerro León Arch area. Negative values in meters. Sonic logs from wells Toro-1, Gato-1 and Cerro León-1 were used for depth control. See Fig. 34 for location of seismic lines utilized.

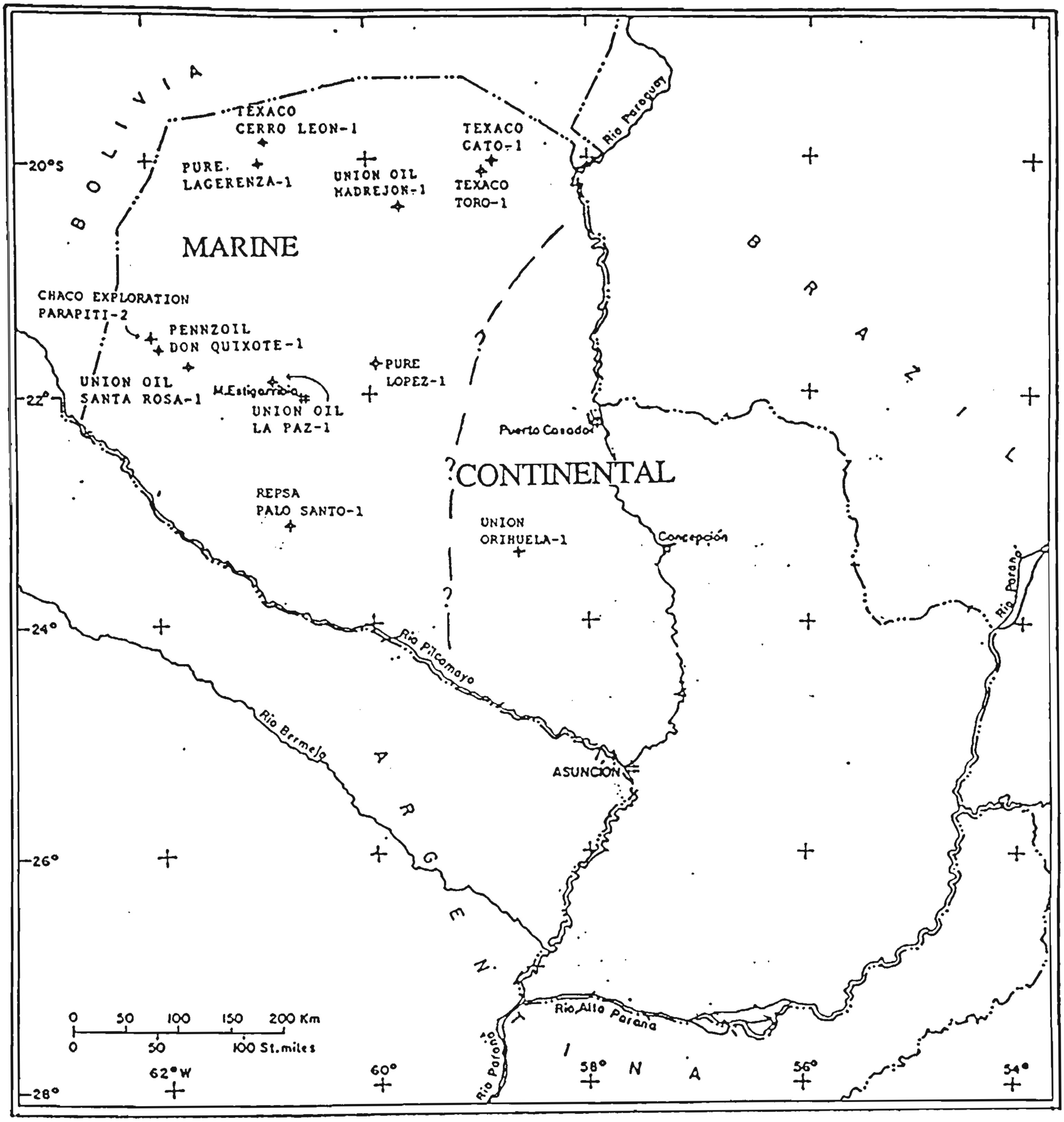


Fig. 36. Gedinnian-Siegenian (Early Devonian) paleogeography of the Paraguayan Chaco.

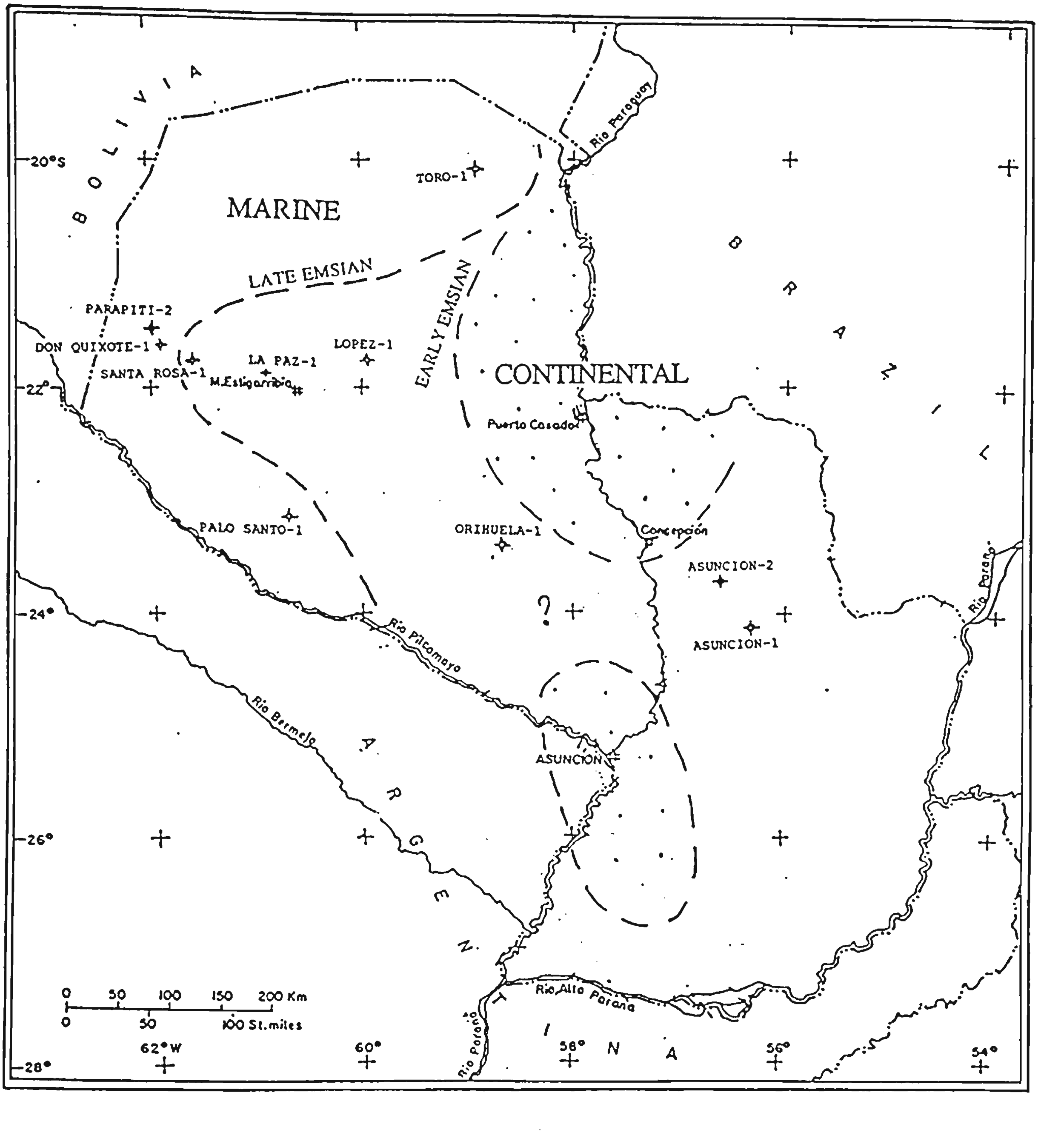


Fig. 37. Early and late Emsian (Early Devonian) paleogeography of the Paraguayan Chaco.

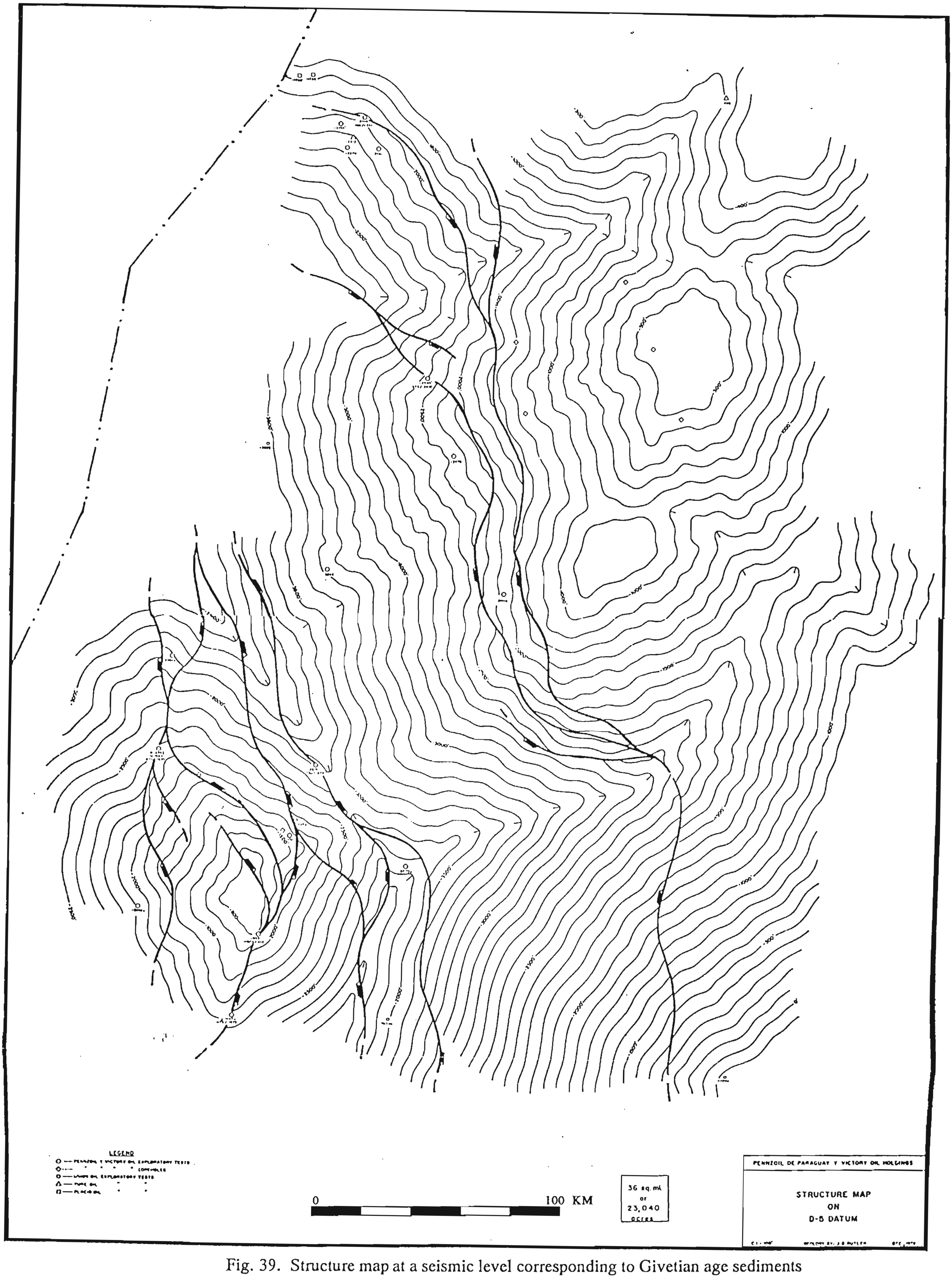


Fig. 39. Structure map at a seismic level corresponding to Givetian age sediments within the Los Monos Formation in the Carandaity Subbasin. Values in feet (Pennzoil, 1972a).

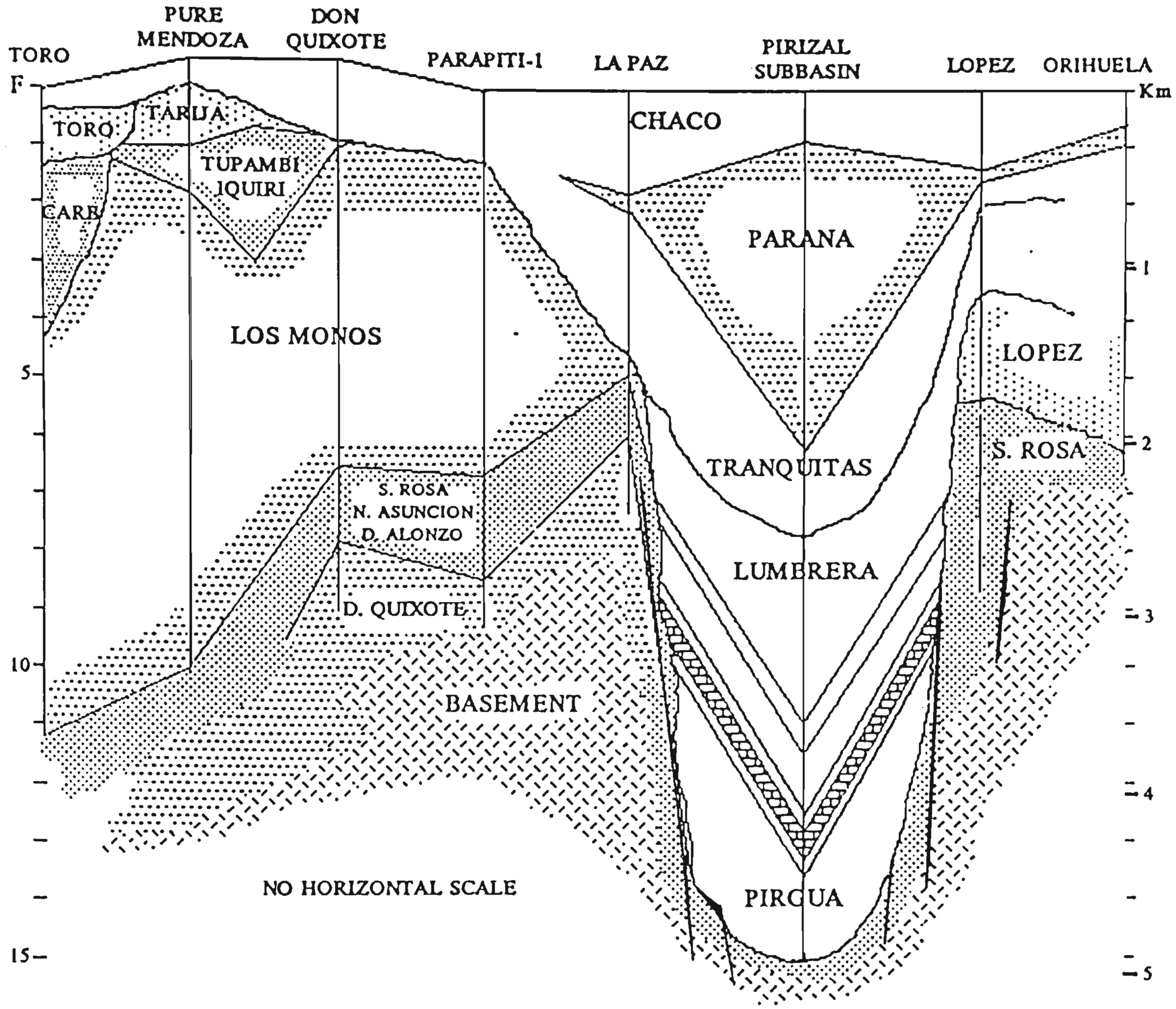


Fig. 40. Schematic stratigraphic cross section of the Paraguayan Chaco.

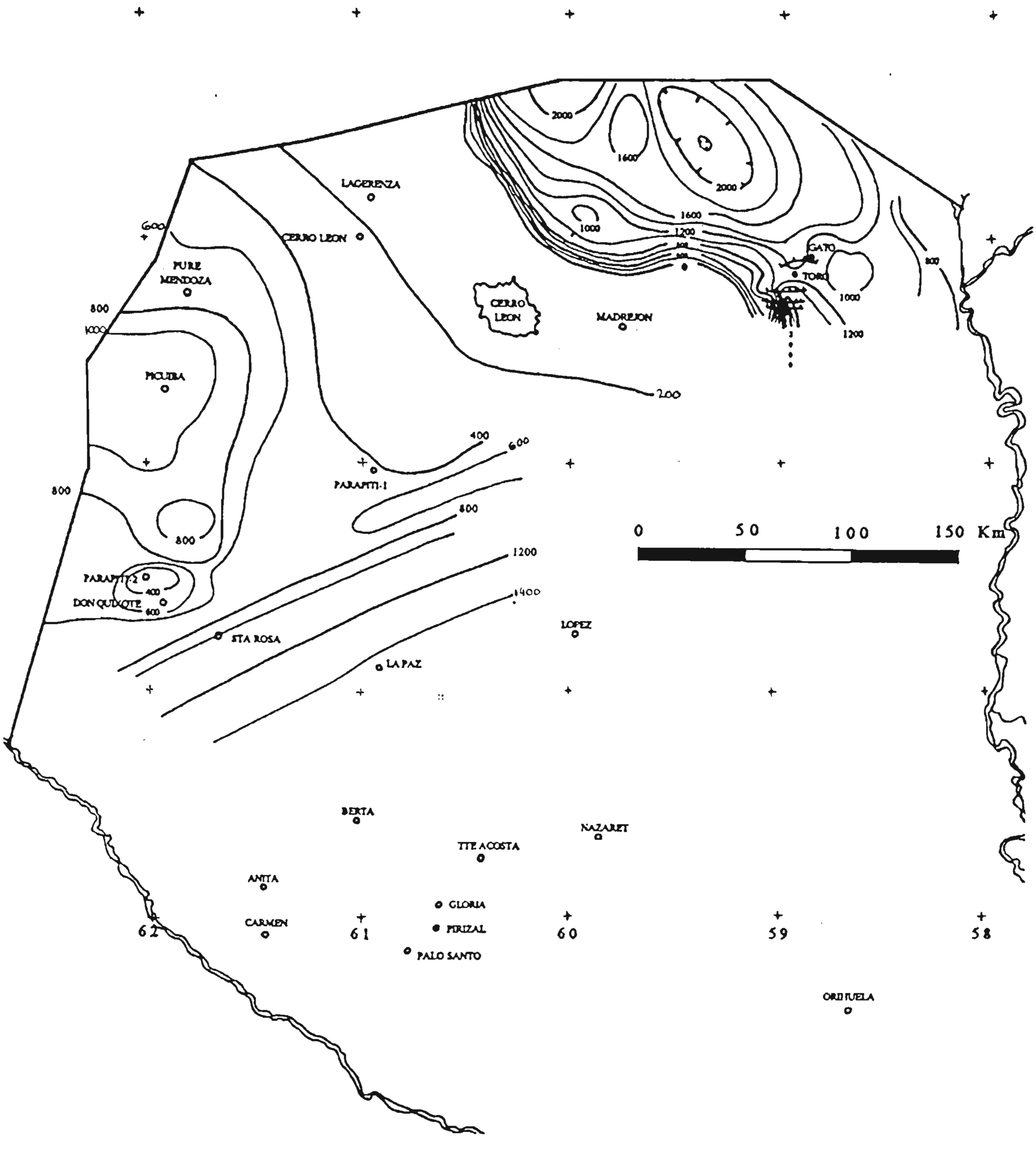


Fig. 41. Structure map of the top of the Los Monos Formation in the Paraguayan Chaco. Carandaity Subbasin values are based on well data, and Curupaity Subbasin values are based on seismic lines in Fig. 34. Negative values are in meters.

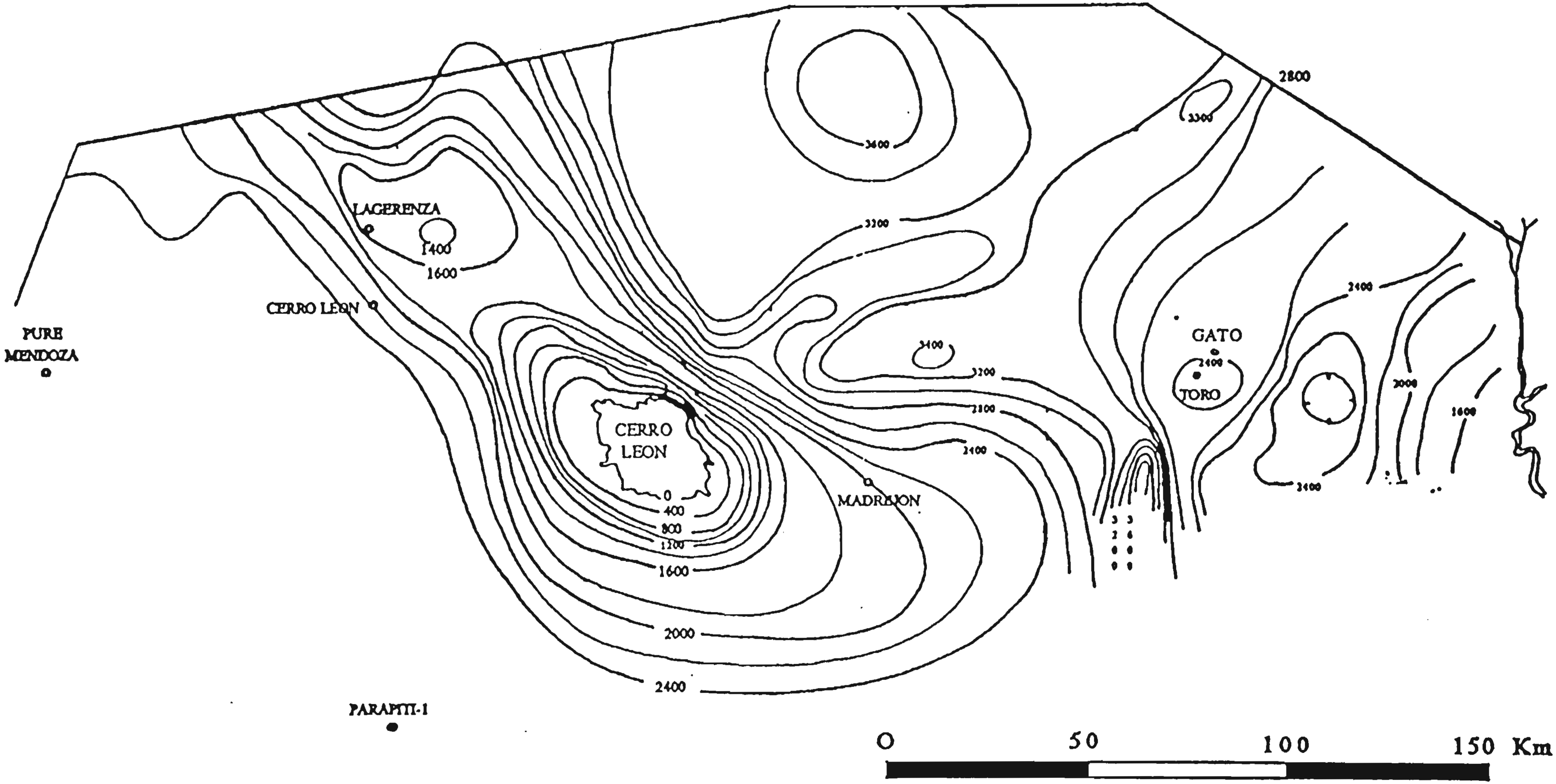


Fig. 42. Isopach map of the Los Monos Formation in the Curupaity Subbasin and Cerro León Arch. Negative values in meters.

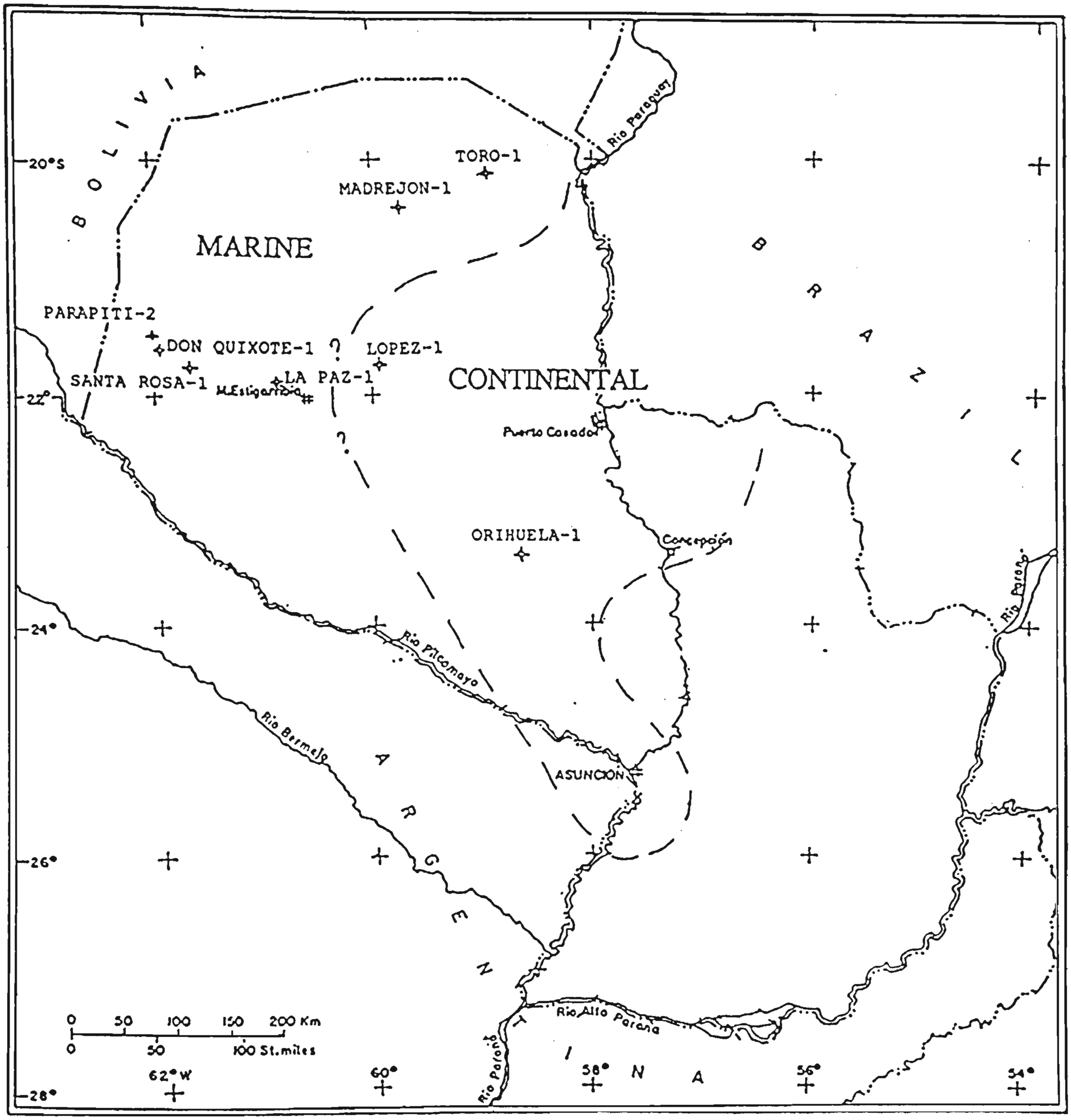


Fig. 43. Eifelian (Middle Devonian) paleogeography of the Paraguayan Chaco.

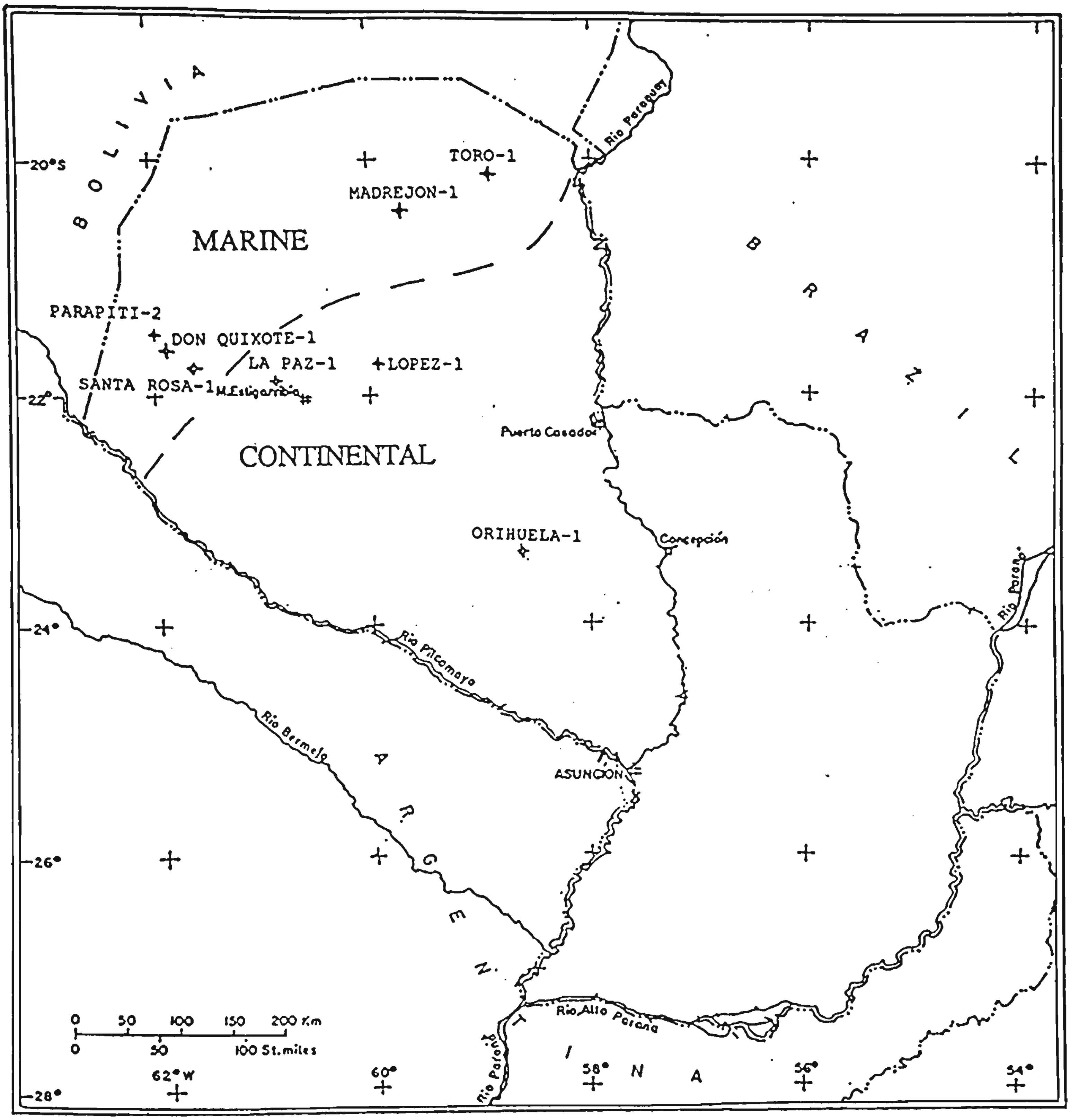


Fig. 44. Givetian (Middle Devonian) paleogeography of the Paraguayan Chaco.

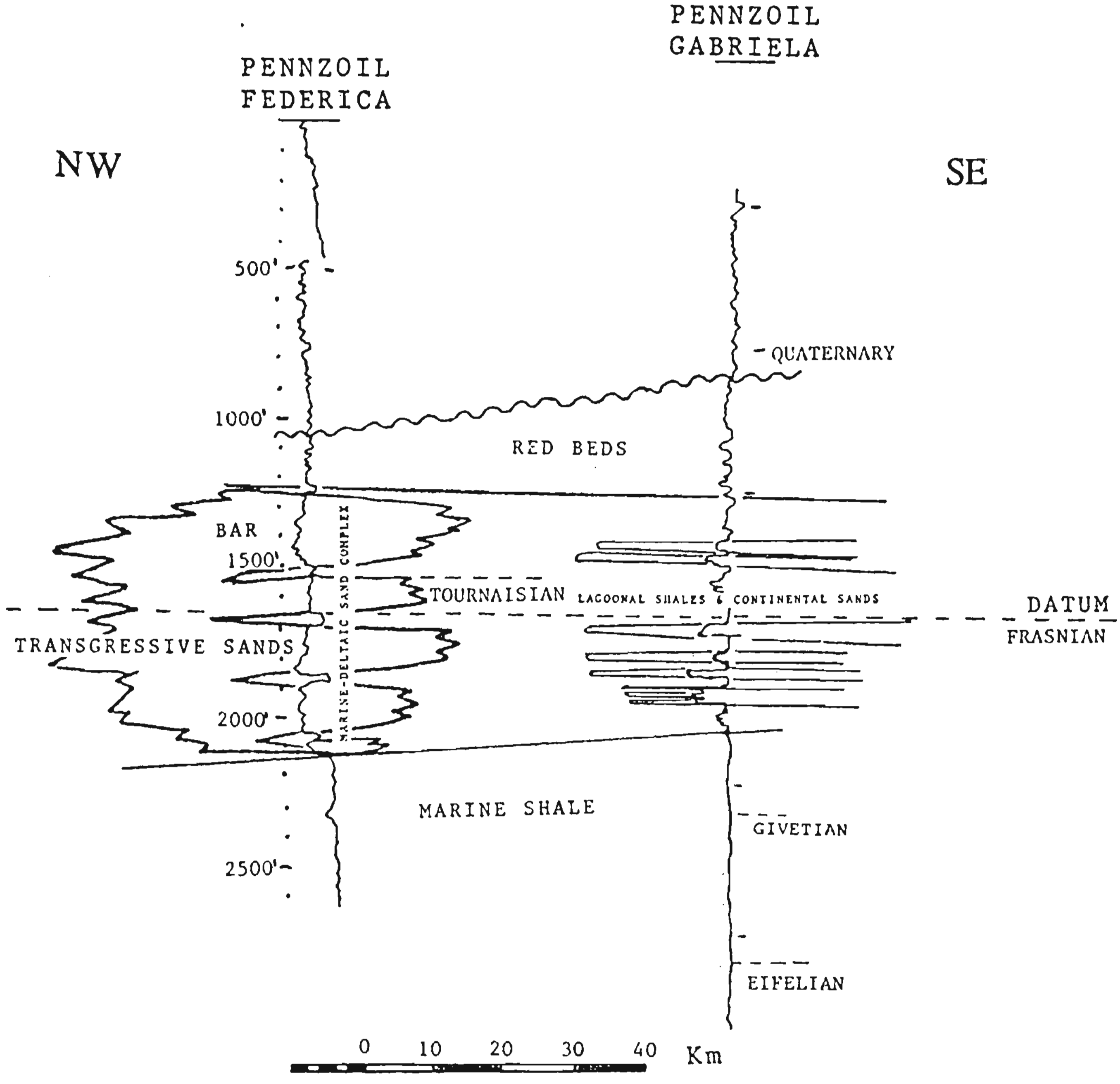


Fig. 45. Southeast-Northwest cross section of the Carandaity Subbasin between Pennzoil Gabriela and Federica wells (spontaneous potential logs) showing environments of deposition based on palynology. Datum is top of Frasnian. See Fig. 1 for location of cross section.

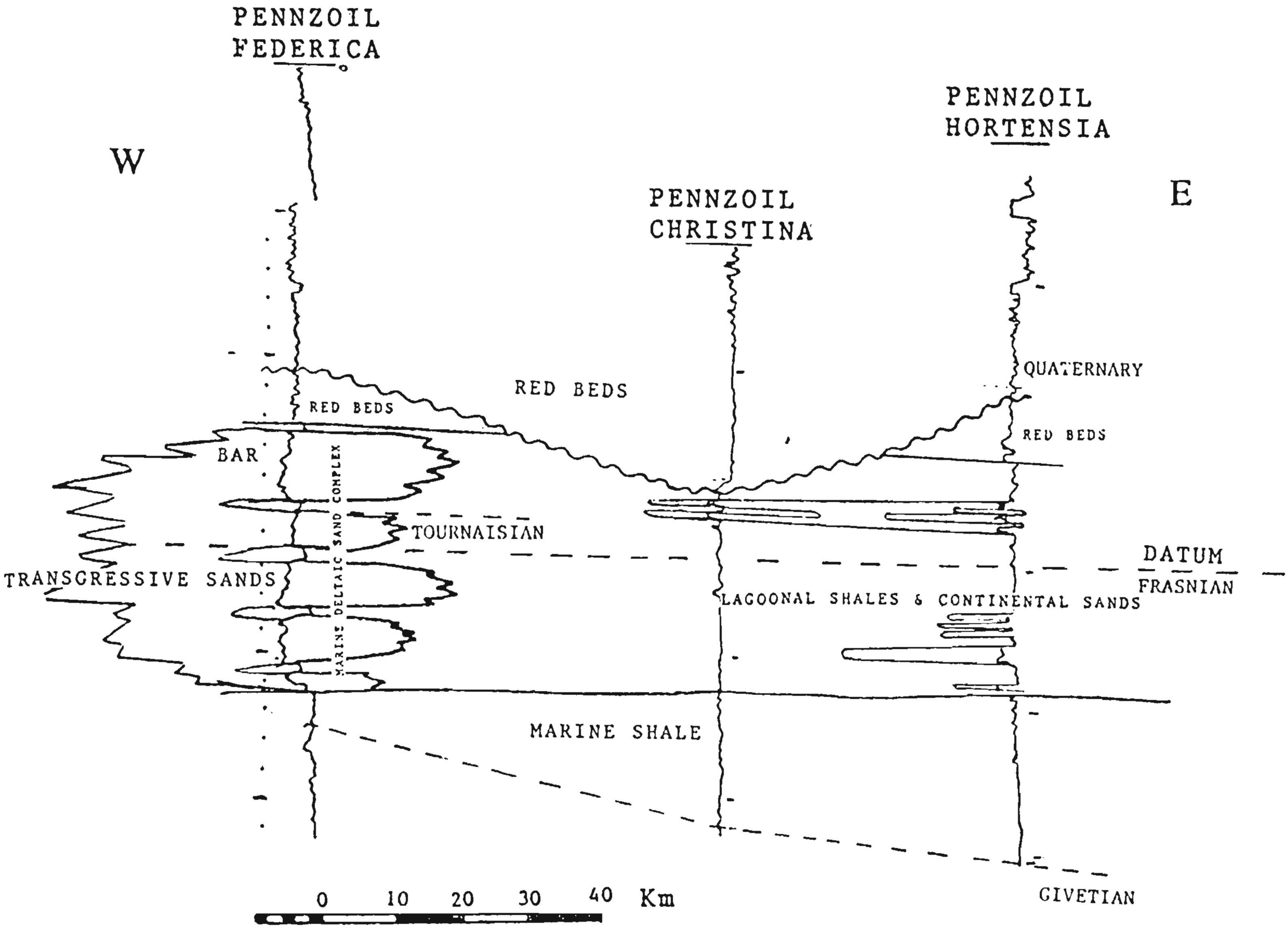


Fig. 46. East-West cross section of the Carandaity Subbasin between Pennzoil Hortensia-Christina-Federica wells (spontaneous potential logs) showing environments of deposition based on palynology. Datum is top of Frasnian. See Fig. 1 for location of cross section.

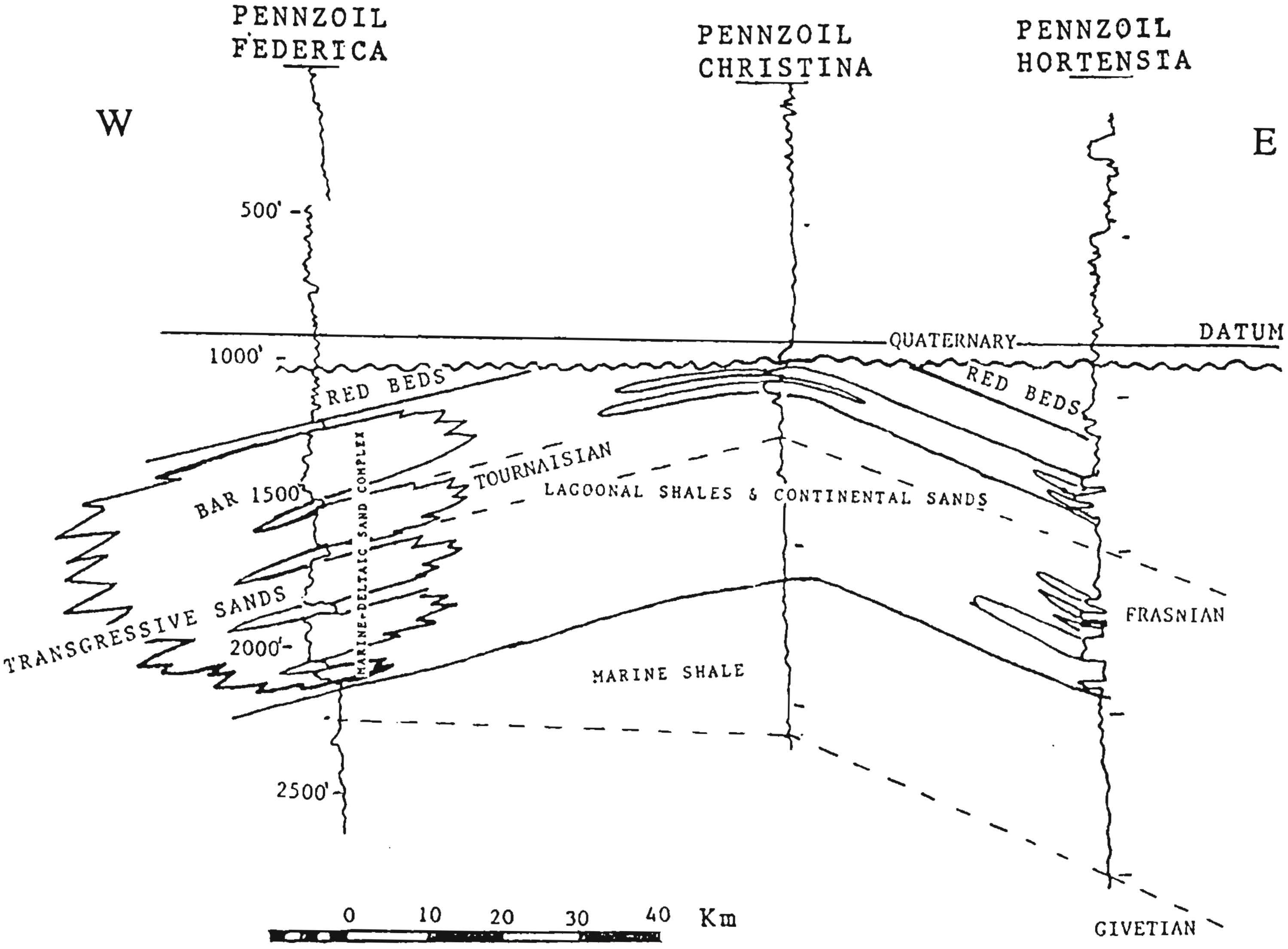


Fig. 47. East-West cross section of the Carandaity Subbasin between Pennzoil Hortensia-Christina-Federica wells (spontaneous potential logs) showing environments of deposition based on palynology. Datum is sea level. See Fig. 1 for location of cross section.

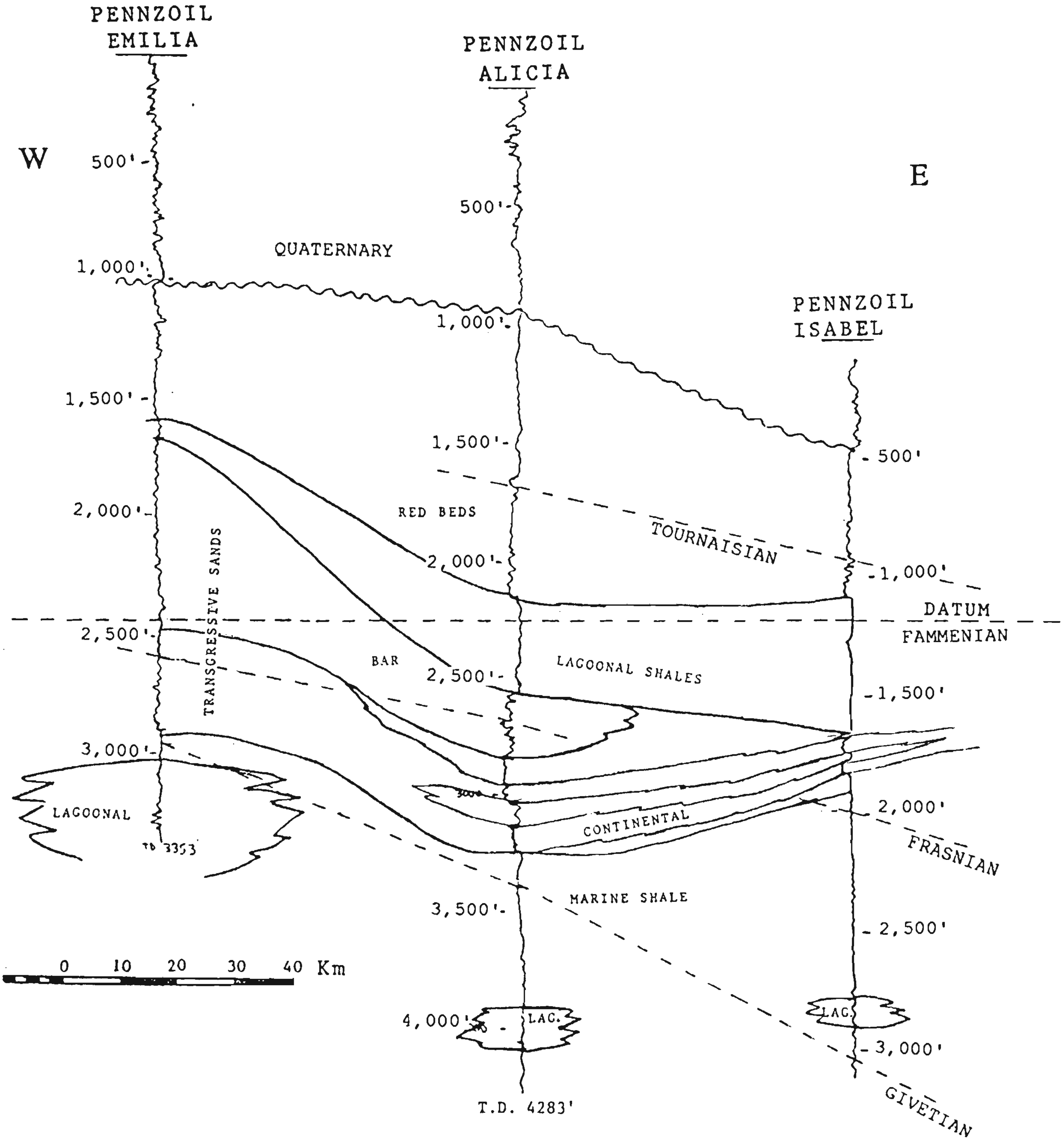


Fig. 48. East-West cross section of the Carandaity Subbasin between Pennzoil Isabel-Alicia-Emilia wells (spontaneous potential logs) showing environments of deposition based on palynology. Datum is top of Fammenian. See Fig. 1 for location of cross section.

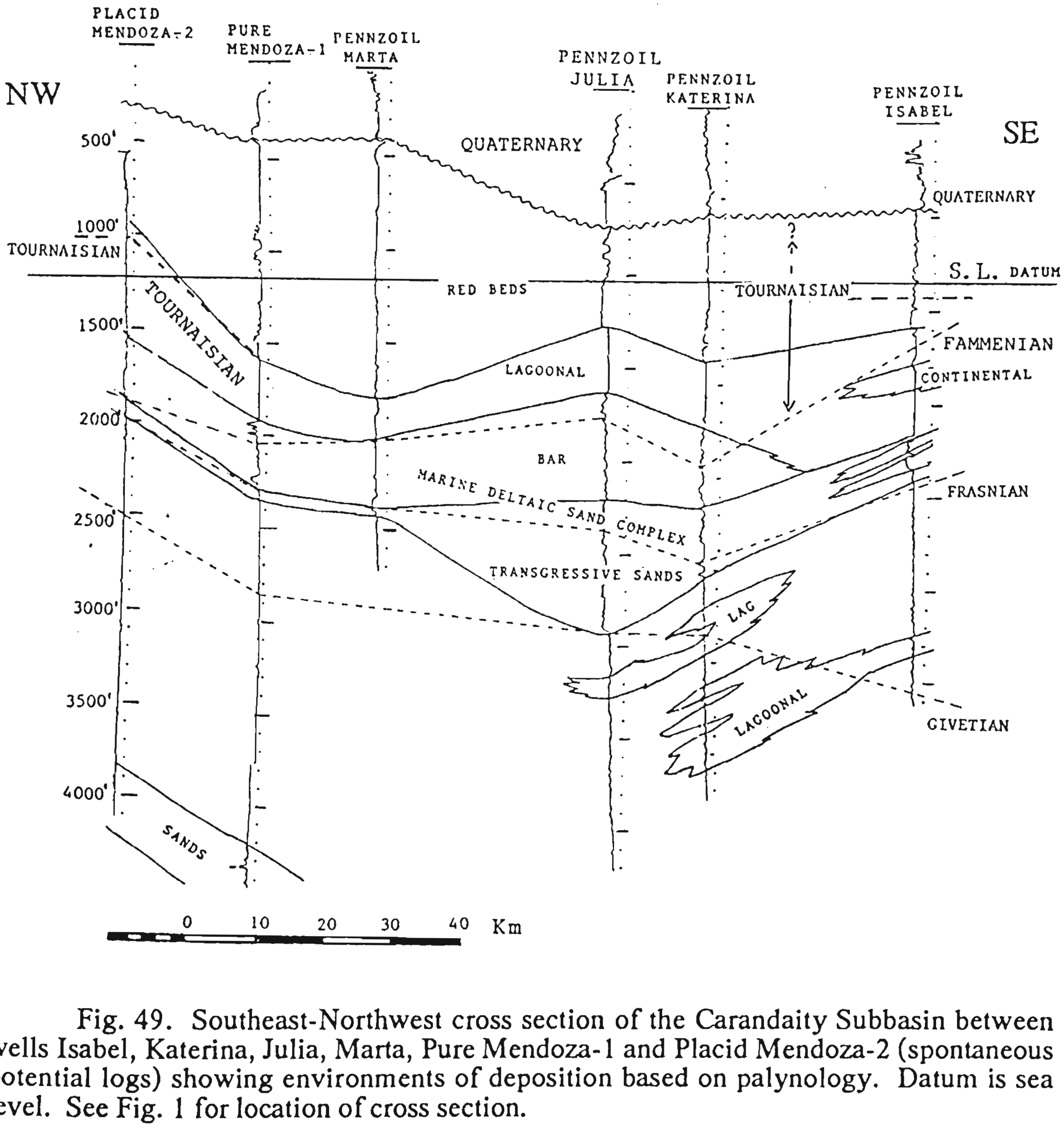


Fig. 49. Southeast-Northwest cross section of the Carandaity Subbasin between wells Isabel, Katerina, Julia, Marta, Pure Mendoza-1 and Placid Mendoza-2 (spontaneous potential logs) showing environments of deposition based on palynology. Datum is sea level. See Fig. 1 for location of cross section.

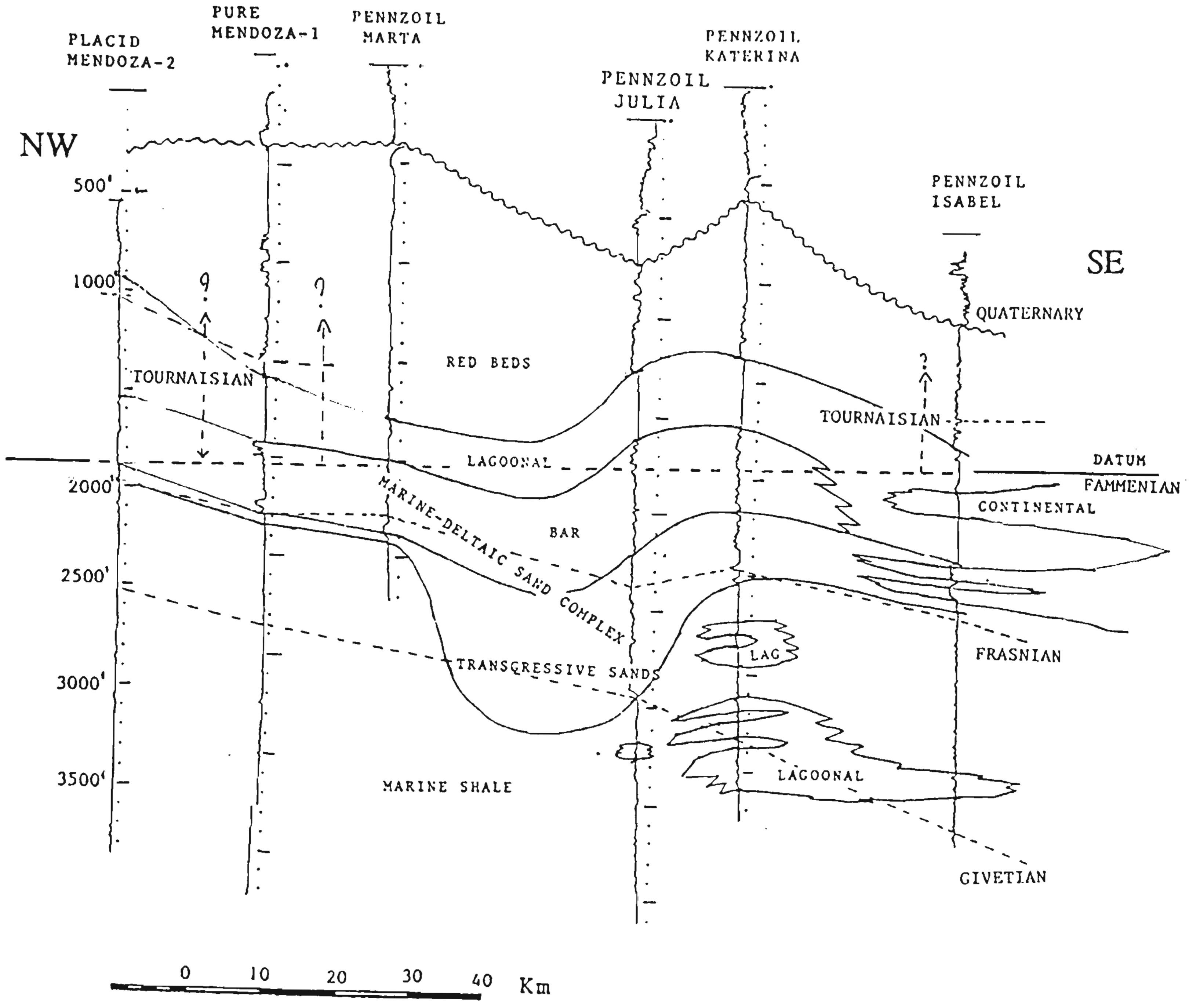


Fig. 50. Southeast-Northwest cross section of the Carandaity Subbasin between wells Isabel, Katerina, Julia, Marta, Pure Mendoza-1 and Placid Mendoza-2 (spontaneous potential logs) showing environments of deposition based on palynology. Datum is top of Fammenian. See Fig. 1 for location of cross section.

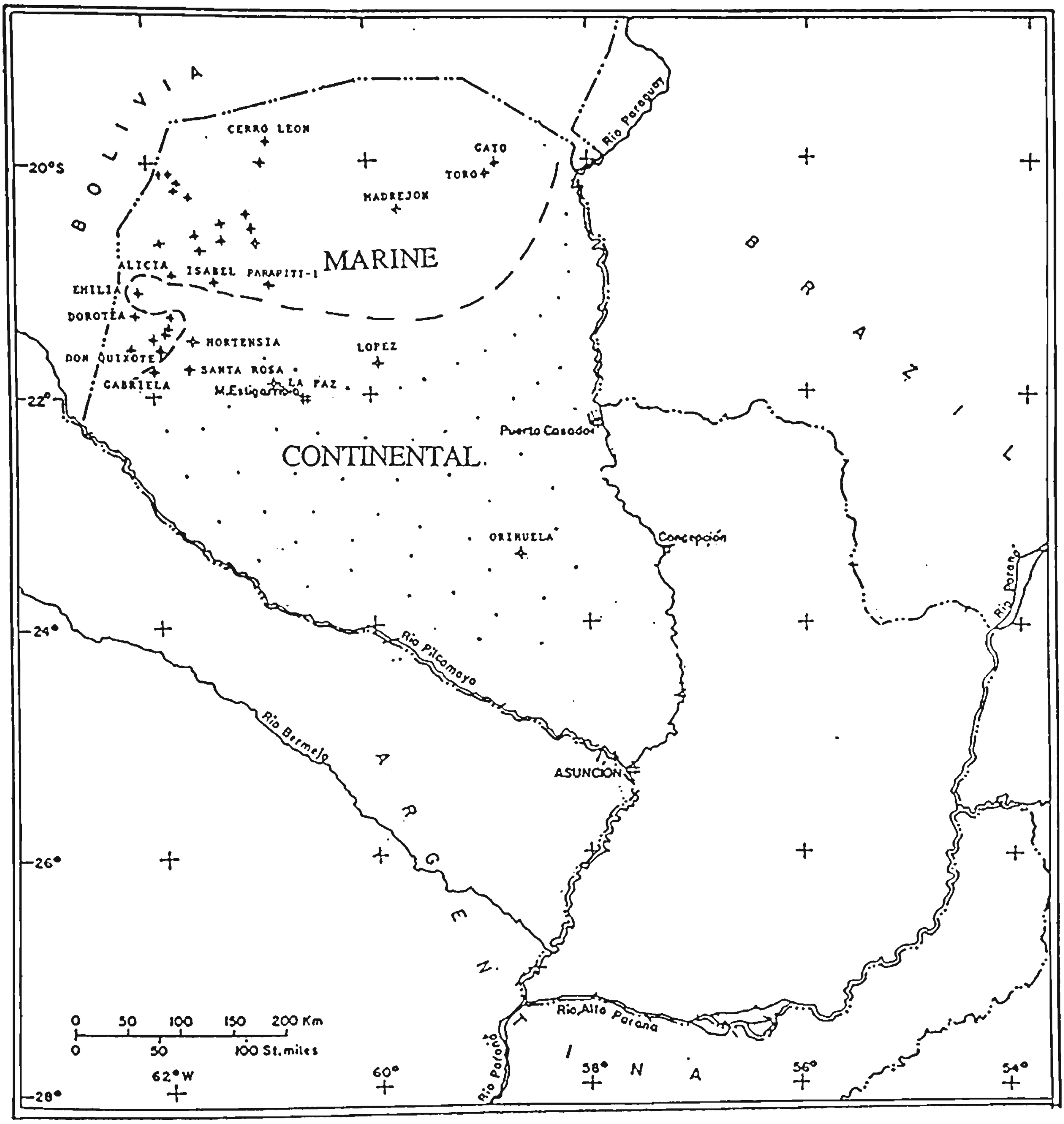


Fig. 51. Frasnian-Fammenian (Late Devonian) paleogeography of the Paraguayan Chaco.

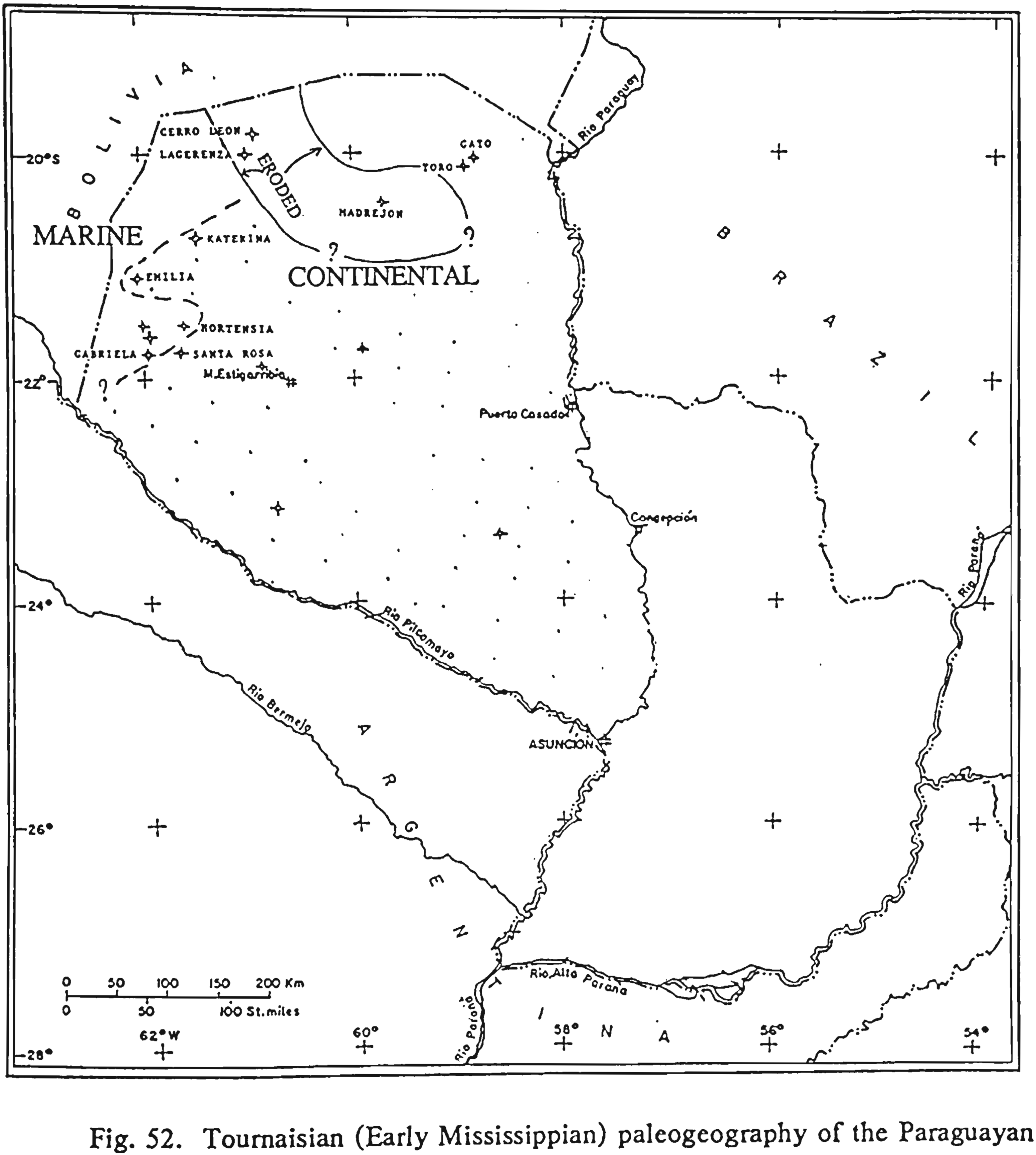


Fig. 52. Tournaisian (Early Mississippian) paleogeography of the Paraguayan Chaco.

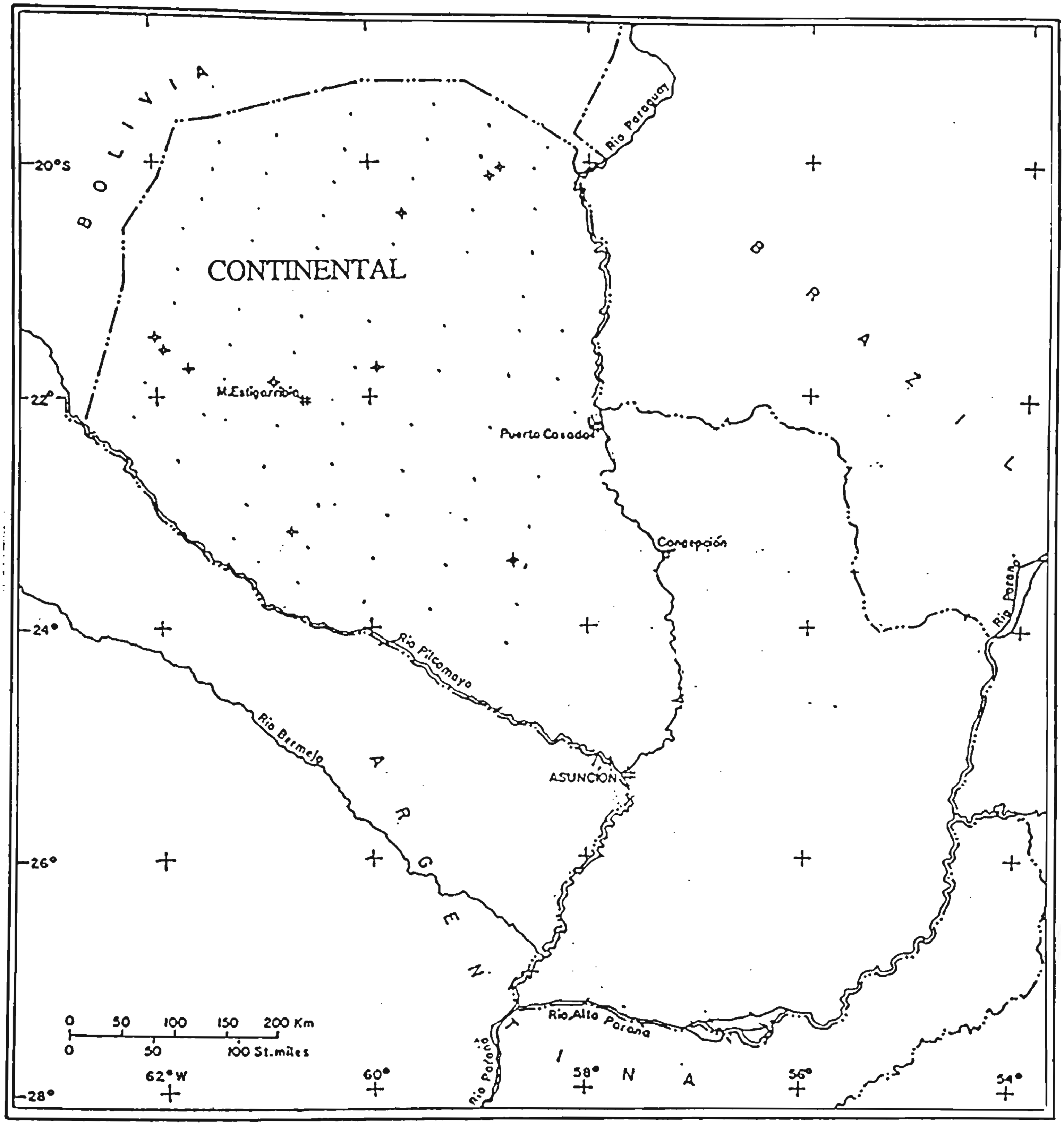


Fig. 53. Early Pennsylvanian paleogeography of the Paraguayan Chaco.

Fig. 54. Photograph of seismic line Texaco LN 75-13 of the Curupaity Subbasin. The Precambrian section has a non layered response, and the Santa Rosa Formation is marked blue. An angular unconformity (pink) separates the Devonian Los Monos Formation from the (Late?) Carboniferous section. The Late Permian-Early Triassic (Scythian) Toro Formation is separated from the Carboniferous section by an unconformity (green). Vertical scale in seconds.

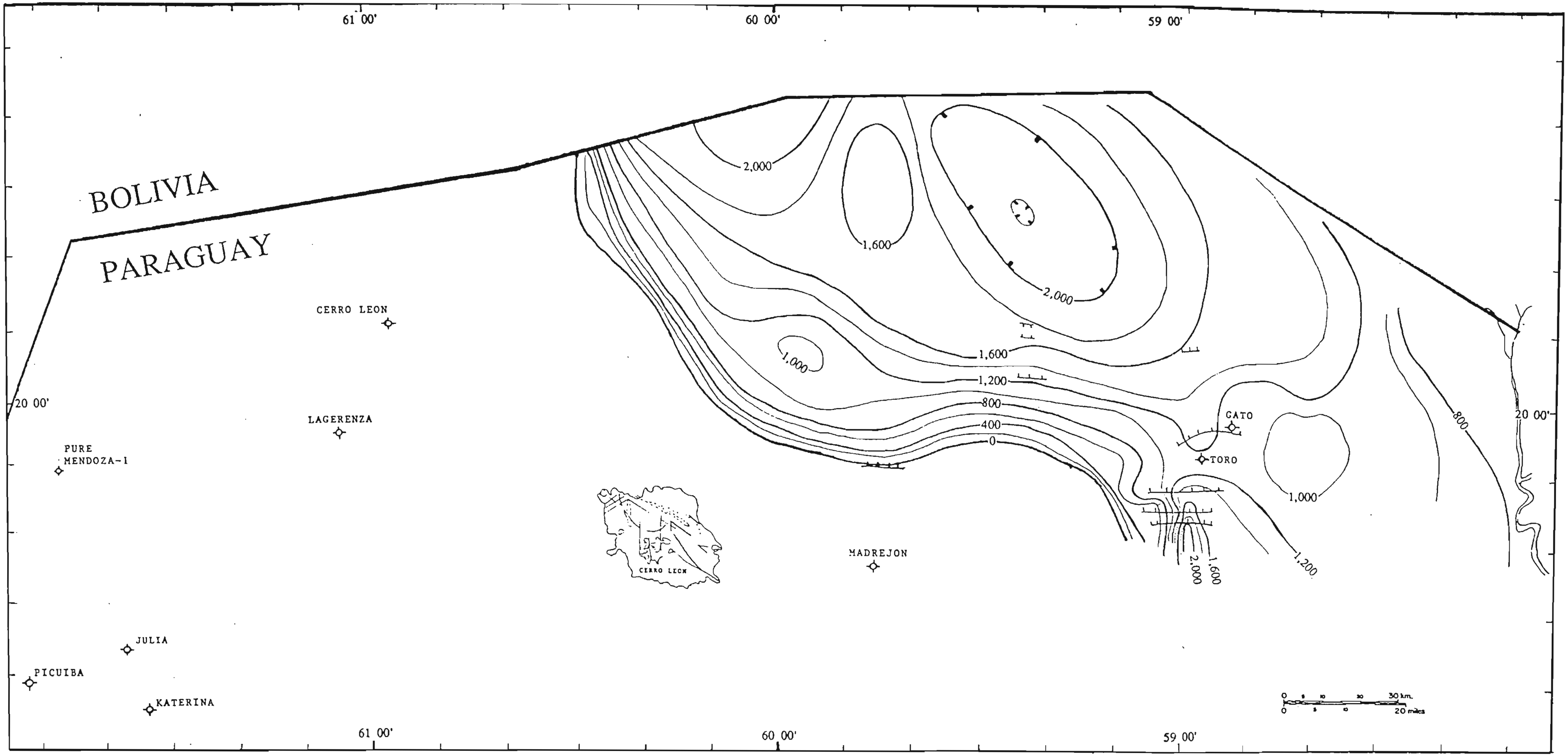


Fig. 55. Structure map of the Carboniferous-Devonian angular unconformity in the Curupaity Subbasin showing the areal distribution of the Carboniferous sediments. Values are negative in meters. The western border is limited by the eastern flank of the Cerro León Arch. Sonic logs from wells Toro-1 and Gato-1 were used for depth control. See Fig. 34 for location of seismic lines utilized.

CHAPTER III

STRATIGRAPHY OF THE PIRIZAL SUBBASIN

The Pirizal or Pirity Subbasin, known in Argentina as the Lomas de Olmedo Subbasin, is the northeastern extension into Paraguay of the Northwest or Orán Basin of northwestern Argentina (Fig. 56). Only eight wells have so far been drilled in the Pirizal Subbasin in Paraguay. Because no outcrops occur in Paraguay, most of the information available in this country is of indirect nature, especially seismic sections.

Most of the information and nomenclature of the Northwest Basin originated in Argentina. Sections crop out in several locations in that country, especially towards the Subandean region. Also, a larger number of wells have been drilled in Argentina, mostly by the Argentinian national oil company, Yacimientos Petrolíferos Fiscales (YPF), in the search for hydrocarbons. The Palmar Largo field, located in the northwestern part of the Argentinian Province of Formosa, approximately twenty two kilometers from the Paraguayan border (Fig. 1), was discovered in the 1980's. This is the first discovery outside the Subandean Belt of this part of South America and created renewed interest in the Northwest Basin.

The Pirizal Subbasin was formed by the rifting of the Paleozoic sequence, which underlies the Cretaceous to Quaternary fill. Two sedimentary packages constitute the basinal fill in Argentina: Salta Group, followed by the Palo Santo Group (Fig. 57 and 58).

Identification and correlation of formations in the Pirizal Subbasin were made mainly by log response and lithology. Paleontological information from three wells (Berta-1, Palo Santo-1 and Carmen-1) were available for this study, as well as one radiometric age determination of an intrusive igneous rock in the Palo Santo-1 well. Thick sections appear barren of palynomorphs and where present, are commonly inconclusive for age determination because of their long time ranges. A brief overview of the Paleozoic sequence will be made, followed by a more lengthy description of the Cretaceous, Tertiary and Quaternary sections.

Paleozoic Basement

Paleozoic sediments were found in all the wells immediately surrounding the Pirizal Subbasin in Paraguay. In the Boquerón or Michicola Arch (Fig. 3), a total of 4,154 feet (1,266 meters) of Eodevonian fossiliferous shales were penetrated in the Santa Rosa-1 well (Fig. 12). Barren quartzites below the fossiliferous section suggest the presence of Eodevonian or Silurian beds. The La Paz-1 well penetrated at least 300 feet (91 meters) of Devonian dark marine shales underlain by approximately 1,100 feet (335 meters) of intercalated shales, sandstones, siltstones and quartzites assigned to Devonian, Silurian and Ordovician ages. Approximately 1,300 feet (396 meters) of dark marine shales of possible Ordovician age continue down to total depth.

In the Central Chaco High area (Fig. 3), the Pure López-1 well penetrated 2,270 feet (692 meters) of continental Devonian sediments, consisting of red bed clay shales and sandstones that rest on a cored unconformity on 300 feet (91 meters) of grayish black quartzites with black siliceous shales (Figs. 12 and 13). The Orihuela-1 well (Fig. 13) penetrated 435 feet (132 meters) of hard, white quartzite and quartzitic sandstone, considered to be of Paleozoic age based on lithology. These rocks underlie a section of redbeds of unknown age.

Of the eight wells drilled in the Pirizal Subbasin proper, only two (Palo Santo-1 and Carmen-1) reached Paleozoic sediments (Fig. 1). Palo Santo-1 contained palynological evidence, while only lithologic evidence was obtained from Carmen-1. Palo Santo-1 penetrated 332 meters (3,432 to 3,764 meters TD) of marine sandstones of Devonian age. The preservation of palynomorphs was rather poor, precluding a precise age determination.

An Early Devonian age is suggested by the association of the acritarchs Neoveryhachium carminae and Baltisphaeridium cf. denticulatissium with the spore Emphanisporites sp. Chitinozoans, including forms similar to Angochitina comosa and Angochitina toyetae support the Early Devonian age (Millioud, 1975). The age and lithology would assign this Paleozoic section to the Santa Rosa Formation. Carmen-1 penetrated 86 meters of white "quartzite" with interbedded claystones considered to be of Paleozoic age (probably Devonian or Silurian) based on lithology (Carmen-1 final drilling report by Occidental, 1986).

According to Carle et al. (1989), three wells in the northwestern area of Formosa Province of Argentina reached levels considered to be Paleozoic (Ordovician) in age, and were assigned to the Las Breñas Formation. No fossils were reported, and the age assignation is based on lithologic correlation and location in the basin (Mingramm, 1965, in Carle et al., 1989; Russo et al., 1979, in Carle et al., 1989). This formation was recognized only in the subsurface in the Argentinian provinces of Santiago del Estero, Chaco and Formosa. It is composed of white to light gray, partly purple quartzarenites of fine- to coarse-grained, well-rounded grains, with micas, silica cement, and intercalated with pink grayish micaceous mudstones. Sedimentary structures described are crossbedding towards the base, and some mudcracks in the mudstones. This formation is considered practically impermeable, and therefore the economic basement for hydrocarbon exploration in Argentina (Carle et al., 1989). Figure 59 shows an approximate distribution of Paleozoic rocks in northwestern Argentina.

Salta Group

The post-Paleozoic sediments that comprise the sedimentary fill of the Pirizal Subbasin are divided into the Salta Group (Turner, 1959) and the Palo Santo Group (Figs. 57 and 58). The Salta Group extends from the Lower Cretaceous to the Upper Paleocene-Lower

Eocene, and consists of three subgroups: Pirgua, Balbuena and Santa Bárbara. The overlying formations extend from the Tertiary to the present.

Pirgua Subgroup

In Argentina, the Pirgua Subgroup (Reyes and Salfity, 1973) consists of three formations identified in the Alemanía Subbasin, from top to bottom: La Yesera, Las Curtiembres and Los Blanquitos (Fig. 57). These formations were previously considered as members (Reyes, 1970) of the Pirgua Strata of Vilela (1951) or Pirgua Formation, as it was called by some authors. The type section occurs in outcrops along the Pirgua River in Salta Province where it overlies Precambrian basement, and is overlain by the Lecho Formation. The La Yesera Formation consists mainly of breccia-like polymictic conglomerates (Reyes and Salfity, 1973). The Las Curtiembres Formation consists mainly of claystones with intercalated sandstones, especially at the base, and thin layers of fine-grained conglomerates. This formation has a general grayish red color. Basaltic flows and pyroclastic rocks, and sometimes sills and dikes also occur in it. The Los Blanquitos Formation is composed mainly of sandstones of lighter colors than the underlying formations (Reyes and Salfity, 1973).

The age of the Pirgua Subgroup in the Northwest Basin is determined by volcanic cycles (to be discussed later), some fossils, and by its stratigraphic position. The first two volcanic cycles --out of a total of three identified so far-- occur in the Subgroup (Galliski and Viramonte, 1985). The few fossils in this largely barren sequence represent frogs like Saltenia ibañezi in the Quebrada Las Conchas (Ibañez, 1960 and Reig, 1959) and dinosaur bones (Danieli and Porto, 1968, in Moreno, 1970). Stratigraphically, the Pirgua Subgroup was observed to underlie the Yacoraite Formation in Argentina (Salfity and Marquillas, 1986). This indicates a time span from Neocomian (Hauterivian, 128 +/- 5 m.y.) to approximately Campanian.

Gómez Omil et al. (1989) studied the Salta Group in the subbasins of Tres Cruces, Metán and Lomas de Olmedo (Fig. 56). Unfortunately, the location and nature of the 300 control points used in that study were not given. The authors divided the Pirgua Subgroup into two main tectosedimentary units (UTS I and UTS II) --separated by unconformities-- with several other minor units present. The sedimentary model developed by the aforementioned authors is typical of a rift basin in the early stages of development, in which the type and distribution of the graben sediments are controlled by the tectonic behavior of the faults delineating the basin. The deep, normal-down-to-the-basin active faults along the basin's borders were the conduits for the extrusion of volcanic rocks. The relief created by the active faults generated a typical sequence of lithofacies thinning towards the center of the basin. Towards the center of the basin the lithofacies indicate that sediments were deposited in environments that include alluvial fans, braided fluvial systems, eolian dunes, and distal playa lakes.

The tectosedimentary units I and II are separated by erosional unconformities along the basinal margins. UTS I contains extrusives of the First Effusive Cycle. UTS II was deposited in a basin with a higher base level than for UTS I --reflected in the deposition of shales and carbonates-- and produced by the partial filling of the basin by UTS I. Both units have the same lithofacies, with UTS II having an additional lithofacies comprised of oolitic carbonates (in the Río de los Salteños area) and carbonate nodules (in the Tres Cruces Subbasin). The carbonate nodules and oolitic carbonates are both related to red and green shales. UTS II contains extrusives of the Second Effusive Cycle.

The Pirgua sediments in Paraguay consist of reddish brownish, usually fine-grained, sandstones interbedded with reddish brown claystones. They contain abundant loose sand composed mainly of clear quartz. A few sandstones are cemented by calcite and some dolomite cement. Trace amounts of gypsum and anhydrite also are present. Distribution of these sediments in the basin is tectonically controlled and therefore, great lateral changes in thicknesses occur (Figs. 60 and 61).

The Pirgua sediments overlie marine Eodevonian sandstones in the Palo Santo-1 well. These palynologically dated Paleozoic sediments are intruded by a quartz latite porphyry (rhyodacite, an extrusive rock) dated at 126 +/- 3.5 million years (Palo Santo-1 composite log by REPSA-CPC, 1975a). The Pirgua-Paleozoic contact occurs at a depth of 3,432 meters. Basalt grains interspersed in quartzarenites occur at levels 3,242-3,430, 3,427-3424 and 3,418-3,415 meters. One hundred eleven meters above the basal contact, at levels 3,379-3,370 and 3,325-3,319 meters, 20 to 30% of the ditch samples were identified as tuff; the remainder of the samples are composed of sandstones (Palo Santo-1 well site sample description by REPSA-CPC, 1975b). If one considers the possibility that the basalt grains in the basal 27 meters of the Pirgua sediments and the tuff levels further up in the section are the pyroclastic counterparts of the igneous rock intruding the Eodevonian rocks, then one could speculate to assign to the Pirgua sediments the same age of 126 +/- 3.5 m.y. This would correspond to a Valanginian-Hauterivian (Neocomian) age, and correlate with the lower levels of the Alto de Las Salinas Volcanic Complex of 128 +/- 5 m.y. (Bossi and Wampler, 1969, in Galliski and Viramonte, 1985; Fig. 57 of this report). This age is the only one obtained in Paraguay for the Pirgua Subgroup, and no fossils have been found in this country. The position of the Palo Santo igneous rocks is aligned with the known occurrences of igneous extrusions of similar age along the Los Blancos and Isonza lineaments in Argentina (Fig. 56).

The lack of outcrops and small number of wells in the study area did not allow a detailed lithofacies study. However, the results obtained by Gómez Omil et al. (1989) should be correlatable to Paraguayan territory. Figure 62 shows the structure map and distribution of the top of the Pirgua basin in Paraguay. The northern and southern faults tectonically controlled the sedimentation of the Pirgua Subgroup basin. The northern and southern faults are the only ones reaching the top of the subgroup, and determine the boundaries of the Pirgua basin. The faults inside the basin are not expressed at the top of the Pirgua Subgroup, and are drawn to show the direct relationship between faults inside the Pirgua Subgroup and structures revealed by the structure maps of overlying sediments.

Balbuena Subgroup

The Balbuena Subgroup (Moreno, 1970) consists of three formations, upward from the base: Lecho, Yacoraite and Olmedo (Fig. 58, 63 and 64). YPF geologists place the Olmedo Formation in the overlying Santa Bárbara Subgroup based on unpublished work by De Spirito (1979). No clear explanation of this classification has been available. Therefore, in this study, the Olmedo Formation will be included in the Balbuena Subgroup as it has been interpreted by the published literature. Gómez Omil et al. (1989) refer to the contact between the Yacoraite and Olmedo Formations as being marked by a sedimentological discontinuity, a "eustatic rupture," and a "tensional tectonic rupture." The contact between the Pirgua and Balbuena subgroups appears to be concordant throughout the Northwest Basin, especially towards the basinal centers, with the exception of some marginal areas (Salfity, 1980).

Carle et al. (1989) indicate that a hiatus separates the Olmedo Formation from the Mealla Formation (base of the Santa Bárbara Subgroup) in northwestern Formosa Province in Argentina, and that this is supported by paleontological evidence produced by several unmentioned authors. Formation changes within this subgroup are transitional in the study area and appear to be so throughout the Pirizal Subbasin.

Lecho Formation

The Lecho Formation (Turner, 1959) constitutes the basal sandstones of the Balbuena Subgroup, and was deposited in a basin of very low relief. According to Salfity and Marquillas (1981), the Lecho Formation normally overlies the Los Blanquitos Formation and locally the La Yesera Formation. The contact can be sharp or gradational, and is recognized in Argentina mainly by a change in color from reddish (Pirgua) to whitish (Lecho) sandstones and loose sands. The Lecho Formation is transgressive, and is commonly in direct contact with the Paleozoic basement in the margins of the basin (Salfity, 1980).

Gómez Omil et al. (1989) interpret the Lecho and Yacoraite formations as being lateral equivalents produced by the same transgressive event. The marginal areas correspond to the terrigenous clastic Lecho Formation, whereas the central, deeper parts of the basin are occupied by the carbonate facies of the Yacoraite Formation.

The paleontological content of the Lecho Formation is very sparse throughout the Northwest Basin. The forms are usually very difficult to identify or have not been studied (Salfity, 1980). Among the few paleontological references are: remains of dinosaurs and birds in the El Brete area in extreme southern Salta Province, from which a Late Cretaceous (Senonian) age was determined (Bonaparte et al., 1977); remains of tetrapods assigned to the top of the Los Blanquitos Formation (Pirgua Subgroup) and to the marginal facies of the Lecho and Yacoraite formations (Bonaparte and Bossi, 1967; Reyes and Salfity, 1973); remains of dinosaur bones reported by Fernández et al. (1973) as occurring in the Lecho Formation east of Aguilar, Jujuy Province.

The Palmar Largo Extrusives (Vulcanitas de Palmar Largo) (70 +/- 5 m.y.) of northwestern Formosa Province, in an area directly adjacent to this study area (Fig. 1), are intimately related to the Lecho Formation (Carle et al., 1989). These volcanic rocks appear during the final stages of deposition of the Pirgua Subgroup, and at the base of the Lecho Formation. This gives a Late Cretaceous age (Campanian-Maastrichtian) to the formation in the area.

In the study area, according to well cuttings from the Palo Santo-1 well and sample descriptions from the three Occidental wells (Carmen-1, Tte. Acosta-1 and Nazaret-1), the

Lecho Formation consists of white to reddish brown arkoses and loose sands with some dolomite cement. It has a very fine- to fine-grained texture in the deeper areas (Carmen-1), and medium- to fine-grained texture towards the margins (Nazaret-1).

Wireline cores, sidewall cores and cuttings of Carmen-1 and Tte. Acosta-1 show that the main detrital grains consist of angular to subrounded quartz and feldspar (Fig. 65). The cement consists mainly of quartz overgrowths and some dolomite. Grain coating hematite also was present in the Tte. Acosta-1 cored interval 3,781-3,778.25 meters and exerted a dominant control on permeability when present (Tte. Acosta-1 final drilling report by Occidental, 1987). Figures 66 and 67 show thin sections of sidewall cores of the Lecho Formation in Carmen-1. The formation has good primary porosity in the Tte. Acosta-1 well ,with an average value of 17.9%, as determined from core analysis (Eslinger, 1987).

According to Eslinger (1987), the diagenetic sequence included: (1) Compaction of detrital grains, except in localized areas where the formation of an early carbonate cement (now dolomite) prevented compaction from occurring. (2) It was followed by the dissolution of feldspars, resulting in the formation of authigenic K-feldspar, albite, lathy illite, hematite and anatase, and formation of titanium oxide minerals. Some secondary (moldic) porosity resulted from the dissolution of feldspars. (3) Quartz (dominant cement) and some feldspar overgrowths followed the hematite coatings and dolomite cements. No fossils or dated igneous rocks have been reported in the study area within the Lecho Formation.

Yacoraite Formation

Gómez Omil et al. (1989) divide the Yacoraite Formation (Turner, 1959) in three members: Lower, Middle (Puesto Guardián Member), and Upper (Las Avispas Member). These members are difficult to separate in the Lomas de Olmedo Subbasin, and are presented here for a regional insight and an illustration of facies and environments in the

Northwest Basin. These authors interpret the Yacoraite Formation as the subaqueous equivalent of the Lecho Formation, which represents the continental facies of a transgressive sea. The Lower Member was defined in the Tres Cruces Subbasin, where it consists of a lower "clastic-carbonate" (high water level), and an upper shaly (lower water level) sections. The Lomas de Olmedo, Alemanía and Metán subbasins, however, contain the predominantly continental sandy eolian and fluvial facies, namely the Lecho Formation, with the upper shaly section missing. The depositional environment in the Tres Cruces Subbasin includes: fluvial, eolian, littoral plain (clastic-carbonatic with periodic flooding), carbonate flat (with periodic subaerial exposure), and a shallow basinal center that dried out periodically.

The Middle Member of the Yacoraite Formation, also defined in the Tres Cruces Subbasin, is known in the Lomas de Olmedo Subbasin as the Puesto Guardián Member. It has a lower carbonate section in the deeper parts of the basin, representing a new rise in water level. An upper shaly section would represent a lowering of the water level with hiatuses and erosional surfaces towards the basin margins. The basinward environments are fluvial, eolian system, clastic-carbonate littoral plain, carbonate plain that desiccated periodically, and a shallow basinal center that dried up periodically.

The Upper Member, also known as the Las Avispas Member, was defined in the Lomas de Olmedo Subbasin. The predominant facies consists of carbonates, with its base corresponding to the widest areal incursion of the water body. This member overlaps the Paleozoic basement with carbonates in some areas in Argentina. This cycle ends with a lowering of base level resulting in carbonate-shaly and evaporitic facies with some karstic features in inner parts of the basin, and hiatuses and erosional surfaces towards the margins. The sedimentary model for the southern flank of the Lomas de Olmedo Subbasin is interpreted by Gómez Omil et al. (1989) as a sequence of fluvial and/or eolian; littoral plain (carbonate-clastic) with periodic flooding; carbonate flats with periodic flooding; and a shallow shaly-carbonate depocenter with periodic dessication.

In the study area, the Yacoraite Formation shows a coarsening trend away from the deeper parts of the subbasin in Carmen-1 towards the shallower areas of Tte. Acosta-1 and Nazaret-1 wells. In the Carmen-1 well, the formation was described macroscopically as consisting predominantly of light brownish gray to gray dolomitic mudstones with occasional interbeds of siltstones and claystones. Microscopic studies, however, indicate it to be mostly detrital with dolomite cement (Eslinger, 1987).

The lithology in the Tte. Acosta-1 well consists of claystones, siltstones and sandstones. The color is generally brown to reddish brown, except for the dolomite-cemented clastic sediments, which are dark yellow brown to light gray. Siltstones are subplaty with gypsum inclusions. Claystones are slightly dolomitic to noncalcareous with traces of gypsum. The sandstones are slightly friable and consist of very fine- to fine-grained, subangular to subrounded clear quartz, sometimes with an argillaceous matrix and sometimes with traces of dolomitic cement (Tte. Acosta-1 final drilling report, Occidental, 1987). In the Nazaret-1 area, the Yacoraite Formation shows a much coarser clastic facies and consists of loose sand and sandstone with thin interbeds of siltstone and claystone and traces of dolomite in the basal section (Nazaret-1 final drilling report, Occidental, 1988).

Petrographic studies of cores, sidewall cores and cuttings of the Carmen-1 well show that the Yacoraite Formation in this area is basically composed of dolomite-cemented sandstones, siltstones and mudstones (Eslinger, 1987). The main detrital grain is quartz, with feldspar present in substantial amounts. Illite is abundant. Besides dolomite, ferrodolomite, described by Eslinger as an intermediate phase between magnesite ($Mg CO_3$) and siderite ($Fe CO_3$), was observed in most samples. Cuttings and sidewall core samples match the lithologies found in 9 meters of core obtained from the upper section of the formation from 3,796 to 3,805 meters (Fig. 68). Only the lithology of sidewall core at

3,921 meters was different, and consisted of a quartzarenite with extensive quartz overgrowths, and in parts with a matrix rich in hematite (Fig. 69 of this report; Eslinger, 1987). The core (3,796-3,805 meters) consists of two basic facies interbedded throughout the core: (1) Massive looking fine grained quartz siltstones and sands cemented by dolomite (Fig. 70), and; (2) Laminated dolomite-cemented siltstones and sandstones (Fig. 68 and 71). The massive siliceous siltstones contain abundant clays and are extensively bioturbated (Eslinger, 1987; Saller, 1986). The laminated dolomite-cemented siltstones consist of horizontal laminations of sand and silt, graded beds, containing fractures and water escape structures (Saller, 1986).

In Paraguay, the Yacoraite Formation developed a clastic facies with dolomite cement. This is supported by comparisons with the maps of Gómez Omil et al. (1989). Figure 64 shows the deepest penetration of sea waters in Paraguay.

Depositional Environment of the Yacoraite Formation

The marine or continental nature of the Yacoraite Formation has long been the subject of controversy in the Northwest or Orán Basin. Following are an overview of the studies completed in Argentina and the results of information obtained in Paraguay.

Very few paleontological and paleoenvironmental studies have been published to the present. All these studies refer to areas in Argentina and its correlative El Molino Formation in Bolivia.

Moroni (1982), in a study of the Subandean region, reports the presence of dinoflagellate cysts indicating a brackish environment. This study refers to the wells YPF St. LO. x-3 (Lomas de Olmedo), YPF St. MDT. x-3 (Martínez del Tineo) and YPF St. P. Gu. x-2 (Puesto Guardián). The author reported two palynological associations, one of which is Maastrichtian and the other Paleocene in age. He also reports that the Yacoraite Formation encompasses a Paleocene age in these wells.

Papu and Melendi (1984), in unclear reports, refer to both the Yacoraite Formation in Jujuy Province and the Paso del Sapo Formation in the Chubut Province in southern Argentina without indicating the origin of the samples. They mention macerals of *Azzolla cretacea* indicating a low energy freshwater environment, and morphologies of dinoflagellates that are clearly marine. These authors indicate a mixed environment for the Yacoraite Formation and a probable Maastrichtian age.

Musacchio (1972) reports charophytes from the Yañi Chico and Tres Cruces areas in Jujuy Province. Ostracodes associated with the charophytes are of non-marine origin, but he does not rule out the possibility of marine influence mentioned by other authors. The age for the levels with *Porochara gildemeisteri* and *Amblyochara* sp. is Late Cretaceous, presumably Campanian-Maastrichtian.

Kielbowicz and Angelozzi (1984) studied samples from the Subandean region of the Lomas de Olmedo Subbasin from eight wells: El Vinalar x-2, Martínez del Tineo a-3, Estación Pizarro x-1, Pozo Escondido x-1, Puesto Guardián x-2, Lomas de Olmedo x-3, x-7 and x-8. Only the first two provided workable fossils, the other six were barren or provided only unidentifiable samples of ostracodes. The calcareous microfossils, foraminifers ostracodes, and charophytes indicate a brackish littoral, probably restricted environment.

Méndez and Viviers (1973) report foraminifers and ostracodes from outcrops and well samples located between 64° 30’ to 65° 40’ West and 23° 30’ to 25° 10’ South. No specific locality or well is given by these authors. The environment of deposition is interpreted as being coastal marine or with permanent connection with the sea, calm waters and low salinity, which could be a lagoonal setting. The depositional environment is interpreted as having changed in short periods of time with wide areal extension. The interpreted age is Senonian.

Powell (1979) interprets a nearshore marine or estuarine environment with warm waters based on the occurrence of the chondrichthyes (fish) Pucapristis branisi. The assigned age is uppermost Maastrichtian. This same fossil was found in the El Molino Formation of Bolivia (Schaeffer, 1963).

Benedetto and Sánchez (1972) report the occurrence in the upper section of the Yacoraite Formation in Salta Province of the pycnodontiform fish Coelodus toncoensis. The fossil indicated a Late Cretaceous age. They also point out the absence of ammonites in both the Yacoraite and El Molino formations as an indication of the shallowness (less than 100 meters) of the marine transgression.

Palma (1984), in describing the Cretaceous-Tertiary transitional boundary between the Yacoraite and Mealla formations in an outcrop called the Perfil Esquina Blanca in Jujuy Province, interprets the depositional environment of the Yacoraite Formation as lacustrine with facies close to, and transitional to the shoreline. This interpretation is based on a faunal association, sedimentary structures and lithologies.

Marquillas (1985), in a regional study of the Yacoraite Formation between 24° and 26° 20' South, refers to the depositional basin of the Yacoraite Formation as a shallow restricted carbonate basin. A marine transgression occurred towards the end of the Senonian (Maastrichtian), but did not maintain a permanent connection with the sea, which gives the basin its special characteristics. According to her, there are no typical marine faunas or evidence of tidal action which would allow the division of sediments into sub-, inter-, and supratidal environments.

The presence of dinoflagellate cysts has been mentioned to the author of this study by several geologists of companies exploring for hydrocarbons in the Northwest Basin in Argentina. Their distribution however is localized in the individual sections. This observation, combined with the ones mentioned above, suggests some marine incursion or incursions that provided marine organisms followed by increased influence of brackish environments from rivers flowing into the basin.

The following evidence supports a marine incursion in the study area at the end of the Cretaceous-Early Tertiary (Maastrichtian-Paleocene): (1) Ostracodes were found in limestones in the interval 3,428-3,437 meters in the Berta-1 well. A Paleocene age (probably Late Paleocene) was assigned to the limestones based on the type of ostracode and its wall and hinge morphology. The environment was interpreted by Levinson (1976, in Stover, 1976) as shallow marine, inner neritic. (2) Palynomorphs in Carmen-1 from a section extending from the Lecho to the Mealla formations were identified by Baldis (1986, in Carmen-1 final drilling report). Although no precise age determination was possible because of the poor preservation and the long time range of the palynomorphs, the depositional environment for the section was interpreted as nearshore marine to swamp. (3) Amorphous organic matter from selected samples from the Olmedo and Yacoraite formations in Carmen-1 were identified geochemically as being of marine origin (Palmer, 1986, in Carmen-1 Final Drilling Report, 1986). No marine dinoflagellates or other clearly marine fossils have been reported in Paraguay for this formation. Based on the information obtained in Paraguay, a marine incursion can be inferred to have occurred in the study area (Fig. 69).

It was not possible to determine the depositional environment of the Yacoraite Formation in Carmen-1 from petrological observations of the cores and cuttings because of the lack of diagnostic structures and the absence of fossils in them. The laminated dolomite-cemented layers may indicate pulsating deposition in the form of graded beds in Bouma sequences. The massive siliceous mudstones may indicate slow deposition (Saller, 1986).

Olmedo Formation

The Olmedo Formation (Moreno, 1970) was recognized in subsurface in the well S. LO. x-1, Lomas de Olmedo, in Salta Province, Argentina (Moreno, 1970). It consists regionally of claystones with halite in the deeper areas, and of siltstones towards marginal areas. Thicknesses in Argentina range from 65 meters in basin margins to a maximum of 205 meters in central areas (Carle et al., 1989). Gómez Omil et al. (1989) indicate that the upper contact corresponds to a tectosedimentary reactivation, manifested by erosional surfaces at the margins and along tensional faults, coarsening sediments, and localized igneous extrusives. They mention conglomerates with clasts of up to 15 centimeters in diameter of the Yacoraite Formation at the base of the Mealla Formation in the Alemanía Subbasin.

An Early Paleocene age is assigned to the formation based on fossil evidence in Argentina. Palynological data from three Argentinian wells --Lomas de Olmedo x-2 (I), Martínez del Tineo x-2, and Lomas del Baqueano x-1-- indicate a Paleocene age for the lower section of the Olmedo Formation (Bianucci et al., 1981).

The Olmedo Formation represents an increasingly restricted environment with high evaporation, which allowed the precipitation of halite in the deeper areas of the Lomas de Olmedo Subbasin, as well as the occurrence of dolomite and gypsum. The facies distribution in the better known Argentinian side indicate a bull's eye pattern of interdigitating lithologies progressing towards the center. The facies spectrum begins at the basin margins with a sandy fluvial plain; silty-clayey mud plain; clayey saline mud plain with anhydrite nodules; and halite at the center (Gómez Omil et al., 1989).

In the Carmen-1 well, the Olmedo Formation represents the typical deeper basin sequence with two claystone intervals separated by a middle halite interval (Fig. 72). This sequence also is found in the Argentinian wells located in a central position in the Lomas de

Olmedo Subbasin, where some thin intervals of the sulfates, anhydrite and gypsum are reported. In the study area, the Olmedo Formation appears to have transitional upper and lower contacts.

The halite interval called the Saline Member (Miembro Salino) was found in the study area only in the Carmen-1 and Anita-1 wells (Fig. 64). It is 30 meters thick in Carmen-1, of which the lower 25 meters consist of pure halite, and the upper 5 meters contain scattered claystones. The Saline Member is approximately 100 meters thick in Anita-1, and has thin claystone intercalations. The basal claystone section in Carmen-1 is dark grayish black and contains traces of anhydrite, while the upper section is grayish brown to dark brown and also contains traces of anhydrite. It is the difference in color, not always evident in basin margin areas, that separates the Olmedo from the Mealla Formation, which is reddish brown.

The other wells in the study area, located in more marginal positions, do not contain the halite interval. They consist of reddish brown claystones and siltstones with thin intercalations of dolomite and traces of anhydrite. The Nazaret-1 section had, in addition to these lithologies, a basal loose sand, and the contact with the overlying Mealla Formation is marked by an increase in resistivity in log response (Fig. 72).

A Paleocene age (probably Late Paleocene) is assigned to the Olmedo Formation in Paraguay based on palynological studies of samples from Berta-1 (Stover, 1976) and Palo Santo-1 (Millioud, 1975). Geochemical analyses of selected samples of the Yacoraite and Olmedo formations from Carmen-1 indicate the presence of amorphous organic material of marine origin (Palmer, 1986, in Carmen-1 final drilling report, Occidental, 1986).

Santa Bárbara Subgroup

The Santa Bárbara Subgroup (Moreno,1970) consists of three formations from bottom to top: Mealla, Maíz Gordo and Lumbrera (Figs. 57 and 58). The subgroup is separated from the subjacent Balbuena Subgroup by a hiatus in the northeastern part of the Olmedo Subbasin, in northwestern Formosa Province, and the top is eroded and overlain by the Palo Santo Group in the study area (Fig. 58). The upper erosional surface can be observed in some parts of the study area in seismic sections. The boundaries between the three formations of the Santa Bárbara Subgroup appear to be transitional in the study area.

The Santa Bárbara Subgroup has a much wider areal distribution than the Balbuena Subgroup (Figs. 62 and 73). All three formations in the study area have essentially the same lithologic composition and color, a reddish brown claystone. The eastern part of the study area shows a thicker accumulation of the Santa Bárbara Subgroup sediments, with up to 1,700 meters thick, as opposed to the area closer to the Argentinian border (Fig. 74). A shift of the depocenter occurred during the deposition of this subgroup. The deeper parts of the Pirizal Subbasin during the deposition of the Balbuena Subgroup corresponded to the areas towards the Argentinian border, while the Santa Bárbara Subgroup formed a smaller subbasin eastward, towards the Teniente Acosta-1 and Nazaret-1 areas (Fig. 74).

In the Salta-Jujuy area of Argentina, marls occur in addition to claystones. The Mealla Formation is reddish brown, and was originally known as the Lower Red Marls (Margas Coloradas Inferiores; Schlagintweit, 1936). The Maíz Gordo Formation is greenish gray, and was originally known as the Green Marls (Margas Verdes; Schlagintweit, 1936). The Lumbrera Formation is again reddish in color, and was named, also by Schlagintweit (1936), the Upper Red Marls (Margas Coloradas Superiores).

Mealla Formation

The Mealla Formation (Moreno, 1970) was called Wi by Hagerman (1933) and Lower Red Marls (Margas Coloradas Inferiores) by Schlagintweit (1936). Carle et al. (1989) indicate a hiatus as separating its base from the subjacent Olmedo Formation and a transitional contact with the overlying Maíz Gordo Formation in northwestern Formosa

Province. They also report 18 to 27 meters of Gray Horizon in the northwestern part of Formosa Province. In other parts of the Northwest Basin in Argentina, the lithology of the Mealla Formation consists of claystones and marls with thin intercalations of sands; it also commonly contains thin layers of gypsum and stromatolitic algae, and reaches a maximum thickness of 400 meters (Salfity, 1981).

The Mealla Formation in Argentina is dated as Late Paleocene or "Riochiquense" of Patagonia --Argentinian division of the Paleocene-- based on a notoungulate mammal fauna containing Simpsonotus praecursor and S. major in the Tres Cruces Subbasin (Pascual, 1978).

Palma (1984) described the Cretaceous-Tertiary boundary in a transitional contact between the Yacoraite and Mealla Formations in the Perfil Esquina Blanca outcrop of Humahuaca Department, Jujuy Province. The Yacoraite Formation is interpreted as a lacustrine nearshore environment based on faunal associations, sedimentary structures and lithologic textures. The Mealla Formation exhibits paleosoil profiles, mudcracks, mottling, calcretes, roots and rhizoconcretions associated with unnamed sedimentary structures. The depositional environment is interpreted as anastomosing fluvial with low hierarchy channels and extensive flood plains. Palma (1984) considers these characteristics can be extrapolated to other sectors of the Northwest Basin. Carle et al. (1989) interpret the deposits of the Mealla Formation in northwestern Formosa Province as an interior basin, continental, centripetal, of very low energy, with shallow waters and rapid desiccation .

Gómez Omil (1989) describes the facies of the Mealla Formation as very similar to that of the Olmedo Formation. These facies consist, from the center outwards, of: (1) Halite, gypsum nodules and dark gray to reddish shales, restricted to the depocenter of the Lomas de Olmedo Subbasin and to the upper middle segment of the unit; (2) Red and green shales with nodular gypsum and cryptalgal boundstones; (3) Red shales and "graywackes"; and (4) Red sandstones and conglomerates. The Gray Horizon member

(Franja Gris) is composed of laminated dark gray calcareous silty shales with thin intercalated levels of "graywackes" and fine-grained sandstones, ripple marks and cryptalgal boundstones. This member has a wide regional distribution constituting a stratigraphic and seismic guide level. The depositional environment was interpreted by Gómez Omil et al. (1989) as a very restricted, hypersaline lake, interdigitating outwardly with a saline mud flat; mud plain; and a fluvial plain. The Franja Gris, however, represents a rapid flooding, and later desiccation of a very shallow basin.

The Mealla Formation in the study area consists of reddish brown claystones and siltstones with occasional traces of anhydrite, gypsum or dolomite. The Gray Horizon (Franja Gris) member of the Mealla Formation consists of brownish gray to greenish gray claystone with a maximum thickness of 33 meters in the central part of the subbasin in Carmen-1, thinning to 5 meters in Tte. Acosta-1 and approximately 1 meter in Nazaret-1 (Fig. 72). This member serves as a regional stratigraphic and seismostratigraphic guide level. A Paleogene (probably Paleocene) age is assigned to the formation in Paraguay based on abundant Ulmoideipites pollen in Palo Santo-1 (Millioud, 1975).

Maíz Gordo Formation

The Maíz Gordo Formation (Moreno, 1970) was originally known as Ws (Hagerman, 1933), Green Marls or Margas Verdes (Schlagintweit, 1936) and Sunchales Formation (Cockerell, 1936). In the northwestern part of Formosa Province, the formation consists of claystones and mudstones with a slightly calcareous content and thin intercalations of greenish gray claystones. Some wells registered 10-15 meters of a gray to light brown mudstone at the top of the formation (Carle et al., 1989).

In the rest of the Northwest Basin, the Maíz Gordo Formation reaches up to 500 meters in thickness. It consists of greenish gray and whitish green mudstones, claystones and marls with numerous intercalations of stromatolitic boundstones, and also abundant paleosoils (Marquillas, 1991, written communication). It has a transitional contact with both the underlying Mealla Formation and with the overlying Lumbrera Formation (Salfity and Marquillas, 1981).

According to Gómez Omil et al. (1989), the base of the Maíz Gordo Formation reflects a strong tectonic reactivation that modified the paleogeography, creating a steeper gradient in the southern border of the Alemanía-Metán area, and in the northern flank of the Lomas de Olmedo Subbasin (Fig. 56). This reactivation caused erosion of the Franja Gris member and an important initial clastic progradation in these areas. Later, a slow rise of the base level occurred. According to these authors, the depositional environment would correspond to a shallow lake in slow and pulsating expansion over a mud plain, and a fluvial system. The facies present contain shallowing sequences. The facies spectrum from deep to shallow areas, would include: (1) Dark gray laminated calcareous silty shales with thin beds of "lithoclastic-oolitic mudstone-packstones." This facies corresponds to the subtidal, internal lake environment. (2) Algal boundstone containing mudstones, intraclasts and sandstones; green gray fine graywackes and shales with abundant evidence of subaerial exposure. This corresponds to the intertidal environment. (3) Shales and red "wackes" (supratidal environment), predominant in the Tres Cruces Subbasin and in Formosa Province. (4) Conglomerates and sandstones (fluvial environment), well developed along active margins of the Metán and Alemanía subbasins and the northern flank of the Lomas de Olmedo Subbasin.

Among the fossils found distributed in several parts of the Northwest Basin in Argentina are fish like Coridoras revelatus and numerous species of Coleoptera (Curculionidae; Cockerell, 1936), as well as remains of chelonians in the upper section. The age should be considered similar to its over- and underlying units, namely Late Paleocene-Early Eocene or Casamayorense-Riochiquense of the Argentinian stratigraphic division (Fig. 57). Pothe de Baldis (1972, in Quattrochio, 1978) assigns a Paleocene age to the Maíz Gordo Formation based on palynological studies.

In the study area, the Maíz Gordo Formation attains a thickness of up to 188 meters in Nazaret-1 (Fig. 72), and consists of reddish brown claystone with thin interbedded siltstone, and is locally slightly calcareous. The upper and lower boundaries appear to be transitional. This lithology is very similar to that observed in the directly adjacent area of northwestern Formosa Province. Samples of the Palo Santo-1 well contain abundant Ulmoideipites pollen, and the formation is assigned to the Paleogene (probably Paleocene; Millioud, 1975).

Lumbrera Formation

The Lumbrera Formation (Moreno, 1970) was originally called V by Hagerman (1933), and Upper Red Marls (Margas Coloradas Superiores) by Schlagintweit (1936). Throughout most of the Northwest Basin the Lumbrera Formation consists of monotonous brick red claystones with thin interbeds of fine-grained sands. The Green Horizon member has a characteristic greenish to grayish green color, and consists of claystones, fine sandstones, mudstones and calcareous silts. This member has a rich insect fauna and palynomorphs. Quattrocchio (1980) studied the palynology of the Faja Verde in the locality of Pampa Grande, Salta Province. There it consists of two green and gray layers, which were assigned a Late Paleocene to Early Eocene age. The Franja Verde I (lower unit) contains the mammal Albertogaudrya? carahuensis assigned to the Early Eocene (Casamayorense) by Carbajal et al. (1977). The same Early Eocene age was assigned to the Lumbrera Formation by Pascual (1978) based on remains of jawbones of the marsupials Prepidolops didelphoides and Bonapartherium hinakusijum. Fernández et al. (1973) assigned a Paleocene to Eocene age to the formation based on the presence of the fish remains of Lepidosiren paradoxa.

The Lumbrera Formation has the widest areal extent of any of the formations of the Salta Group, overlapping the underlying Maíz Gordo and Mealla formations in several border areas of the basin (Salfity and Marquillas, 1986). According to Moreno (1970), the Green Horizon member represents transgressive freshwater levels on a regional scale. Quattrocchio (1980) reports the absence of marine microplankton in the Fajas Verdes I and II near Pampa Grande, Salta Province. She interprets the red sediments of the Lumbrera Formation as alluvial plain deposits. In Salta Province, the Fajas Verdes I and II consist of green and gray shales with intercalation of limestones and sandstones. The lithology and cyclicity of the Fajas Verdes suggest to her a lacustrine environment. This aspect, associated with the absence of marine microplankton, would confirm the continental nature of Lumbrera deposits in that region.

Gómez Omil et al. (1989) divide the Lumbrera Formation into three units based on lithology and tectonic characteristics: Lower Member, Franja Verde, and Upper Member. Both Lower and Upper Members were deposited in environments similar to those of the Mealla Formation except for the hypersaline lake. The environments include a saline mud flat with gypsum nodules, a mud plain, and a sandy fluvial plain. The Franja Verde environmental spectrum would have been very similar to that of the Maíz Gordo Formation. It represents a very quick flooding and drying up of the basin, but with a very wide areal distribution. Its depositional environment would include a shallow lake with gray green laminated calcareous shales and intercalated sandstones and stromatolitic boundstones associated with intraclasts. This facies interdigitates with mud flats containing red shales and an outer fluvial plain with sediments ranging from shales to conglomerates.

In the study area the Lumbrera Formation is the thickest formation of the Santa Bárbara Subgroup with a thickness of 1,101 meters in Tte. Acosta-1 well (Fig. 72). The lower contact with the Maíz Gordo Formation is transitional, and the upper one is erosional with the Tranquitas Formation of the Palo Santo Group.

The Lumbrera Formation consists of reddish brown claystones and silty claystones with gypsum interbeds in the Carmen-1 well and in northwestern Formosa Province, where it is also slightly calcareous, containing calcareous nodules and gypsum (Carle et al., 1989). The Tte. Acosta-1 and Nazaret-1 wells revealed an intercalation of sand, sandstone, siltstone and claystone.

The Lumbrera Formation contains the Green Horizon member (Franja Verde), which is a regional seismic and stratigraphic marker (Fig. 72). It consists of greenish gray to brownish gray claystone. It was described as a siltstone in the Nazaret-1, and as a light gray to grayish red calcilutite and light olive gray oolitic limestone in the Tte. Acosta-1 (Carmen-1, Tte. Acosta-1 and Nazaret-1 final drilling reports). The Gray Horizon thins out into Paraguay from Formosa Province, where it is 15-20 meters thick (Carle et al., 1989). It is approximately 10 meters thick in Carmen-1, approximately 5 meters in Tte. Acosta-1, and even thinner in Nazaret-1. The sediments of the Franja Verde in the study area are clearly coarser than in Argentina, except in the central areas of the Pirizal Subbasin, towards Carmen-1. Sediments in Teniente Acosta-1 and Nazaret-1 have more similarities with the coarser facies of the Lower and Upper members of Gómez Omil et al. (1989).

Palo Santo Group

Three formations: Tranquitas, Paraná and Chaco comprise the herein referred to as Palo Santo Group. The name is derived from the well Palo Santo-1. These formations are part of one continuous depositional cycle, as determined palynologically in the well Palo Santo-1. The sequence of sediments overlying the Santa Bárbara Subgroup reflects in part an overlapping of sediments from the Chaco Paraná Basin from the southeast into the Northwest Basin. The lowermost unit is believed to be the Tranquitas Formation (Schlagintweit, 1938, in Mingram, 1979), which is part of the Metán Subgroup in the the northern Salta Province, and also known as part of the Subandean Tertiary (Zunino, 1944, in Russo et al., 1980).

According to Russo et al. (1980), a marine transgression took place in the Chaco-Pampean Plain (Llanura Chaco Pampeana), starting in Middle Miocene and extending into the Pliocene (Fig. 75). The transgression of the Paranense sea produced a sedimentary cycle composed of the Paraná Formation and the gradationally overlying Entre Ríos Formation. The age of these two formations is Miocene-Pliocene, based on micro- and macropaleontological data (Russo et al., 1980). The Paraná Formation was deposited during the transgressive phase of the sea, and is comprised almost entirely of greenish, bluish or yellowish gray claystones containing marine fossils. In the western sector of the Chaco Pampean plains, the green sediments of the Paraná and Entre Ríos formations interdigitate with the reddish brown sediments of the Chaco Formation. However, where the Paraná and Entre Ríos formations are missing, the whole section is occupied by the Chaco Formation, which represents the continental facies. The Chaco Formation extends, in the areas where the Paraná and Entre Ríos formations are missing, from Eocene to Pliocene (Russo et al., 1980).

In the study area the upper part of the Tranquitas Formation was increasingly affected by an expanding Atlantic sea penetrating from the Buenos Aires Province area (Fig. 75). This increasing influence of marine characteristics resulted in the blue green claystones of the Paraná Formation, which interdigitates in marginal areas with the reddish brown Chaco Formation (Fig. 76).

In the study area the Tranquitas Formation shows an areal distribution of textures controlled by the depth of the Pirizal Subbasin. Well sample descriptions from more proximal areas like the Tte. Acosta-1, Nazaret-1 and La Paz-1 wells indicate brown to yellowish orange, occasionally conglomeratic, sand and sandstones, whereas reddish brown claystones were found in the distal areas around Carmen-1 and Anita-1 wells (Figs

72 and 76). The upper part of the Tranquitas Formation appears to change gradationally into the Paraná Formation, whereas the basal contact with the Lumbrera Formation is erosional. The Paraná and Chaco Formations appear to have transitional contacts, as observed in seismic sections, geophysical logs, and the fossil and stratigraphic evidence from the study area (Figs 72, 76 and 77).

The presence of the Paraná Formation in the study area is based on the occurrence of marine microorganisms, such as acritarchs, dinoflagellates and microforaminifers in the Palo Santo-1 well, in the interval 465-1,637 meters (Figs. 76). The areal distribution of the formation is based on the observation of the bluish green, green to greenish gray shale well cuttings, and sample descriptions of wells for which no samples were available for this study (Fig. 76, 77 and 62). The exact correlation of the Tranquitas, Paraná and Chaco formations in the Carmen-1 well was not possible because of the lack of samples and detailed lithologic descriptions (Fig. 72).

In the Palo Santo-1 well, two samples at 315 meters and shallower contain abundant small Compositae pollen and a significant percentage of Graminae pollen, suggesting a Pliocene age (Fig. 76). The remainder of the interval, down to 1,709 meters, was dated as Pliocene-Miocene based on abundant Malvaceae and Chenopodiaceae-Amaranthaceae pollen; Tricolporites sp. Gymnosperm pollen is also common in the interval. The microplankton scattered in that interval consists of Cleistosphaeridium sp. 465-1,523 meters; the freshwater algae Pediastrum sp. 1,036-1,709 meters; dinoflagellates (genera and species undetermined) 1,163-1,637 meters; and microforaminifera 1,178-1,412 meters. The presence of dinoflagellates and microforaminifera from 465 to 1,637 meters, in association with the other palynomorphs, suggest a neritic or maybe a lagoonal environment (Millioud, 1975).

The study area appears to be a coalescing area of the Tranquitas and Chaco formations (Fig. 76). The fossil evidence from Palo Santo-1 suggests a transition of environments comprising an ingression and regression of a body of water with marine influence, as indicated by the presence of the acritarch Cleistosphaeridium, dinoflagellates and microforaminifers. Observation of well cutting samples of the Palo Santo-1 well, indicates that sediments of the Tranquitas Formation are distinguishable from the Chaco Formation sediments only by the reddish brown color, as opposed to the light brown color of the Chaco Formation. In Berta-1, towards the northern flank of the Pirizal Subbasin, both formations are reddish brown, as observed in well cuttings, and are no longer distinguishable from each other. The extent of the penetration of the Paranense Sea in the study area is shown in Figure 62.

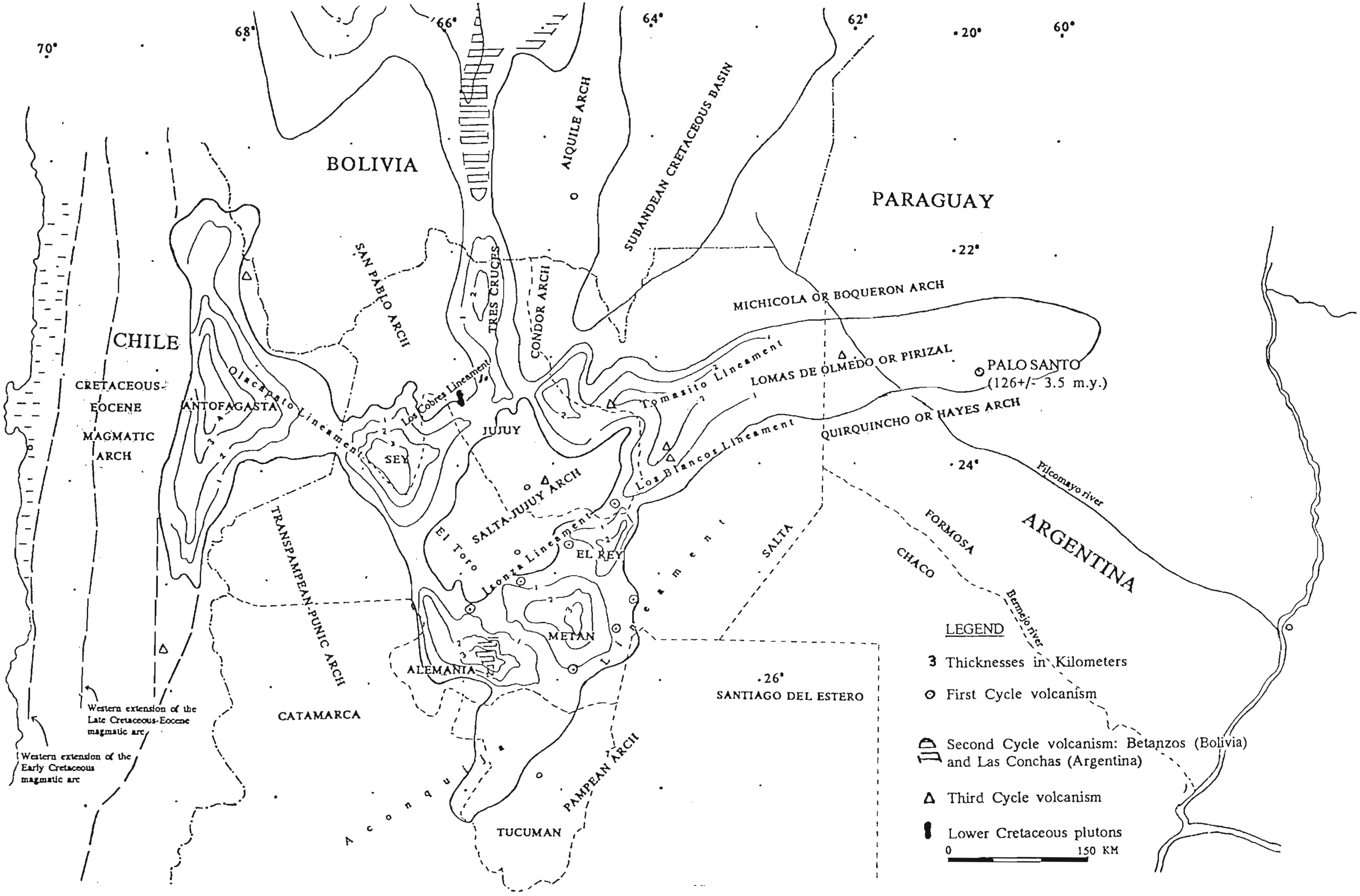


Fig. 56. Location map of the Northwest or Orán Basin. Its subbasins are the Alemanía, Metán, El Rey, Lomas de Olmedo (with its extension into Paraguay, Pirizal or Pirity Subbasin), Tres Cruces, Sey and Antofagasta (modified from Salfity and Marquillas, 1986).

FOSSILIFEROUS AND RADIOMETRIC DATA AND CORRELATIONS OF THE SALTA GROUP

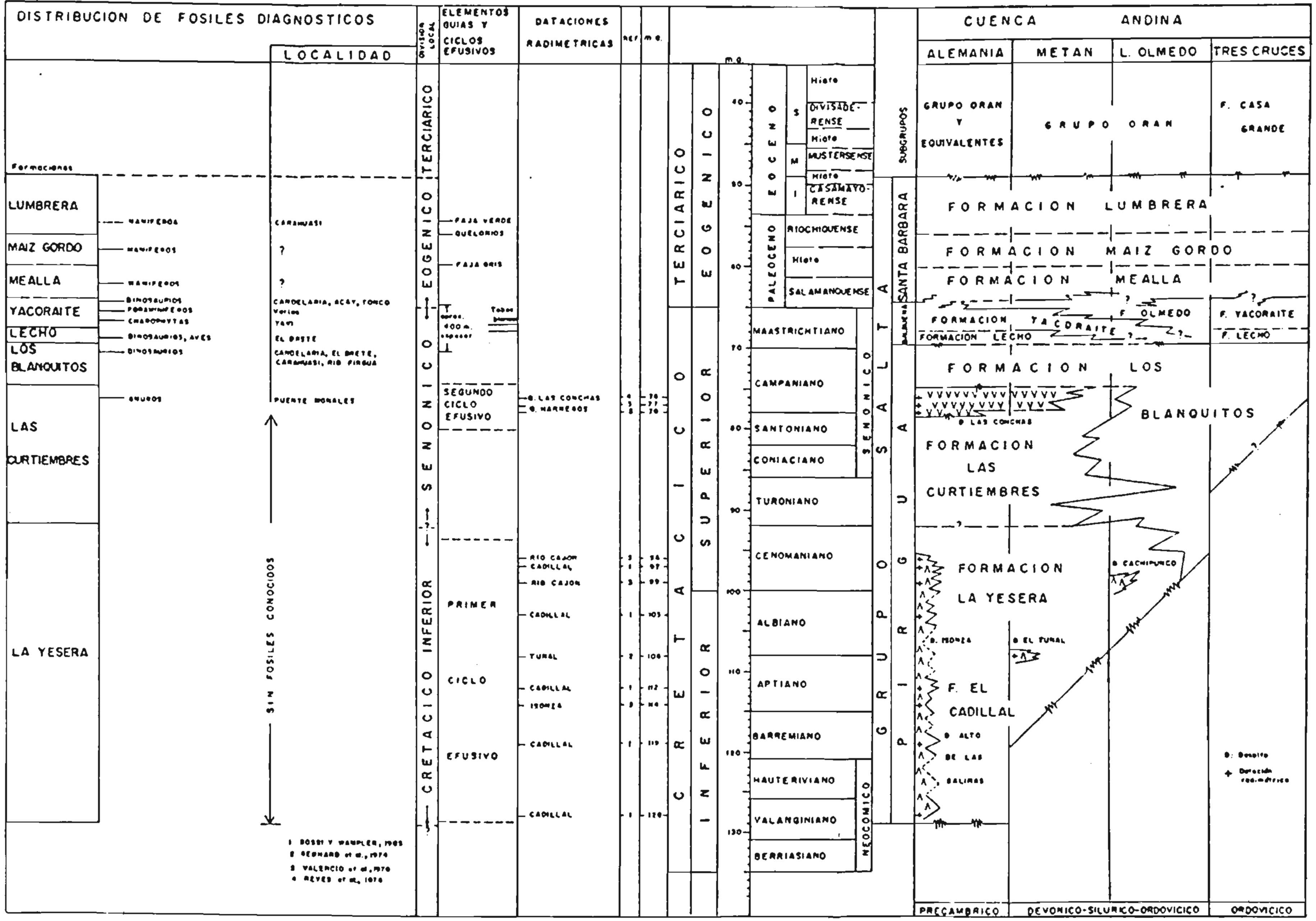


Fig. 57. Correlation chart of the Northwest or Orán Basin in Argentina, including fossiliferous and radiometric evidence of the Salta Group (Salfity, 1980).

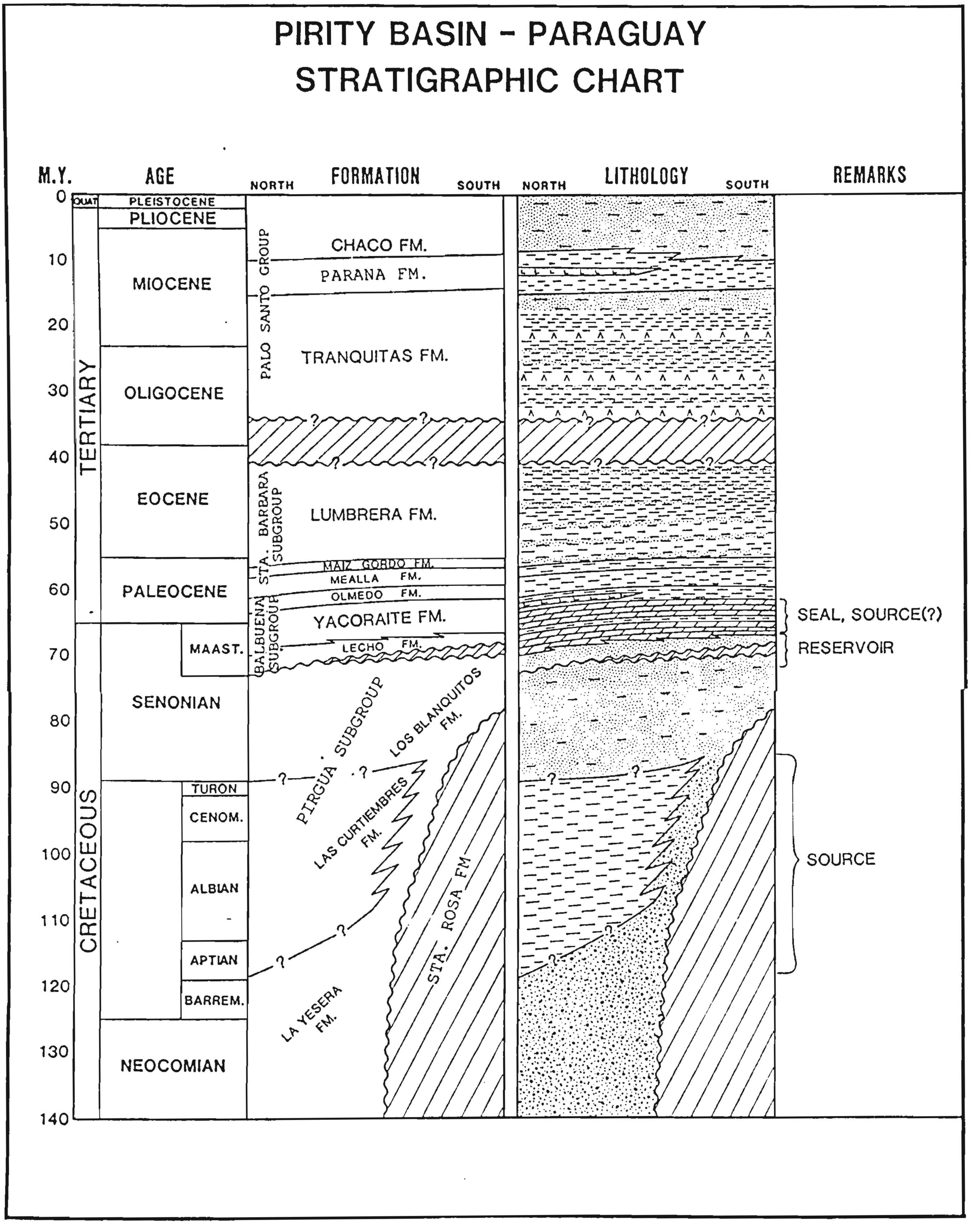


Fig. 58. Stratigraphic correlation chart of the Pirizal or Pirity Subbasin in Paraguay (modified from Carmen-1 final drilling report, Occidental, 1986).

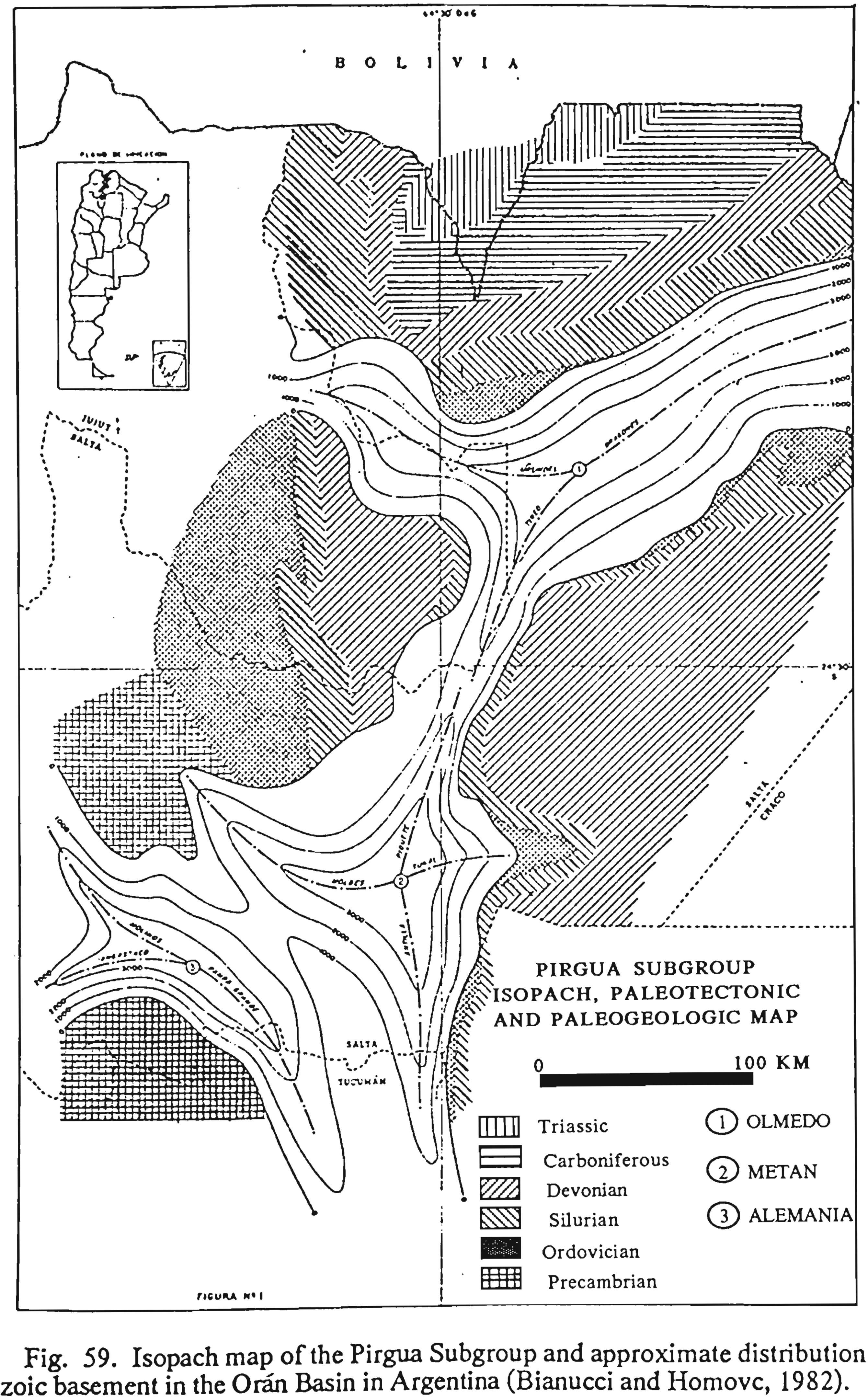


Fig. 59. Isopach map of the Pirgua Subgroup and approximate distribution of the Paleozoic basement in the Orán Basin in Argentina (Bianucci and Homovc, 1982).

Fig. 60. Segment of the N-S seismic line Oxy 86-166.5 showing the structural control of the distribution of the Pirgua Subgroup by the deep Balbuena fault, which establishes the northern Pirgua basin border. Note the thick wedge-shaped accummulation of the Pirgua Subgroup along the Balbuena growth fault. Also, note the preservation of a thick Paleozoic section in the deepest part of the basin, to the right of the Balbuena Fault, and the total absence of it due to erosion to the left of the fault. Top of Pirgua Subgroup (brown), Lecho Formation (yellow), Yacoraite Formation (green), Olmedo Formation (red), near top Maiz Gordo Formation (orange), top Lumbrera Formation (yellow), top Tranquitas Formation (blue), Chaco marker -a regional seismic marker- near the top of the Paraná Formation (pink), unconformity (U). Vertical scale in seconds See Fig. 34 for location of seismic line.

Fig. 61. Southern segment of the N-S seismic line Oxy 86-154 showing the structural control of the distribution of the Pirgua Subgroup by faults in the southern flank of the Pirizal Subbasin. Unconformity (U). Vertical scale in seconds. See Fig. 34 for location of seismic line.

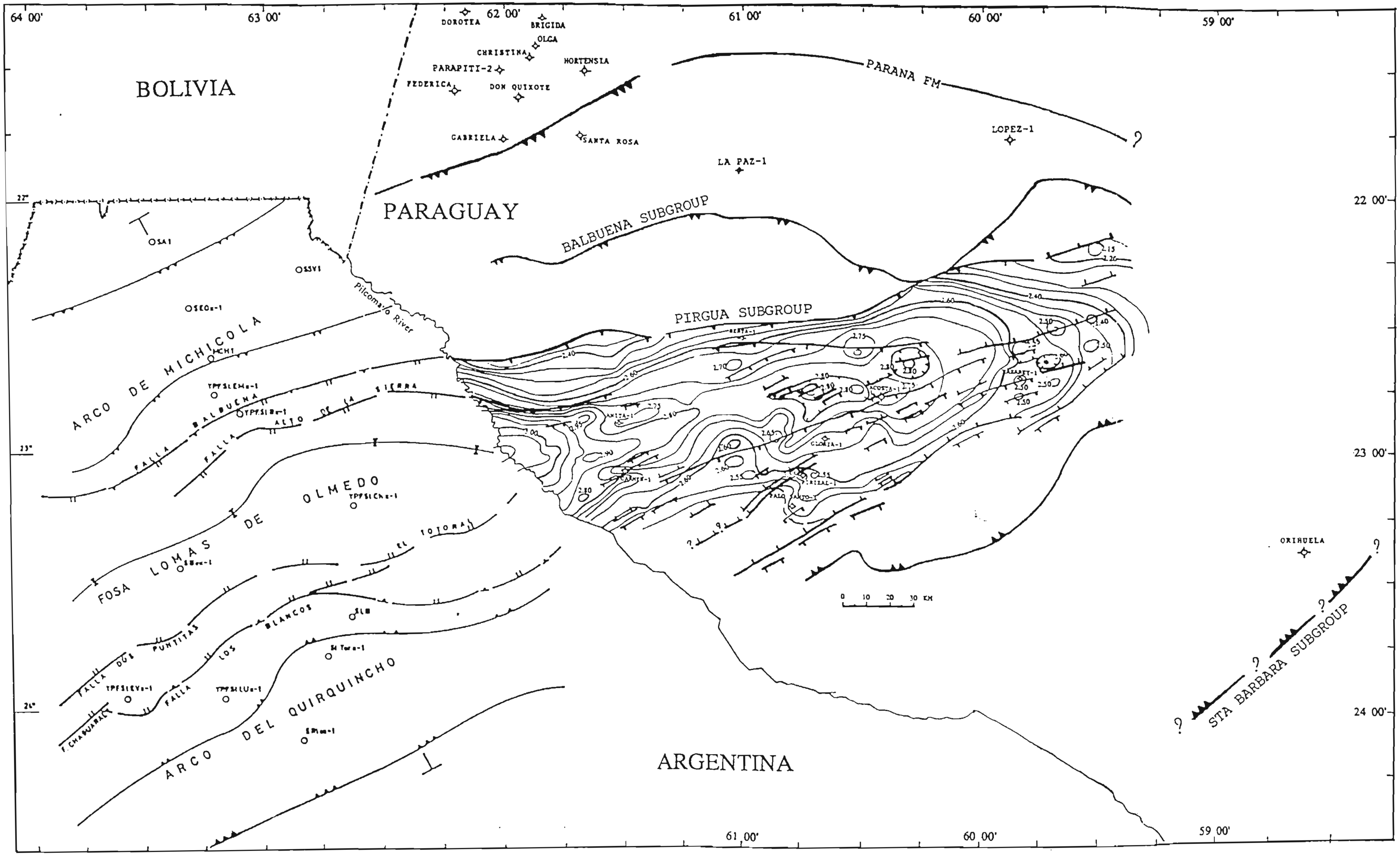


Fig. 62. Composite paleotectonic and paleogeographic map of the Salta Group, and extent of penetration of the Miocene Paraná Formation in the Lomas de Olmedo or Pirizal Subbasin in Paraguay and NW Argentina with isopach map of the Pirgua Subgroup in Paraguay. Note the fault control of the Pirgua basin. The Argentinian section is from Bianucci and Homovc (1981), and the Paraguayan side corresponds to this study. Values are in seconds.

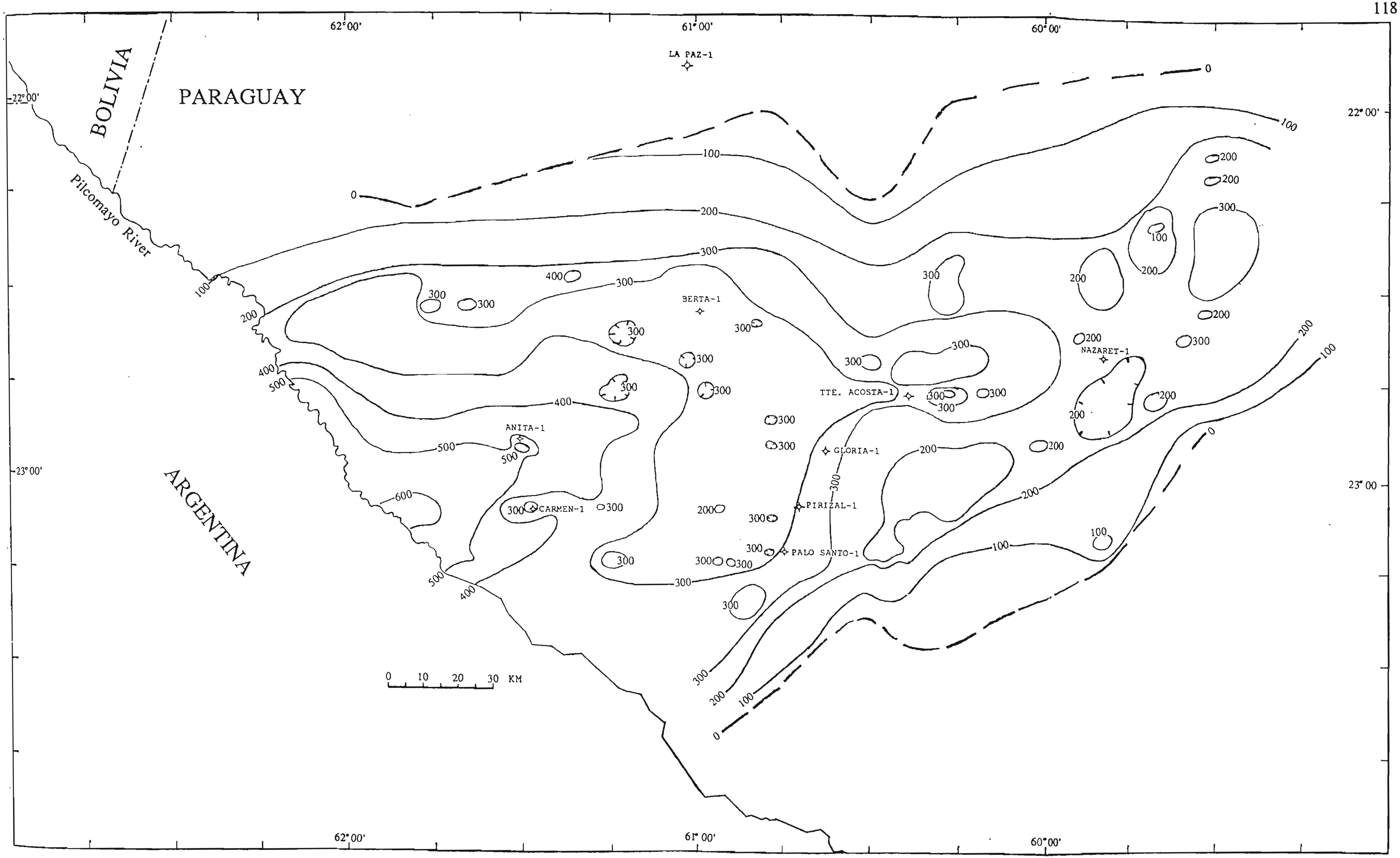


Fig. 63. Isopach map of the Balbuena Subgroup (Lecho, Yacoraite and Olmedo formations). Values are in meters, and were calculated from velocities of the Carmen-1 well. See Fig. 34 for location of seismic lines.

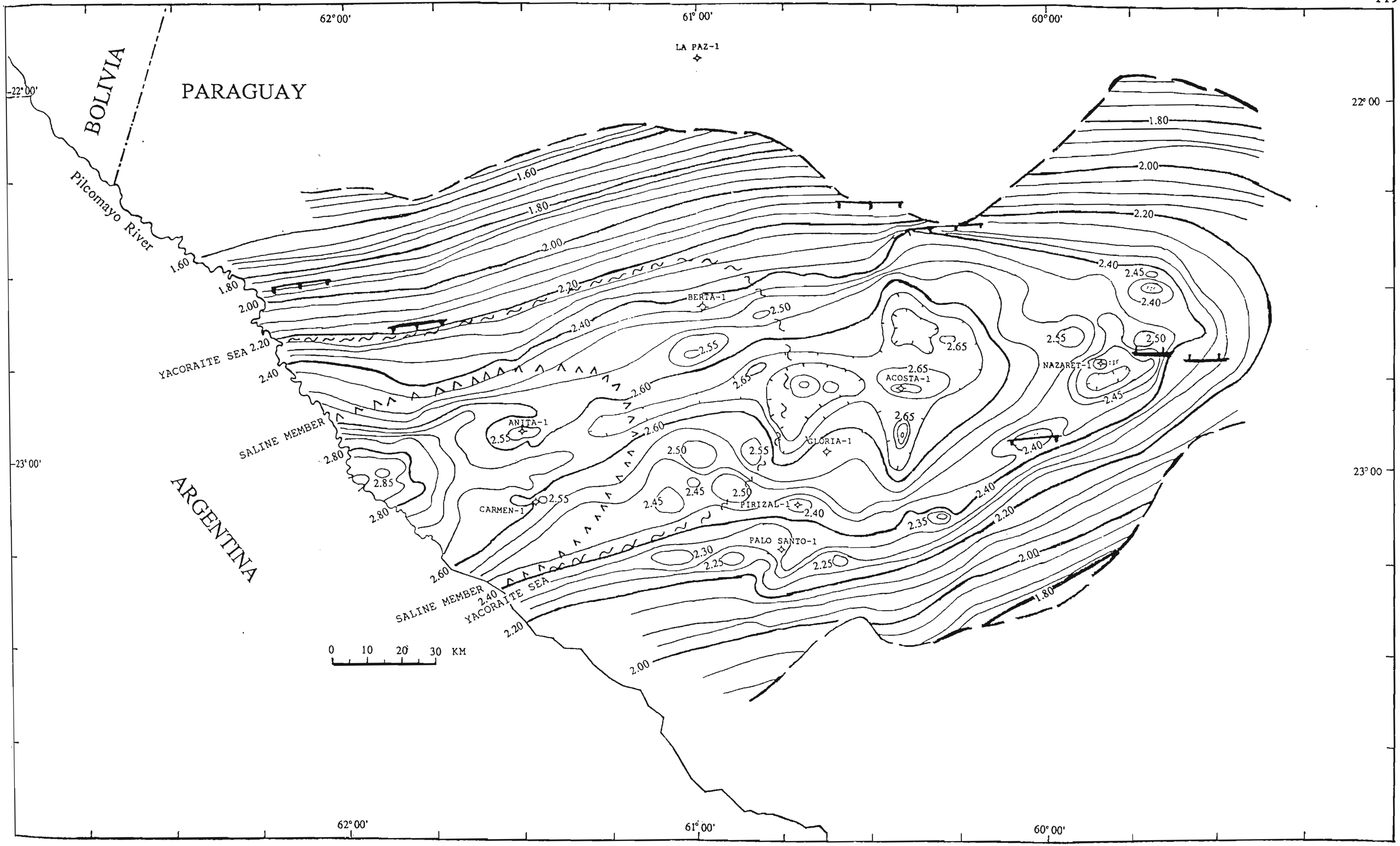


Fig. 64. Time contours of the top of the Balbuena Subgroup (top of Olmedo Formation). Note distribution of the Olmedo Saline Member, and penetration of Yacoraite Sea. Values are in seconds. See Fig. 34 for location of seismic lines.

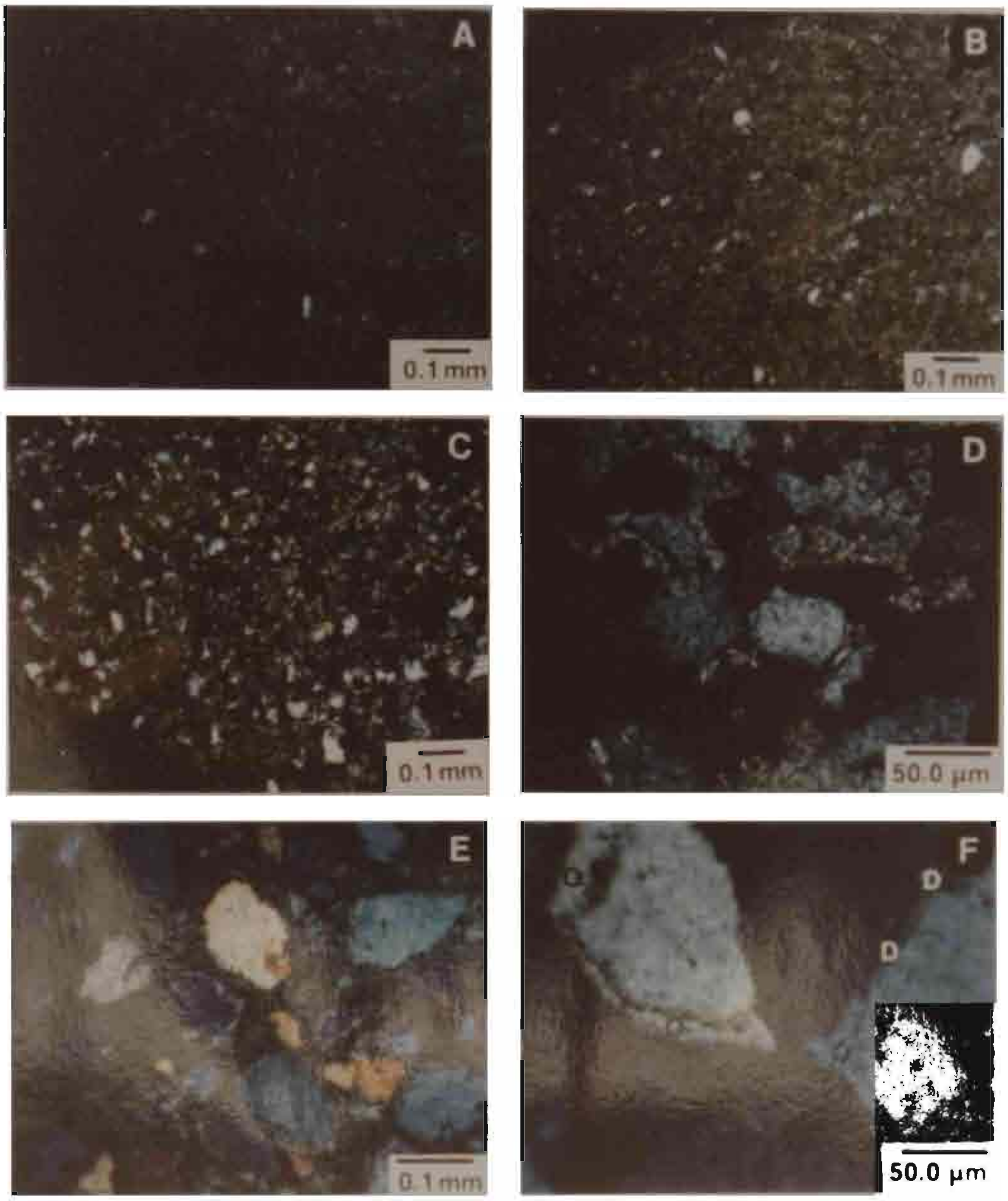


Fig. 65. Thin sections of cuttings of Yacoraite (A-D) and Lecho (E-F) formations of the Carmen-1 well. (A) Mudstone. (B) Siltstone with some fine grained quartz and feldspar grains. (C) Fine grained feldspathic micaceous sandstone with dolomite cement. (D) Quartz grains cemented with quartz overgrowths and dolomite cement. All with crossed nicols. A,B,C: 3,777-3,780 m; D: 3,870-3,873 m. E-F taken with crossed nicols and gypsum plate. (E) Dolomite cemented sandstone (3,990-3,993 m). (F) Quartz grains tightly cemented with quartz overgrowths (O) and some dolomite cement (D) (3,978-3,981 m). From Saller (1986).

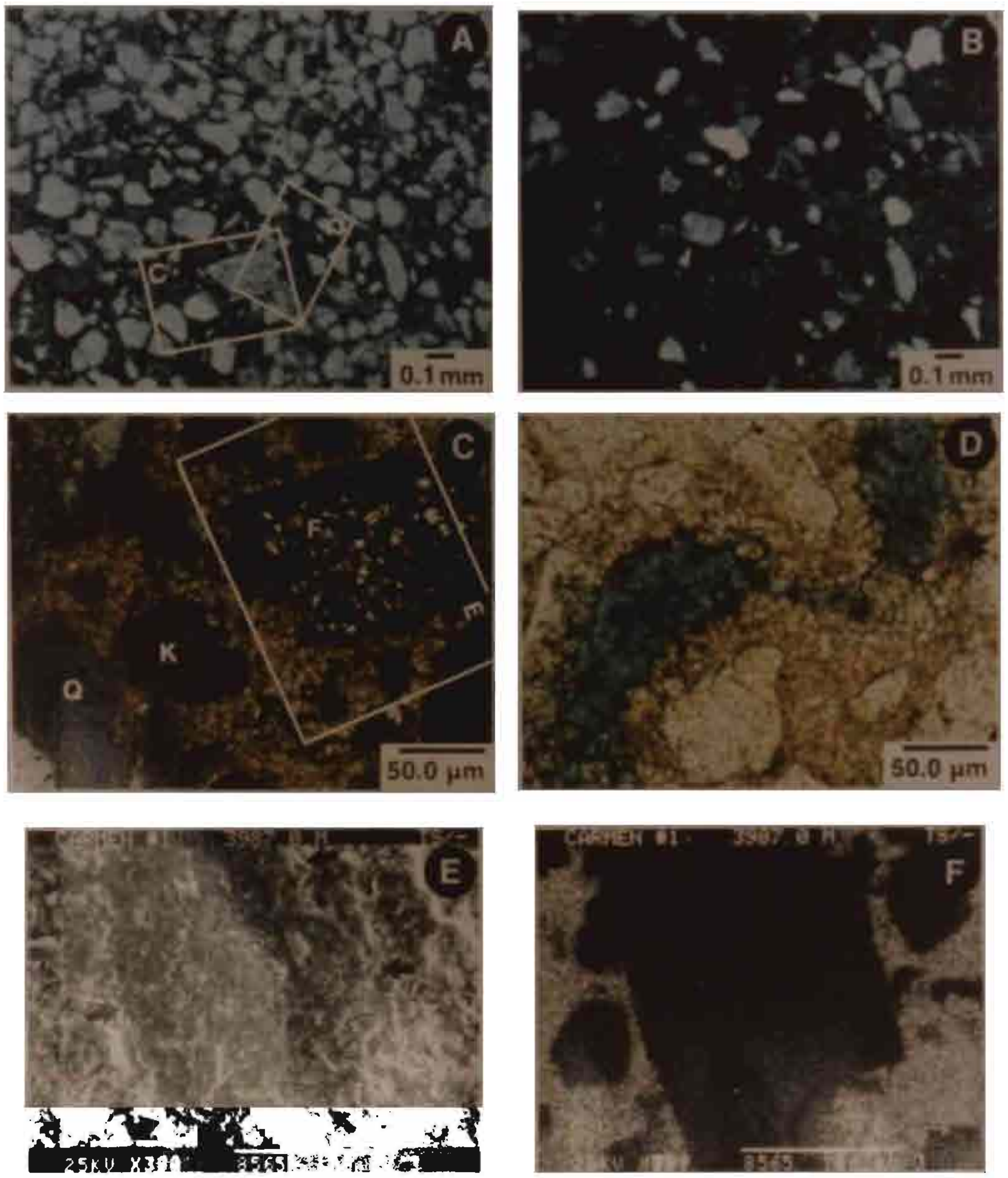


Fig. 66. Sidewall core of the Lecho Formation, Carmen-1, (3,987 m). (A) Dolomite- and quartz-cemented feldspathic sandstone. (B) Same view as A, but with crossed nicols. (C) Quartz (Q), potassium feldspar (K), and Na- and K-feldspar with muscovite inclusions (F). Cement is dolomite. (D) Dolomite rhombs (arrows) projecting into pore space (blue). (E) SEM view of portion of alkali feldspar grain shown in C. Edge of grain is indicated by arrows. (F) Calcium "dot map" around feldspar shown in E shows location of dolomite cement between grains. (Eslinger, 1986)

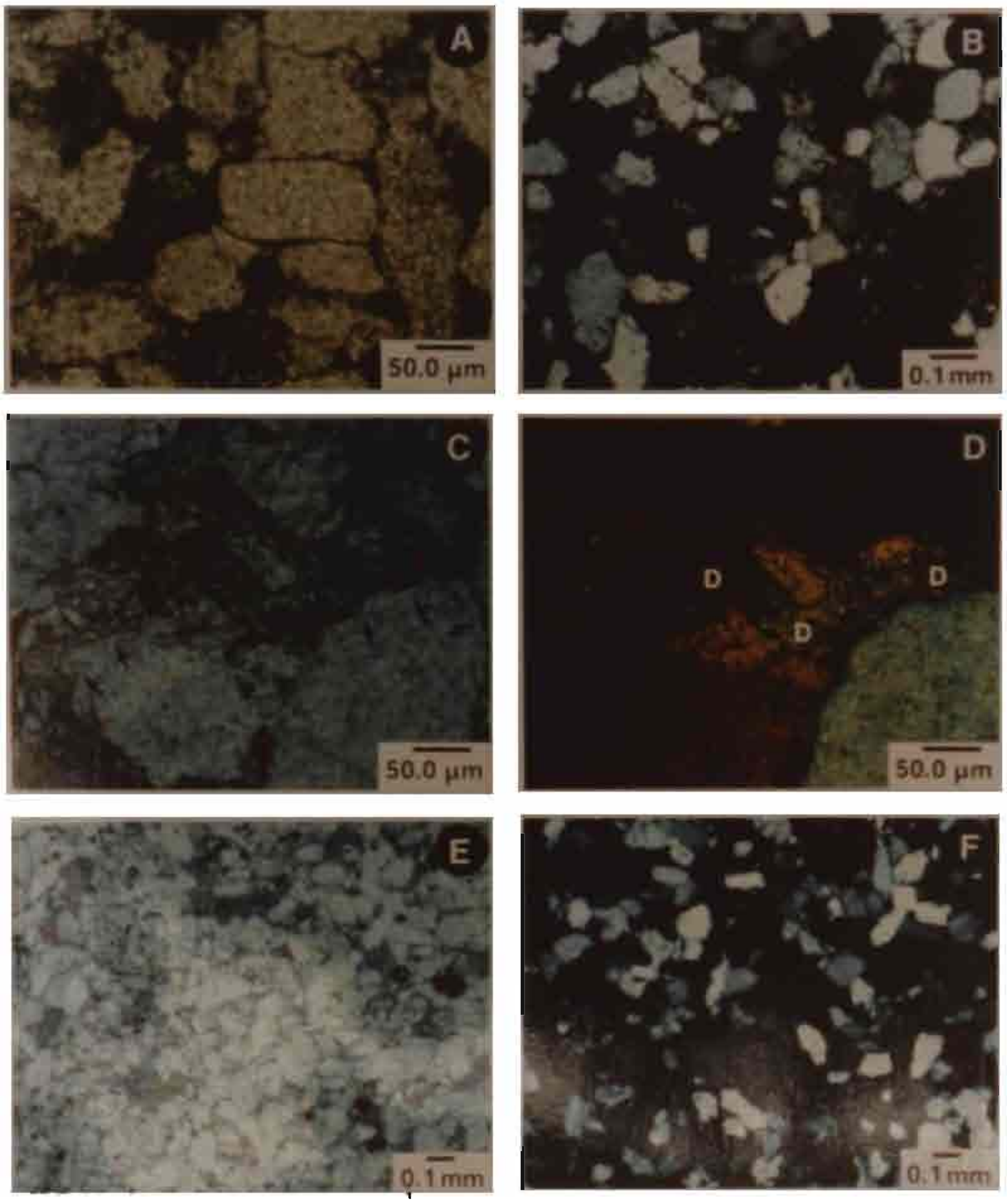


Fig. 67. Photomicrographs of sidewall cores of the Lecho Formation, Carmen-1. (A) Note pore spaces (blue) and quartz overgrowths (3,939 m). (B) Arkose cemented by dolomite. Crossed nicols (3,939 m). (C and D) Same views: D with crossed nicols and gypsum plate. Note quartz overgrowths in C indicated by arrows. The four to five orange grains shown in the center of D are remnants of a single plagioclase grain that has been partially replaced by dolomite (D) (3,943.4 m). (E and F) Same views. Blue in E is porosity. View in F is with crossed nicols (3,956 m). (Eslinger, 1986).

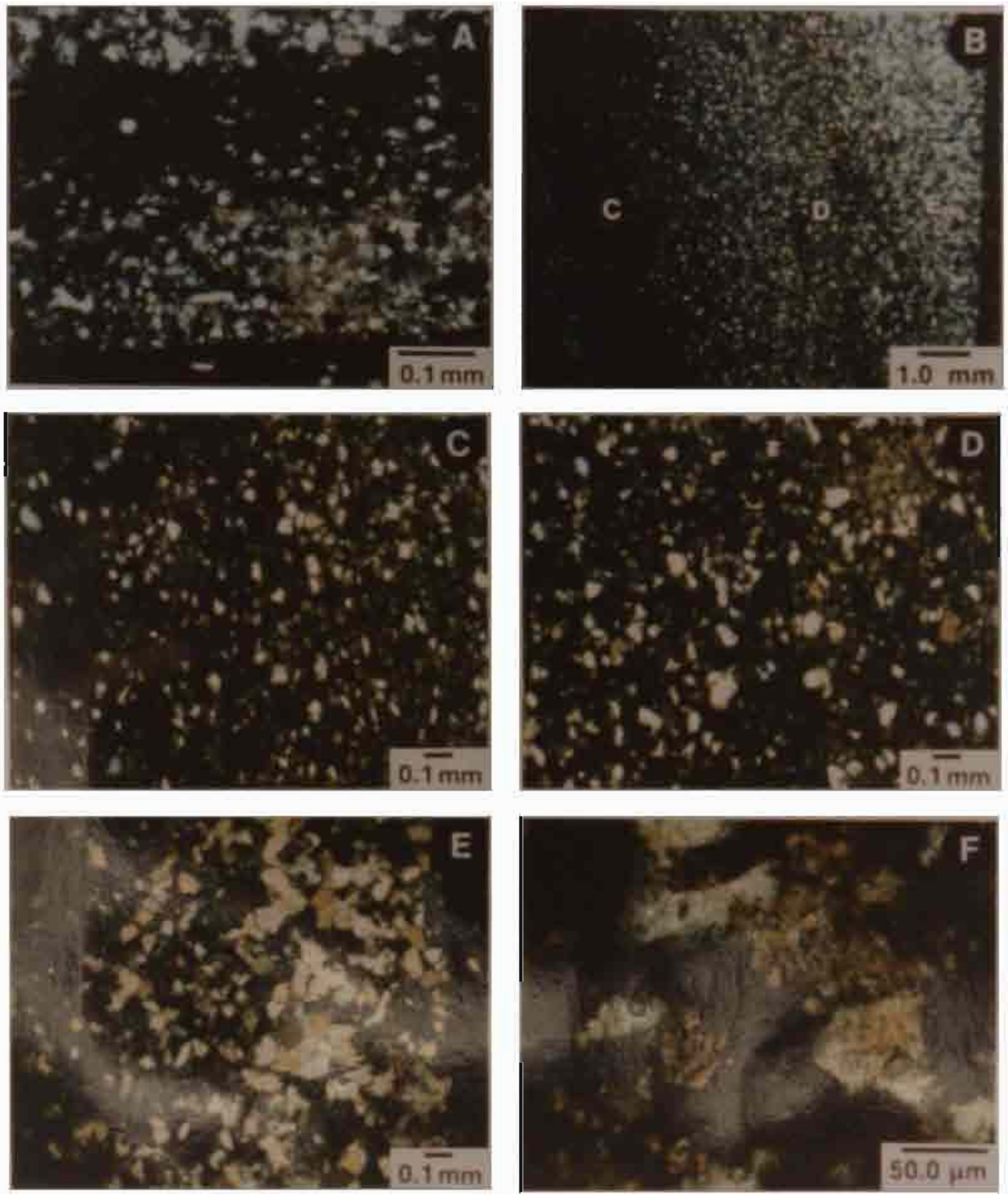


Fig. 68. Photomicrographs of cores of the Yacoraite Formation, Carmen-1, 3,804.85 m. (A) Sequence of micro-graded beds. Grains of quartz and feldspar are cemented by dolomite (tan). Up-section is towards top of photograph. (B) A thicker graded section than in A. Up-section is towards left. (C, D and E) Three views taken at the same magnification, at the positions marked 'C', 'D' and 'E' in B. Up-section is to the left in each photograph. (F) Dolomite rhombs (D) as cement and quartz grains (Q). (Eslinger, 1986).

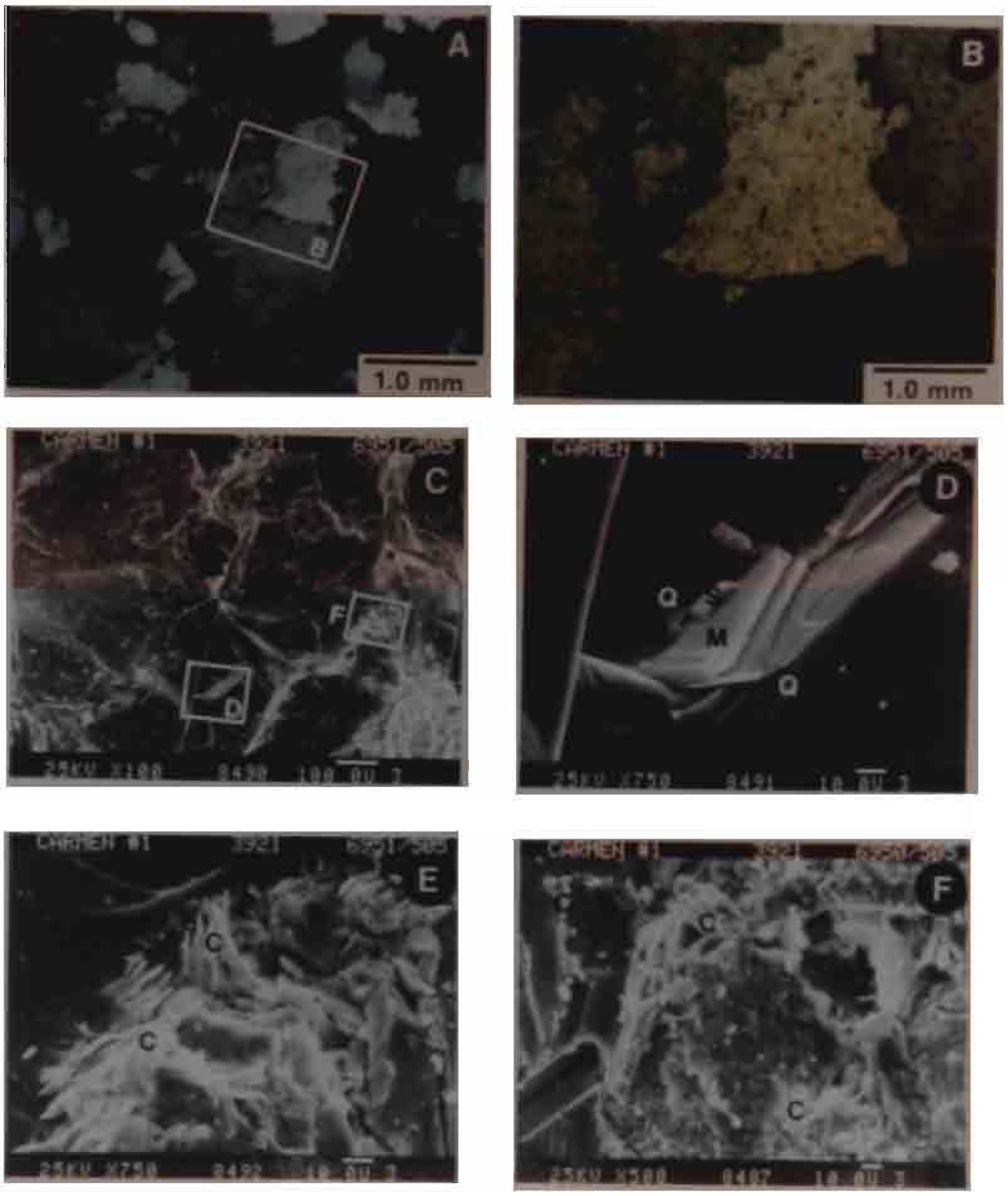


Fig. 69. Photomicrograph of a sidewall core showing a quartzarenite of the Yacoraite Formation, Carmen-1, 3921 m. A) Note interlocking, sutured contacts between quartz grains. Nearly all grains are quartz. Clay (illite?) and some large mica grains are about the only other minerals identified. This sample is anomalous compared with the other samples. Crossed nicols. B) Enlargement of center of A. Crossed nicols. C) SEM micrograph. Note tight suturing (arrows) between grains caused by merged quartz overgrowths. D) Mica (M) and siderite (S) engulfed among quartz overgrowths (Q). E) Illitic clay (C) occurs among quartz overgrowths. F) Note small amount of illitic clay (C), some occurring between quartz overgrowths. (Eslinger, 1986).

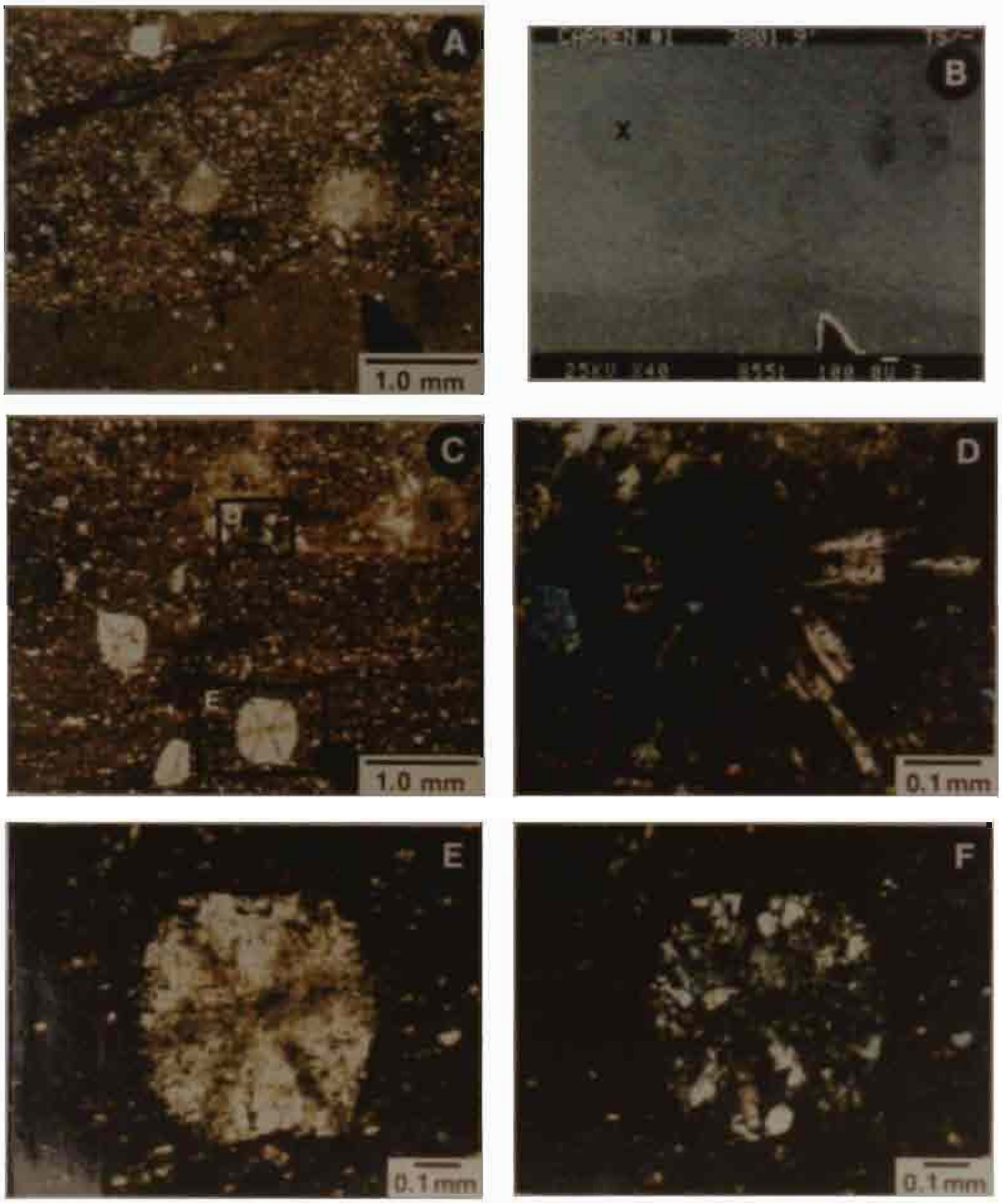


Fig. 70. Photomicrographs of a core of an arkose of the Yacoraite Formation, Carmen-1, 3,801.9 m. (A) Massive mudstone in the lower third of the micrograph is separated by a stylolite from a siltstone above. B) SEM micrograph of A. The feature marked (X) is composed mostly of Fe-rich dolomite (ankerite?) and magnesite-siderite, plus some quartz, mica and feldspar. The siltstone matrix is mostly silicates and some dolomite. The mudstone below is mostly dolomite and some silicates, mostly quartz. C) Siltstone. Features marked (X) correspond to the one described in B; feature (D) is enlarged in D), and consists of magnesite-siderite (small arrows) and small crystals of barite (through EDX). Feature (E) is believed to be organic; it is enlarged in E and F; it has flat top and bottom; its six dark rays are dolomite-rich, and the areas in between have some quartz intergrown. (Eslinger, 1986).

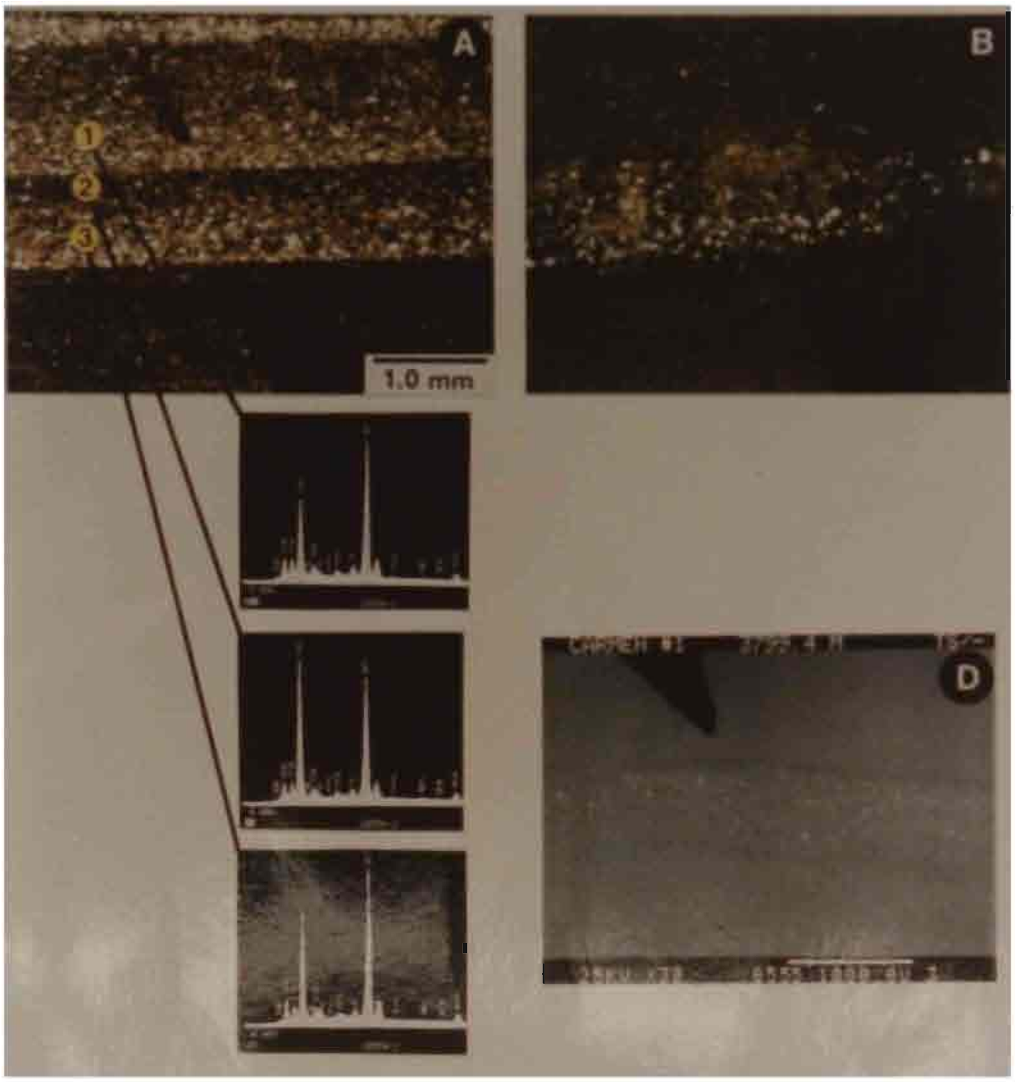


Fig. 71. Core of the Yacoraite Formation, Carmen-1, 3,796.8 meters. (A) Photomicrograph of graded beds. EDX spectra 1, 2 and 3 indicate how the Ca/Si (dolomite/quartz) ratio varies with position in a graded bed. The Ca/Si ratios are higher in the coarser grained areas. (B) Photomicrograph of a poorly developed lens-shaped graded bed. EDX analysis of spots within the lens contain quartz, K-feldspar, magnesite-siderite, zircon, and rutile. The mudstone matrix surrounding the lens is mostly dolomite. (D) Backscatter SEM view of same view in B. Bright spots are zircon and rutile grains. (Eslinger, 1986).

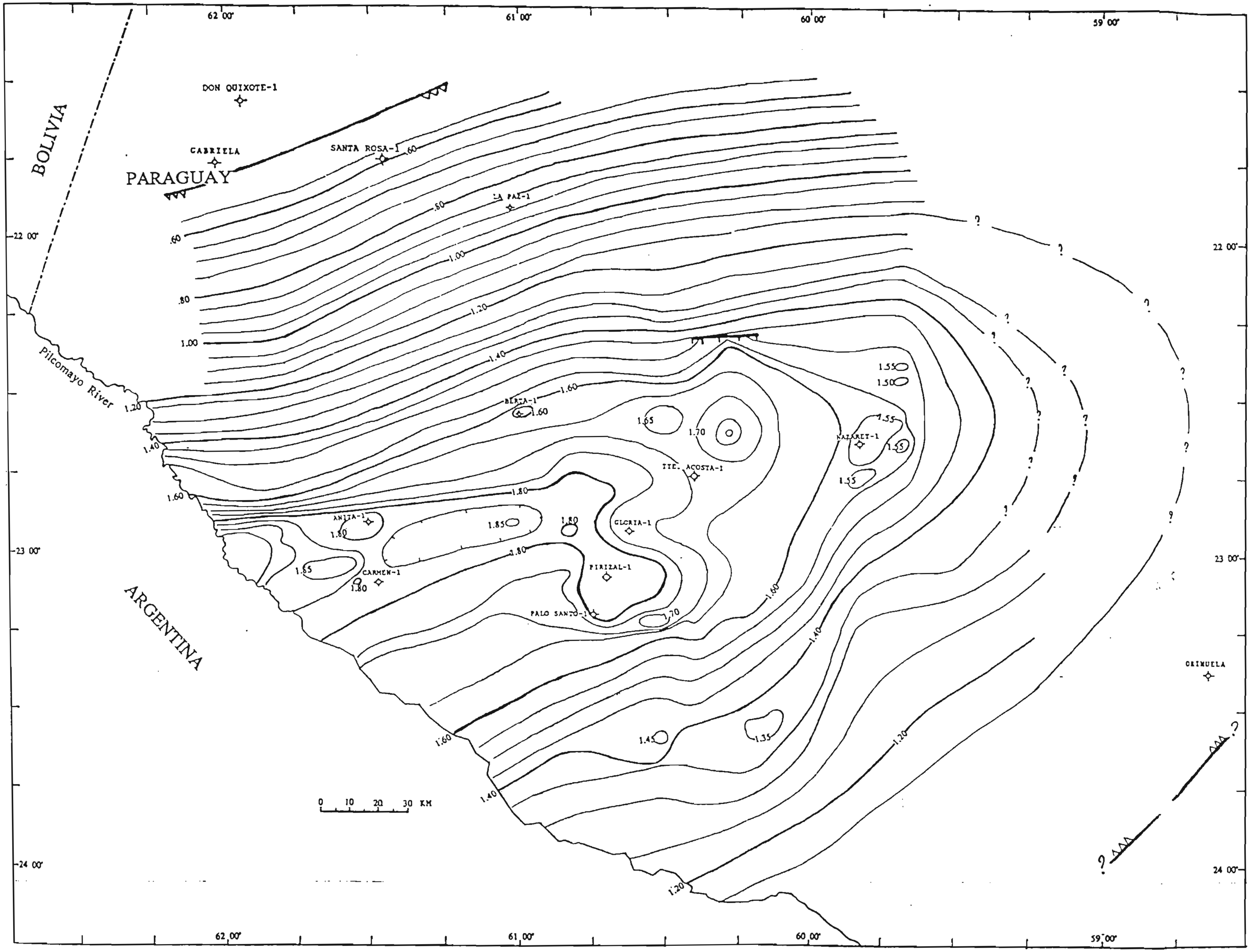


Fig. 73. Paleotopography of the top of the Lumbrera Formation (top of Santa Bárbara Subgroup). Values are in seconds.

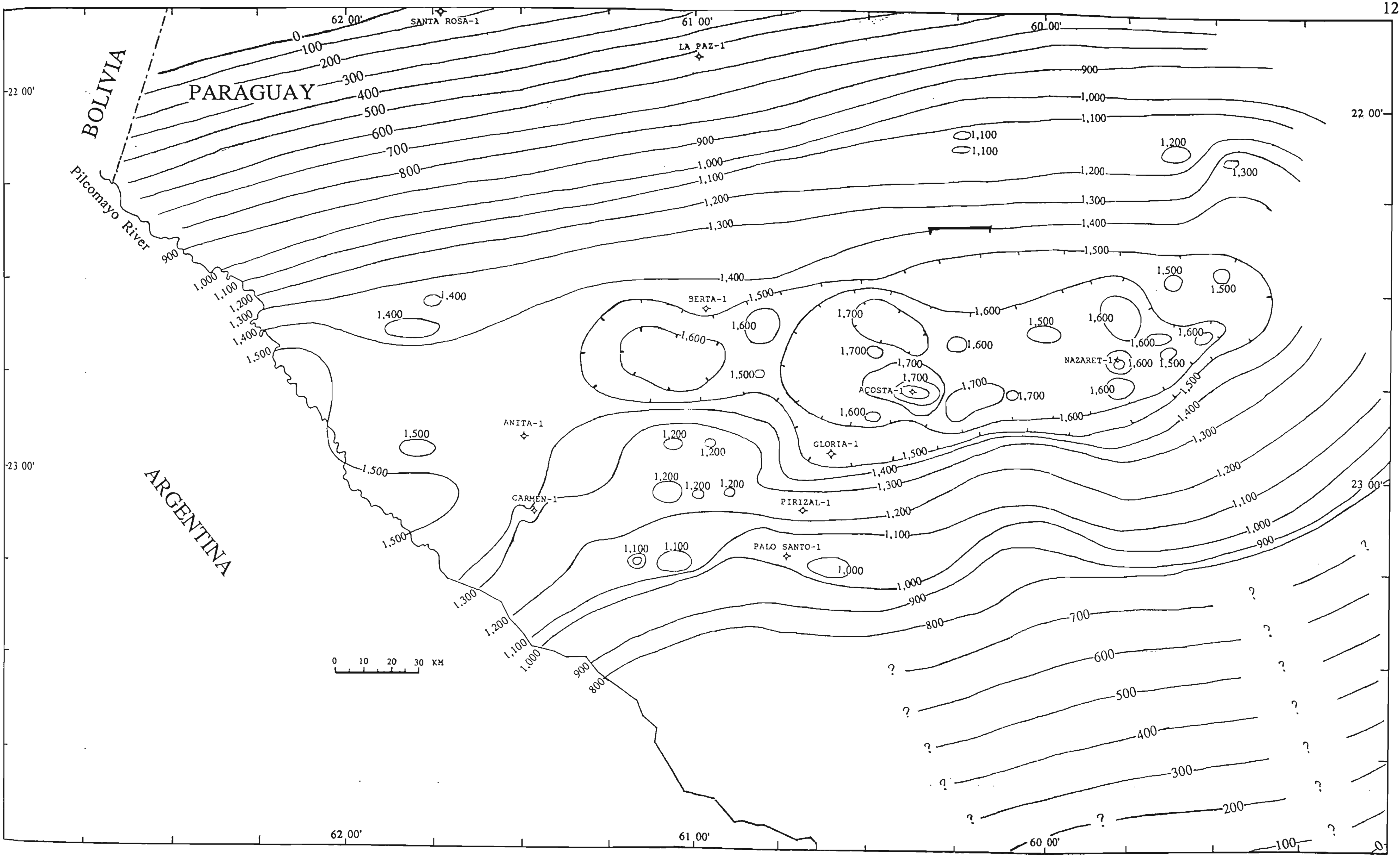


Fig. 74. Isopach map of the Santa Bárbara Subgroup. Values are in meters. Note the thicker section towards the east, where a local depocenter developed. The Balbuena Fault continued to be active during the deposition of this subgroup. See Fig. 34 for location of seismic lines.

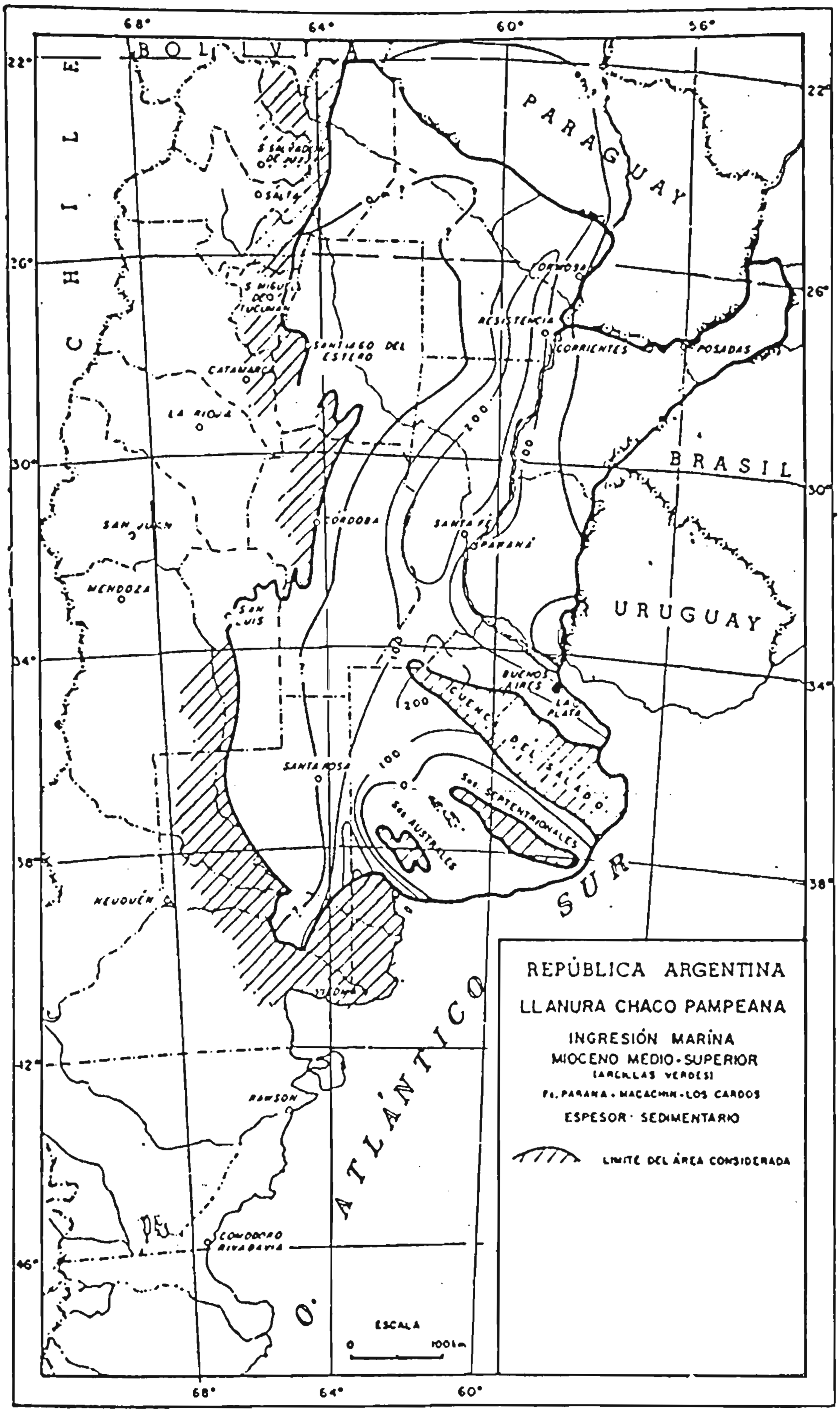


Fig. 75. Atlantic marine transgression during Middle-Late Miocene. Modified from Russo and others (1980).

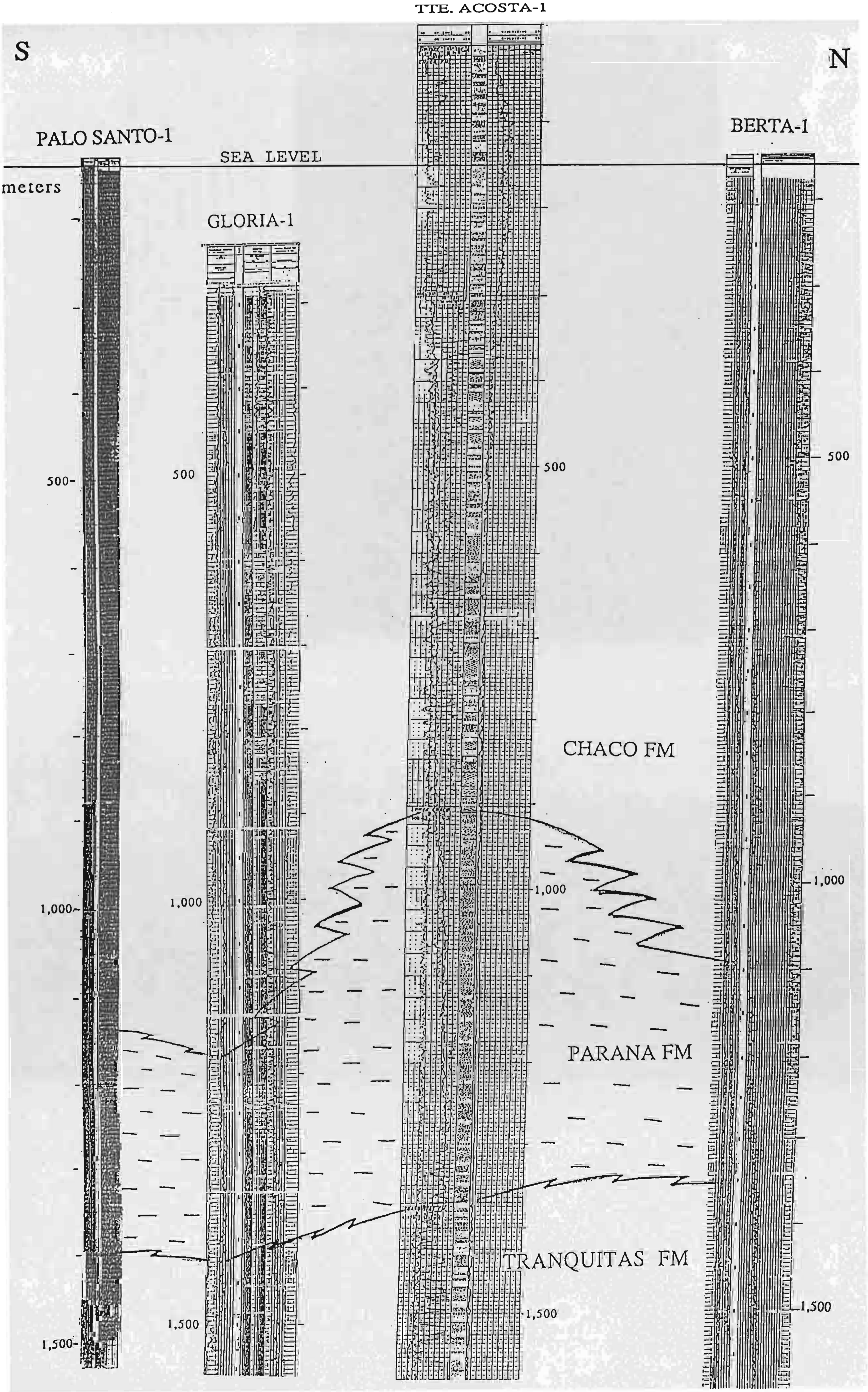


Fig. 77. N-S cross section of the Pirizal Subbasin showing the distribution of the green shales of the Paraná Formation.

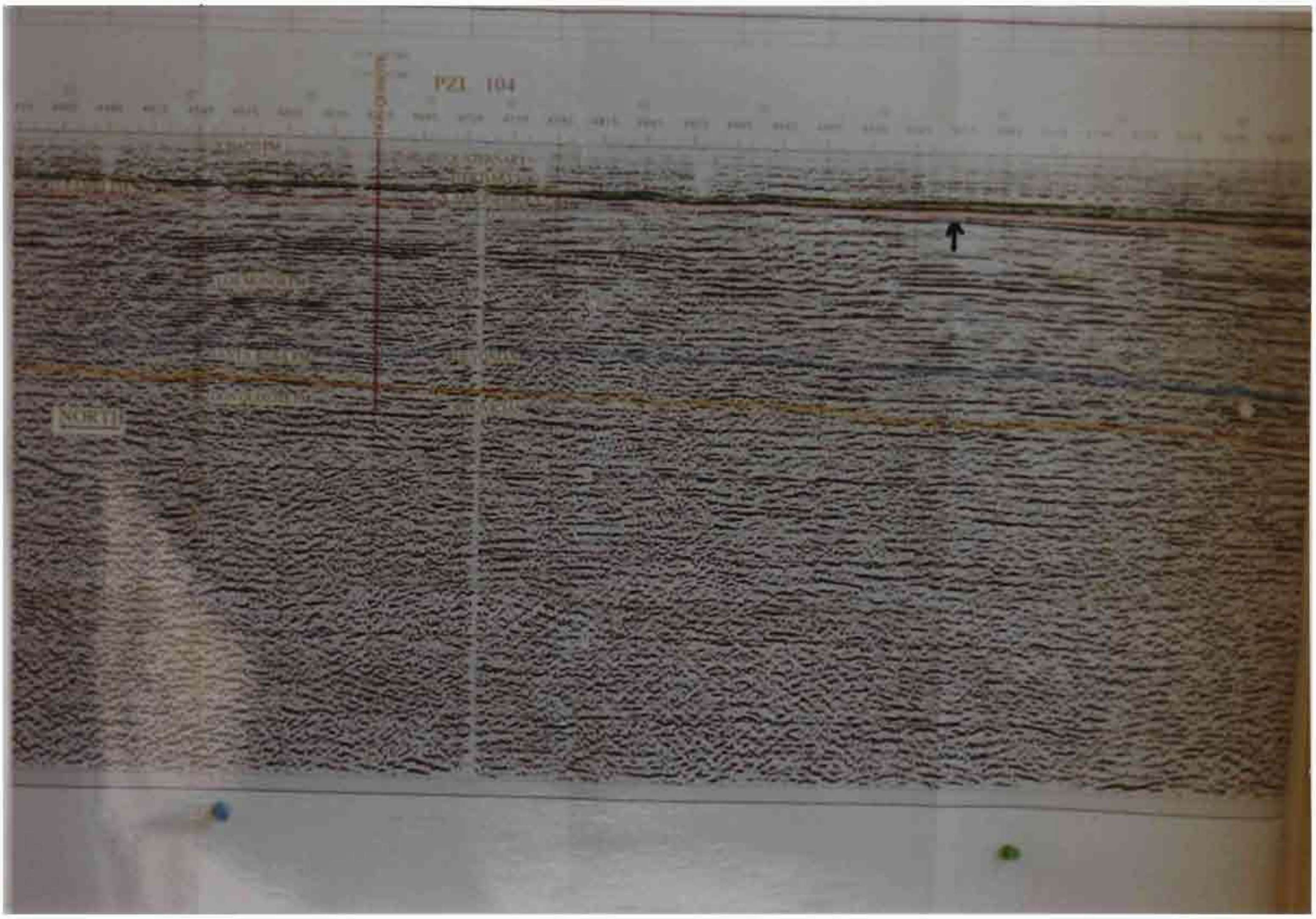
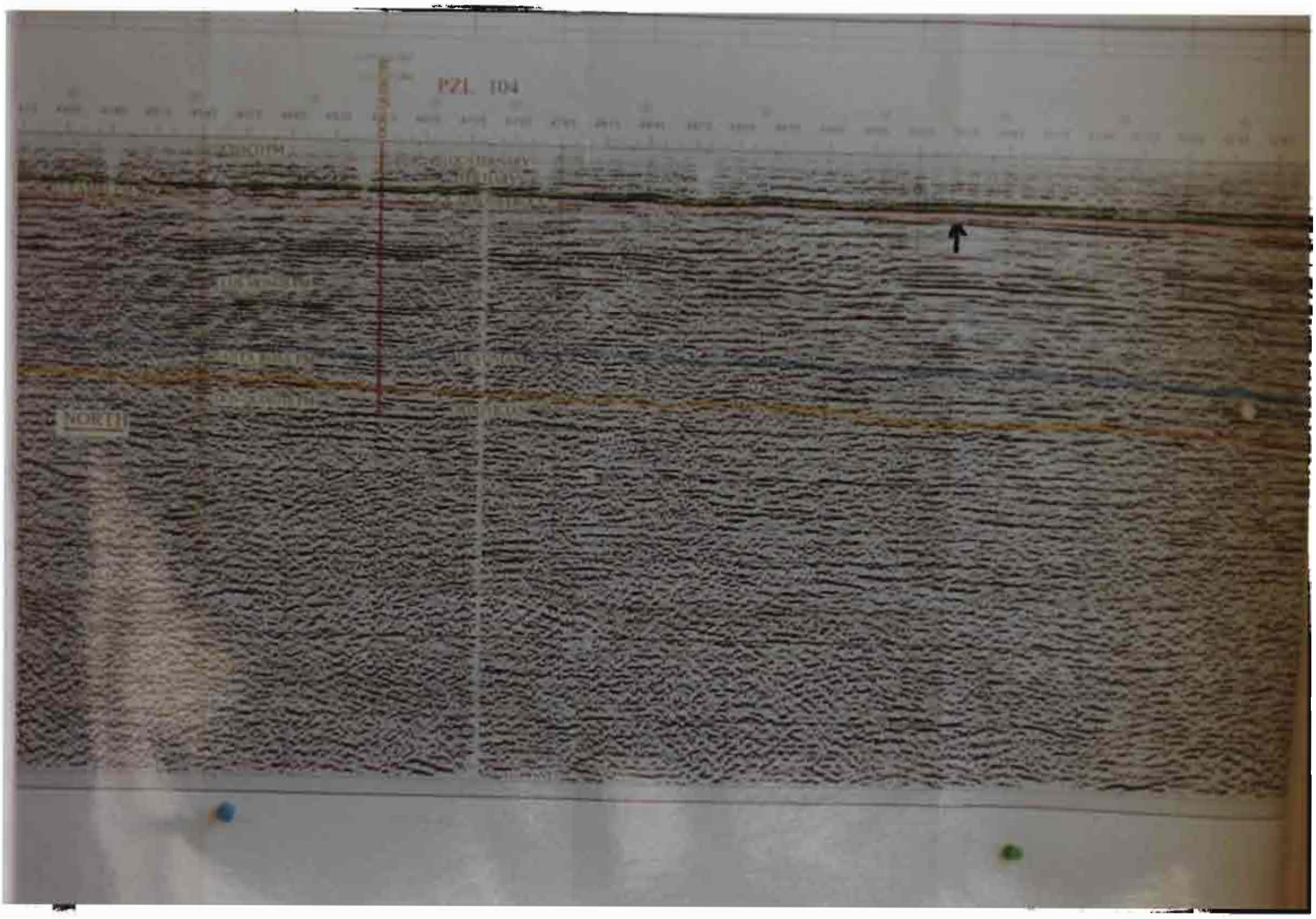


Fig. 78. Photograph of the reprocessed 2-fold stack seismic line Pennzoil 104 of the Carandaity Subbasin through well Don Quixote-1. Formation tops are brown (Don Quixote Formation; Upper Ordovician), blue (Santa Rosa Formation; Lower Devonian), pink (Los Monos Formation; Lower to Upper Devonian), and green (Tupambi Formation; Mississippian). The contact between the Los Monos marine shales and Tupambi transitional sands is erosional in this area (arrow). This angular unconformity is more pronounced towards the margins of the Carandaity Subbasin, but is absent in the deeper parts of the subbasin. The contact between the Tupambi and Chaco formations is also unconformable. Vertical scale is in seconds. See Fig. 34 for location of seismic line.



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CHAPTER IV

TECTONIC EVOLUTION OF THE PARAGUAYAN CHACO

The tectonic history of the Paraguayan Chaco can be divided, based on its tectonic characteristics, into Paleozoic Cretaceous and Cenozoic events. The Paleozoic events defined the structural frameworks of the Carandaity and Curupaity subbasins; the Cretaceous events formed the Pirizal Subbasin, and the Cenozoic events placed the Paraguayan Chaco in a foreland setting.

Paleozoic Events

Evidence in the Paleozoic sedimentary package indicate diastrophic events during the Devonian, Carboniferous, and Late Permian. An additional diastrophic event may have been recorded at the base of the Silurian.

During most of the Paleozoic the Paraguayan Chaco was part of a tectonically relatively stable shallow marine to continental platform that extended along the western margin of the Brazilian Shield. The Cambrian Itapucumí carbonate and clastic sequence (Fig. 10) is exposed around the Apa High in Eastern Paraguay and in isolated outcrops on the western margin of the Paraguay River around Puerto Casado. The Itapucumí sequence represents a shallow marine environment of deposition. The ensuing Paleozoic sequence in the Paraguayan Chaco is comprised of clastic sediments.

The absence of the Late Ordovician sequence in the Parapití-1 well (palynological evidence; Gilbert Boyd, 1988, oral communication) --as opposed to a complete Ordovician sequence in the Don Quixote-1 well (Urban, 1972)-- suggests the possibility of an erosional event or hiatus at the base of the Silurian deposits in the eastern part of the Carandaity Subbasin. Unfortunately, no seismic sections of the Parapití-1 area were available for this study, and geophysical log responses do not indicate any major change in response at the Ordovician-Silurian contact (Fig. 13).

Russo et al. (1980) report a regional unconformity in the Chaco-Paraná Basin at the base of the Silurian sequence, corresponding to the base of the Zapla Tillites of Llandoverian-Wenlockian age (Lobo, 1976). In Bolivia the base of the Silurian is also marked by a regional unconformity at the base of the Cancañiri Formation (Chamot, in Branisa et al., 1972) dated palynologically as Llandoverian to Wenlockian age (Lobo et al., 1976).

The Pecten well Asunción-1, located in the San Pedro Trough in Eastern Paraguay (Figs. 1 and 3), penetrated Middle to Late Ordovician (and possibly Early Ordovician) sandstones (Asunción-1 final composite log, 1982). The overlying sediments are sandstones of Early Silurian age, suggesting continuous deposition from Ordovician to Silurian times.

An unconformity was inferred within the Devonian sequence in the López-1 well (Figs. 12, 13 and 40), as interpreted herein from descriptions of well cores made by Harris (1959). The contact between the marine Santa Rosa Formation and the overlying continental Devonian redbeds was described by the aforementioned author as having a weathered quartzite surface with angular clasts of quartzite. One quartzite cobble had an 8 inch (20 centimeter) diameter as measured in the cores.

A pronounced erosional surface affects the top of the Devonian and Carboniferous sediments in large portions of the Paraguayan Chaco (Figs. 12, 13, 16, 40, 41, 54, and 78, through 81). This diastrophic movement elevated the arches of Boquerón and Cerro León (Fig. 82). An (Upper?) Carboniferous (Lobo, 1989) section rests on this unconformity over Devonian shales in the Curupaity Subbasin (Figs. 54, and 79 through 81).

Only in the deeper parts of the Carandaity Subbasin (>800 meter contour line, Fig. 41) was the Devonian section not affected by this unconformity. A complete Devonian section occurs in the deeper parts of the subbasin, with transitional environments into Tournaisian (Lower Mississippian) to Upper Mississippian-Lower Pennsylvanian sediments (Figs. 45 through 50). The elevation of the Cerro León and Boquerón arches served as source areas for the coarser Carboniferous sediments of the Curupaity and Carandaity subbasins. The unconformity at the base of the Carboniferous sequence is of regional extent, affecting Devonian sediments in the Bolivian Subandean Belt (Oblitas, 1972) and in the Chaco Salteño (Russo et al., 1980).

An erosional unconformity transects the Carboniferous sequence in the Curupaity Subbasin (Fig. 16, 54 and 79 through 81). Sediments of Late Permian to Early Triassic (Scythian) age (Lammons, 1978), herein informally referred to as the Toro Formation, overlie the Carboniferous sequence. This formation is equivalent to the Misiones Formation of the Paraná Basin. Faulting in the Curupaity Subbasin is characterized by small vertical displacements, except in the Toro-1, Gato-1 area, where some faults affect substantial thicknesses of the sedimentary package, but are of only local importance (Fig. 81). Figure 82 shows the symmetrical, gently bulging Cerro León Arch, with only minor faulting.

Cretaceous Events

The herein referred to as Cretaceous events range from Early Cretaceous to Late Paleocene-Early Eocene, and correspond to the deposition period of the Salta Group. These events affected mainly the Pirizal Subbasin. The Pirizal Subbasin shows an evolution typical of rift basins. An initial thermal arching exposed and eroded a substantial thickness of Paleozoic sediments. Intense faulting throughout the subbasin caused differential vertical movements, generating a tectonically controlled graben. Igneous activity took place along the faults. The sedimentary fill is mostly continental, with brief, possibly periodic marine influence. As sediments overlapped the tectonically controlled graben, the axis of the basin shifted so that the basin fill became distributed symmetrically with the thickest segment in the center of the basin.

According to Mitchell and Reading (1986), the marginal rim or lip of a rift basin is generally the highest topographic feature in rift basins, as can be clearly observed along the East African Rift. Clastic sediments are limited to material provided from nearby fault scarps and uplifted blocks inside the basin. The main transport agents are rivers, and the predominant sediments are of alluvial fans, fluvial and lacustrine deposits of fresh and saline waters.

Evidence for the arching of the basement can be seen in some seismic lines, especially in line OXY 86-114, by the dipping of the Paleozoic layers perpendicular to and away from the axis of the basin (Fig. 83), and the areal distribution of basement rocks (Fig. 59). In the Argentinian segment of the basin, the Cretaceous-Tertiary sequence was deposited on eroded Paleozoic and Precambrian rocks, which were exposed in bands roughly parallel to the axis of the basin and dipping away from it. These bands become younger away from the axis (Bianucci and Homovc, 1982).

In northwestern Formosa Province, only two wells reached levels assigned to the Paleozoic by basinal position and lithologic correlation (Carle et al., 1989). In Paraguay, the well López-1, located in the Central Chaco High area, reached continental Devonian sediments of the López Formation (Figs. 12, 13 and 40). The Palo Santo-1 well (Fig. 1), located along the southern rim of the Pirizal Subbasin, penetrated marine Eodevonian sediments. The La Paz-1 well, on the Boquerón Arch, may have terminated in the Ordovician, whereas the Santa Rosa-1, farther west, may have reached down to the Silurian (Fig. 12).

The erosion surface that transects the Pre-Cretaceous basement in the flanks, cuts increasingly older sequences toward the actual center of the basin (Fig. 83). This relationship is reversed in the deepest part of the basin, where collapsed blocks preserved a thicker Paleozoic section (Figs. 60, 84 and 85). The seismic response of this angular unconformity is much more evident in the western half of the northern flank where it affects younger Paleozoic levels than in the southern flank, where the erosion appears to have affected much deeper strata, including what is interpreted herein as the Pre-Paleozoic basement (Fig. 61).

The northern flank exhibits increased faulting and more tectonic mobility than the southern flank, which has fewer faults. However, the southern flank apparently was elevated higher, because almost complete removal of the Paleozoic sequence occurred. This increased elevation in the southern flank could be due in part to an isostatic response to the thick sedimentary wedge deposited in the deepest part of the Pirgua Subbasin adjacent to the northern border along the Balbuena Fault in Paraguay.

In the eastern half of the subbasin, however, both northern and southern flanks lack the typical layered response of the Paleozoic sequence seen in the western half of the northern flank, as can be seen in the seismic line OXY 166.5 (Figs. 61 and 85). This might reflect a greater uplift of the eastern portion of the subbasin, or simply a reduced thickness of the original Paleozoic sequence, because this area is closer to the Asunción and Apa Highs, which were elevated areas, and the source areas of the Paleozoic sediments.

The Pre-Cretaceous section of the Pirizal Subbasin is affected by a system of NE-SW faults parallel to the basin's axis and "en echelon." The faults along both the northern and southern flanks are of the normal-down-to-the-basin type, and are better developed along the northern flank. Some of these faults extend upwards into the Pirgua Subgroup and control its sedimentation. A few of these faults transect younger sediments. The most prominent of these faults is the Balbuena Fault, which extends from Argentina throughout the basin in Paraguay, setting the northern limit of the Pirgua Subgroup sediments (Figs. 62 and 85). The Balbuena Fault transects the Chaco Formation at the northern border of the Pirizal Subbasin in the proximity of the Tte. Acosta-1 well (Fig. 60). Some authors infer that reactivation of faults in Argentina in later stages was accompanied by transcurrent movements (Chiarenza and Ponzoni, 1989).

The initial rift or graben fill of the Pirizal Subbasin consists of the Pirgua Subgroup. Figure 62 shows a map view of the top of the Pirgua Subgroup and the distribution of the fault system. Two major sets of mostly continuous faults, dipping towards the center of the subbasin, occur at the northern and southern borders, and continue through most of the extension of the Pirizal Subbasin in Paraguay. Minor block faults throughout the subbasin account for numerous structures which are reflected in younger sediments as slight archings and flexures, and constitute structural traps for possible hydrocarbon accumulations (Fig. 86). In the easternmost part of the Pirizal Subbasin, east of Nazaret-1, most faults from the southern to the northern flank dip towards the north and have relatively large displacements (Fig. 62).

The northern border of the Pirgua Subgroup basin is determined by the Balbuena Fault, which extends into Argentina (Fig. 62). The second most prominent northern fault is known in Argentina as the Alto de la Sierra Fault, and it continues only a relatively short distance into Paraguay (Figs. 60 and 62). The southern faults of the study area are less prominent and do not have such clearly defined boundaries as the northern ones (Fig. 61). Nevertheless, they appear to be continuous and also structurally controlled the sedimentation of the Pirgua Subgroup.

The structural style of the Pirizal Subbasin is best observed in seismic lines oriented perpendicular to the basin axis (Figs. 84 and 85). Movements of blocks are especially evident towards the north of the subbasin, where normal-down-to-the-basin faults control the displacement and rotation of blocks of Paleozoic sedimentary rocks. The central zone of the Pirizal Subbasin shows the collapsing nature of the blocks (Fig. 60). The blocks were formed by a system of principal and secondary faults which were initiated very early in the development of the basin. These faults were the conduits for intrusive and extrusive igneous rocks, which were abundantly distributed throughout the basin, especially during Early Cretaceous to Paleocene.

Observation of seismic sections of the Pirizal Subbasin allows the identification of a number of seismostratigraphic units. These seismostratigraphic units are: (1) a possibly Precambrian section; (2) Paleozoic section; (3) Pirgua Subgroup; (4) Balbuena and Santa Bárbara subgroups; (6) Tranquitas Formation; (7) Paraná Formation; and (8) Chaco Formation (Fig. 85).

The Pre-Cretaceous basement consists of what is herein interpreted as being a Precambrian basement, identified based on the aspect of its homogeneous non-layered reflection, and a Paleozoic sequence with a layered aspect. The change in the seismic response is a very marked one. A clearly identifiable angular unconformity, dipping towards the center of the basin, separates the Paleozoic basement from the overlying Cretaceous and Tertiary sequences. A much thicker Paleozoic sequence is preserved in the northern deepest part of the basin in downthrown blocks of normal down to the basin faults, where the contact with the overlying Cretaceous and Tertiary sequences appears to be almost parallel (Figs. 60 and 85).

The seismostratigraphic unit ascribed herein to the Pirgua Subgroup is identified by its restriction to the graben area, limited by faults, wedge shape, and its position immediately above the Paleozoic sequence. The northern limit consists of the very deep Balbuena growth fault, which determines the location of the thickest part of this unit, as well as the deepest part of the Pirizal Subbasin.

The first group of sediments expanding beyond the graben faults, and overlapping the arches of Boquerón and Hayes to the north and south respectively, is the Balbuena

Subgroup. The water level was elevated during the deposition of this subgroup. Periodic incursion of marine sedimentation occurred during this time, reaching a maximum expansion with the deposition of the Yacoraite Formation. The basin waters receded during the deposition of the Olmedo Formation, and desiccated during the deposition of the Saline Member of the Olmedo Formation. The top of the Olmedo Formation shows a strong reflection that can easily be followed in the study area (Fig. 86).

The overlapping unit represents the maximum expansion of the Salta Group sediments and corresponds to the Santa Bárbara Subgroup, the uppermost member of the Salta Group. An unconformity separates the Salta Group from the overlying Tranquitas Formation of the Palo Santo Group. The seismic response of the Balbuena and Santa Bárbara subgroups is relatively homogeneous through most of the study area. The very thick sediments of these subgroups and thermal cooling probably caused the sinking of both, the Boquerón and Hayes arches. The basin axis shifted from the northern Balbuena Fault area, during Pirgua times, towards the center of the basin during Balbuena and Santa Bárbara times. This resulted in a symmetrical distribution of sediments in the basin, as can be seen in all structure maps in this study. Movement along faults was reduced to a minimum, with only small adjustments along the Balbuena Fault. It is at the end of the deposition of the Lumbrera Formation that some uplifting in the region occured. This uplift corresponds to the Incaic diastrophic phase (Salfity and Marquillas, 1981), and is manifested in the area by the slight erosional surface at the top of the Lumbrera Formation.

Volcanism

Associated with widespread faulting are extrusive igneous rocks, which were extruded to the surface along fault planes. Three extrusive igneous cycles were recognized in the Northwest Basin in Argentina (Fig. 57).

The First Cycle was identified in the Alto de Las Salinas Volcanic Complex. Rocks of this cycle have an Early Cretaceous age, between 130 and 100 m.y., corresponding to the Neocomian-Albian (Galliski and Viramonte, 1985). They were emplaced along the Isonza Lineament and are contemporaneous with Lower Cretaceous plutons (Halpern and Latorre, 1973) emplaced along the southern flank of the San Pablo Arch (Fig. 56). Alkaline extrusives predominate in this cycle. Extrusive rocks include trachytes, basanites and foidites (Galliski and Viramonte, 1985).

The igneous manifestations of this cycle occur in a NE-SW direction along the lineaments of Aconquija, Isonza and Los Cobres (Salfity, 1979; Fig. 56 of this report). This volcanism occurs at the base of the La Yesera Formation above the Precambrian and Paleozoic basement, and is intercalated within the lower levels of this formation (Reyes et al., 1976; Fig. 57 of this report).

The Palo Santo-1 well penetrated a section of 153 meters (3,611-3,764 m, T.D.) consisting of Devonian quartzitic sandstones and igneous rock dated at 126 +- 3.5 m.y. The igneous rock (a rhyodacite) was described in a composite geophysical log of Palo Santo-1 well (REPSA-CPC, 1975) as a "quartz latite porphyry, highly altered, shallow intrusive." Basalt grains occur in the upper 10 meters of the Devonian section, and continue into the lower 27 meters of the Pirgua sediments. Cineritic tuff is abundant in the lower section of the Pirgua sediments 111 meters above the Devonian-Pirgua contact. The age of these igneous rocks in Palo Santo-1 would suggest that the igneous activity of the first cycle might have been distributed throughout the fault system in the Olmedo Subbasin, and that the rifting could have been synchronous in this subbasin. Further drilling might reveal more rocks of similar age in the Pirizal Subbasin.

The Nazaret-1 well reached its total depth 504 meters inside the Pirgua Subgroup. The bottom 23 meters of this well consist of igneous rock. This igneous rock was not dated, and was described as grayish red, altered, aphanitic material, with anhedral quartz phenocrystals, feldspars and mafic minerals (Nazaret-1 final drilling report, Occidental, 1988).

The Second Effusive Cycle (80-75 m.y., Campanian) corresponds to the Las Conchas Basalt (Fig. 57). These rocks were structurally controlled by the Los Loros Threshold during the accumulation of the Las Curtiembres Formation in the middle section of the Pirgua Subgroup (Reyes et al., 1976). This cycle has been identified in the Alemania and Metán subbasins, and is related to the Peruvian orogenic phase (Salfity and Marquillas, 1986). These rocks are correlated to the Betanzos Basalt (Reyes, 1972; Reyes and Salfity, 1973; Cherroni, 1977). This cycle has an alkaline suite containing basanites, hawaiites and tephriphonolites (Galliski and Viramonte, 1985).

The Third Cycle (65-60 m.y., Early to Late Paleocene; Galliski and Viramonte, 1985) corresponds to the Caimancito Basalt, reported first by Schlagintweit (1937), and occurs within the Balbuena Subgroup (Bianucci et al., 1981; Bercowski, 1982; and Mädel, 1984). These lava flows occur to the east of the Salta-Jujuy Arch, in the Lomas de Olmedo (Pirizal) Subbasin, and west of the San Pablo and Traspampean-Punic Arches in Chile (Fig. 56). The rocks consist of lamproitic sills and basic lava flows (Galliski and Viramonte, 1985).

The lava flows that constitute the reservoir rocks in the Palmar Largo field in Argentina (Fig. 1), were dated radiometrically at 70 +- 5 m.y. (Maastrichtian; Carle et al., 1989). Extrusions in this field occurred through fracture systems oriented NE-SW and NW-SE. The lava flows occurred on top of the Pirgua Subgroup, and were overlain by the Lecho Formation. Rapela and Aragón (1984, in Carle et al., 1989) described these rocks microscopically, and observed a magmatic differentiation. More basic rocks occur at the base, and become "intermediate leucocratic" towards the top. The sequence from bottom to top is: olivine andesites, andesites, andelacites and leucoandelacites. Merodio (1984; in Carle et al., 1989) reports the chemical composition to be moderately sodic at the base and moderately potassic to potassic towards the top of the lava flows. A number of other lithologic types were found between these lava flows: (1) a volcanic agglomerate of pumice in a "volcanic matrix"; (2) volcanic breccia; (3) conglomerate with oligomictic volcaniclasts and a "lithic matrix"; and (4) lithic tuffs formed by ash-size lithic clasts with a calcitic and sometimes analcimic matrix.

Cenozoic Events

The erosional surface separating the Salta Group from the overlying Palo Santo Group is the manifestation in the Orán Basin and the Paraguayan Chaco of the beginning of tectonic events taking place to the west in Bolivia. According to Mingramm et al. (1979), these tectonic events extend from Eocene (Incaic diastrophic phase) to the present, and resulted in the elevation of the Andean region, placing the Paraguayan Chaco in a foreland basin position.

The elevation of the Eastern Cordilleras started in the Eocene (Incaic diastrophic phase), and reached its present elevation during the Pliocene (Salfity et al., 1984; Mingramm et al., 1979). The Subandean Belt was compressed during the Miocene and folded and thrusted toward the end of the Pliocene. This folding and Thrusting continued with less intensity into the Pleistocene (Mingramm et al., 1979). According to Salfity et al. (1984), the elevation of the Western Cordillera volcanic belt was initiated during the Diaguita diastrophic phase at the Tertiary-Quaternary border.

In the study area, the thick sediments of the Palo Santo Group were deposited in a foreland setting with the Andean region constituting an important western source area. Tertiary and Quaternary deposits cover most of the Paraguayan Chaco. In the Paraguayan and Argentinian Chaco, the modern tributaries of the Paraguay and Paraná rivers like the Pilcomayo, Bermejo and numerous minor ones, reflect the elevated Andean source area in their parallel NW-SE flow.

The Tranquitas Formation is conspicuous in seismic sections (Fig. 60). Strong reflections with poor lateral continuity distinguish it from both the subjacent Lumbrera Formation and the poorly reflecting overlying Paraná Formation. The Chaco Formation, again, has a slightly stronger reflection than the Paraná Formation and has poor lateral continuity. Minor reactivation of the Balbuena Fault affects up to the lower section of the Chaco Formation.

The tectonic evolutionary model for the Pirizal Subbasin envisioned here consists of three basic stages:

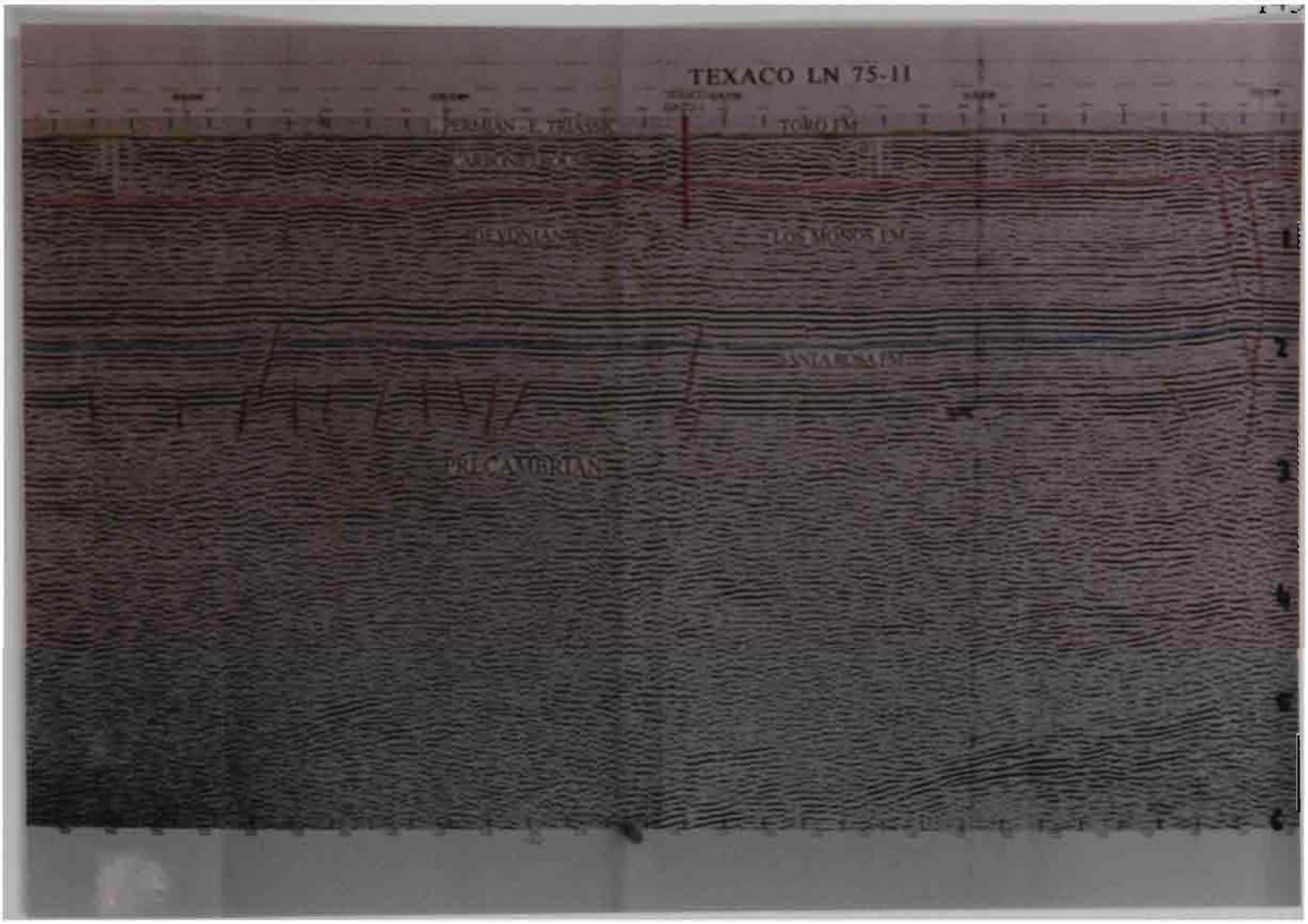
1. Uplift and arching of pre-Cretaceous basement, resulting in the erosion of the basement.

2. Faulting of the pre-Cretaceous basement accompanied by intrusions and extrusions of igneous rocks along these faults, and deposition of the Pirgua Subgroup in a fault-controlled wedge-shaped graben fill.

3. The formation of an interior sag caused by cooling of the lithosphere and the weight of thick post Pirgua sediments deposited in an overlapping and expanding basin. This caused the flanks to sink and resulted in a symmetrically-shaped basin. Limited vertical adjustments continued, and possibly transcurrent movements. Renewed igneous activity occurred along these faults.

Fig. 79. Photograph of seismic section Texaco LN 75-11 of the Curupaity Subbasin through well Gato-1 showing the Precambrian (non layered response), Paleozoic (layered), top of Santa Rosa Formation (blue), the Carboniferous-Devonian unconformity (pink), and the unconformity separating the Upper Permian to Lower Triassic Toro Formation from the Carboniferous sequence (green). Vertical scale is in seconds. See Fig. 34 for location of seismic line.

Fig. 80. Photograph of seismic section Texaco LN 75-1A showing the Precambrian (yellow), Carboniferous-Devonian (pink) and Permian (green) unconformities in the Curupaity Subbasin. The southeastern extreme of the seismic section originates at the town of Bahía Negra on the Paraguay River. Vertical scale is in seconds. See Fig. 34 for location of seismic line.


TEXACO LN 75-11
L. PERMIAN - E. TRIASSIC
TORO FM
CARBONIFEROUS
DEVONIAN
LOS MONOS FM
SANTA ROSA FM
PRECAMBRIAN
1
2
3
4
5
6

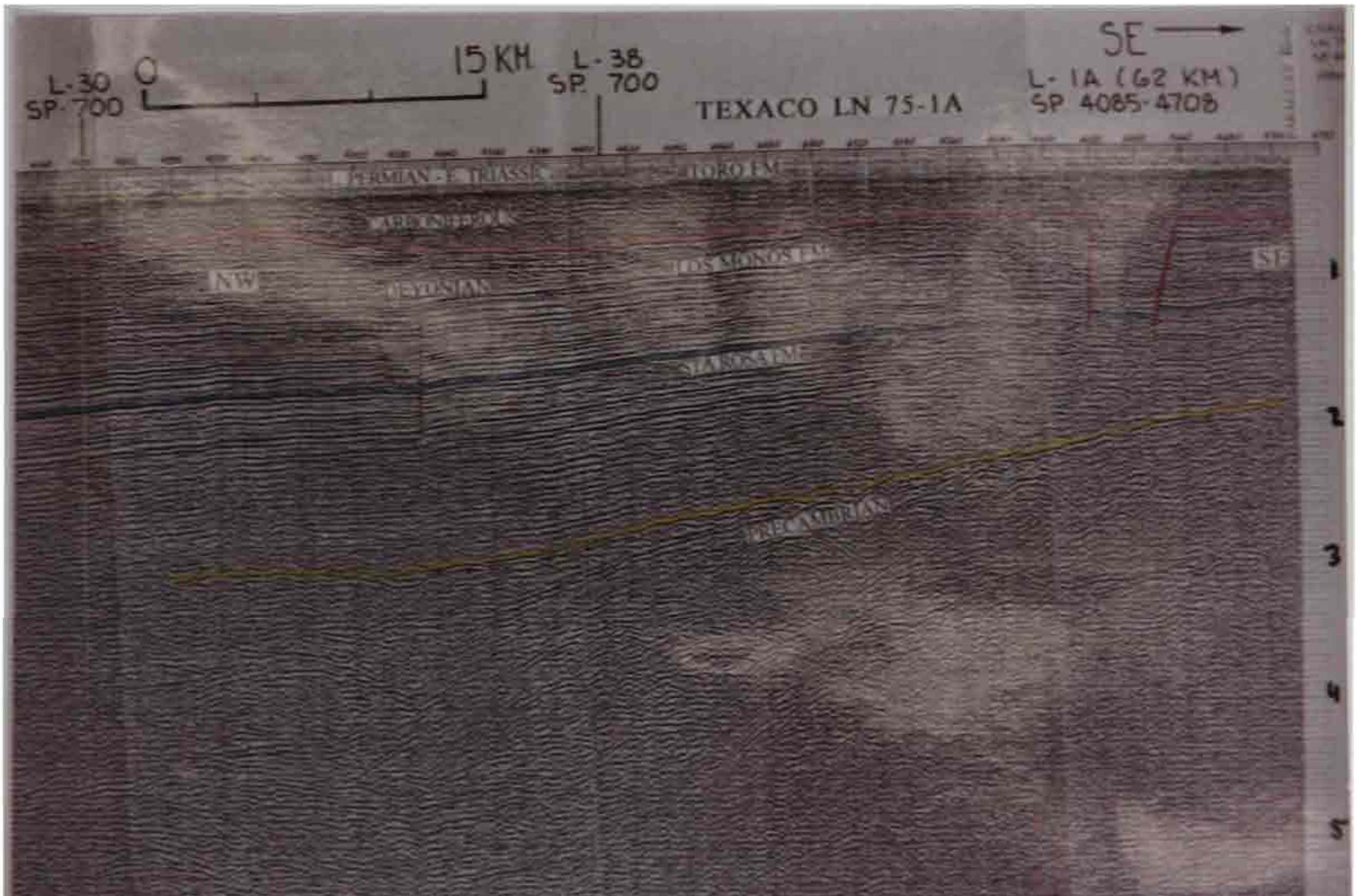
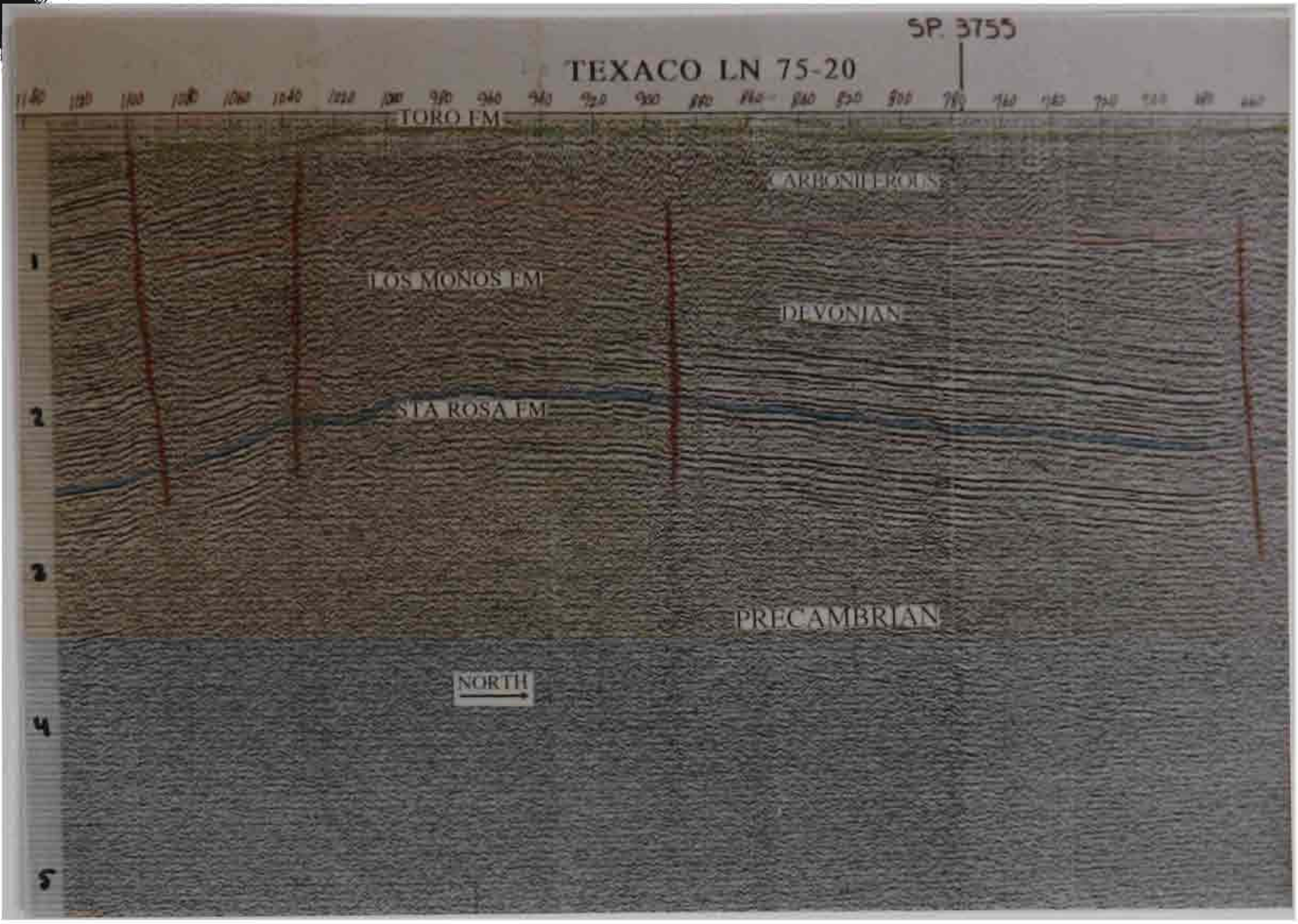

L-30
SP 700
0
15 KM
L-38
SP 700
TEXACO LN 75-1A
SE
L- 1A (62 KM)
SP 4085-4708
L. PERMIAN - E. TRIASSIC
TORO FM
CARBONIFEROUS
LOS MONOS FM
NW
DEVONIAN
SE
STA ROSA FM
PRECAMBRIAN
1
2
3
4
5

Fig. 81. Photograph of seismic section Texaco LN 75-20 showing the most prominent faults observed in 2,264 kilometers of seismic sections of the Curupaity Subbasin. Some faults appear to have been the conduit for igneous intrusions, which might be responsible for the relatively high temperature gradients observed in the Toro-1 area. Vertical scale is in seconds. See Fig. 34 for location of seismic line.

Fig. 82. Photograph of seismic section Texaco LN 75-6 of the Curupaity Subbasin showing the symmetrical shape of the Cerro León Arch. Note the almost total absence of faults. Vertical scale is in seconds. See Fig. 34 for location of seismic line.


SP. 3755
TEXACO LN 75-20
1140
1120
1100
1080
1060
1040
1020
1000
980
960
940
920
900
880
860
840
820
800
780
760
740
720
700
680
660
TORO FM
CARBONIFEROUS
LOS MONOS FM
DEVONIAN
STA ROSA FM
PRECAMBRIAN
NORTH
1
2
3
4
5

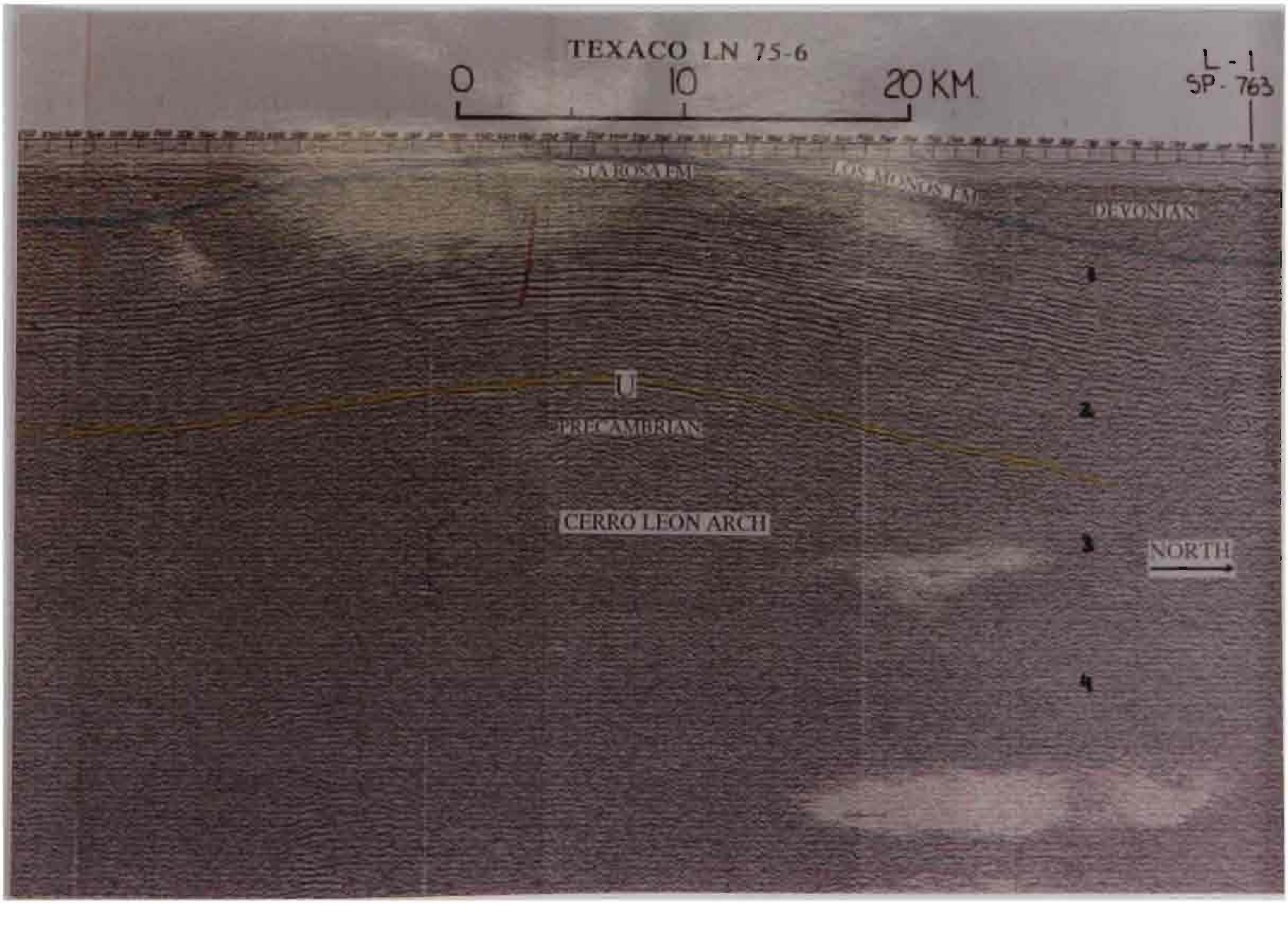
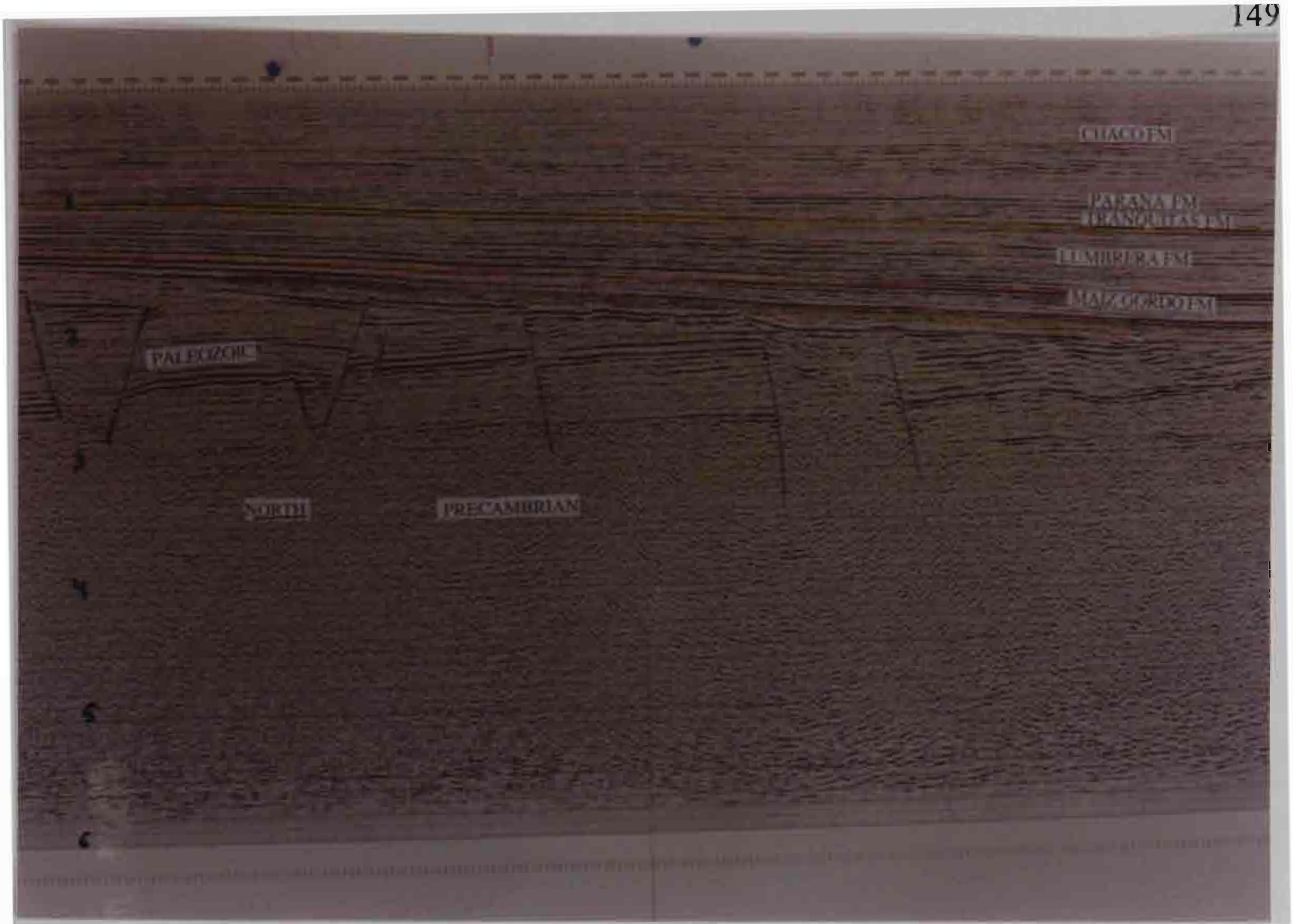

TEXACO LN 75-6
0
10
20 KM
L - 1
SP - 763
STA ROSA FM
LOS MONOS FM
DEVONIAN
1
U
2
PRECAMBRIAN
CERRO LEON ARCH
3
NORTH
4

Fig. 83. N-S seismic line OXY 86-114 showing the northern flank of the Pirizal Subbasin. The Paleozoic sequence is eroded more deeply towards the center of the basin to the right. This indicates an arching of the pre-Cretaceous basement. Vertical scale is in seconds. See Fig. 34 for location of seismic line.

Fig. 84. N-S seismic line OXY 86-154 showing the central part of the Pirizal Subbasin and the Balbuena Fault. A thick Paleozoic section is preserved to the right of the fault. Vertical scale is in seconds. See Fig. 34 for location of seismic line.


CHACO FM
PARANA FM
TRANQUITAS FM
LUMBRERA FM
MAIZ GORDO FM
PALEOZOIC
NORTH
PRECAMBRIAN
1
2
3
4
5
6

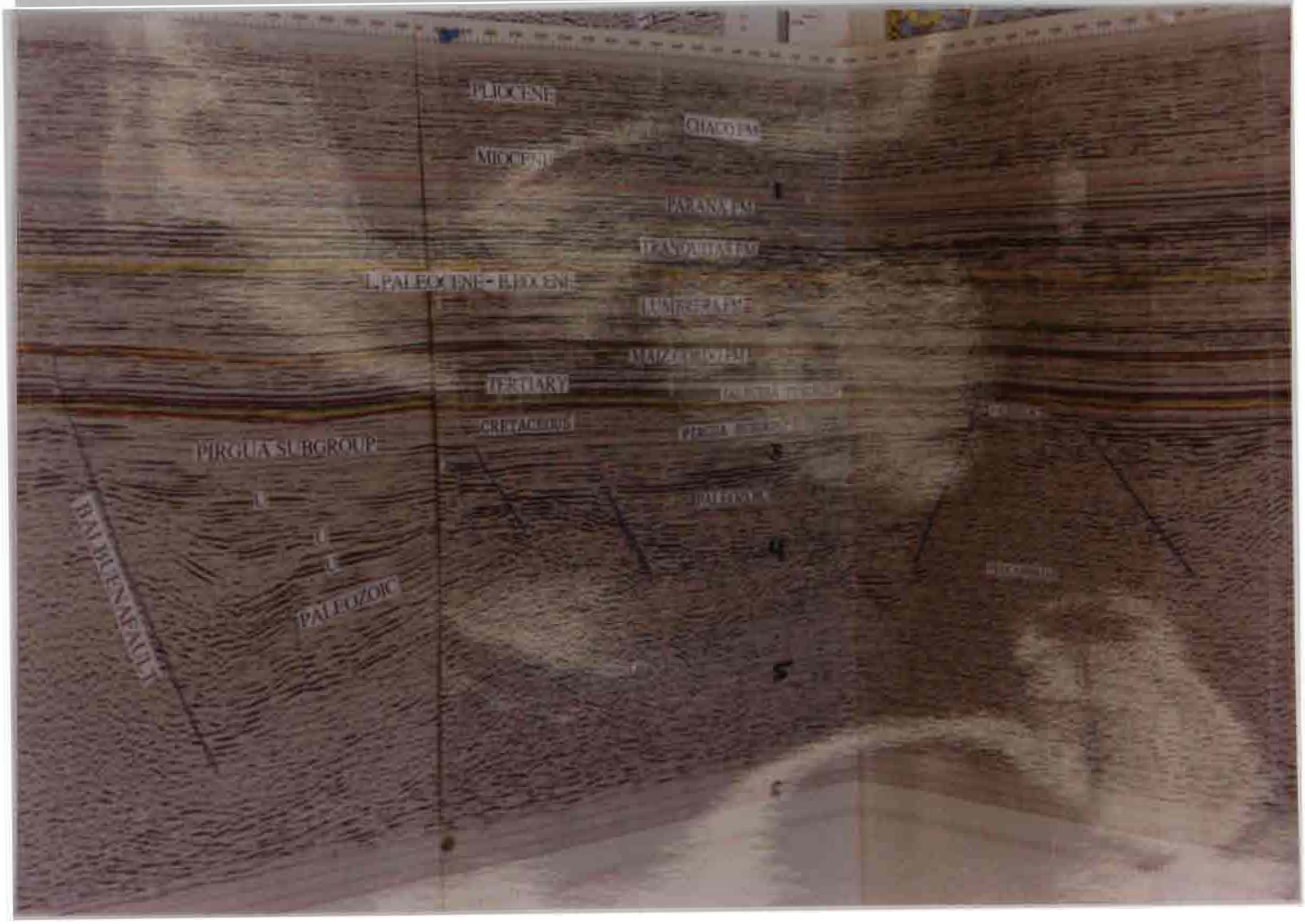

PLIOCENE
CHACO FM
MIOCENE
1
PARANA FM
TRANQUITAS FM
L. PALEOCENE - E. EOCENE
LUMBRERA FM
MAIZ GORDO FM
TERTIARY
CRETACEOUS
PIRGUA SUBGROUP
3
PALEOZOIC
BALBUENA FAULT
4
PALEOZOIC
5
6

Fig. 85. N-S seismic lines OXY 86-114 (top), 86-154 (middle) and 87-166.5 (bottom) showing the northern Boquerón Arch area. Line 114 is in the westernmost section of the Pirizal Subbasin near Argentina, while lines 154 and 166.5 are increasingly towards the east of the subbasin. Note in line 114 how the unconformity erodes deeper into the Paleozoic section towards the center of the subbasin to the right. The unconformity in line 154 appears to have been affected more by the subvertical movements of blocksthan by the erosion of a homogeneously uplifting arch. Line 166.5 shows a practically complete removal of the Paleozoic sequence towards the eastern part of the subbasin.

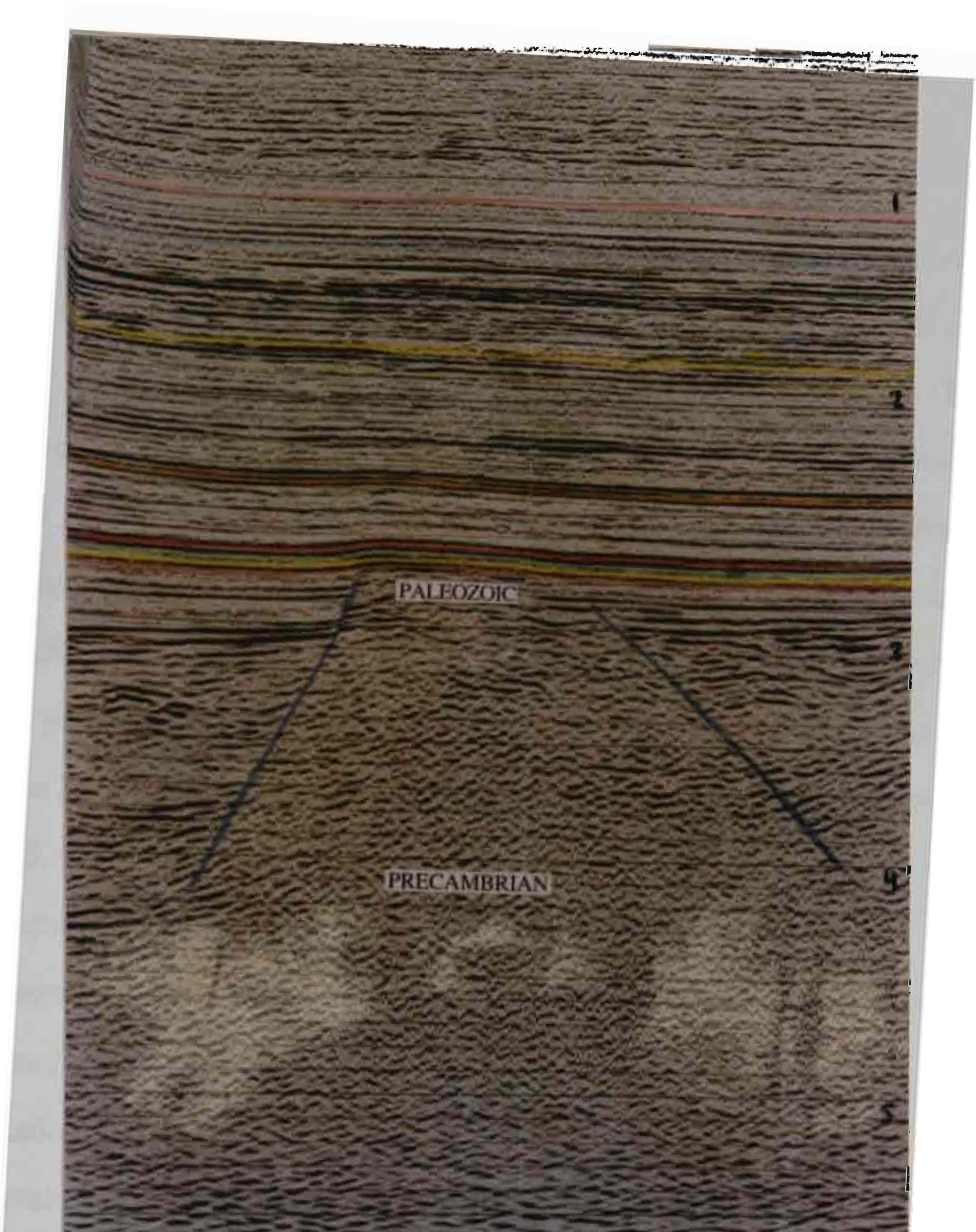


Fig. 86. Post-Paleozoic layers drape over a pre-Cretaceous horst in the central part of the Pirizal Subbasin. Note strong reflection of the Olmedo Formation (red). Seismic line OXY 86-154. See Fig. 34 for location of seismic line. Vertical scale in seconds.

CHAPTER V

GEOCHEMISTRY OF THE PALEOZOIC SECTION AND HYDROCARBON EXPLORATION POTENTIAL OF THE PARAGUAYAN CHACO

Although no commercial oil or gas deposits have yet been discovered in the Paraguayan Chaco, geochemical analyses indicate that shales of the Paleozoic sequence did produce oil and gas. Samples from Don Quixote-1 and Katerina-1 wells (Fig. 1) were analyzed geochemically by Van Delinder (1972a and 1972b) for Pennzoil-Victory Oil for source rock potential. The Katerina-1 well showed an immature shale section (stage 1 to 1+) in the interval 2,450 to 3,747 feet (747 to 1,142 meters). The Don Quixote-1 interval I, from 1,650 to 5,850 feet (503 to 1,783 meters) showed oil source character with mature shales that passed through an oil generation phase. The shales are rated as stages 2- at the top to stage 3+ at the bottom of the section. The iC4/nC4 ratios for this zone are between 0.2 and 0.5, which are the same for the Katerina-1 section from 2,450 to 3,747 feet (747 to 1,142 meters).

An organic boundary is interpreted to occur in Don Quixote-1 between this section and the underlying sediments. There is an abrupt change in organic geochemical characteristics.

Interval II, from 5,850 to 9,496 feet (1,783 to 2,894 meters T.D.) has different and considerably higher iC4/nC4 values (0.8+- against 0.3 +-). The organic facies boundary at 5,850 feet (1,783 meters) could correspond to an unconformity. Interval II has an upper shale section from 5,850 to 6,980 feet (1,783 to 2,128 meters), corresponding to the Devonian Los Monos shaly section; a medial sand section from 6,980 to 8,100 feet (2,128 to 2,469 meters), corresponding to the lowest part of the Devonian section, the Silurian, and Upper Ordovician (Santa Rosa, Nueva Asunción and Siracuas formations); and a lower shale section from 8,100 to 9,496 feet (2,469 to 2,894 meters T.D.), ranging from Lower to Upper Ordovician (Don Quixote Formation).

The upper shale section of interval II consists of dark gray micaceous shales difficult to differentiate lithologically from the shales in interval I. Total organic carbon content is relatively constant throughout the interval, and is also similar (approximately 0.5 %) to interval I. The difference in composition of the light hydrocarbons appears to indicate a different organic facies from interval I. This upper shale section is a very mature organic facies with oil source character. There is increased geothermal maturation with depth, as indicated by a progressive decrease with depth of the percent gas wetness, the C4-C7 hydrocarbons and the C15+ hydrocarbon contents. The TOC is relatively constant with a uniform type of indigenous organic content. This section has produced high gravity oil near the top, passing to wet gas and condensate towards the base.

The middle section (Lower Devonian, Silurian and Upper Ordovician) of very fine, clean quartz sands and silts is tightly cemented by silica. If these sands were porous and permeable, they would produce gas, because it is within a very mature facies.

The lower shale section from 8,100 to total depth of 9,496 feet (2,469 to 2,894 meters) is in a very mature organic facies, corresponding to stage 4- at 8,400 feet (2,560 meters). Only gaseous hydrocarbons (methane) would be found in this interval. In the lower 600 feet (183 meters), the shales have a slate-like appearance.

The northern section of the Carandaity Subbasin produced important gas shows. In the Pure Mendoza-1 well, Drilling Stem Tests revealed gas accumulations:

> # 2 1932-1956'. Open 40 minutes. Gas at once --burned with 50' flame on 2 inch orifice. Flowing pressure 640-1020#. Hydrostatic pressure 1020#. Shut in pressure 640-1020#. Temperature 120 F. Recovered 200' drilling mud.

> # 3 1957-1990'. Open 30 minutes. Gas to surface in 2 minutes, burned 15' flame on 2 inch orifice. Recovered 40' drilling mud. Flowing pressure 245-110#. Hydrostatic pressure 1100#. Shut in pressure 630#.
>
> # 4 1990-2040'. Open 17 minutes. Gas in 2 minutes --burned 6' flame on 2" orifice. Recovered 10' drilling mud and 180' slightly saline water. Flowing pressure 110-162#. Hydrostatic pressure 1100#. Shut in pressure 630#.
>
> # 13 8527-8572'. Open 41 minutes. Gas in 5 minutes gauged 87,530 cubic feet. Flowing pressure 295-140#. Hydrostatic 5350#. Shut in pressure 850# after 15 minutes, still rising at constant rate. (Final Report of the Exploratory Well Pure Oil Company of Paraguay, Inc. Mendoza # 1, 1959).

The interval tested by the first 3 Drill Stem Tests listed here corresponds to the coastal sequence of Frasnian, Fammenian and Tournaisian age (Figs. 13 and 50). The interval 8,527-8,572 feet (2,599-2,613 meters) corresponds to a fractured shale section of the lower section of the Los Monos Formation. The volume of gas in the interval 1,927-1,956 feet (587-596 meters) was calculated at 5 MMCFGPD (Mauri, 1959). No oil shows were reported in this well.

As a result of the encouraging gas shows of the Pure Mendoza-1 well, other wells tested the Paleozoic sequence in the area close to Pure Mendoza-1. Placid Oil Company drilled three wells to test the same upper intervals of the Paleozoic sequence of the area. In the Placid Mendoza-1 well, the DST No. 2, 1,722-1,729.5 feet (525-527 meters) showed a "Weak blow of gas --30 mins. Burnt small dry gas flame at tip of 1/2" test tool hose during 30 mins." The DST No. 3, 1,687-1,694 feet (514-516 meters) showed "Weak blow of gas to surface in 25 minutes. Burnt 4 foot dry gas flame at end of 2 3/8" flow line during 35 mins." (Placid Oil Company, Summary of Mendoza No. 1, 1967a).

The Placid Mendoza-2 DST No. 3, 1,966-2,015 feet (599-614 meters) produced a "Weak blow of gas --45 mins. Burnt 2 foot dry gas flame at end of 2 3/8" flow line during 15 minutes." (Placid Oil Company, Summary of Mendoza No. 2, 1967b).

Encouraging results were found in a thick section of the Los Monos Formation in the Toro-1 well: "4900-5700'. Cuttings exhibit good oil shows with uniform yellow white to dull yellow gold fluorescence, slow to very fast streaming yellow white to white solvent fluorescence, no visible cut." (Toro-1 composite log, Texaco, 1977).

Total organic carbon values between 0-6,000 feet (0-1,829 meters) range between 0.33 and 2.13 %, with a mean value of 0.70 %. Minimum and maximum vitrinite reflectance (% Ro) values are 1.02 and 1.25 at 200 feet (61 meters), and 1.85 and 2.17 at 3,300 feet (1,006 meters) according to Texaco (1978).

Temperature gradients follow contours that delineate the main morphostructural units of the study area (Fig. 87), indicating that the thermal history of the sediments was strongly influenced by their tectonic history. Areas along the arches of Cerro León and Boquerón have relatively high gradients, while more central positions in the Carandaity Subbasin have low values and should be oil prone according to the temperature values. The elevation of the Cerro León Arch was accompanied with a substantial rise in temperature. Faults in the Toro-1 area (Fig. 81) of the Curupaity Subbasin served as conduits of igneous rocks resulting in high temperature gradients. The highest temperature gradient (Table 5.1) was determined in well Lagerenza-1 with 2.85 °F/100. The area around the Don Quixote-1 and Parapití-2 wells correspond to highs in the aeromagnetic and temperature gradient values, indicating igneous activity.

Exploration Potential

Six areas with exploration potential are identified in the Paraguayan Chaco. Two are in the Pirizal Subbasin and four in the Carandaity and Curupaity subbasins. The most promising areas are related to the parts of the Pirizal Subbasin with Late Cretaceous-Paleocene source rocks, and the transitional Late Devonian-Carboniferous sandstones of the Carandaity Subbasin.

The main area of interest in the Pirizal Subbasin is determined by the presence of the source rocks of the Maastrichtian-Paleocene marine incursion. Figure 64 shows the extent of this sea penetration --the Yacoraite Sea. Source rocks are the Yacoraite Formation and, possibly, collapsed blocks of Paleozoic shaly formations. Reservoirs are the Pirgua sediments, the Lecho and Yacoraite formations. Seals are the Yacoraite Formation and the shales and saline member of the Olmedo Formation. Areas farther inside Paraguay along the axis of the Pirizal Subbasin, but outside the source rock deposition area, are less favorable. Relatively large structures occur eastward in Paraguay, and were tested by the Tte. Acosta-1 and Nazaret-1 wells. However, the absence of hydrocarbons indicates that no migration occurred updip along the basin axis.

The second area of interest in the Pirizal Subbasin is related to the contact of the Devonian Los Monos shales (source rock) and the Cretaceous-Tertiary sediments (reservoir) covering the shales across the angular unconformity. The distribution of the Los Monos shales appears to be restricted along the western part of the northern flank, and possibly in some collapsed blocks in the deeper parts of the subbasin. On the southern flank, only well Palo Santo-1 was deep enough to reach Lower Devonian sediments, which consisted of marine sandstones of the Santa Rosa Formation. The southern flank in the study area is closer to the source area of the Asunción High, and therefore, it is unlikely that it would contain potent, if any, Devonian shales that could serve as source rocks. Structures in the Pirizal Subbasin are mostly related to horst and graben features that faulted Paleozoic and Pirgua sediments, and are reflected in the overlying formations as potential hydrocarbon traps.

The Carandaity and Curupaity subbasins contain potent Devonian shales of the Los Monos Formation. Thicknesses exceed 2,500 meters in the Carandaity Subbasin, and in the deeper parts of the Curupaity Subbasin they exceed 3,600 meters (Figs. 13 and 42). In the Carandaity Subbasin, the target consists of the Upper Devonian and Mississippian transitional sands (Iquiri and Tupambi formations) and possibly the Lower Pennsylvanian continental Tarija Formation. These three formations are transected by the steep Tertiary unconformity, and are overlain by the Chaco Formation. The Los Monos Formation serves as source rock, the Paleozoic sands as reservoir, and the unconformity and Chaco Formation as potential seal (Fig. 40). Seismic lines with good resolution are necessary to identify structures in the Carandaity Subbasin.

In the Curupaity Subbasin, the pronounced angular unconformity at the top of the Los Monos shales puts the source rocks in contact with sands, silts and shales of the thick Carboniferous section, which could result in oil accumulations.

In the Carandaity and Curupaity subbasins, sandy horizons within the Los Monos Formation shales are also possible targets, because they are surrounded by source rocks. This target would be dependent on the occurrence of permeable or fractured/faulted units. The seal would be provided by the Los Monos shales.

In the Carandaity Subbasin, Lower Devonian to Middle Ordovician sandstones (Santa Rosa, Nueva Asunción and Siracuas formations) are between Ordovician (Don Quixote Formation) and Devonian (Los Monos Formation) source rock shales. In areas close to the subbasin borders, these sandstones are surrounded by shales in a mature facies, and would produce only gas. In more central areas of the Carandaity Subbasin they would produce oil, because of the lower thermal gradient (Fig. 87). However, these sandstones and quartzites have low porosities and permeabilities or are tight. Low porosities and permeabilities also are found in Bolivia and Argentina. Consequently, areas subjected to fracturing and faulting, or with a different diagenetic history would be more promising.

Table 2

Temperature gradients of wells drilled in Paraguay

All calculations are based on a surface temperature of 80 °F (Asquith, 1983).

Well	**BHT**		**Total Depth**		**Gradient**	
	(°F)	(°C)	(Ft)	(M)	(°F/100Ft)	(°C/100m)
Alicia-1	132	55.55	4,283	1,305.4	1.21	2.21
Anita-1	300	148.88	13,543	4,127.9	1.62	2.96
Asunción-1			10,574	3,223.0	1.16	2.11
Asunción-2			9,599.9	2,926.0	1.0	1.82
Berta-1	328	164.44	15,723	4,792.4	1.58	2.87
Brigida-1	138	58.89	4,963	1,512.7	1.17	2.13
Carmen-1	346	174.44	14,800	4,511.0	1.80	3.27
Cerro León-1	210	98.88	6,462	1,970.1	2.01	3.66
Christina-1	101	38.33	2,110	643.1	1.00	1.81
Don Quixote-1	252	122.22	9,496	2,894.4	1.81	3.30
Dorotea-1	112	44.44	2,800	853.4	1.14	2.08
Emilia-1	124	51.11	3,353	1,022.0	1.31	2.39
Federica-1	104	40.00	2,624	800.0	0.91	1.66
Gabriela-1			3,332	1,015.6		
Gato-1	170	76.66	5,400	1,646.3	1.67	3.03
Gloria-1	286	141.11	13,173	4,015.1	1.56	2.85
Hortensia	106	41.11	2,510	765.0	1.03	1.89
Isabel-1	117	47.22	3,100	944.9	1.19	2.17
Julia-1	128	53.33	4,200	1,280.1	1.14	2.08
Katerina-1	123	50.55	3,739	1,139.6	1.15	2.09
La Paz D-1			7,251	2,210.1		
Lagerenza-1	350	176.66	9,480	2,889.5	2.85	5.19
López-1	180	82.22	5,679	1,730.9	1.76	3.20
Luciana-1	114	45.55	2,688	819.3	1.26	2.30
Madrejón-1	226	107.77	5,668	1,727.6	2.57	4.69
Mallorquín-1						
Marta-1	112	44.44	2,715	827.5	1.18	2.15
Nazaret-1	277	136.11	13,205	4,025.0	1.46	2.71
Nola-1	110	43.33	2,493	760.1	1.20	2.19
Olga-1	130	54.44	3,843	1,171.3	1.30	2.37
Orihuela B-1			6,715	2,046.7		
Palo Santo-1	270	132.22	12,350	3,765.2	1.54	2.80
Parapití-1	244	117.77	9,296	2,834.2	1.76	3.21
Parapití-2	220	104.44	7,711	2,350.9	1.82	3.30
Pennzoil Stratigraphic-1						
Pennzoil Stratigraphic-2	96	35.55	1,078	328.6	0.93	2.70
Pennzoil Stratigraphic-3	81	27.22	1,137			
Pennzoil Stratigraphic-4	76	24.44	1,021			
Pennzoil Stratigraphic-5	82	27.77	1,015	309.4		
Picuiba B-1			7,516	2,290.9		
Pirizal D-1			10,331	3,148.9		
Placid Mendoza-1	144	62.22	2,598	791.8	2.46	4.49
Placid Mendoza-2	148	64.44	4,090	1,246.6	1.67	3.03

Table 2 Continued

Well	BHT		Total Depth		Gradient	
	(°F)	(°C)	(Ft)	(M)	(°F/100Ft)	(°C/100m)
Placid Mendoza-3	131	55.00	2,275	693.4	2.24	4.08
Pure Mendoza-1	315	157.22	10,639	3,242.7	2.21	4.02
Santa Rosa-1			7,577	2,309.4		
Teniente Acosta-1			14,002	4,268.0		
Toro-1	303	150.55	11,210	3,417.7	1.99	3.62

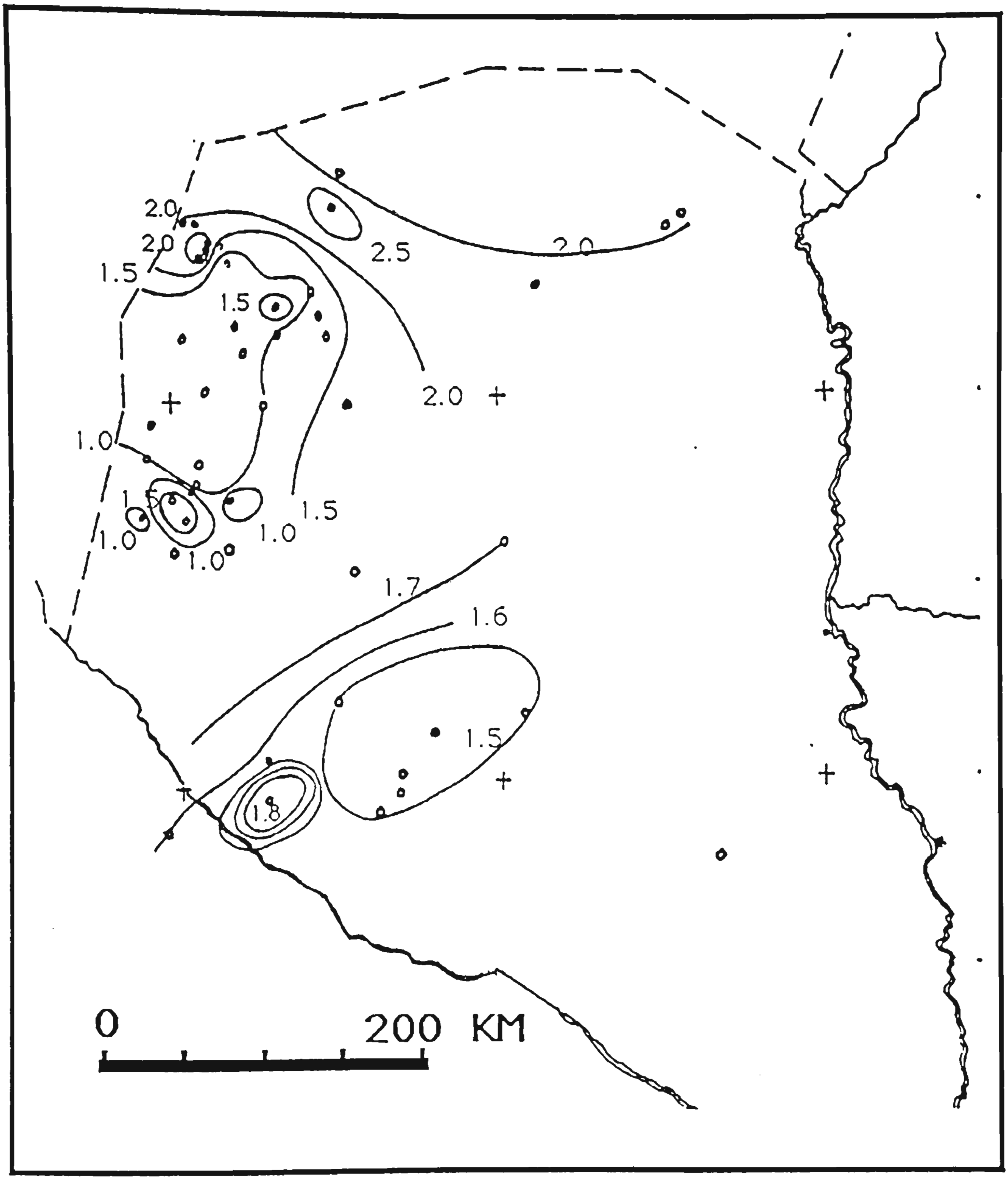


Fig. 87. Temperature gradient contour map of the Paraguayan Chaco. Values are in °F/100 feet.

CHAPTER VI

X-RAY DIFFRACTION ANALYSIS

Twenty-nine samples from wells Don Quixote-1, Katerina-1 and Julia-1 (Fig. 1) of a section of over 7,000 feet (2,133.6 meters) of Paleozoic sediments of the Carandaity Subbasin were studied by x-ray diffraction methods in order to characterize the clay minerals. The sediments are source rocks for oil and gas deposits in the adjacent countries of Bolivia and Argentina. Ages of the studied sediments extend from Middle Ordovician to Late Devonian.

Sample analysis included the use of bulk powder, oriented slides, and ethylene glycol-treated oriented slides. A relatively simple mineralogy was observed. Clay minerals consist of illite, kaolinite and chlorite. No expansive clays were identified through glycolation, as expected, consistent with the Paleozoic age of the sediments. Major reflection peak intensity variations were observed as a quick method to determine trends in the composition of the sediments. Peak intensities reflect changes in lithology. Non-clay minerals decrease markedly, and clay minerals increase at the base of the Los Monos Formation shales, with a reversal occurring in the underlying coarser formations (Santa Rosa, Nueva Asunción and Siracuas formations). The relative changes in peak intensities suggest changes in environments, which is confirmed through lithologic and paleontological evidence.

The section analyzed consists almost in its entirety of black marine shales of the Los Monos and Don Quixote formations and the intercalated sands, silts and shales of the Santa Rosa, Nueva Asunción and Siracuas formations (Fig. 88). These shales constitute important source rocks in the region, and generated oil and gas in the Carandaity subbasin.

Only one sample from Julia-1, and 4 samples from Katerina-1 were available. Fortunately, a large number of samples were available from the deepest well (Don Quixote-1) and 24 samples were selected based on lithology and age. Sample analysis included:

1. Bulk powder;
2. Air-dried oriented slides of the <2 micron fraction; and
3. Ethylene glycol-treated oriented slides of the <2 micron fraction.

Bulk powder samples were studied to determine the general mineralogical composition of the sediments. Oriented slides were analyzed to identify the clay fraction. These oriented slides were then treated with ethylene glycol to determine the unlikely presence -- due to the ages of the sediments involved-- of expandable clays (i.e., smectites). The variation of major reflection peak intensities was evaluated to recognize trends in the compositional characteristics of the sediments.

The samples were analyzed utilizing a Philips Norelco x-ray diffractometer operated at 40 kV and 20 mA, using Ni-filtered Cu $K\alpha$ radiation, a 2K scale factor, scanning speed of 2°/min., and a chart speed of 1 inch/min. Ground samples of approximately 50 micron size particles were provided by Pennzoil. The randomly oriented bulk powder samples were scanned in the range 2° through 65° 2Θ. Charts presented in this study, however, show peak intensity reflections up to 30° 2Θ, because this range covered the minerals present.

Two samples, Don Quixote-1, 3,300 and 9,496 feet (1,006 and 2,894 meters), did not produce a stable suspension during the preparation of oriented slides, and had to be treated with a deflocculant (0.25 % solution of Na-dithionate) to obtain an adequate suspension. The air dried and glycolated oriented slides were scanned in the range 2° through 35° 2Θ. Major reflection peak intensities were evaluated to identify trends in mineralogical contents through the sedimentary section.

Interpretation

Non-Clay Minerals

The non-clay mineralogy of the entire section consists mainly of two minerals, quartz and albite (Figs. 88, 89 and 90). The reflection intensities measured and compared were, for quartz, the 101 reflection, and for albite, the 002 reflection.

The reflection intensities for quartz and albite start with relatively low values at 1,900 feet (579 meters; Fig. 91), and increase sharply to reach their highest value at 2,400 and 2,900 feet (732 and 884 meters), respectively. These values decrease steadily with depth through the Los Monos shales towards the base of this formation. The decrease towards the base of the Los Monos Formation corresponds to a rise in sea level, as determined by lithologic and paleontologic information. This decrease in non-clay minerals is interpreted here as being related to the decrease in energy of the environment of deposition, resulting in the deposition of finer sediments. An increase in intensities --although below the high values of the middle and upper sections of the Los Monos Formation-- occurs in the coarser section corresponding to the Santa Rosa, Nueva Asunción and Siracuas formations. This increase reflects coarser sediments due to a shallower environment in a retreating sea. The sample in the Middle Ordovician shales at 9,496 feet Total Depth (2,894 meters) shows a marked decrease in reflection intensities for all minerals. The relative suppression of all reflection intensities at this depth could be due to unsatisfactory deflocculation during sample treatment.

Clay Minerals

The clay minerals, as evaluated in the <2 microns fraction in oriented slides and glycolated oriented slides, indicate varying concentrations of illite, kaolinite and chlorite (Figs. 89, 90, 92 and 93). The glycolated oriented slides did not reveal any expansion of clays (Figs. 89 and 90). The absence of smectites was expected because of their general absence in Paleozoic rocks. Smectites that were originally present would have all been transformed into illite (Garrels and McKenzie, 1971), and this is confirmed by this data.

Intensities of the reflections used for the observation of compositional trends are the (002) for illite, (002) for kaolinite, and (004) for chlorite. The sufficient number of samples of the Don Quixote-1 well --unlike the small number of the other two wells-- allows for the observation of some trends in reflection intensities.

Chlorite shows a relatively uniform sequence of intensity values (Fig. 91). Exceptions occur at 3,300 and 9,496 feet Total Depth (1,006 and 2,894 meters), with the lowest values, and at 6,800 feet (2,073 meters) with a high value. As with all other minerals, a significant drop in peak intensity (due probably to improper sample preparation) is observed in the last sample at 9,496 feet (2,894 meters) corresponding to the Middle Ordovician Don Quixote Formation.

Kaolinite shows a steady increase in reflection intensities in the section. Steep decreases occur at the base of the Los Monos Formation shales at 6,400 feet (1,951 meters), and at total depth of 9,496 feet (2,894 meters) in the Don Quixote Formation. The increase in kaolinite reflection intensities is accompanied by a decrease in albite reflection intensities. This relationship indicates an authigenic origin for at least part of the kaolinite minerals. The alteration of feldspars in the Santa Rosa Formation was confirmed through observation of petrographic thin sections (see Chapter II).

All mineral reflections, clay and non-clay, show a decrease in intensities at 3,300, 6,400 and 9,496 feet Total Depth (1,006, 1,951, and 2,894 meters). Moderate values occur in the coarse section (Santa Rosa, Nueva Asunción and Siracuas formations). As mentioned above, deflocculants had to be added to samples at 3,300 and 9,496 feet (1,006 and 2,894 meters). Nevertheless, reflection intensities remained low in both samples. No unusual conditions were noticed during the preparation of the 6,400 feet (1,951 meters) sample.

Summarizing, a relatively simple mineralogy comprises the sediments of the thick Paleozoic sequence of the Carandaity Subbasin. Albite and quartz reflection intensities show a general decreasing trend with depth, with an increase in the coarser section of the Santa Rosa, Nueva Asunción and Siracuas formations. Kaolinite, on the other hand, has a general trend of increasing reflection intensity values with depth, suggesting a connection between kaolinite and albite, in which albite is altered, resulting in the increase of kaolinite reflection intensities. The general decrease of reflection intensities at depths 3,300 and 9,496 feet (1,006 and 2,894 meters) might be due to inadequate sample preparation. Reflection intensity trends reflect changes in lithologies, and to a certain degree environmental characteristics. Non-clay mineral reflection intensities decrease in shaly, relatively deeper environments, and increase in coarser, shallower environments; and the reverse is true for clay minerals. The base of the Los Monos Formation at approximately 6,800 feet (2,073 meters) shows a decrease of non-clay minerals, and an increase in all clay minerals relatively to the underlying coarser sediments of the Santa Rosa, Nueva Asunción and Siracuas formations and the immediately overlying section of the Los Monos Formation. These marked changes in reflection intensities suggest a change of environments with a rise in sea level, as is indicated by paleontological and lithological evidence.

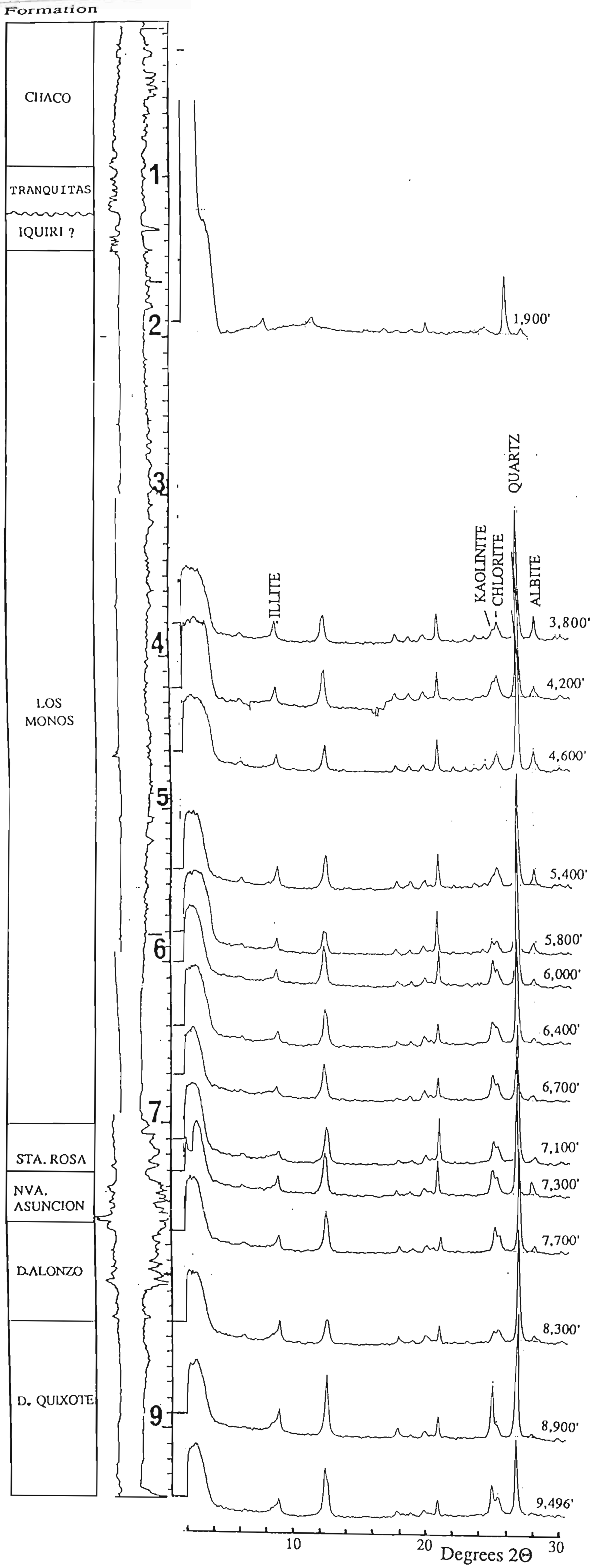


Fig. 88. Randomly oriented bulk powder x-Ray diffraction patterns of Don Quixote-1 well.

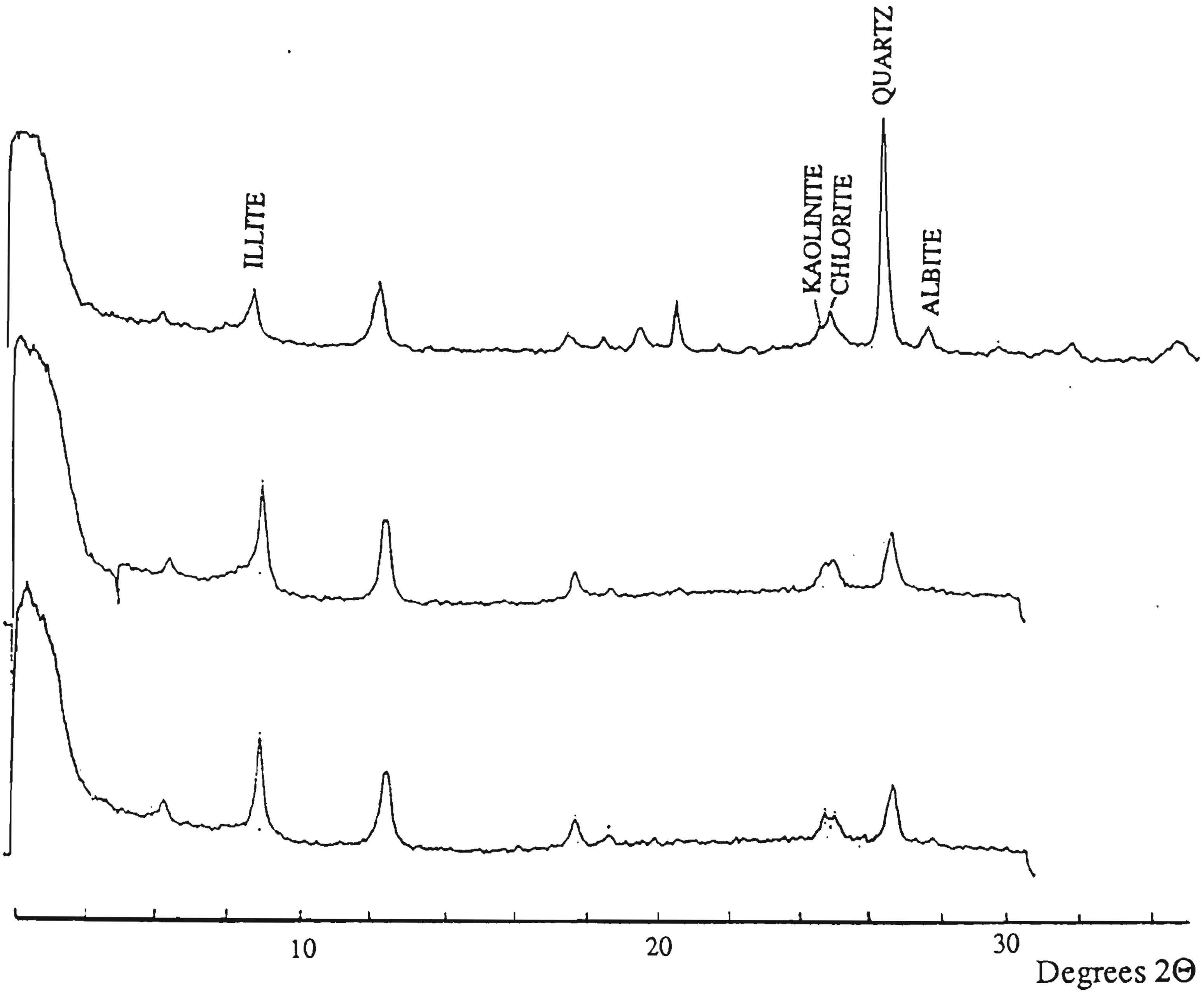


Fig. 89. X-Ray diffraction patterns of Julia-1 well (4,179 feet). Randomly oriented bulk powder (top pattern), oriented slides (middle pattern), and ethylene glycol-treated oriented slides (bottom pattern).

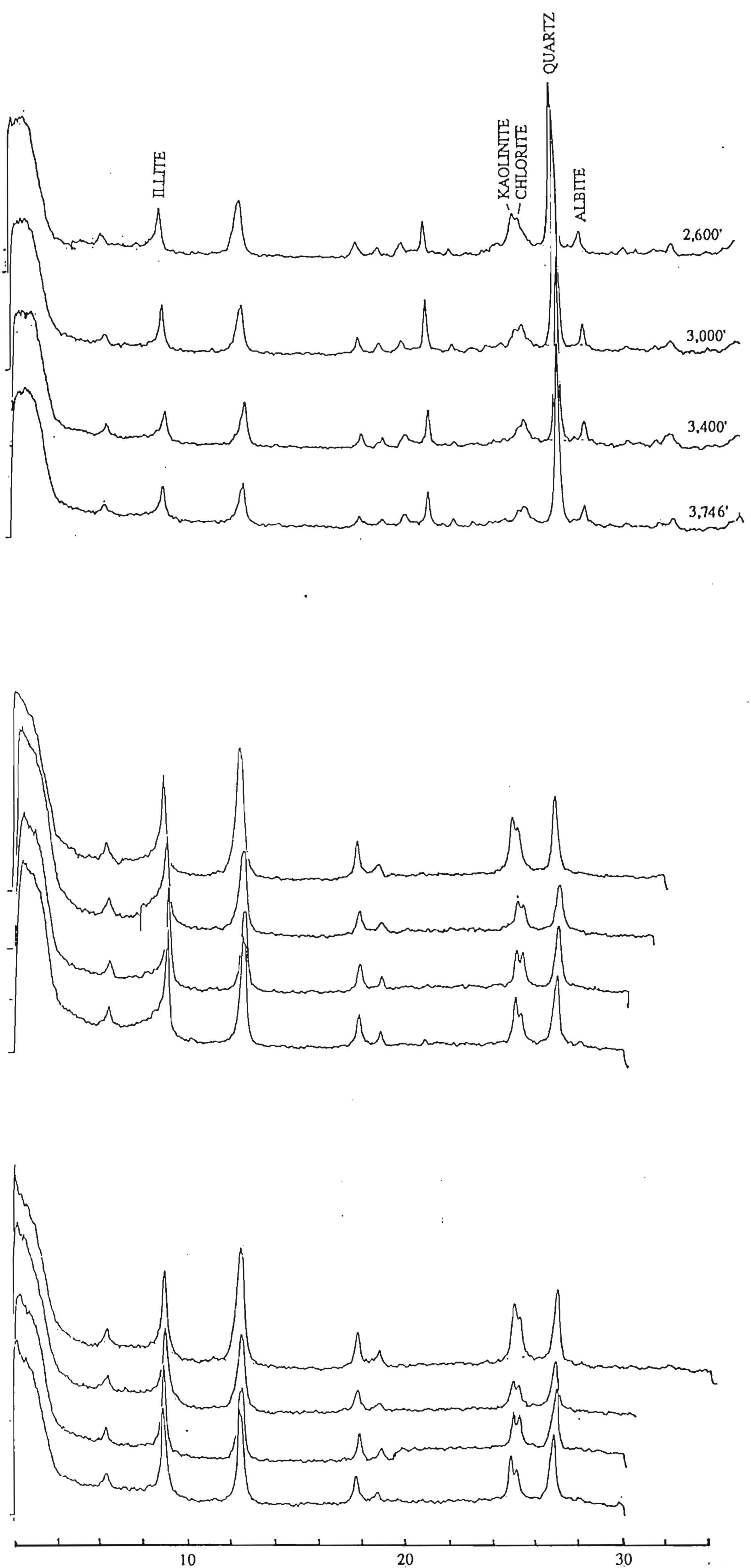


Fig. 90. X-Ray diffraction patterns of Katerina-1 well. The top set corresponds to randomly oriented bulk powder patterns; the middle set to oriented slides patterns, and the bottom set to ethylene glycol-treated oriented slides.

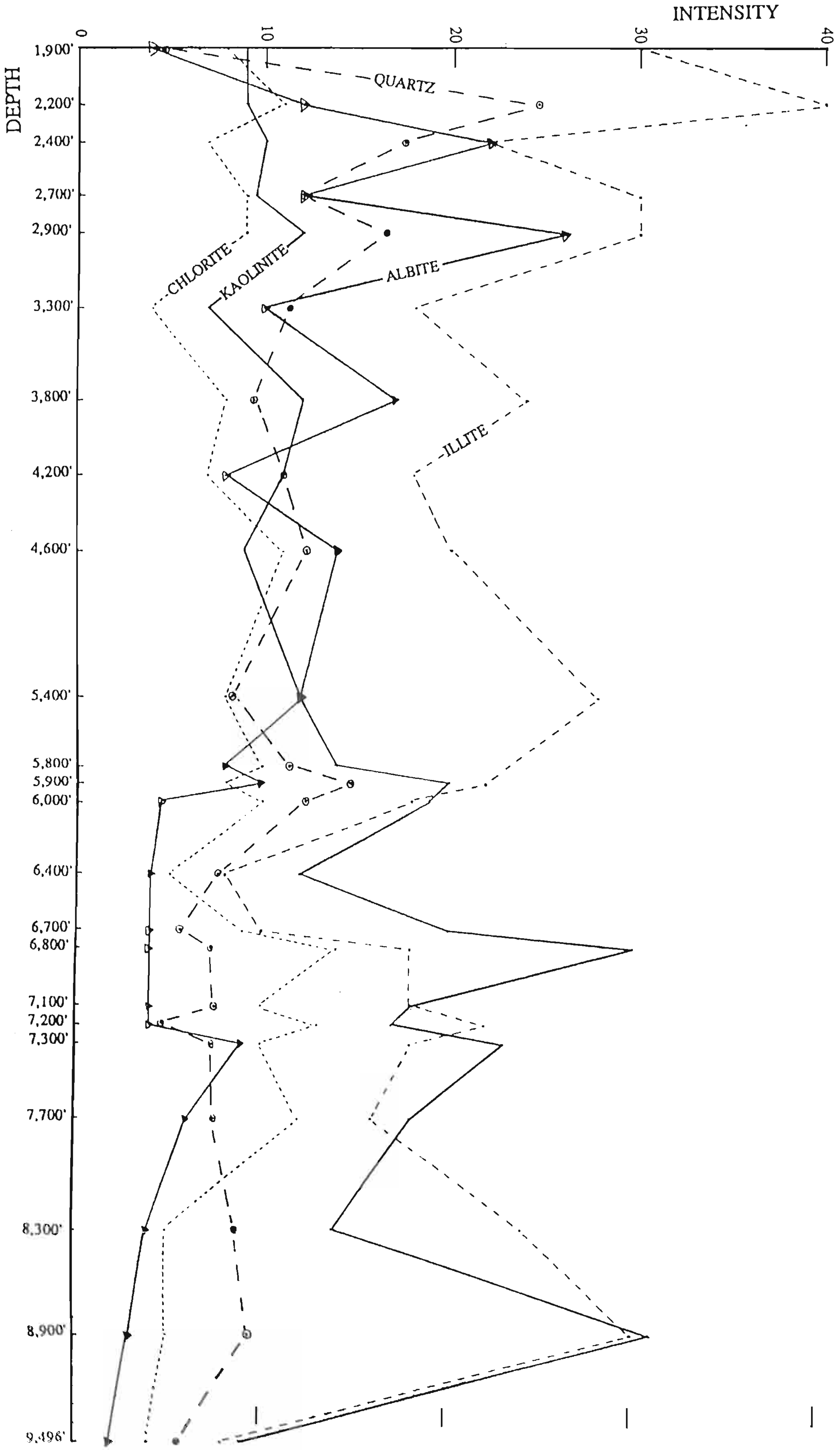


Fig. 91. Intensity X Depth chart of the five minerals determined in the Don Quixote-1 well samples. Albite and quartz peaks were obtained from bulk powder samples. Quartz values are 1/10 of the peak values measured. Intensity values of the clay minerals illite, chlorite and kaolinite were measured from oriented slides.

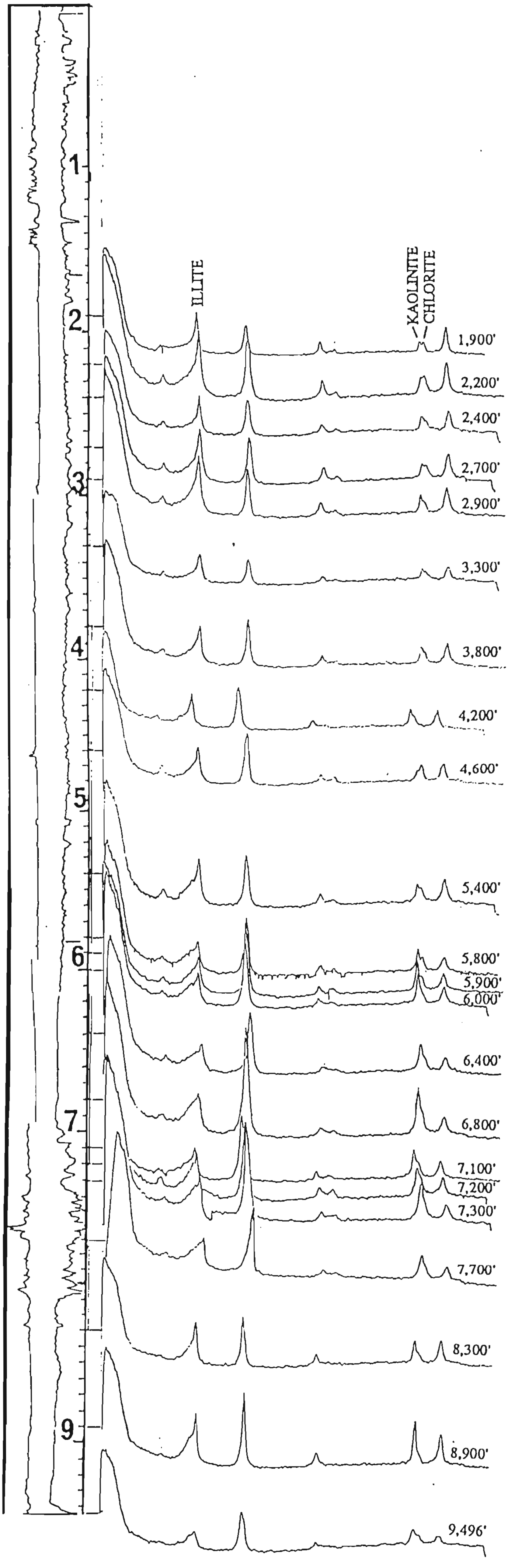


Fig. 92. X-Ray diffraction patterns of oriented slides of Don Quixote-1 well.

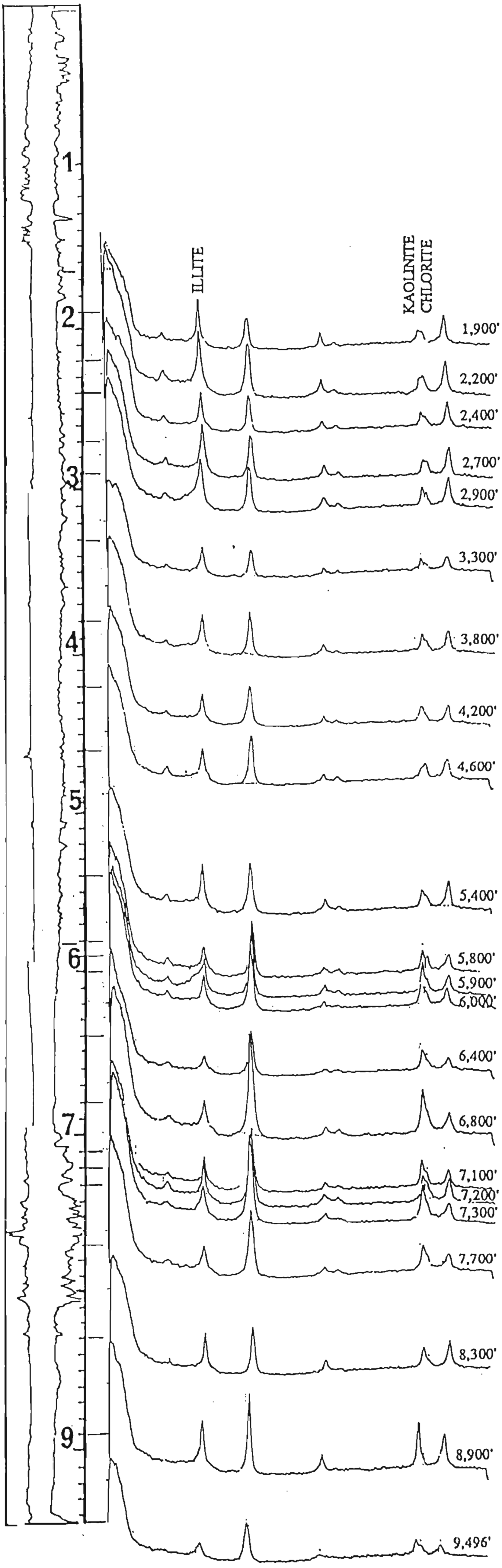


Fig. 93. X-Ray diffraction patterns of ethylene glycol-treated oriented slides of Don Quixote-1 well.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The Paraguayan Chaco occupies an area of approximately 240 thousand km^2 with virtually no outcrops. Four subbasins are found in the Paraguayan Chaco (Carandaity, Curupaity, Pirizal and Pilar). Direct information is very scarce. Only 38 wells -mostly shallow tests- were drilled to the present. Twenty-five wells were drilled in the Carandaity, 8 in the Pirizal and 3 in the Curupaity subbasins, and 2 in the remaining areas. No well tested the Pilar Subbasin.

Paleozoic sediments constitute most of the sedimentary fill of the Carandaity and Curupaity subbasins, and are very potent, exceeding 5,200 meters (>17,000 feet) in the Curupaity Subbasin. An almost complete Paleozoic section encompassing Lower Ordovician to Upper Permian sediments was penetrated in the study area. No well reached the crystalline basement or Cambrian sediments.

The presence of Cambrian sediments in the Paraguayan Chaco is likely to occur at greater depths than drilled thus far. This is because Cambrian sediments occur in Eastern Paraguay (Itapucumí carbonates and clastics), along the western margin of the Paraguay River, and in the surrounding areas in Bolivia and Argentina.

A thick section of Ordovician marine shales ranging from Early to Late Ordovician, not reached in the Southern Subandean Belt and Chaco of Bolivia, is herein informally referred to as the Don Quixote Formation. The name is derived from the first well that confirmed its age through palynology.

The stratigraphic interval from Upper Ordovician to Lower Devonian contains a sequence of intercalated fine sandstones, silts and shales. The Upper Ordovician segment of this unit is herein informally referred to as the Siracuas Formation.

The Silurian section in the Paraguayan Chaco is unlike the tilloid-containing Cancañiri or Zapla formations of Bolivia and Argentina, respectively, or the black shale Kirusillas Formation found in both countries. The Silurian section found in the study area consists of intercalated sandstones, silts and shales, and is herein informally referred to as the Nueva Asunción Formation in reference to the town in the western Chaco near the Don Quixote-1 well.

The Upper Ordovician to Lower Devonian section of intercalated sandstones, siltstones and shales probably extends throughout the Chaco, and may have connected with the sequences found in Eastern Paraguay. It is conceivable that at some time during the Ordovician, Silurian and/or Early Devonian, the Chaco continental platform waters connected with the Paraná Basin through the San Pedro Trough, given the occurrence of similar marine sediments in both areas and the proximity between the San Pedro Trough and the Orihuela-1 well, where marine sandstones of unknown age occur.

The Devonian System contains the thickest Paleozoic section in the Chaco, with over 3,600 meters in the Curupaity Subbasin. The Devonian sediments consist mostly of monotonous gray to black micaceous shallow marine shales representing distal facies. The earliest Devonian sediments were found in the Curupaity Subbasin. They were dated as Gedinnian, and correspond to the Santa Rosa Formation. The most active shallow depocenter during the Early Devonian was in the Santa Rosa-1 well area, with up to 1,200 meters (3,900 feet) of uniform shallow marine shales. Subsidence matched sediment supply in the Santa Rosa-1 well, as indicated by the uniform macrofauna.

Over 600 meters (1,970 feet) of Devonian continental redbeds (herein interpreted as Lower Devonian) occur in the López-1 well. This unit is herein informally referred to as the López Formation in reference to the well where it was penetrated.

The uppermost part of the Devonian (Frasnian-Fammenian) and parts of the Lower Mississippian (Tournaisian) show a transitional sequence of shallow marine to lagoon and marine-deltaic to continental environments in the Carandaity Subbasin. Few and scattered fossils of Early Pennsylvanian age were found in redbeds overlying the Lower Mississippian section. The presence of the Lower Mississippian sediments confirm the occurrence of the Tupambi Formation, and the Lower Pennsylvanian redbeds confirm the occurrence of the Tarija Formation in the Paraguayan Chaco.

The Pirizal Subbasin is a rift basin based on its tectonic evolution and sedimentary fill. The sedimentary fill of the Pirizal Subbasin is comprised of the Salta and Palo Santo Groups. The Salta Group consists of the Pirgua, Balbuena and Santa Bárbara Subgroups, whereas the Palo Santo Group (informal name used herein) consists of the Tranquitas, Paraná and Chaco formations. The Pirgua Subgroup corresponds to an early stage continental graben fill wedge controlled tectonically by faults. The thicker section is located along the northern Balbuena Fault. The top of the Pirgua sediments filled the graben and levelled the basin.

The Balbuena Subgroup (Lecho, Yacoraite and Olmedo formations) represents a transgressive interval and overlapped onto the Boquerón and Hayes arches. These three formations show evidence of some marine influence. The Olmedo Formation represents a regression of waters. The basin desiccated during the deposition of its Saline Member halite deposits. The Balbuena Subgroup and the thick continental deposits of the Santa Bárbara Subgroup have a symmetrical distribution along the axis of the Pirizal Subbasin.

An Atlantic marine incursion occurred during the Miocene, resulting in the deposition of the blue-green shales of the Paraná Formation. Marine and freshwater fossils and lithologies indicate a transition of environments between the upper Tranquitas, Paraná and Chaco formations.

Three sets of tectonic events affected the Paraguayan Chaco: Paleozoic, Cretaceous and Cenozoic events. Paleozoic tectonic events occurred during the (Early?) Devonian, (Late?) Carboniferous, Late Permian, and possibly at the base of the Silurian section. The

(Early?) Devonian event is reflected in an unconformity in the Central Chaco High separating (Lower?) Devonian marine from continental sediments. The Cerro León arch was elevated during the Carboniferous tectonic event, and separated the Carandaity from the Curupaity Subbasin. This Carboniferous event produced an erosional unconformity throughout the Curupaity Subbasin and most of the Carandaity Subbasin. Only the deeper areas of the Carandaity Subbasin were not affected. These deeper areas of the Carandaity Subbasin have a continuous section of Devonian to Carboniferous sediments deposited in westward regressing marine, transitional to continental environments. Renewed erosion during the Permian transected the (Upper?) Carboniferous section in the Curupaity Subbasin. The overlying sediments are of Late Permian to Early Triassic (Scythian) age. The Permian to Triassic section is also transected by an angular unconformity, and overlain by probable Tertiary to Quaternary sediments.

Cretaceous events affected mostly the rift-type Pirizal Subbasin, and range from Early-Cretaceous to Paleocene. Tectonic events in the Pirizal Subbasin include arching, erosion of the arch, faulting associated with volcanic activity, and a predominantly continental fill with some marine influence. Differential uplift occurred during the arching. The Hayes Arch and the easternmost part of the subbasin were uplifted higher, with erosion removing most or all of the Paleozoic sequence in these areas. Igneous rocks (126 +/- 3.5 m.y.) of the First Effusive Cycle in Palo Santo-1 suggest a synchronous rifting of the Pirizal Subbasin and its extension into Argentina. Movements along faults ceased almost completely after the Pirgua Subgroup was deposited, except in a few areas along the Balbuena Fault, where some minor adjustments occurred into the Miocene.

During the Cenozoic events the top of the Lumbrera Formation was eroded during the Late Paleocene-Early Eocene. This erosional surface marks the contact between the Salta and Palo Santo groups and is the effect in the Pirizal Subbasin of the elevation of the Eastern Cordilleras in Bolivia. This event placed the Chaco in a foreland basin position.

Over 1,300 meters (>4,265 feet) of the Devonian Los Monos Formation, in the Don Quixote-1 well, have source character (0.5% TOC) with mature shales that were subjected to an oil generation phase. The Lower Devonian shales in the Don Quixote-1 well generated high gravity oil near the top and wet gas and condensate towards the base. Devonian shales in the Curupaity Subbasin (Toro-1 well) also generated oil and gas. Ordovician shales (0.5% TOC), in the Don Quixote-1 well of the Carandaity Subbasin, are in a very mature organic facies (stage 4-) and generated only gaseous hydrocarbons (methane).

Relatively high temperature gradients occur in the proximity of the Cerro León and Boquerón arches, with values of approximately 2 °F/100 feet and higher. Temperature gradients in more central positions of the Carandaity Subbasin are approximately 1 °F/100 feet. The Toro-1 well of the Curupaity Subbasin has a relatively high temperature gradient with 1.9 °F/100 feet, which is probably related to faulting occurring to the south of the well. The Gato-1 well, however, has a significantly lower value of 1.6 °F/100 feet.

Areas of hydrocarbon exploration interest are determined by the distribution of Paleozoic and Upper Cretaceous-Lower Tertiary (Maastrichtian-Lower Paleocene) source rocks. Areas of interest in the Pirizal Subbasin are restricted to the western half of the subbasin (Yacoraite Formation source rock occurrence) and to the western half of the northern flank, with preserved sections of Devonian Los Monos Formation shales. In the Carandaity and Curupaity subbasins, potential targets are the Carboniferous section, sandy intervals (low porosity) within the Los Monos Formation shales, and the Upper Ordovician-Lower Devonian sandy section (Siracuas, Nueva Asunción and Los Monos formations). The Upper Ordovician-Lower Devonian section is mostly tight in the wells of the study area, and has low porosity and permeability in Argentina and Bolivia. This section's viability as a reservoir will depend on the location of fractured zones, or a different diagenetic history that resulted in higher porosities and permeabilities.

X-ray analysis of the Paleozoic section of the Don Quixote-1 well showed a relatively simple mineralogy. Non-clay minerals consist of quartz and albite. Clay minerals consist of illite, kaolinite and chlorite. No expansive clays were found. A direct relationship exists between the decrease in albite and the increase of kaolinite with depth, indicating an authigenic origin of some of the kaolinite from albite.

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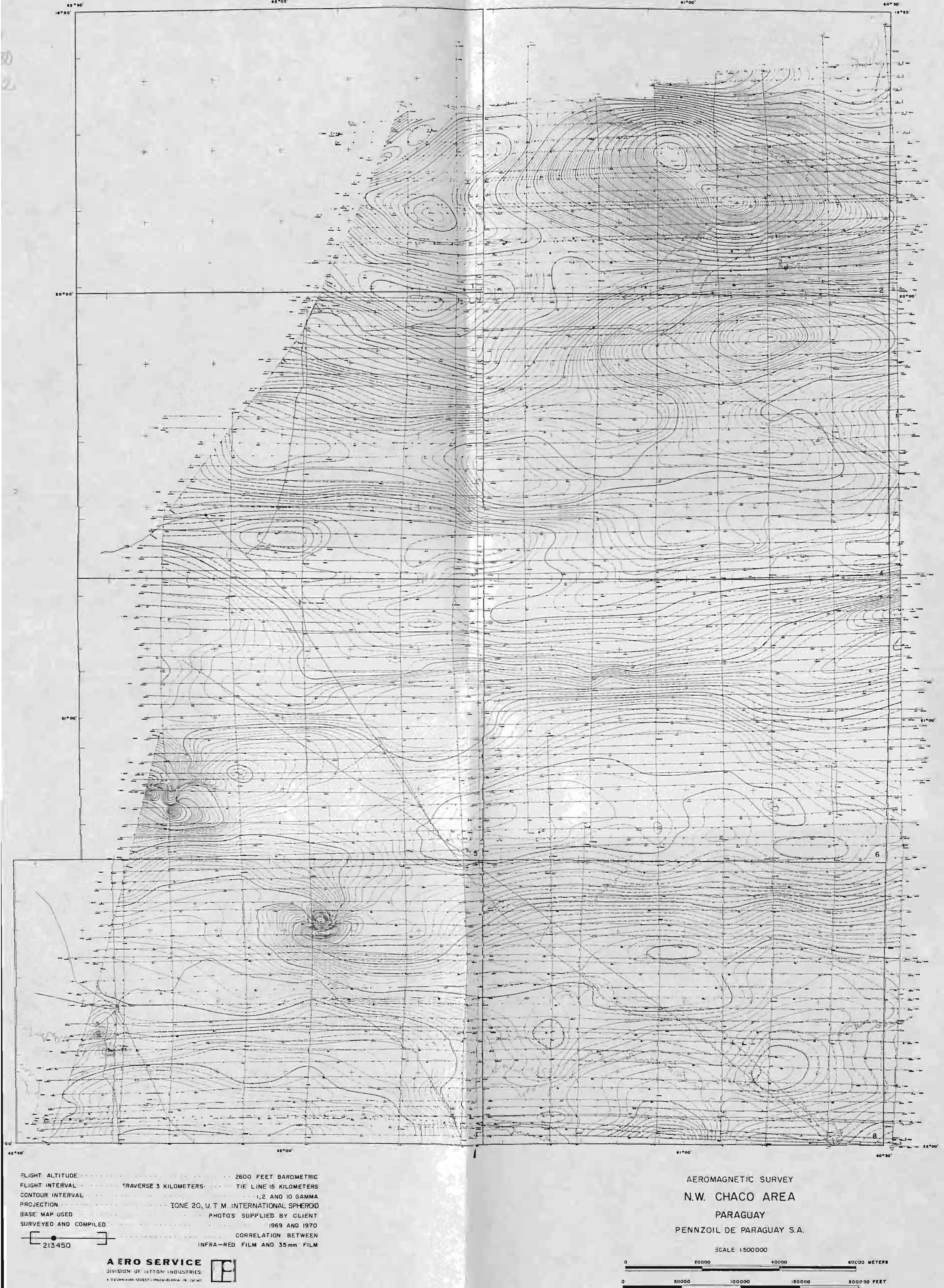

Fig. 38. Aeromagnetic map of parts of the Carandaity Subbasin and Cerro León Arch

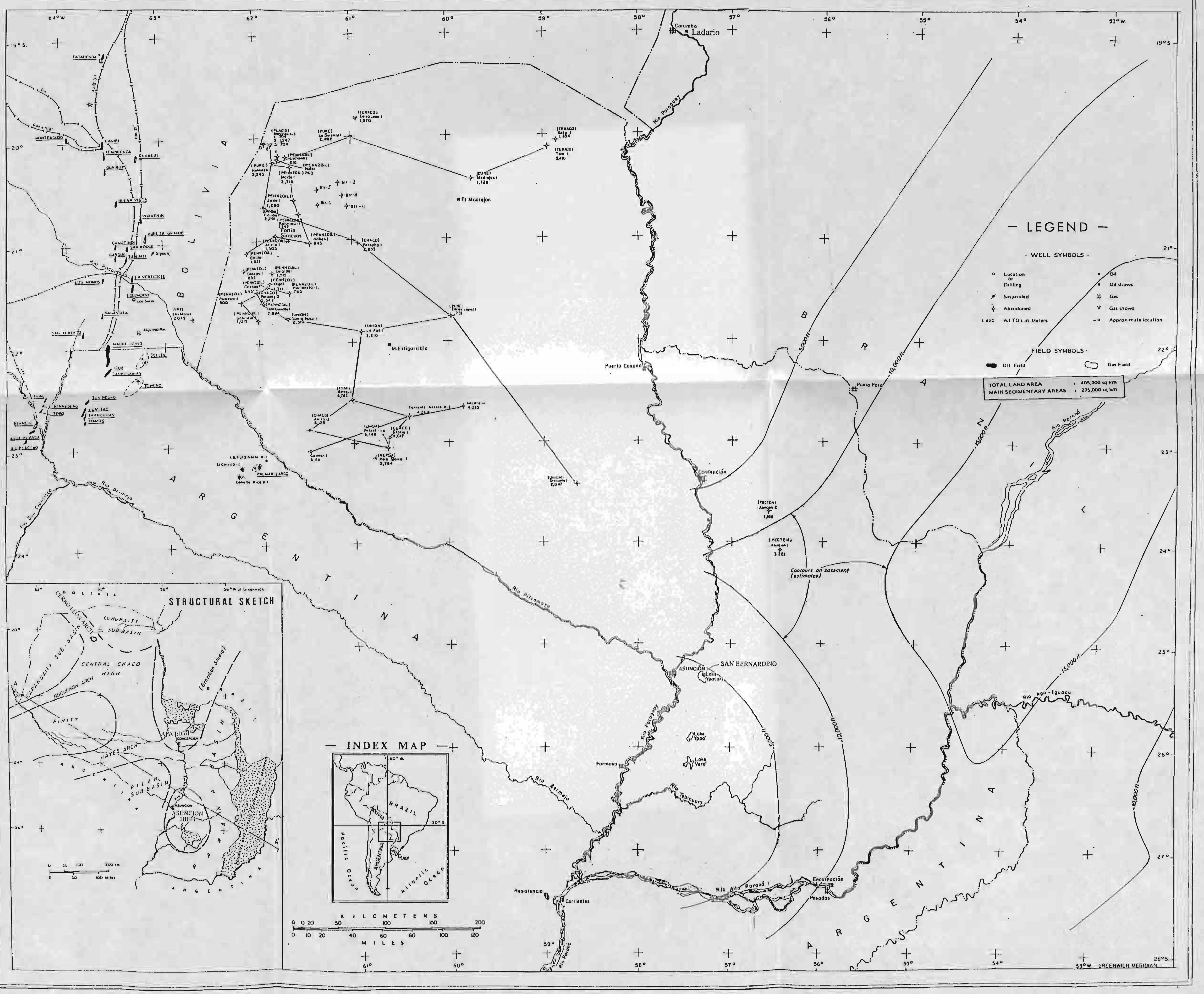

Fig. 1. Location map of the Paraguayan Chaco and surrounding areas. Modified from Banks and Robinson (1988).

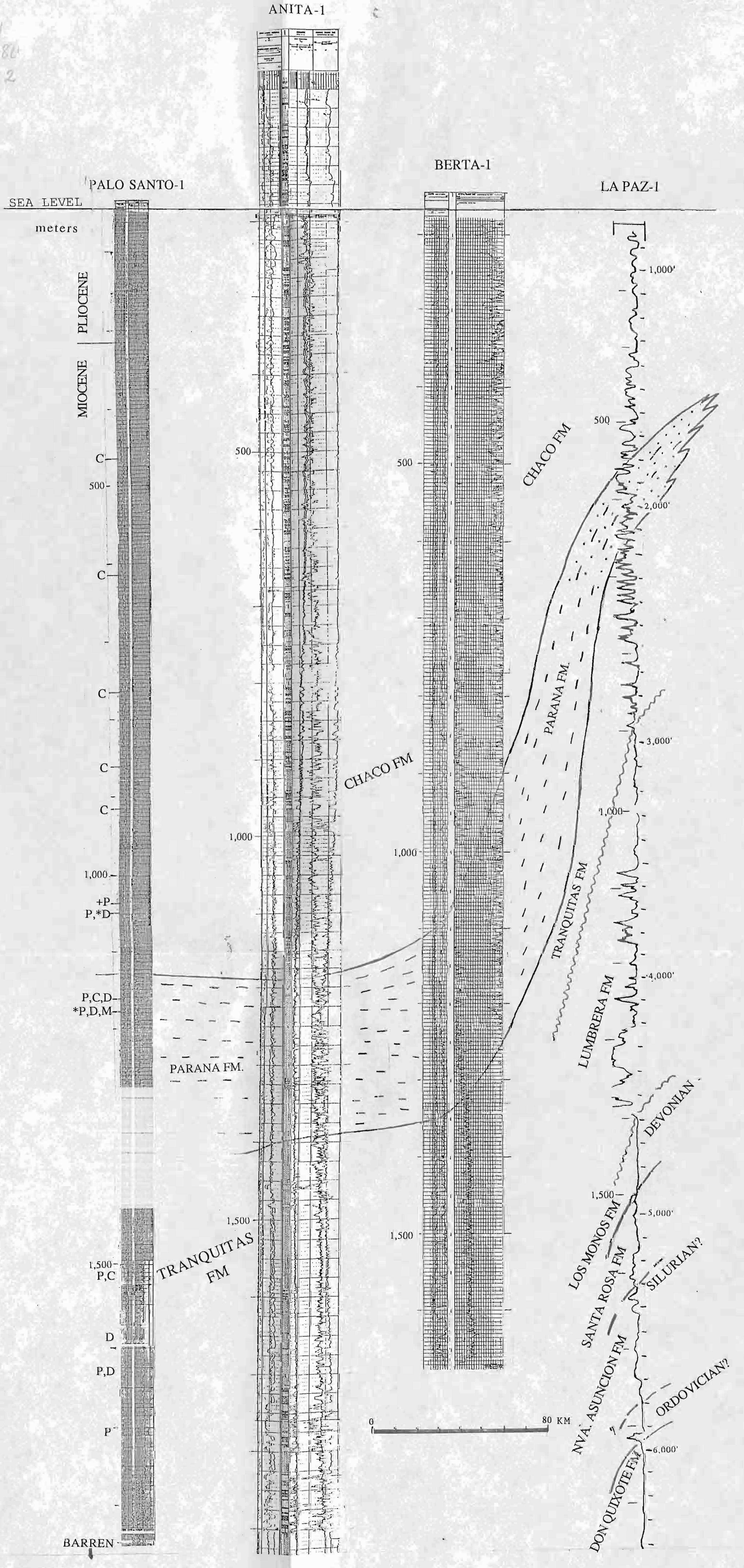

Fig. 76. N-S cross section showing the distribution of the green shales of the Paraná Formation. Fossils found in the Palo Santo-1 are: Cleistosphaeridium (C), Pediastrum (P), dinoflagellates (D), microforaminifers (M). (+) abundant, (*) common.

991
No.80
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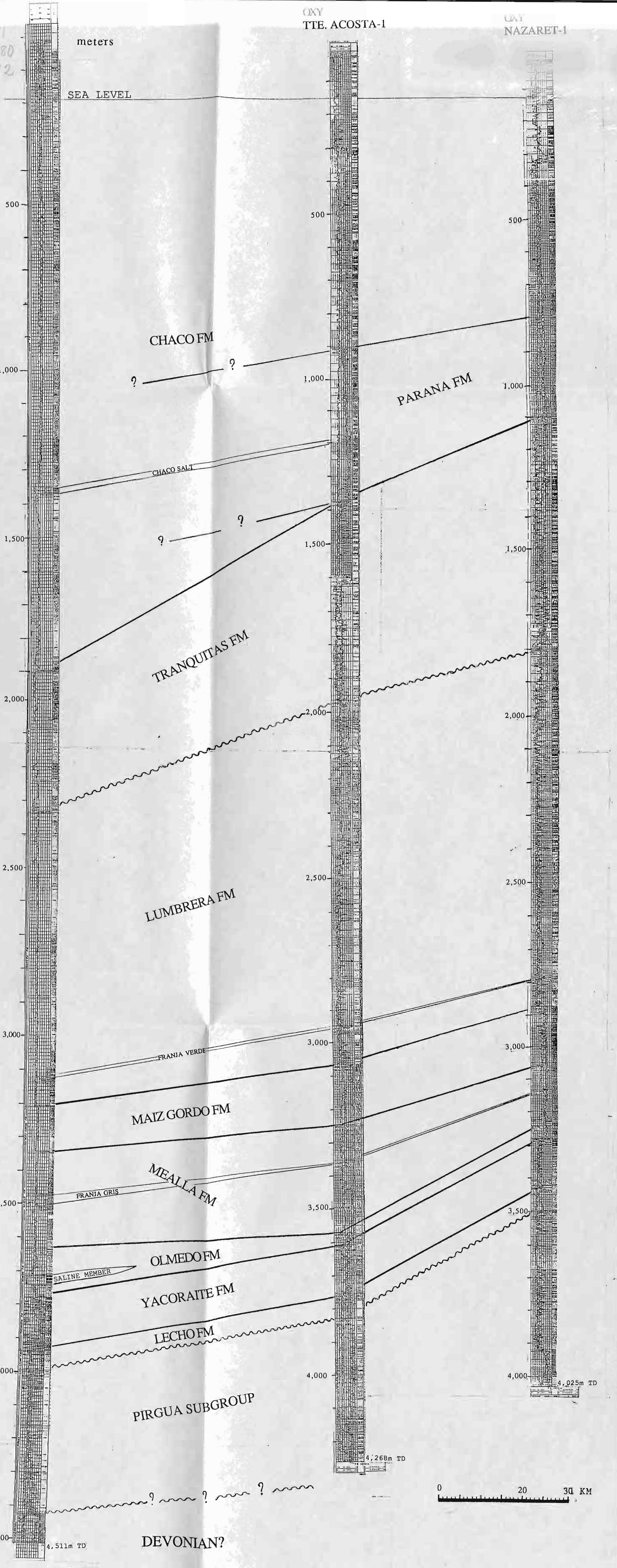

Fig. 72. SW-NE cross section along the axis of the Pirizal Subbasin between Occidental wells Carmen-1, Teniente Acosta-1 and Nazaret-1.