Phanerozoic Tectonics and Sedimentation in the Chaco Basin of Paraguay, with Comments on Hydrocarbon Potential

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Abstract

This study of the Chaco basin is based on field studies of outcrops and on exploration data. The Chaco basin covers 246,725 km^2 of western Paraguay and consists of several depocenters or subbasins, each with a unique tectonostratigraphic record. In the northwest, the Curupaity and Carandaity subbasins contain a well-developed Paleozoic succession. In contrast, Mesozoic subsidence was marked in the southern Pirity and Pilar subbasins and in the shallow Bahia Negra platform and San Pedro low to the east. These depocenters are separated by structural highs. Uppermost Proterozoic–Recent sedimentary sequences are present in the Chaco basin.

The subsidence history of the Chaco basin is recorded in four major unconformity-bounded sequences. Northwest- and northeast-oriented structural lineaments of Eocambrian Brasiliano origin controlled the patterns of subsidence. Mesozoic extensional tectonics related to the opening of the South Atlantic reorganized the structural pattern of the Chaco basin; this episode is expressed in a system of half-grabens. Cenozoic Andean orogenesis imposed the final structural readjustment and established the Chaco area as a modern foreland basin.

Upper Devonian marine shales and Upper Cretaceous shales and carbonates are the primary source rocks for hydrocarbons. The principal reservoir zones are Carboniferous channel sandstones in the Curupaity and Carandaity subbasins and stratigraphic and structurally controlled sandstone reservoirs of Mesozoic age in the Pirity subbasin.

Resumen

Este trabajo se basa en datos de secuencias estratigraficas aflorantes y de actividades exploratorias. La cuenca del Chaco ocupa con 246,725 km^2 la región occidental del Paraguay y consiste de varios depocentros o subcuencas, cada uno con un registro tectono-estratigráfico único. Al noroeste las subcuencas de Curupaity y Carandaity representan áreas con secuencias paleozoicas bien desarrolladas. En contraste, subsidencia mesozoica es marcada en las subcuencas de Pirity y Pilar al sur, como también en la plataforma de Bahía Negra y el bajo de San Pedro al este. Estos depocentros están separados por altos estructurales. Sedimentos desde el Proterozoico superior al reciente estan presentes en la cuenca del Chaco.

La historia de subsidencia de la cuenca del Chaco es registrada en cuatro ciclos secuencionales principales, limitados por discordancias. Lineamentos estructurales orientados al noroeste y noreste, de origen eocámbrico del ciclo Brasiliano, controlaron el estilo de la subsidencia. La tectónica distensional mesozoica relacionada a la apertura del Atlántico Sur reorganiza la disposición estructural de la cuenca del Chaco. Este episodio es manifestado en un sistema de subcuencas asimétricas. La orogénesis Andina del Cenozoico impone los últimos reajustes estructurales y establece el área del Chaco en una planicie promontoria moderna.

Lutitas marinas del Devónico superior y lutitas-carbonatos del Cretácico superior son las principales rocas generadoras para hidrocarburos. Areas de mayor potencial de reservorio son areniscas de paleocauces carboníferos en las subcuencas de Curupaity-Carandaity, y trampas estratigráficas-estructurales del Mesozoico en la subcuenca de Pirity.

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INTRODUCTION

The Chaco basin covers more than 60% of the Republic of Paraguay, an area of 246,725 km^2 (Figure 1). The Chaco is a broad Quaternary plain with an average elevation of only 160 m above sea level. Outcrops of Paleozoic and Mesozoic strata occur in the northern Chaco and along the Paraguay River (Figure 2). The Paraguayan Chaco borders Bolivia to the north and west. To the south and east, the Chaco continues into Argentina and connects to eastern Paraguay and Brazil. Hence, it is also known as the Chaco-Paraná basin.

Interpretation of the stratigraphic and tectonic evolution is based on outcrop as well as subsurface hydrocarbon and groundwater exploration data (PNUD, 1978; Wiens, 1989). Several hundred water wells have been drilled throughout the Chaco. Hydrocarbon exploration activities from 1947 to 1993 have contributed a further 41 exploration wells (see Appendix). These data are complemented by 11,500 km of seismic lines and a general coverage by aeromagnetic surveys of the southwestern, western, and northern Chaco.

There are four subbasins in the Paraguayan Chaco (Figure 3): (1) the Curupaity subbasin in the north, containing 3 hydrocarbon test wells; (2) the Carandaity subbasin in the west, with 28 hydrocarbon test wells; (3) the Pirity subbasin in the southwest, with 8 hydrocarbon wells; and (4) the Pilar subbasin in the south, which has no test wells to date. These four subbasins were periodically yoked together to form the broader Chaco basin complex.

The Curupaity and Carandaity subbasins are essentially Paleozoic depocenters, while the Pirity and Pilar subbasins are attributed to Mesozoic extension. The Paleozoic–Mesozoic San Pedro low to the east is a westward extension of the Paraná basin and has no wells on the Chaco side. Finally, the Paleozoic Bahia Negra platform to the northeast, also without wells, is largely interpretative (Figure 3). These depocenters are separated by intervening arches.

The Chaco basin (Figure 4) is a modern foreland basin between the Andean ranges to the west and the Brazilian shield to the northeast. Toward the east and south, it merges with the Paraná and Pampa basins, respectively. The tectonic style of the Chaco basin is characterized by northwest- and northeast-oriented structural lineaments of Eocambrian Brasiliano cycle origin. Differential reactivation of these fabrics through Phanerozoic time resulted in four distinct phases of subsidence: early Paleozoic, late Paleozoic, late Mesozoic, and Cenozoic (Figure 5). The phases are separated by erosional unconformities or marked by nondeposition or low sedimentation rates. While the Paleozoic phases reflect mild subsidence and local structural readjustments, the Mesozoic basins were subjected to a general reorganization of the structural styles by extension along predominantly northeast-oriented lineaments related to the Atlantic opening. Finally, a Cenozoic phase was caused by the Andean orogeny and accompanying regional structural adjustments.

Figure 1—Map of South America showing the location of the Paraguayan Chaco basin and its regional geologic setting.

The Phanerozoic Chaco basin is characterized stratigraphically by three episodes and styles of sedimentation (Figures 4, 5). First, clastic and carbonate sedimentation from the latest Proterozoic to Early Permian occurred in marine and continental environments on a platform and locally subsiding basins. Second, terrigenous clastic and carbonate sedimentation of Late Jurassic–Early Cretaceous to middle Eocene age formed thick continental fills in rift basins, with local marine transgression. Third, terrigenous clastic and evaporitic sedimentation with local marine incursions occurred from the middle Eocene to Quaternary throughout the Chaco basin in a foreland basin setting.

GEOLOGIC SETTING

The tectonic history of the Phanerozoic Chaco basin started during the intense thermotectonic Brasiliano cycle (680–450 Ma), when carbonate and clastic sequences of the Eocambrian Itapucumí Group were deposited. The Brasiliano basins evolved through extensional and compressional phases (Zalan, 1987). Thrusting along the edges of the basins and acid magmatism (680–580 Ma) affected southeastern and northeastern Paraguay (Cordani, 1984; Wiens, 1986). This Brasiliano event marks the initiation of the Chaco and Paraná basin subsidence

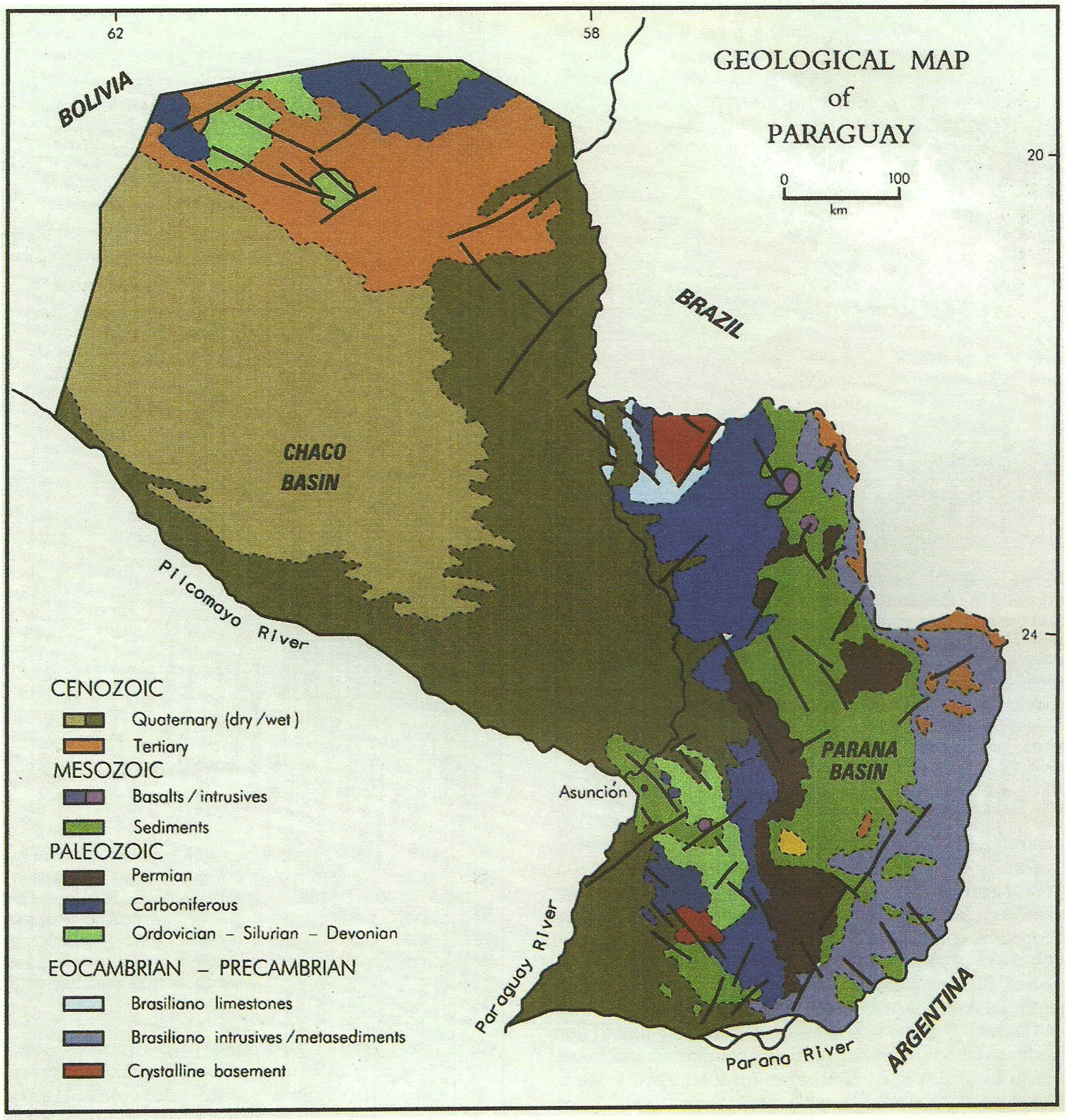

Figure 2—Simplified geology of Paraguay. The study area of the Paraguayan Chaco basin is on the western side of the Paraguay River.

(Zalán, 1987) and establishment of the northwest-southeast and northeast-southwest structural framework (Figure 6).

This complex tectonic fabric is expressed as basement highs such as the Río Apa and Río Tebicuary subcratonic blocks, platforms on which the carbonate Itapucumí Group was deposited, and local areas of subsidence in the Carandaity and Curupaity regions (Figure 5).

Paleozoic

For much of the Paleozoic, the Chaco basin was part of a relatively stable area of shallow marine and continental sedimentation south of the Brazilian shield (Figures 1, 5). The Paleozoic succession is dominated by terrigenous clastics.

An almost complete Ordovician sequence of the Cerro

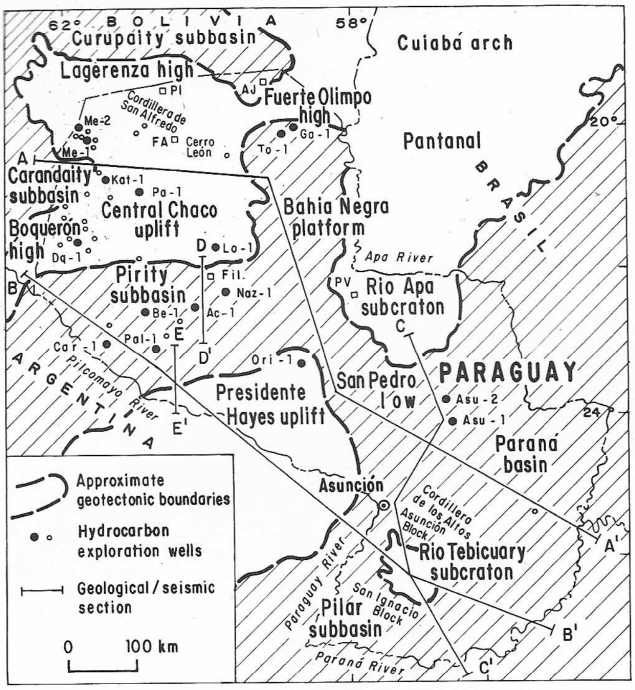

Figure 3—Major Cretaceous tectonic units of Paraguay showing the distribution of hydrocarbon exploration wells and the locations of geologic and seismic sections mentioned in the text. Abbreviations: Fil, Filadelfia; PV, Puerto la Victoria; AJ, Adrian Jara; FA, Fortin Aroma; PI, Palmar de las Islas; Me-1, Mendoza-1 well; Me-2, Mendoza-2 well; To-1, Toro-1 well; Ga-1, Gato-1 well; Kat-1, Katerina-1 well; Pa-1, Parapití-1 well; Dq-1, Don Quijote-1 well; Lo-1, Lopez-1 well; Car-1, Carmen-1 well; Pal-1, Palo Santo-1 well; Be-1, Berta-1 well; Ac-1, Tte.Acosta-1 well; Naz-1, Nazareth-1 well; Ori-1, Orihuela-1 well; Asu-1, Asunción-1 well; Asu-2, Asunción-2 well.

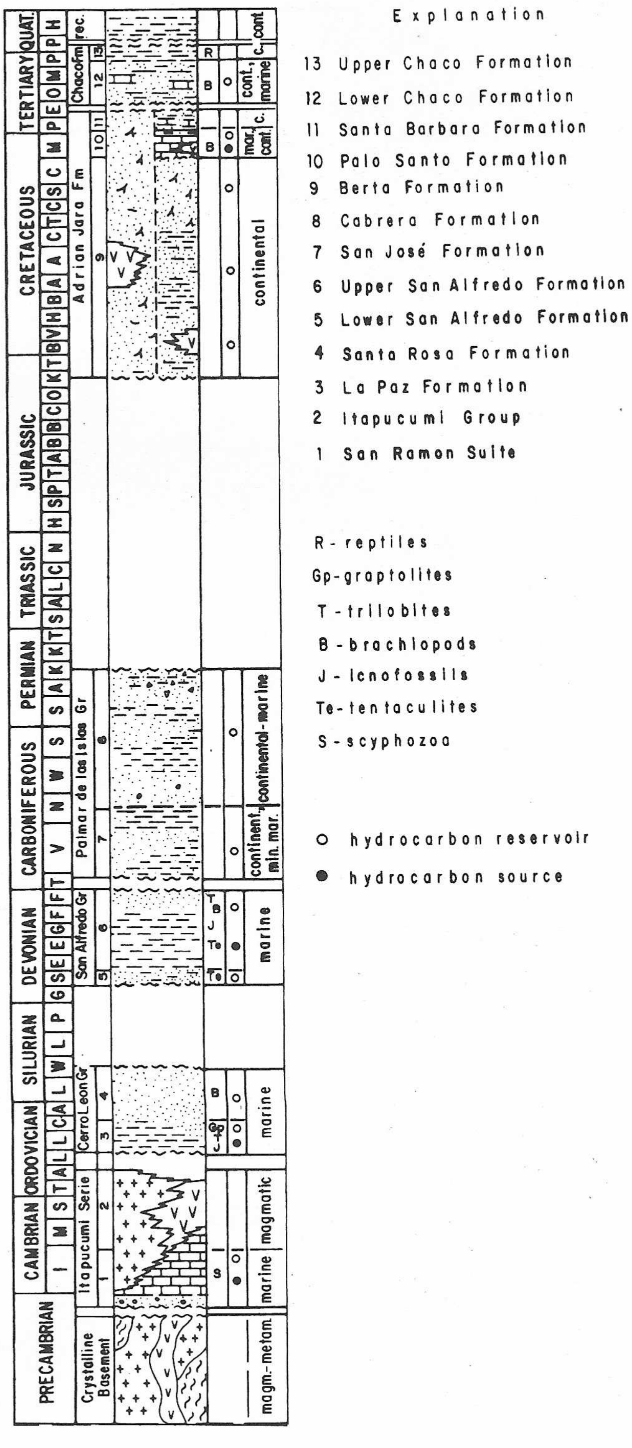

Figure 4—Simplified lithostratigraphic column of the Paraguayan Chaco basin.

León Group is preserved in the Don Quixote-1 well in the Carandaity subbasin. The Asunción-1 well in the San Pedro low contains Middle–Upper Ordovician sedimentary rocks of the Caacupé Group. Elsewhere, the succession is thin or absent, suggesting differential subsidence and local erosion.

Outcrop geology in southeastern Paraguay and in the northern Chaco basin suggests that continuous sedimentation in Ordovician–Devonian time resulted from a major transgressive-regressive cycle. A regional Lower Silurian unconformity associated with the Zapla tillites in the Chaco basin (Russo et al., 1979) has not been recognized in the Paraguayan Chaco. Local Devonian transgression deposited the San Alfredo Group in western and northern Chaco (Harris, 1959).

The broadscale geology suggests that a large sedimentary platform was established in the Ordovician and persisted until the Mesozoic. Only the Curupaity, Carandaity, and San Pedro depocenters experienced continuous subsidence, apart from the main Paraná basin.

A pronounced angular unconformity separates the Devonian and Carboniferous successions in much of the northwestern Chaco. Subsequent tectonism resulted in movement of structural basement blocks and local erosion across uptilted crests where Upper Carboniferous continental glacial sediments and Lower Permian shallow marine sequences of the Palmar de las Islas Group have an erosional contact. Locally the Permian rests on Devonian shales (Lobo et al., 1976). Only in the deeper western parts of the Carandaity subbasin is a complete section of Devonian–Upper Carboniferous and

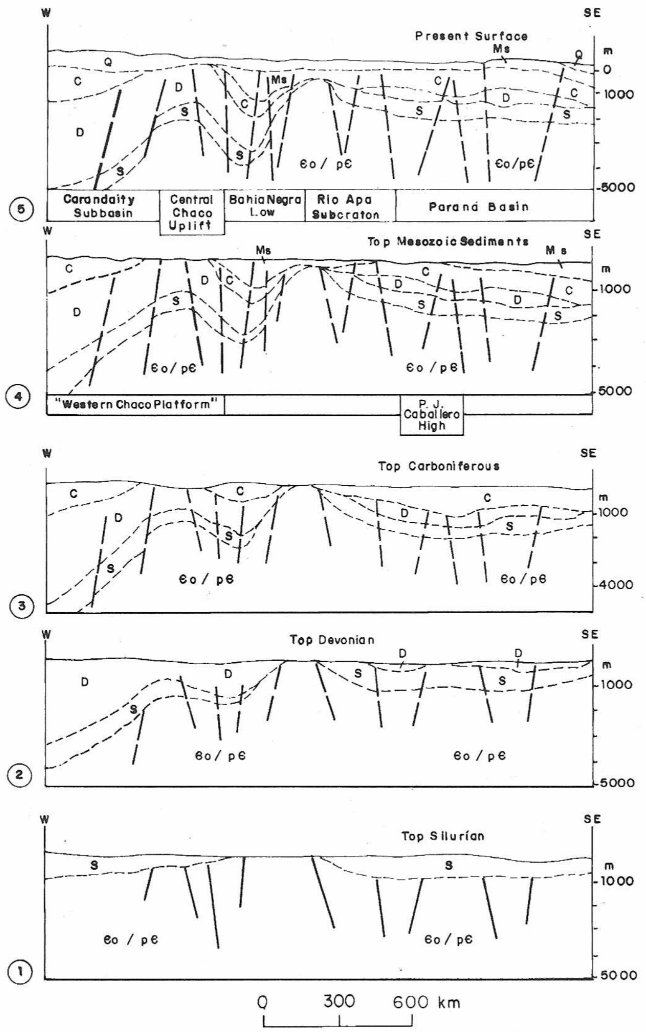

Figure 5—West-southeast cross sections showing the Phanerozoic evolution of the Paraguayan Chaco basin and the western Paraná basin (Ordovician–Silurian to Recent surface) (section A–A' on Figure 3). Note the Paleozoic migration and diversification of depocenters, as well as the Mesozoic structural reorganization and Cenozoic readjustment and inversion features.

Lower Permian sedimentary rocks preserved. In the Curupaity subbasin, an erosional unconformity separates Carboniferous–Permian and Mesozoic sequences.

Paleozoic sedimentation in the Chaco basin was controlled by northwest and northeast Eocambrian block-type structural trends. Vertical and horizontal movements were generally minor, but nevertheless sufficient to form depocenters and intrabasinal highs, as well as controlling the distribution of sedimentary facies.

Mesozoic

Fluvial and eolian sedimentation during the Triassic filled depressions (Bianucci et al., 1981). In the northern Chaco, the environment changed gradually to a desert landscape, blanketing the remaining topography. These strata are included in the lower Adrian Jara Formation. A major Mesozoic extensional event corresponding to the opening of the South Atlantic (230–65 Ma) is recorded for the main Adrian Jara Formation in the Curupaity subbasin. Its equivalents in the Pirity subbasin are the Berta, Palo Santo, and Santa Barbara formations.

The tectonic style reflects pervasive extension from Early Cretaceous to middle Eocene time (Figure 6). Figures 7 and 8 show the seismic expression of these Mesozoic rift basins. The geometry of the former subbasins and highs was modified substantially. The Carandaity and Curupaity subbasins became relatively stable, with only low sedimention rates. Further uplift of existing highs established new depositional centers.

Three new subbasins subsided along northeast-southwest axes: the Pirity and Pilar subbasins and the Bahía Negra platform. Continental sedimentation was widespread. In the Pirity subbasin, a short marine incursion of Late Cretaceous age came from the southwest. Basic to alkaline magmatism (135–108 Ma and about 70 Ma) is characteristic. Mesozoic rifting is believed to have established the principal structures and initiated maturation of potential source rocks for hydrocarbon generation. The final configuration of the subbasins, structural highs, and platforms was only completed toward the end of the Atlantic phase of extension (Zalán, 1987).

The Pirity subbasin is the best explored of the subbasins in the Chaco. Intense en echelon faulting in northeast-southwest and NNE-SSW directions caused differential vertical and transverse movements, resulting in an asymmetric half-graben structure. Local basic magmatic activity accompanied the event.

The sedimentary infill is mostly continental, except for periodic marine influence from the southwest as far as the Acosta-1 well, depositing the main section of the Palo Santo Formation. Sediments were deposited in alluvial fan, fluvial, and lacustrine settings, with local eolian tracts. The marine sediments are represented by carbonates, clastics, and evaporites. The thickness of this sedimentary succession varies up to 4000 m.

Toward the northeast in the Filadelfia area, the Pirity subbasin gradually loses its identity and records minor sedimentation. The extensional deformation shifts into the Bahía Negra platform and the initiating Pantanal subbasin.

Cenozoic

The growth of the Andean ranges to the west of the Chaco basin (50–35 Ma) created a new source for sediments and essentially excluded marine influence from that direction. Tectonic and magmatic responses are recorded in the Asunción and San Ignacio blocks along the edge of the basement in eastern Paraguay as inverted rift basin remnants with local nephelinitic magmatism (49–40 Ma).

The subbasins and highs of the Chaco basin that were established during the Mesozoic became covered by the thick continental cover of the Chaco Formation. Slight reactivation of structures in the Mesozoic are attributed

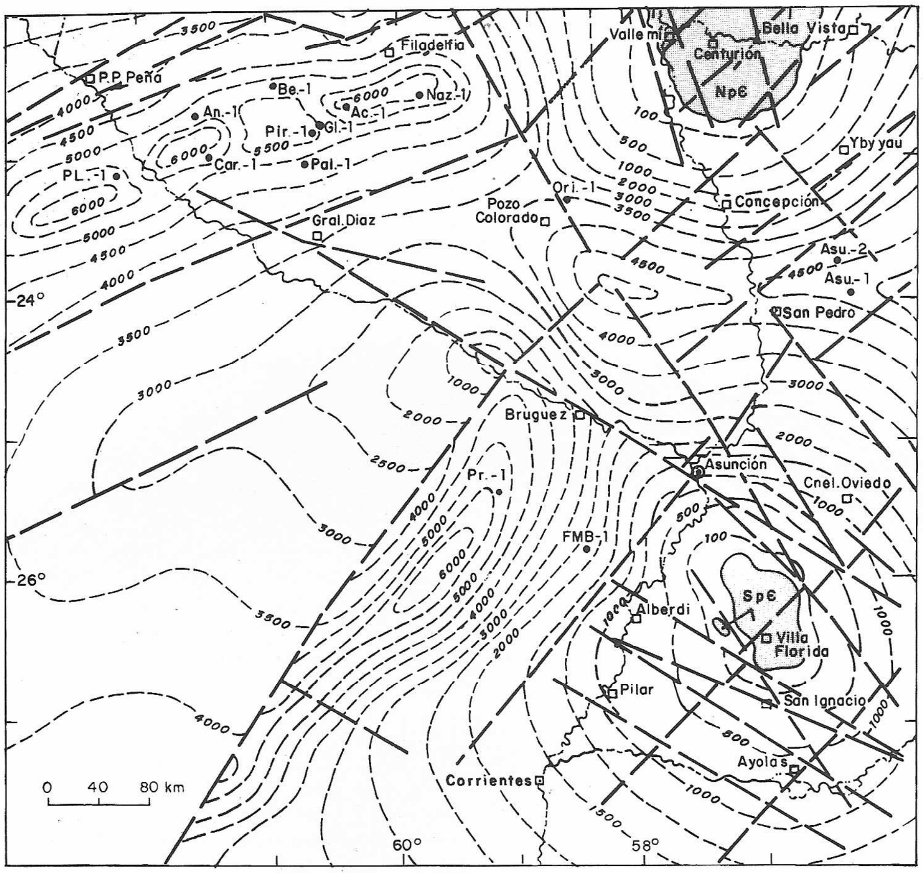

Figure 6—Southern Paraguay showing regional tectonosedimentary framework (thickness contours in meters). Abbreviations: NpЄ, Río Apa subcraton; SpЄ, Río Tebicuary subcraton; Be-1, Berta-1 well; An-1, Anita-1 well; Car-1, Carmen-1 well; Pir-1, Pirizal-D1 well; Gl-1, Gloria well; Pal-1, Palo Santo-1 well; Ac-1, Acosta-1 well; Naz-1, Nazareth-1 well; Asu-1, Asunción-1 well; Asu-2, Asunción-2 well; FMB-1, Mariano Boedo-1 well (Argentina); Pr-1, Pirané-1 well (Argentina); PL-1, Palmar Largo-1 well (Argentina).

to Tertiary tectonism. That some of these structures are still active is evidenced by internal drainage patterns in the Bahía Negra–Pantanal area and weak seismic activity.

PHANEROZOIC STRATIGRAPHY

The Phanerozoic succession in the Paraguayan Chaco ranges from Eocambrian to Recent. This interpretation is based on outcrops in the northern Chaco basin and on exploration data and is accompanied by outcrop and well data from eastern Bolivia (e.g., Tucavaca, Roboré, and Santiago de Chiquitos), outcrop and well data from the sub-Andean belt of Bolivia and Argentina, hydrocarbon exploration data from the Argentinian Chaco, and geologic data from eastern Paraguay (Figures 2, 9). The Precambrian basement beneath the Chaco is poorly understood. Nevertheless, it is believed to resemble the surrounding Río Apa and Río Tebicuary subcratonic blocks of eastern Paraguay or the Brazilian shield of eastern Bolivia.

Paleozoic

The *Itapucumí Group* is of latest Proterozoic–Cambrian age. Outcrops occur along the Paraguay River in the area of Puerto La Victoria. It is correlative to Eocambrian sedimentary rocks of the Corumbá Group in Mato Grosso do Sul, Brazil, and the Tucavaca Group in eastern Bolivia (Wiens, 1986) (Figure 10).

The Itapucumí Group is subdivided into a basal transgressive unit (shale, arkosic sandstone, and conglomerate beds up to 25 m thick) and a major calcareous sequence (Wiens, 1986). The carbonate interval consists of bituminous and laminated limestones that alternate with abundant oolitic and conglomeratic beds and interbedded shales, parts of which show grades of metamorphism. The Itapucumí Group is 250–400 m thick. Biostratigraphic dating is based on algal remains and Scyphozoae remnants and suggests a latest Proterozoic–Cambrian age (Beurlen and Sommer, 1957; Correa et al., 1979; Hahn et al., 1982; Hahn and Pflug, 1985; Aceñolaza et al., 1989). These deposits were generated by transgression over a continental platform, resulting in a shallow, warm marine environment.

The *Cerro León Group* is of Early Ordovician–Silurian age (Figures 4, 9). It crops out in the Cerro León massif in the northern Chaco basin (Wiens, 1991) and in the Cordillera de los Altos area of eastern Paraguay. Only one exploration well in the Carandaity subbasin has reached Lower Ordovician strata (Parapití-1 well) (Figures 11a, b). This section represents a transgressive-regressive cycle linked to the geodynamic evolution of the early Paleozoic Pacific margin.

Although the lowest Ordovician levels reached in the Chaco basin contains dark marine shales and siltstones with lingula (Vistalli, 1989), a conglomeratic unit with skolithos is its equivalent in the Cordillera de los Altos. The lowest Ordovician is the *La Paz Formation* (Wiens, 1989), which in the northwestern Chaco is a black, pyritic

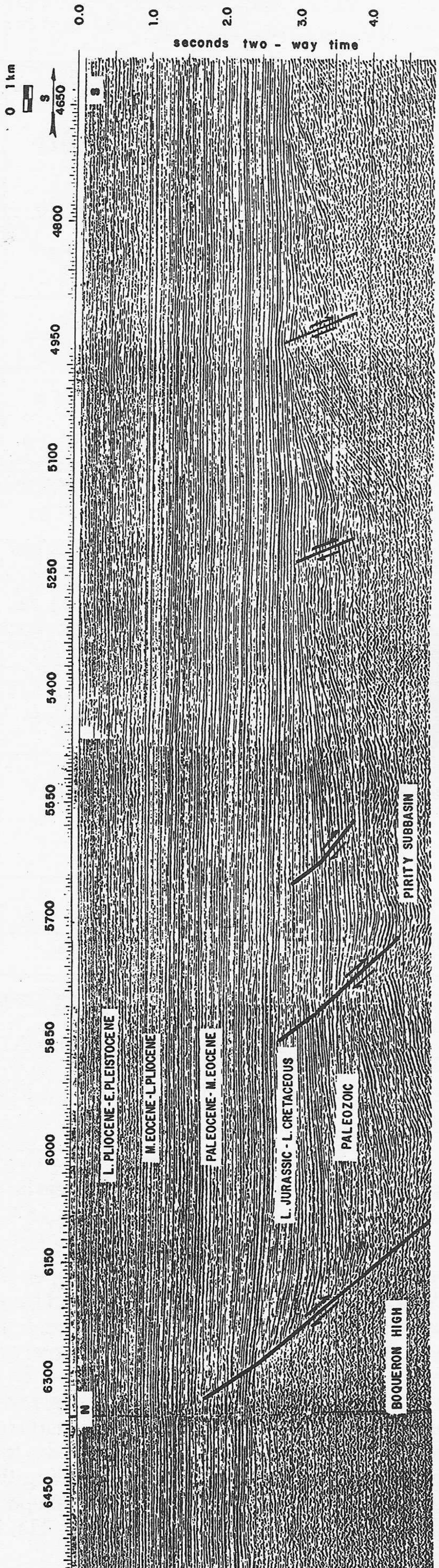

Figure 7—Segment of a north-south seismic line showing the northwestern flank of the Pirity subbasin and subsidence along listric normal faults (southwestern Paraguayan Chaco basin; section D–D' on Figure 3).

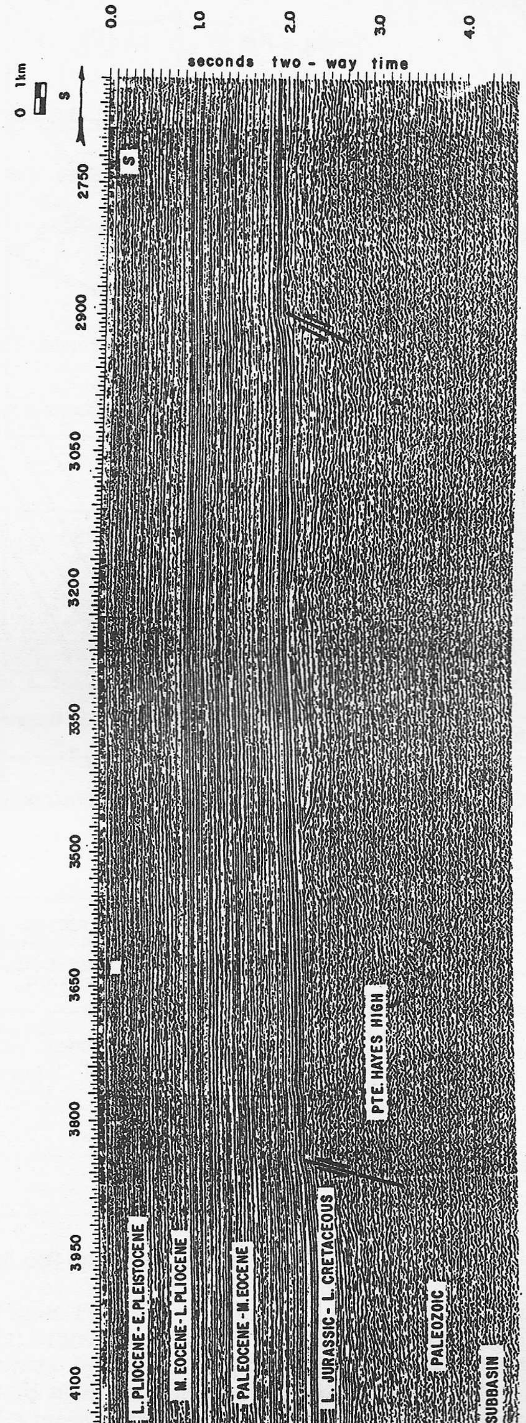

Figure 8—Segment of a north-south seismic line showing the southeastern flank of the Pirity subbasin and disposition along a normal discordance (southwestern Paraguayan Chaco basin; section E–E' on Figure 3).

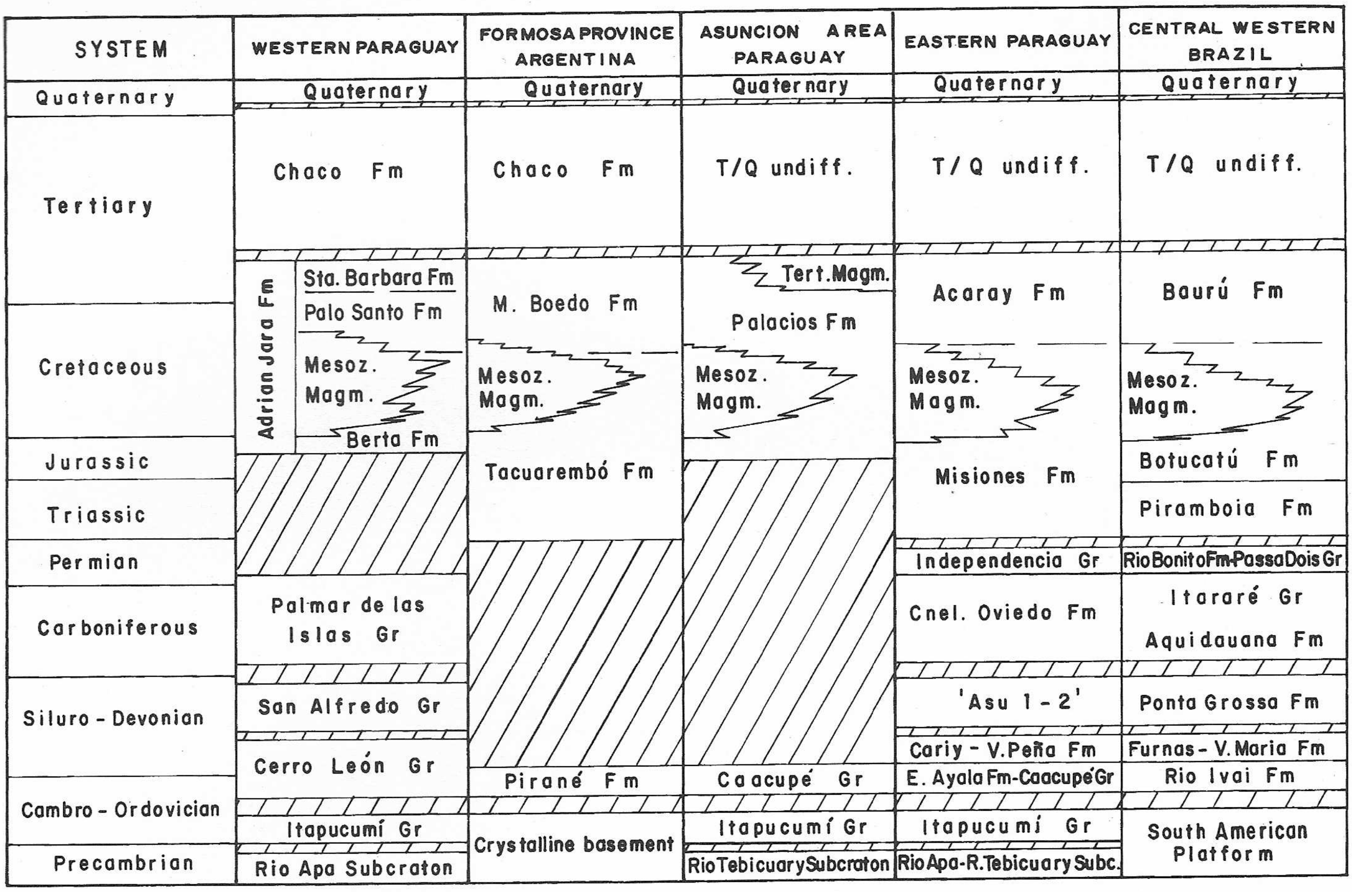

Figure 9—Comparative stratigraphic chart of the Paraguayan Chaco basin, western Paraguay, with adjacent correlative areas in eastern Paraguay, Argentina, and Brazil.

AGE	REGION (BASINS): ALTO PARAGUAY REGION	SERRA DA BODOQUENA	ITAPUCUMI REGION	CORUMBA AREA	TUCAVACA / BOQUI AREA: SOUTHWESTERN ZONE	SOUTHEASTERN ZONE
CAMBRIAN	ALTO PARAGUAY GROUP {·Diamantino Fm ·Sepotuba Fm ·Raizama Fm ·Araras Fm ·Puga Fm	CORUMBA GROUP {·Bocaina Fm ·Cerradinho Fm ·Puga Fm	ITAPUCUMI GROUP {Carbonate Fm, Basal Unit	JACADIGO GROUP {·Band Alta Fm ·Corrego das Pedras Fm ·Urucum Fm	TUCAVACA GROUP {·Murcielago Fm ·Pesenema Fm ·Bocamina Fm ·Motacu Fm ·Pororo Fm	BOQUI GROUP {·Undifferentiated Eugeosynclinal Sequence ·Cahama Fm ·San Francisco Fm
LATE PROTEROZOIC	CUIABA GROUP (incl. BAUXI Fm)	CUIABA GROUP	——	CUIABA GROUP	——	

Figure 10—Stratigraphy of the Eocambrian along the Río Apa subcraton and the southern border of the Guaporé shield in Paraguay, Brazil, and Bolivia.

shale interval with interbedded siltstones and sandstones. Don Quixote-1 well penetrated 172 m of this shaley sequence (Clebsch, 1991). A low-energy lagoon environment is inferred. The entire sequence is an upward-coarsening progradational unit deposited in a restricted environment.

Marine regression persisted throughout the Silurian, depositing thick sandstones with shaley interbeds. These gradational deposits are the uppermost La Paz formation and the *Santa Rosa Formation* (Wiens, 1989). Measured thicknesses vary between 135 m (Don Quixote-1 well) and 335 m (Parapiti-1 well) (Clebsch, 1991). An open-file Pennzoil–Victory Oil (1972) report records crinoid stems in the shales. Wolfart (1961) reports arthrophycus, brachiopods, and gastropods from the coarser intervals near the top. A Llandoverian age is suggested.

The Ordovician–Silurian *Cerro León Group* is widespread, blanketing the Paraguayan Chaco eastward (López-1 and Orihuela-1 wells), across the San Pedro low (Asunción-1 and Asunción-2 wells), and reaching the main Paraná basin (Wood and Miller, 1991). Isopach maps of the lower Paleozoic sequence (Figures 11a, b)

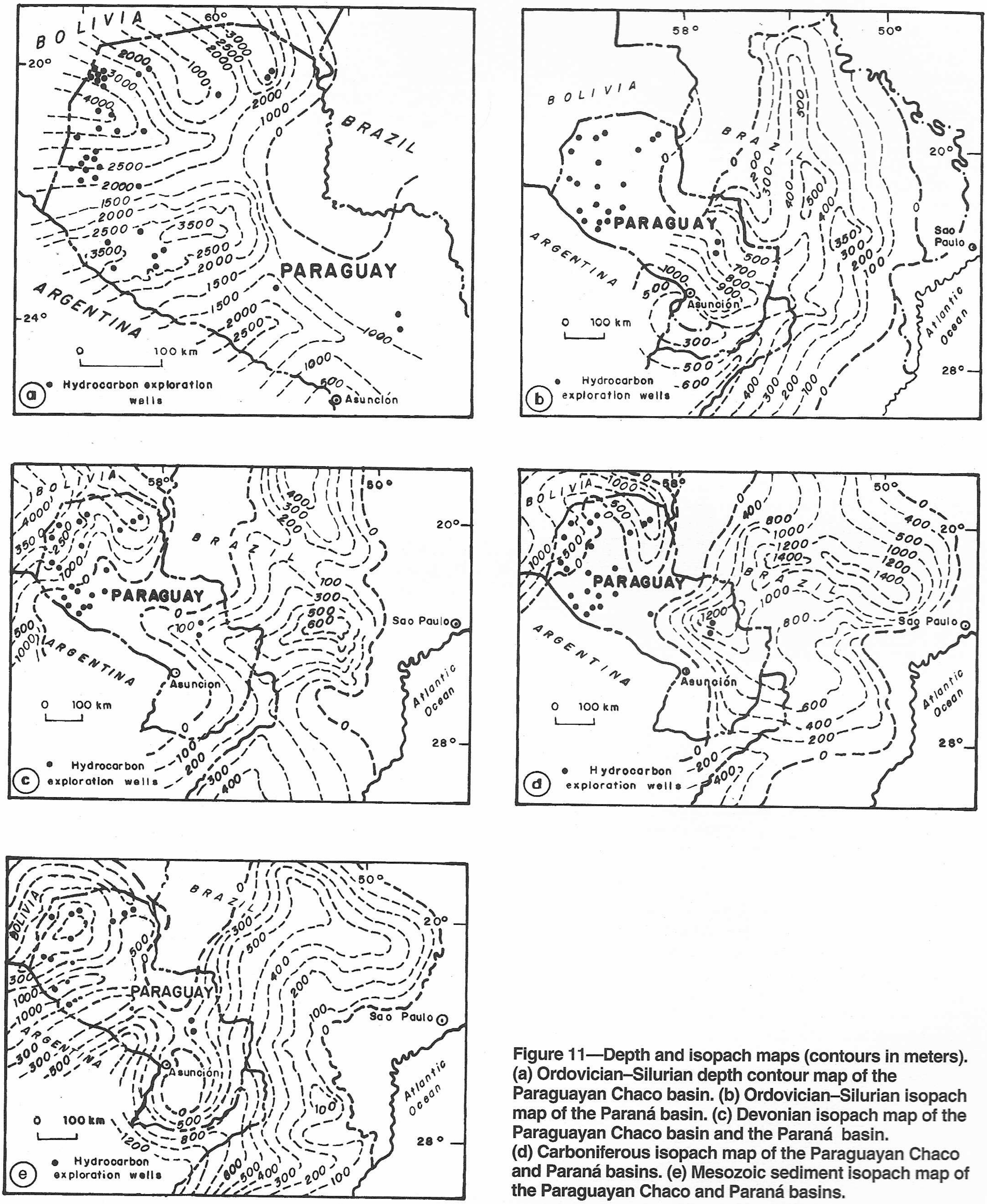

Figure 11—Depth and isopach maps (contours in meters). (a) Ordovician–Silurian depth contour map of the Paraguayan Chaco basin. (b) Ordovician–Silurian isopach map of the Paraná basin. (c) Devonian isopach map of the Paraguayan Chaco basin and the Paraná basin. (d) Carboniferous isopach map of the Paraguayan Chaco and Paraná basins. (e) Mesozoic sediment isopach map of the Paraguayan Chaco and Paraná basins.

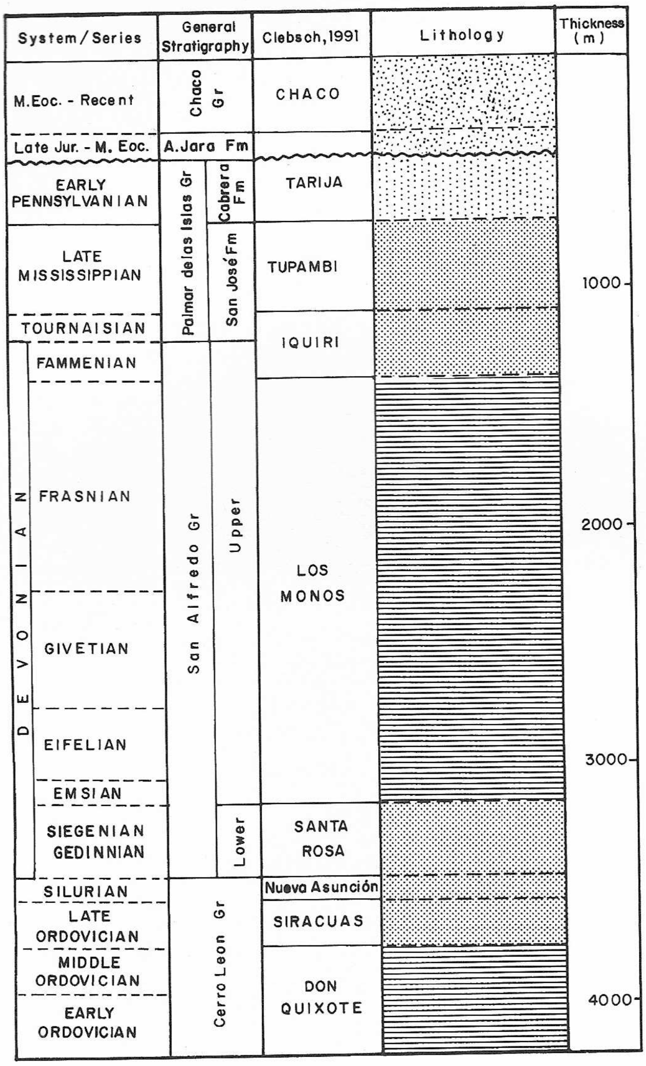

Figure 12—Simplified stratigraphy of the Carandaity subbasin, western Paraguayan Chaco basin. (Modified from Clebsch, 1991.)

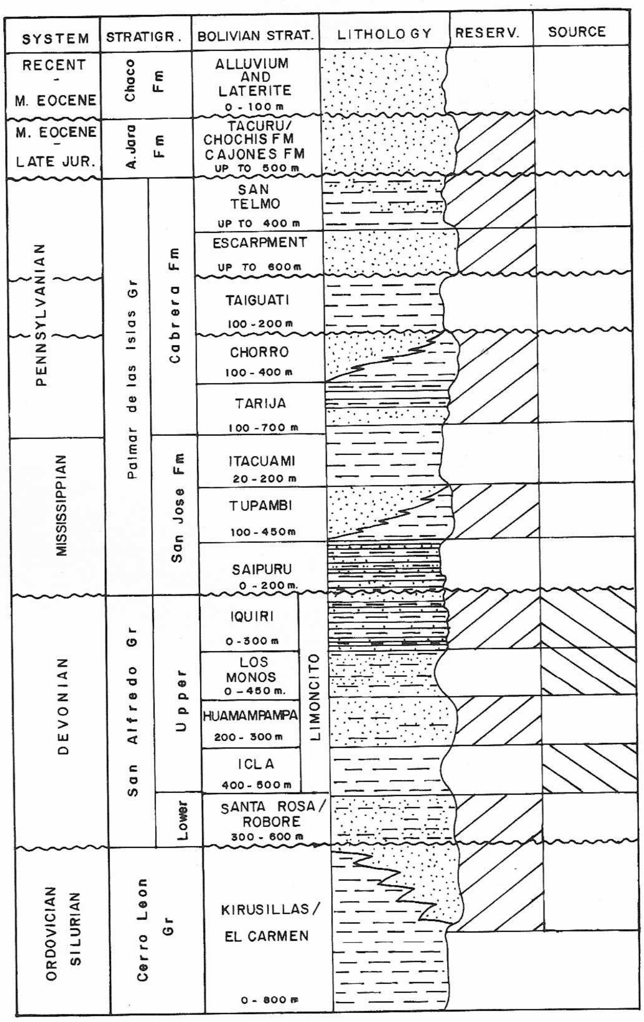

Figure 13—Stratigraphy of the Curupaity subbasin, northern Paraguayan Chaco basin. (Adapted from Lopez Paulsen et al., 1982; Wiens, 1989.)

and stratigraphic correlations confirm a regional marine influence throughout the Chaco and Paraná basins. The various depocenters were yoked together forming a broad epeiric basin.

The *San Alfredo Group* is of Early–Late Devonian age (Figure 9). Extensive Devonian outcrops occur in the Cordillera de San Alfredo and along the western margin of the Cerro León massif. Almost all exploration wells in the western and northern Chaco within the Carandaity and Curupaity depocenters have encountered Devonian sections, as have groundwater surveys throughout the northern Chaco (PNUD, 1991) (Figure 11c).

The thickest Devonian sections occur in the Carandaity (3500 m) (Figure 12) and Curupaity (2000 m) (Figure 13) depocenters. They include a lower sandy interval and a monotonous shaley unit at the top that grades upward into a more arenaceous interval.

A generally transgressive sea inundated the Chaco-Paraná basin complex in Devonian time (Lopez Paulsen, et al., 1982). Continental sedimentation was restricted to the central Chaco uplift (López-1 and Orihuela-1 wells).

The lower San Alfredo Group reflects shore zone to shallow marine environments (Fernandez Garrasino and Cerdan, 1981). White, cross-bedded quartz arenites and less mature sandstones up to 300 m thick contain intercalated siltstones and shales, indicating a variety of sedimentary facies. The presence of leiospheres and chitinozoans in the northwestern Chaco exploration wells (Pennzoil–Victory Oil, 1972) and corals, bryozoans, and crinoids at the Cerro León massif are indicative of a marine depositional environment. Wolfart (1961) interpreted *Favosites* sp., *Leptocoelia flabellites*, *Chonetes falklandicus*, and *Tentaculites stubeli* at Fortin Aroma and the Lagerenza high as evidence for an Early Devonian age. Terrestrial spores at the central Chaco uplift show that sandy coastal facies rimmed the arched areas; basinward the facies are deeper marine (Wiens, 1991). Postdepositional diagenesis, lateral sedimentary variations, and intraformational unconformities characterize reservoir intervals.

The upper San Alfredo Group is represented by dark, thick, fossiliferous, shallow marine shales (Lopez Pugliessi and Suarez-Soruco, 1982). It grades upward into a regressive sequence of continental deposits. Late San Alfredo shale deposition were restricted largely to the Curupaity and Carandaity depocenters. Tentaculites, brachiopods, and crinoids indicate shallow marine facies (Harrington, 1956). Subsequent tectonism and burial maturation have resulted in Devonian shales that range from immature (Carandaity and Curupaity subbasins) to low-grade metamorphic (Lagerenza and Fuerte Olimpo highs).

The uppermost regressive sedimentary rocks range in thickness up to 300 m. The paleontology records a pronounced hiatus between these deposits and the overlying Carboniferous sequence (Lopez Paulsen et al., 1982). Depositional environments were similar to those of the lower San Alfredo Group, although lateral facies changes show a strong continental influence. The deposits record the termination of the Devonian transgressive-regressive cycle in the Paraguayan Chaco basin.

The *Palmar de las Islas Group* is of Early Carboniferous–Early Permian age. Significant Carboniferous outcrops occur in the northern Chaco along the western Lagerenza high and in the area from Palmar de las Islas to Adrian Jara. Favorable reservoir and aquifer characteristics have resulted in numerous wells being drilled throughout the northwestern Chaco (Carandaity and Curupaity subbasins). The Carboniferous isopach map reconstruction is shown in Figure 11d. The succession is up to 1600 m thick and is separated from the Devonian San Alfredo Group by a prominent unconformity (Sanjines, 1982). Depositional environments included shallow marine, continental, and glacial conditions.

The Lower Carboniferous unit is the *San José Formation*, which is characterized by rapid lateral changes in sedimentary facies with only local continuity. Basal sandstones with dark shaley lenses are replaced upward by varved mudstones and reddish diamictites (Lopez Paulsen et al., 1982). While coastal marine conditions are interpreted for the basal section, continental glacial environments dominated the upper levels. Local discordances and variable thicknesses (up to 800 m in the Carandaity subbasin) are characteristic.

The Upper Carboniferous–Lower Permian *Cabrera Formation* has a transitional contact with the underlying San José Formation and is a sandstone-dominated sequence with local basal conglomerates. The sandstones are typically cross-bedded units fining upward into mudstones with oolitic limestone levels. Shallow marine to fluvial depositional processes are inferred (Lopez Paulsen et al., 1982). Reasonable porosity and permeability parameters are laterally variable. The Cabrera Formation in the Curupaity subbasin ranges in thickness up to 1300 m.

Biostratigraphic relationships of the Palmar de las Islas Group are not firmly established because only rare fossils are reported from lower Upper Carboniferous red beds (Lobo et al., 1976).

Mesozoic–Cenozoic

The *Adrian Jara Formation* of Late Jurassic–middle Eocene age (Figures 11e, 14) is a poorly sorted sandstone with interbedded conglomerates and mudstones. It occurs principally in the Curupaity subbasin, although there are broadly contemporaneous deposits in the northern and northwestern Chaco.

The Adrian Jara is separated from the Carboniferous Cabrera Formation below and from the Cenozoic Chaco Formation above by unconformities. Although this formation is imprecisely dated, there is evidence that deposition started in the Late Jurassic, or possibly even earlier (Toro-1 well). The Adrian Jara consists of medium- to fine-grained sandstones that are moderately sorted, horizontal, and cross bedded. Heterogeneous conglomerates overlie local scour surfaces. Each depositional sequence is interbedded with thin mudstones. Fluvial and eolian depositional environments are interpreted.

The Upper Jurassic–middle Eocene stratigraphy of the Pirity subbasin comprises three formations: the Berta, Palo Santo, and Santa Barbara (Figure 14). Mesozoic extensional tectonism formed the Pirity and Pilar subbasins and structurally modified the Bahía Negra platform (Figures 15, 16). The asymmetric half-graben has pronounced step faults on the northern flank (Boquerón high) and a structural flexure along the southern flank (Presidente Hayes uplift). Interpretation is based on exploration wells. Lithologic correlations, paleontologic data, and radiometric ages from intrusives suggest local subdivisions (Salfity and Marquillas, 1981) (Figure 14).

The Upper Jurassic–Upper Cretaceous Berta Formation in the Pirity subbasin represents the early stage of rift subsidence (Yacimientos Petroliferos Fiscales, 1984) (Figure 14). The sediments where deposited in eolian, alluvial fan, braided river, and lagoonal environments. Equivalents of the Berta Formation are shown in Figure 9. The Berta Formation consists of fine-grained reddish sandstones with interbedded mudstones. Its thickness varies up to about 3000 m. Correlation with Argentinian equivalents suggests a Coniacian age (Carle et al., 1991). Absolute ages from basaltoids indicate an Early Cretaceous (Valanginian) age for the formation (128 ± 5 to 126 ± 3.5 Ma) (Galliski and Viramonte, 1985). The basalts were emplaced along northwest-southeast and northeast-southwest fault trends.

The overlying *Palo Santo Formation* is of Late Cretaceous–early Paleocene age. It records transgressive flooding of the Pirity subbasin from the southwest (Moreno, 1970). The Palo Santo Formation is commonly subdivided into three units (Figure 14):

1. The transgressive lower Palo Santo Formation sandstones onlap the margins of the Pirity subbasin. The sandstones were deposited in alluvial fan and braided river plain environments (Turner, 1959). A Campanian–Maastrichtian age for the transgression is indicated by seismic and lithostratigraphic correlations with northern

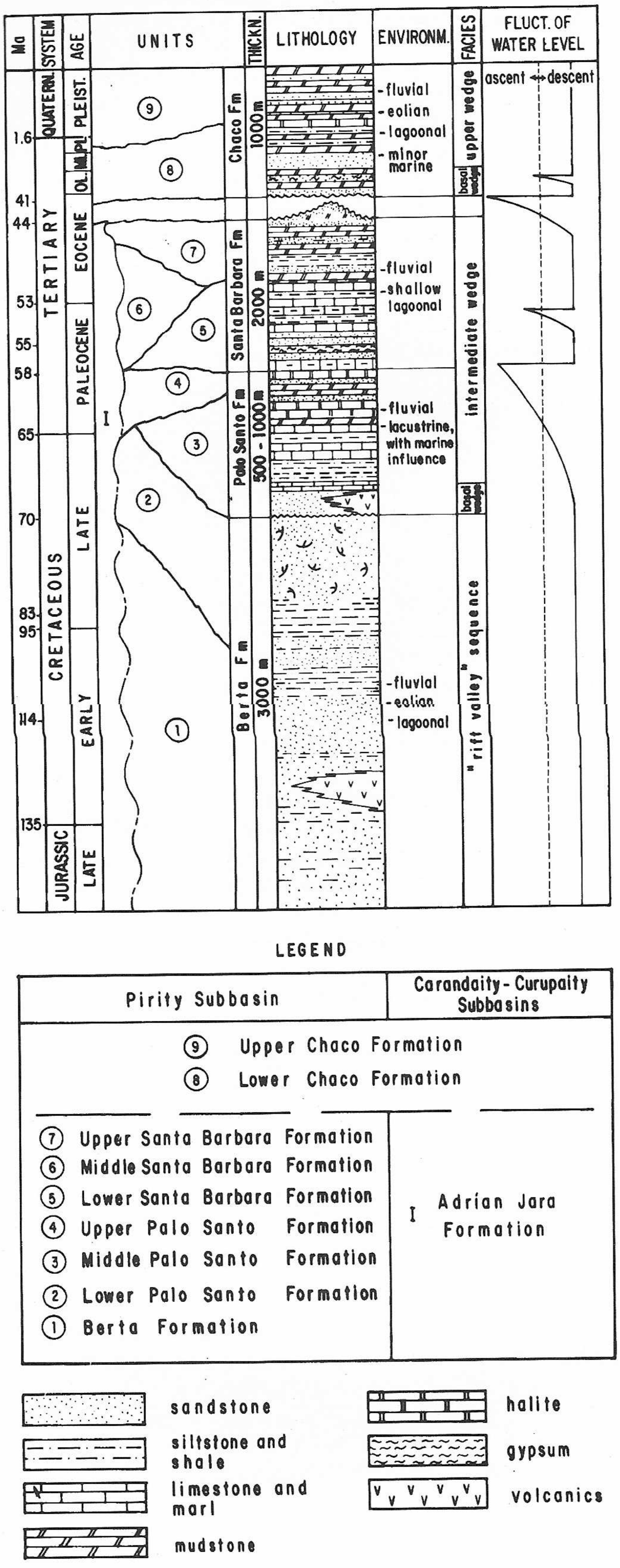

Figure 14—Lithostratigraphic chart of the Cretaceous–Tertiary in the Pirity, Carandaity, and Curupaity subbasins of southwestern, western, and northern Paraguayan Chaco basin.

Argentinian fossil-dated sequences (Reyes and Salfity, 1973; Bonaparte et al., 1977) and by absolute ages from basic extrusives at the base of the lower Palo Santo Formation (70 ± 5 Ma, K/Ar) (Carle et al., 1989). Maximum thickness is 200–220 m.

2. The middle Palo Santo Formation has a gradational base with the lower transgressive interval. It records maximum flooding of the Late Cretaceous–early Paleocene sea from the southwest (Figure 15). At the base, littoral clastics and carbonates interfinger with fluvial and eolian sandstones. With progressive flooding, a carbonate-shale platform with local evaporites developed (Gómez Omil et al., 1989). Comparison of well sections across the Pirity subbasin between the Berta-1 and Palo Santo-1 wells (north-south section), and between the Carmen-1 and Nazareth-1 wells (southwest-northeast section), indicates argillaceous calcite-dolomite cemented sequences in the deeper parts and coarser clastics along the margins of the subbasin. Sporadic ostracods and palynomorphs in Berta-1 well support an interpretation of shallow marine and coastal plain environments in the early Paleocene. Farther away in northern Argentina, Late Cretaceous foraminifera and ostracods suggest shallow marine and even freshwater environments (Mendez and Viviers, 1973; Moroni, 1982).

   In summary, in middle Palo Santo time, the Pirity subbasin was a restricted carbonate basin with fringing brackish lagoonal, fluvial, and eolian environments (e.g., Acosta-1 and Nazareth-1 wells). It is a finely laminated succession indicating overall low-energy conditions. Thickness varies between 200 and 550 m.
3. The upper Palo Santo Formation is a regressive unit containing 100–230 m of evaporites, interbedded mudstones, and marginal sandstones. Halite, gypsum, and dolomite banks indicate typical lagoonal environments with fringing sandy fluvial margins (Gómez Omil et al., 1989).

The lower Paleocene–middle Eocene *Santa Barbara Formation* consists of red mudstones, evaporites, and local carbonates that are attributed to fluvial and lacustrine environments in a desiccated Pirity subbasin. Like the previous unit, it has a threefold subdivision (Figure 14) (Pascual, 1978):

1. The lower Santa Barbara Formation is up to 800 m thick and consists of reddish mudstones with subordinate sandstones and evaporites. Palynomorphs in Palo Santo-1 well indicate a Paleocene age (Gómez Omil et al., 1989).
2. The middle Santa Barbara Formation is up to 190 m thick and consists of claystones, marls, siltstones, and sporadic sandstones. Lacustrine environments are inferred (Millioud, 1975).
3. The upper Santa Barbara Formation is up to 1100 m thick, representing an early–middle Eocene cover of the Pirity subbasin (Pascual, 1978; Quattrocchio,

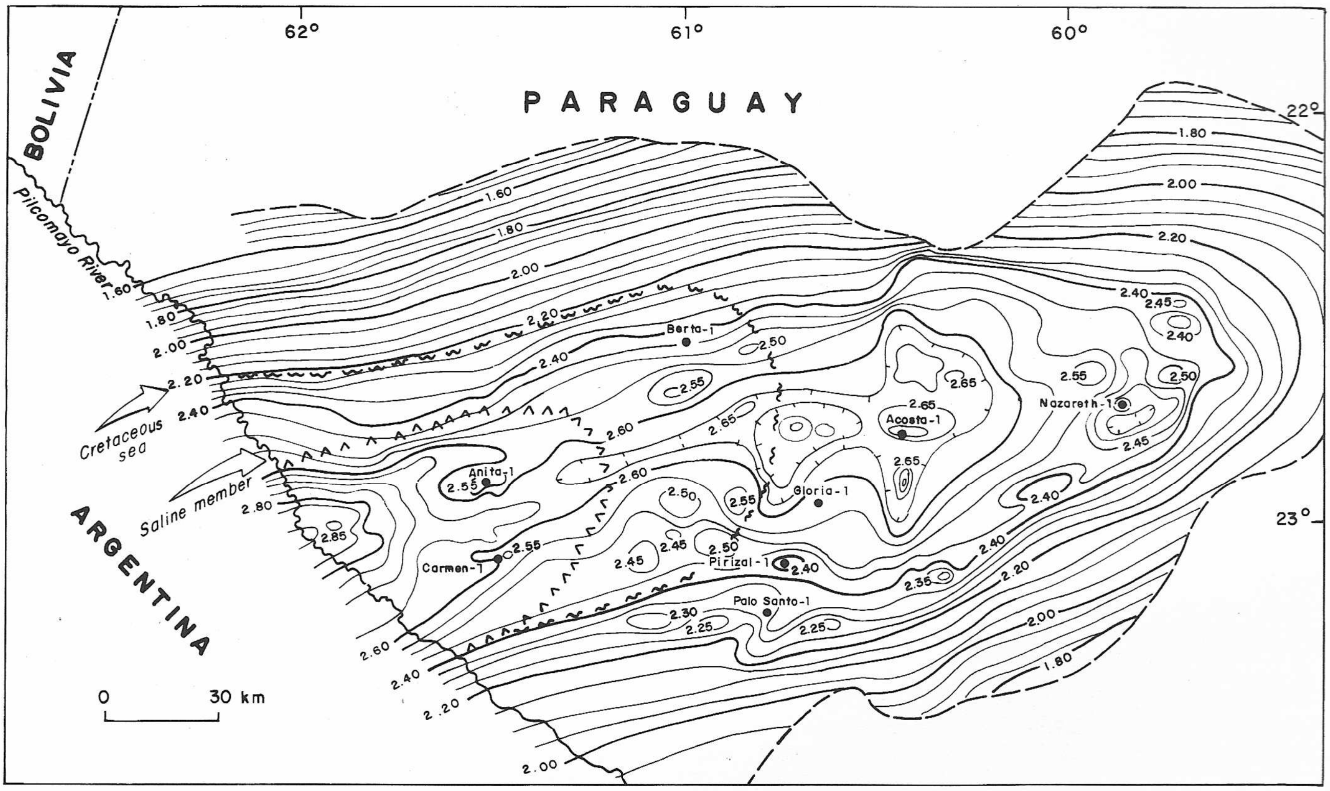

Figure 15—Seismic time contour distribution of the Upper Cretaceous–Lower Paleocene Palo Santo Formation in the Pirity subbasin, southwestern Paraguayan Chaco basin (contours in seconds; ●, hydrocarbon exploration wells). (Adapted from Clebsch, 1991.)

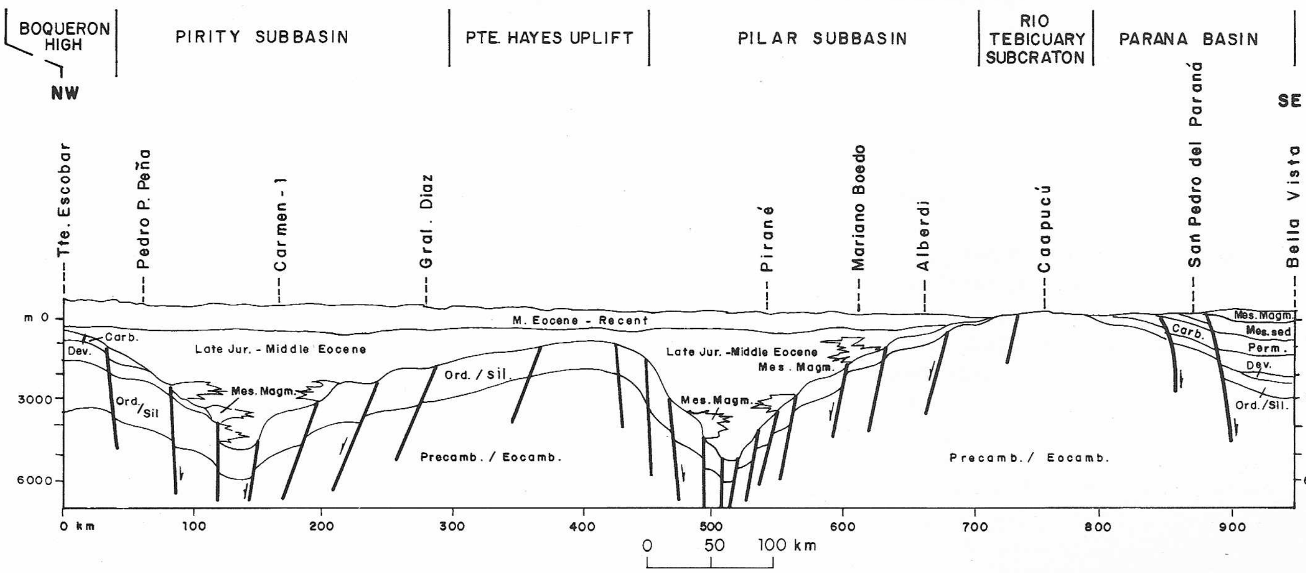

Figure 16—Structural and stratigraphic profile of southwest-southeast Paraguay (section B–B' on Figure 3).

1980). The succession drapes the structural margins of the Pirity subbasin. A period of regional or epeiric basin type of subsidence is indicated. Lacustrine and local ephemeral fluvial environments persisted. These depositional environments have resulted in a monotonous succession of red claystones with thinly interbedded siltstones and fine-grained sandstones. A regional "green horizon" marker bed that originated in a lacustrine setting is characteristic (Gómez Omil et al., 1989). It is a 2–10-m-thick calcareous shale and oolitic limestone with gypsum levels.

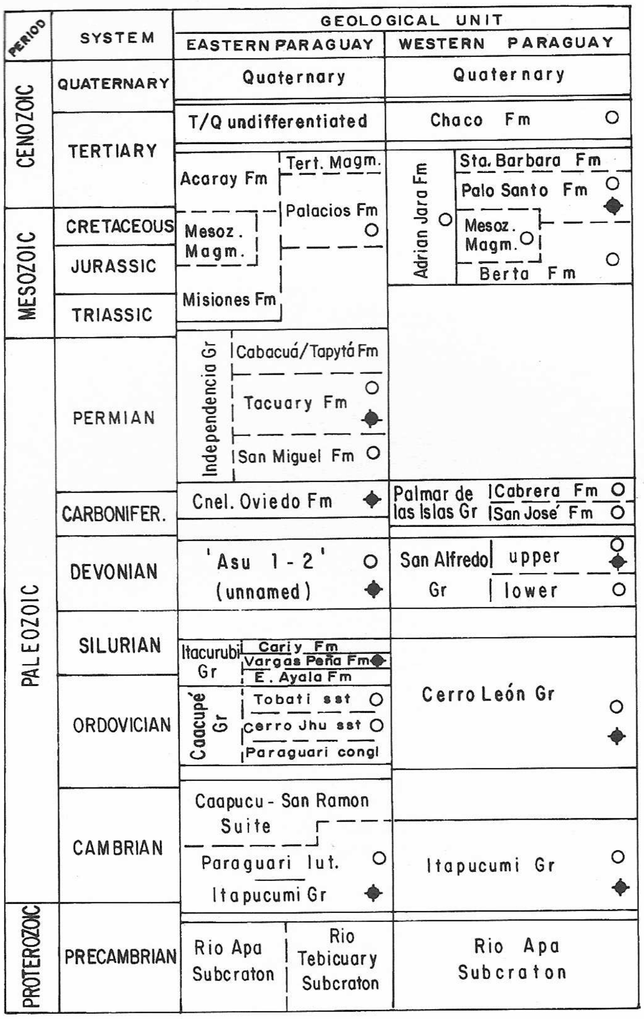

Figure 17—Summary of the Paraguayan stratigraphy and its hydrocarbon potential. ●, source rock; ○, reservoir rock.

The middle Eocene–early Pleistocene *Chaco Formation* is a 500–1000-m-thick cover succession demonstrating that the various depocenters of the Paraguayan Chaco had lost their individual identities. They were replaced in the early Tertiary by an overfilled regional downwarp. The Andean orogen became the major supplier of sediments.

The lower Chaco Formation of middle Eocene–late Pliocene age was dominated by continental deposition (Mingramm et al., 1979), which was interrupted in the southeastern Chaco by a short interlude of shallow marine transgression (middle Miocene) (Russo and Chebli, 1979). This marine incursion from the Atlantic (Chebli et al., 1989) reached as far as the Boquerón high and the central Chaco uplift.

The late Pliocene–early Pleistocene upper Chaco Formation comprises alternating fine-grained sandstone, siltstone, and claystone. The succession coarsens to the west, toward the growing Andean orogen. These sediments represent the most important aquifers in the Paraguayan Chaco (Tullstrom, 1973; Osterbaan, 1988; Godoy, 1990). Stratigraphic relationships suggest an internal drainage basin dominated by ephemeral braided fluvial systems, alluvial fans, playa lakes, and eolian dunes. The cross-sectional geometry (thickness of 800 m in the west, 250 m in the east) is typical of a foreland basin.

The Quaternary (early Pleistocene–Recent) deposits of the Chaco basin reflect a continuation of the Chaco Formation system with heterogeneous depositional parameters (Bertoni, 1939; Hoffstetters, 1978; Presser and Crossa, 1984; Herbst and Santa Cruz, 1985).

HYDROCARBON EXPLORATION POTENTIAL

Hydrocarbon potential in the Paraguayan Chaco is related to the Paleozoic and Mesozoic marine shales and carbonates (Figure 17). Although no commercial hydrocarbon discoveries have yet been made, the Chaco remains a relatively unexplored frontier region.

Hydrocarbon seeps occur in the Tucavaca area of eastern Bolivia in lowermost Phanerozoic Itapucumí Group limestones and shales. Surface gas indications are reported from correlative bituminous sedimentary deposits in northeastern Paraguay and Goias (Brazil).

Paleozoic marine shales and carbonates reach thicknesses of 2500 and 3600 m in the Carandaity and Curupaity subbasins, respectively. Organic material in the upper parts of the succession in the least deformed interior parts of the subbasins (e.g., Katarina-1 well) tends to be immature. In the deeper parts of the section and along the margins of the subbasins, the level of organic maturity ranges from mature to overmature (e.g., Don Quixote-1 well). The increasing geothermal maturity with depth results in decreasing gas wetness. Similar conditions occur along structural highs where increasing geothermal gradients (Figure 18), fracturing, and contemporaneous magmatism have matured the sedimentary rocks, even to low-grade metamorphic conditions (e.g., Toro-1 well).

The part of the sequence with the most hydrocarbon potential is undoubtedly the Devonian San Alfredo shales. The Lower Ordovician Cerro León shaley section also has some potential; in Argentina and Bolivia there are producing fields in this interval. Dry gas (Mendoza-1 and Mendoza-2 wells) and oil shows (Toro-1 well) are noted. High-gravity oil most likely occurs in the upper parts of the sections in the interior of the subbasins, but it probably changes to wet gas, condensate, and even dry gas in the lower sections. Structural highs may be gas prone.

Mesozoic transgressive marine deposits of the Palo Santo Formation are a local hydrocarbon play in the Pirity subbasin. Gas and oil indicators in the Berta and Palo Santo formations suggest potential for smaller oil concentrations (Schlumberger, 1987; Fernandez Garrasino, 1989). This interval contains producing fields in northern Argentina. The sedimentary distribution, local magmatism, and geothermal gradients are restrictive.

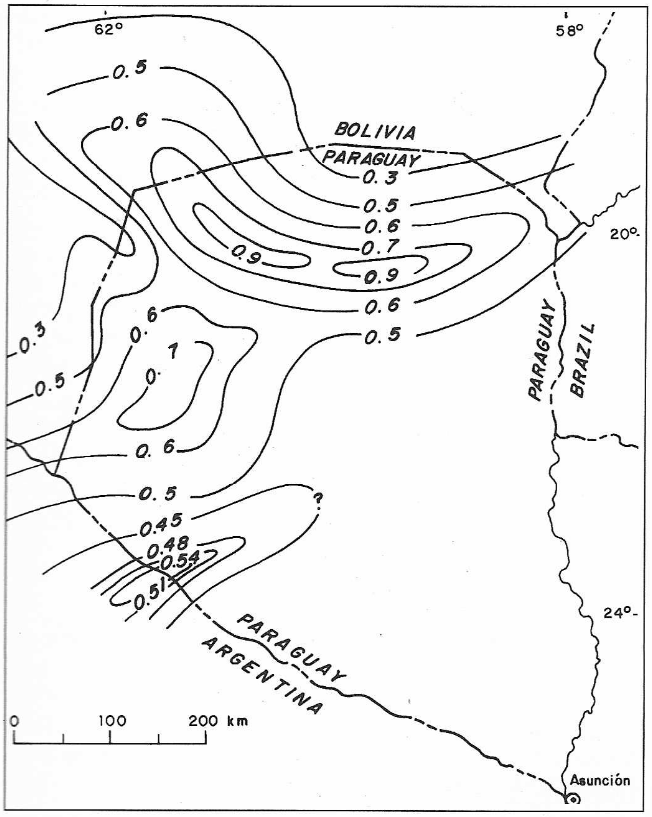

Figure 18—Geothermal gradient pattern in the northwestern Paraguayan Chaco basin (contours in °C/100 m).

The regional distribution of geothermal gradients in the Paraguayan Chaco (calculated on surface temperatures of 37.7°C) traces contours that follow the main structural units (Figure 19), indicating that sedimentary maturity was mostly influenced by tectonism. Geothermal gradients over structural highs may be as high as 0.7–0.9°C/100 m (Lagerenza and Fuerte Olimpo highs), possibly reflecting local magmatic activity as indicated by magnetics and outcrop studies (Cerro León massif). The Toro-1 well has fractures and volcanics as compared to the Gato-1 well, which has no volcanics and lower thermal gradients. High levels of organic maturity and tight reservoir sandstones characterize the structural highs.

Overall, the various subbasins have low geothermal gradients with maturation affecting the lower sedimentary sequences. Basinal structural deformation is not significant. On the basis of sedimentary and diagenetic history, tectonism, magmatism, and geothermal gradients, it is concluded that the Paleozoic section of the western and northern Chaco has the highest hydrocarbon potential; Mesozoic plays are concentrated in the southwestern Chaco.

In the *Curupaity subbasin* (Figure 3), the 3600-m-thick upper San Alfredo shales represent an important hydrocarbon target; an oil show in the Toro-1 well has TOC values between 0.3 and 2.1 wt. %. Slatey shales in the Toro-1 well indicate overmature conditions along the Fuerte Olimpo high, where the rocks are highly fractured, intruded by magmatites, and have geothermal gradients up to 0.6 C°/100 m. The most favorable conditions probably exist along the flanks of the highs. The interior of the Curupaity subbasin is expected to be largely immature.

The best quality reservoir rocks are the Lower Carboniferous San José Formation and Upper Carboniferous Cabrera Formation channel sandstones, which resemble some of the producing reservoirs of the adjacent Bolivian Chaco basin. Excellent reservoir characteristics also occur in the Upper Jurassic–middle Eocene Adrian Jara Formation. The Mesozoic sandstones may have poor seals. Structural traps include Tertiary inversion of Mesozoic extensional fabrics.

The Devonian upper San Alfredo Group shales in the *Carandaity subbasin* (Figure 5) exceed 2500 m in thickness. They represent excellent hydrocarbon source rocks. Early Ordovician Cerro León Group shaly units (TOC content of 0.5 wt. %; Don Quixote-1 well) may represent a secondary source rock. Exploration targets include intercalated uppermost Devonian sandstones and widespread channel sandstones of the Carboniferous Palmar de las Islas Group.

The flanks of basin margin structural highs have mature organic facies. Very mature conditions occur on the crests of the highs (e.g., Mendoza-1 and Mendoza-2 wells) where there are gas shows. The depocenters are immature (e.g., Katerina-1 well). Eocene shale-draped unconformities act as seals along the Lagerenza and Boquerón highs, as well as toward the Central Chaco uplift.

The principal hydrocarbon potential in the *Pirity subbasin* (Figure 14) is the Upper Cretaceous marine source rock of the Palo Santo Formation. Geochemical assays indicate oil-generative conditions in the shales and carbonates of the middle Palo Santo Formation (Carle et al., 1991). Reservoir intervals include the sandstones of the middle Palo Santo or the underlying lower Palo Santo and Berta formations. Brecciated volcanics intercalated in the Berta and Palo Santo formations may offer viable prospects, just as the Palmar Lago field in northern Argentina does.

The western part of the *San Pedro low* (Figure 19) reaches into the Paraguayan Chaco from the Paraná basin with a continuation of Phanerozoic deposits. It contains Lower Ordovician, Silurian, Devonian, and Permian source rocks.

On the *Bahia Negra platform* (Figure 5), oil seeps, gas shows, and high bituminous kerogen content indicate a hydrocarbon source potential in lower Phanerozoic Itapucumí Group sedimentary rocks of the northeastern Chaco. Although there is structural trap potential, reservoir quality is expected to be poor. Nevertheless, this remains an unexplored area.

In the northern part of the *Pilar subbasin*, marine clastics of Ordovician–Silurian age have built a Paleozoic terrace wedge along the margin of the Río Tebicuary subcraton in the southeastern Chaco. These sedimentary rocks are covered by Cretaceous–Paleocene synrift half-graben fills of continental origin. Exploration efforts in Argentina have so far been negative for hydrocarbons.

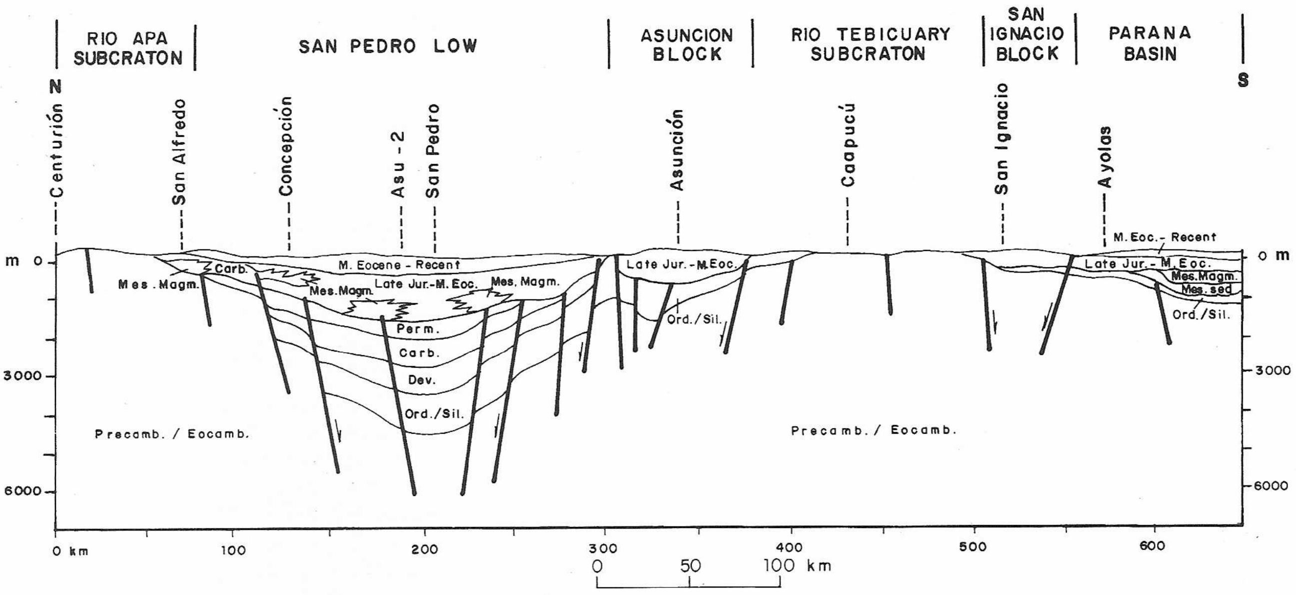

Figure 19—North-south structural and stratigraphic profile of eastern Paraguay (section C–C ' on Figure 3).

CONCLUSIONS

The Chaco basin in Paraguay was formed on continental crust where it reactivated older structural fabrics of the late Precambrian–Cambrian Brasiliano event (680–450 Ma). This basement framework resulted in a complex system of structural blocks with preferential fault trends oriented northwest-southeast and northeast-southwest. The tectonostratigraphic evolution of the Phanerozoic Chaco basin reflects repeated reactivation of these older structural fabrics. Of paramount importance was the relative orientation of the older structures to prevailing stress fields.

There were four distinct subsidence phases during the Phanerozoic: mild extension and regional epeiric basin subsidence characterized the (1) Ordovician–Devonian and (2) Carboniferous–Permian intervals. (3) Vigorous rifting occurred in the Cretaceous–Eocene. (4) The final phase from the Eocene onward was characterized by a return to mild, regionally controlled patterns of subsidence. Each episode preserves a unique record of unconformity-bounded sequences and sedimentation.

The Phanerozoic stratigraphic section in the Paraguayan Chaco ranges from latest Proterozoic to Recent in age. Crystalline basement has so far not been reached by exploration drilling. The chronologic history of events based on surface and subsurface data is as follows:

1. Latest Proterozoic–Cambrian marine clastics and limestones of the Itapucumí Group were deposited.
2. An erosional unconformity separates these rocks from Early Ordovician–Silurian and Early Devonian marine shales and sandstones of the Cerro León and San Alfredo groups.
3. An angular unconformity intervenes between these and Early Carboniferous–Early Permian shallow marine and continental clastic deposits, much of which were glacially influenced (Palmar de las Islas Group).
4. Late Jurassic–middle Eocene continental clastic deposits filled the Carandaity and Curupaity subbasins (Adrian Jara Formation). Mesozoic extension in the Pirity and Pilar subbasins (Berta Formation) was accompanied by magmatism. Angular unconformities separate these Mesozoic synrift sequences from the Paleozoic succession.
5. A Late Cretaceous–early Paleocene marine transgression and deposition of terrigenous clastic and carbonate sediments are recorded in the Pirity subbasin (Palo Santo Formation).
6. An early Paleocene–middle Eocene cover of lacustrine and fluvial sediments (Santa Barbara Formation) reflects a return to regional patterns of subsidence and burying of the remaining structural relief.
7. A pronounced hiatus beneath a westward-thickening middle Eocene–early Pleistocene wedge of continental deposits marks the onset of foreland basin subsidence in front of the Andean orogenic belt (Chaco Formtion). Westward-derived sedimentation was interrupted in the southeastern Chaco by a local marine incursion in the middle Miocene.
8. Early Pleistocene–Recent sediments blanketed the Chaco basin (Quaternary).

Hydrocarbon potential in the Paraguayan Chaco basin is related to Paleozoic and Mesozoic marine shales and carbonates in each of the sedimentary subbasins and to the way these sedimentary sequences abut the structural highs. The Lower Ordovician Cerro León Group and Devonian upper San Alfredo Group shales are source rocks in the Carandaity and Curupaity subbasins. Oil generation is inferred for the lower parts of the sequence in the center of each subbasin and along the flanks of the basin margin highs. Prospective reservoir intervals include Devonian intraformational sandstones, Carboniferous channel sandstones, and Mesozoic sandstones. Mesozoic extension created a variety of structural traps.

Upper Cretaceous marine transgressive deposits of the Palo Santo Formation are the most prospective units in the Pirity subbasin. Along the southeastern flank of the Boquerón high, Devonian shales were block faulted during Mesozoic extension and were unconformably overlain by Cretaceous and Tertiary clastics and shales, forming viable hydrocarbon targets.

The Chaco basin of Paraguay remains largely unexplored. The geology suggests that it has significant hydrocarbon potential. Counterparts of the Paraguayan Chaco basin in Bolivia and northern Argentina are major producers of oil, gas, and condensate.

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Appendix: CHACO BASIN (PARAGUAY): CHARACTERISTICS OF HYDROCARBON EXPLORATION WELLS

No.	Operator	Well Name and No.	Location	Year	Subbasin or Area	Total Depth (m)	TD: Geologic Formation		Hydrocarbon Indication	BHT (°C)	Geothermal Gradient (°C/100m)
1	Union Oil Co.	Santa Rosa - 1	21°45' S 61°41' W	1947	Carandaity (south)	2.310 m	Cerro León Gr	Lower Ord./Sil.	Oil show	—	—
2	Union Oil Co.	La Paz D - 1	21°53' S 60°58' W	1948	Boquerón high	2.210 m	Cerro León Gr	Silurian	—	—	—
3	Union Oil Co.	Pirizal D - 1	23°03' S 60°38' W	1948	Pirity	3.148 m	Sta. Barbara Fm	Lower Tertiary	Oil show	—	—
4	Union Oil Co.	Picuiba B - 1	20°40' S 61°56' W	1949	Carandaity (central)	2.290 m	Low. San Alfredo Gr	Devonian	Oil show	—	—
5	Union Oil Co.	Orihuela B -1	23°24' S 58°40' W	1949	Pte. Hayes uplift	2.046 m	Cerro León Gr	Lower Ord./Sil.	—	—	—
6	Pure Oil Co.	Madrejón - 1	20°25' S 59°29' W	1957	Central Chaco uplift	1.728 m	Cerro León Gr	Lower Ord./Sil.	Oil show	20.34	0.76
7	Pure Oil Co.	Lagerenza - 1	20°00' S 61°00' W	1958	Lagerenza high	2.893 m	Cerro León Gr	Lower Ord./Sil.	Gas show	31.50	0.85
8	Pure Oil Co.	Lopez - 1	21°46' S 59°58' W	1959	Central Chaco uplift	1.737 m	Cerro León Gr	Lower Ord./Sil.	—	16.20	0.52
9	Pure Oil Co.	Mendoza - 1R	20°12' S 61°41' W	1959	Carandaity (north)	3.244 m	Cerro León Gr	Lower Ord./Sil.	Gas blow	28.35	0.66
10	Placid Oil Co.	Mendoza - 1	20°07'30" S 61°45'20" W	1966	Carandaity (north)	794 m	Up. San Alfredo Gr	Upper Devonian	—	12.96	0.73
11	Placid Oil Co.	Mendoza - 2	20°02'20" S 61°52'10" W	1967	Carandaity (north)	1.247 m	Up. San Alfredo Gr	Upper Devonian	Gas blow	13.32	0.50
12	Placid Oil Co.	Mendoza - 3	20°03'10" S 61°53'10" W	1967	Carandaity (north)	704 m	Up. San Alfredo Gr	Upper Devonian	—	11.79	0.67
13	Pennzoil & Vict. Holdings	Alicia - 1	20°57'02" S 61°48'57" W	1971	Carandaity (central)	1.306 m	Up. San Alfredo Gr	Upper Devonian	—	11.88	0.36
14	Pennzoil & Vict. Holdings	Brigida - 1	21°18'50" S 61°55'22" W	1971	Carandaity (central)	1.513 m	Up. San Alfredo Gr	Upper Devonian	Oil show	12.42	0.35
15	Pennzoil & Vict. Holdings	Cristina - 1	21°26'54" S 61°53'26" W	1971	Carandaity (central)	643 m	Up. San Alfredo Gr	Upper Devonian	—	9.09	0.30

(continues)

Appendix: CHACO BASIN (PARAGUAY): CHARACTERISTICS OF HYDROCARBON EXPLORATION WELLS *(continued)*

No.	Operator	Well Name and No.	Location	Year	Subbasin or Area	Total Depth (m)	TD: Geologic Formation		Hydrocarbon Indication	BHT (°C)	Geothermal Gradient (°C/100m)
16	Pennzoil & Vict. Holdings	Dorotea - 1	21°17'01" S 62°08'54" W	1971	Carandaity (central)	854 m	up. San Alfredo Gr	Upper Devonian	—	10.08	0.34
17	Pennzoil & Vict. Holdings	Emilia - 1	20°06'34" S 62°07'14" W	1971	Carandaity (central)	1.222 m	up. San Alfredo Gr	Upper Devonian	—	11.16	0.39
18	Pennzoil & Vict. Holdings	Federica - 1	21°35'02" S 62°11'59" W	1971	Carandaity (south)	800 m	up. San Alfredo Gr	Upper Devonian	—	9.36	0.27
19	Pennzoil & Vict. Holdings	Gabriela - 1	21°46'43" S 62°00'02" W	1971	Carandaity (south)	1.016 m	Up. San Alfredo Gr	Upper Devonian	Oil show	—	—
20	Pennzoil & Vict. Holdings	Hortensia - 1	21°30'29" S 61°39'27" W	1971	Carandaity (south)	765 m	Up. San Alfredo Gr	Upper Devonian	Oil show	9.54	0.31
21	Pennzoil & Vict. Holdings	Isabel - 1	21°01'14" S 61°27'40" W	1971	Carandaity (central)	946 m	Up. San Alfredo Gr	Upper Devonian	—	10.53	0.35
22	Pennzoil & Vict. Holdings	Julia - 1	20°36'05" S 61°37'03" W	1971	Carandaity (central)	1.281 m	Up. San Alfredo Gr	Upper Devonian	Oil show	11.52	0.34
23	Pennzoil & Vict. Holdings	Katerina - 1	20°44'30" S 61°33'50" W	1971	Carandaity (central)	1.143 m	Up. San Alfredo Gr	Upper Devonian	—	11.07	0.34
24	Pennzoil & Vict. Holdings	Luciana - 1	20°10'40" S 61°43'10" W	1972	Carandaity (north)	819 m	Up. San Alfredo Gr	Upper Devonian	—	10.26	0.37
25	Pennzoil & Vict. Holdings	Marta - 1	20°16'31" S 61°40'27" W	1972	Carandaity (north)	828 m	Up. San Alfredo Gr	Upper Devonian	—	10.08	0.35
26	Pennzoil & Vict. Holdings	Nola - 1	20°07'49" S 61°47'13" W	1972	Carandaity (north)	760 m	Up. San Alfredo Gr	Upper Devonian	—	9.90	0.36
27	Pennzoil & Vict. Holdings	Olga - 1	21°25'13" S 61°52'41" W	1972	Carandaity (central)	1.172 m	Up. San Alfredo Gr	Upper Devonian	—	11.70	0.39
28	Pennzoil & Vict. Holdings	Don Quijote - 1	21°37'47" S 61°56'43" W	1972	Carandaity (south)	2.895 m	Cerro León Gr	Lower Ord./Sil.	Oil show	22.68	0.54
29	Repsa & Cía. Petrolera del Chaco	Palo Santo - 1	23°10'20" S 60°46'08" W	1974	Pirity	3.763 m	Cerro León Gr	Silurian	—	24.30	0.46
30	Esso, Aminoil & Chaco Expl.Co.	Berta - 1	22°32'47" S 61°00'38" W	1976	Pirity	4.789 m	Berta Fm	Upper Jurassic	—	29.52	0.47

(continues)

Appendix: CHACO BASIN (PARAGUAY): CHARACTERISTICS OF HYDROCARBON EXPLORATION WELLS *(continued)*

No.	Operator	Well Name and No.	Location	Year	Subbasin or Area	Total Depth (m)	TD: Geologic Formation		Hydrocarbon Indication	BHT (°C)	Geothermal Gradient (°C/100m)
31	Texaco & Marat. Co.	Cerro León - 1	19°49' S 60°56' W	1976	Lagerenza high	1.970 m	Cerro León Gr	Lower Ord./Sil.	Gas show	18.90	0.60
32	Texaco & Marat. Co.	Toro - 1	20°07'58" S 58°57'04" W	1977	Fte. Olimpo high	3.418 m	Cerro León Gr	Lower Ord./Sil.	Oil show	27.27	0.59
33	Texaco & Marat. Co.	Gato - 1	20°03'30" S 58°52'30" W	1978	Fte. Olimpo high	1.646 m	Cerro León Gr	Lower Ord./Sil.	Oil show	15.30	0.50
34	Chaco Expl.Co.	Parapiti - 1	21°00'00" S 61°00'00" W	1977	Carandaity (east)	3.000 m	Cerro León Gr	Lower Ord./Sil.	Gas show	21.96	0.52
35	Chaco Expl.Co.	Parapiti - 2	21°34'00" S 62°00'00" W	1977	Carandaity (central)	2.370 m	Cerro León Gr	Lower Ord./Sil.	—	19.80	0.54
36	Cía. Petrolera del Chaco	Anita - 1	22°53'24" S 61°30'18" W	1978	Pirity	4.129 m	Berta Fm	Upper Jurassic	—	27.00	0.48
37	Cía. Petrolera del Chaco	Gloria - 1	22°56'55" S 60°38'04" W	1979	Pirity	4.016 m	Berta Fm	Upper Jurassic	—	25.74	0.46
38	Occidental	Carmen - 1	23°15'07" S 61°18'14" W	1985	Pirity	4.511 m	Cerro León Gr	Silurian	—	31.14	0.54
39	Occidental	Tte. Acosta - 1	22°44'55" S 60°25'15" W	1987	Pirity	4.268 m	Berta Fm	Upper Jurassic	—	—	—
40	Occidental	Nazareth - 1	22°39'17" S 59°51'37" W	1987	Pirity	4.025 m	Berta Fm	Upper Jurassic	—	24.93	0.43
41	Cano Martinez	Independencia -1	20° 09' 45"S 61°46' 24"W	1993	Carandaity (north)	609 m	Up. San Alfredo Gr	Upper Devonian	Gas blow	—	—