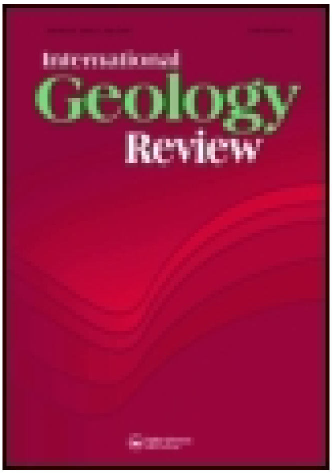

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Abstract

The Paraná Basin is a Western Gondwanan cratonic basin that is better defined as the Paraná depositional site, since it has a diverse history as a basin. Sedimentation started in the Ordovician–Silurian, followed by extensive marine Devonian deposition. A Late Paleozoic/Triassic facies cycle wedge was clearly built during Pangean time. The Early Cretaceous was characterized by extensive basaltic lava flows immediately before the break-up of Pangea. Following these rifting and drifting processes, the basin's structural framework was totally rebuilt, generating new depositional sites in the Late Cretaceous to Tertiary. Based on more recent data, at least two different basins may be defined during the evolution of what was once considered a unique basin. Nevertheless, even if considered as a single basin, the sedimentary pile of the Paraná Basin has considerable economic potential, until now exploited only rudimentarily, except for its groundwater resources. Aggregates, limestones, clays, industrial sands, gems, dimension stones, hydrocarbons, coal, peat, and uranium are some of the potential mineral resources of this basin.

Geologic Setting

THE PARANÁ SEDIMENTARY BASIN is a huge (1,200,000 km^2) cratonic basin located in south-central South America. It occupies 1,000,000 km^2, in Brazil, 100,000 km^2 in Uruguay, and 100,000 km^2 in Paraguay (Fig. 1). Previously, more than 200,000 km^2 belonging to the Chaco Paraná Basin in Argentina also were believed to be a part of the Paraná Basin, but this area was considered a different basin by Zalán et al. (1990). The Paraná is a cratonic interior basin with a complex history and a controversial origin, believed to be related to the installation of a rift complex within the Upper Proterozoic basement in the Early Paleozoic followed by thermal subsidence during the Late Paleozoic (Fulfaro et al., 1982).

Very many papers have been published on this basin since 1827, but most are related to its eastern margin and have specific geological or paleontological objectives. Apart from regional descriptions incorporating very old geological concepts on basin geology in the 1940s, more specific papers on the western margin of the basin began to appear only in the 1950s and then 1970s, and even then with localized stratigraphic objectives (Perinotto, 1997). The first great synthesis of information on the basin appeared only in 1969 (Northfleet et al., 1969).

Since then, exploratory efforts that could lead to a better understanding of the basin's origin and development were irregular until the early 1980s, when risk contracts were authorized by the Brazilian government. Despite different governmental policies, the picture as a whole is not significantly different in Uruguay and Paraguay.

The present Paraná Basin has an oval shape, with a predominant N-S strike of its stratigraphic units (Figs. 1 and 2). Because the Paraná always was considered a single sedimentary basin, the Mesozoic structural framework was the basis for all hypotheses on basin development for many years. Presently, the Paraná Basin is believed to have been the depositional site for at least two different basins—Alto Garças to the north and Apucarana to the south—with the Guapiara megashear zone serving as a hinge line (Fig. 3) (Fulfaro and Perinotto, 1993). The more properly named Paraná depositional site has a total thickness of 6000

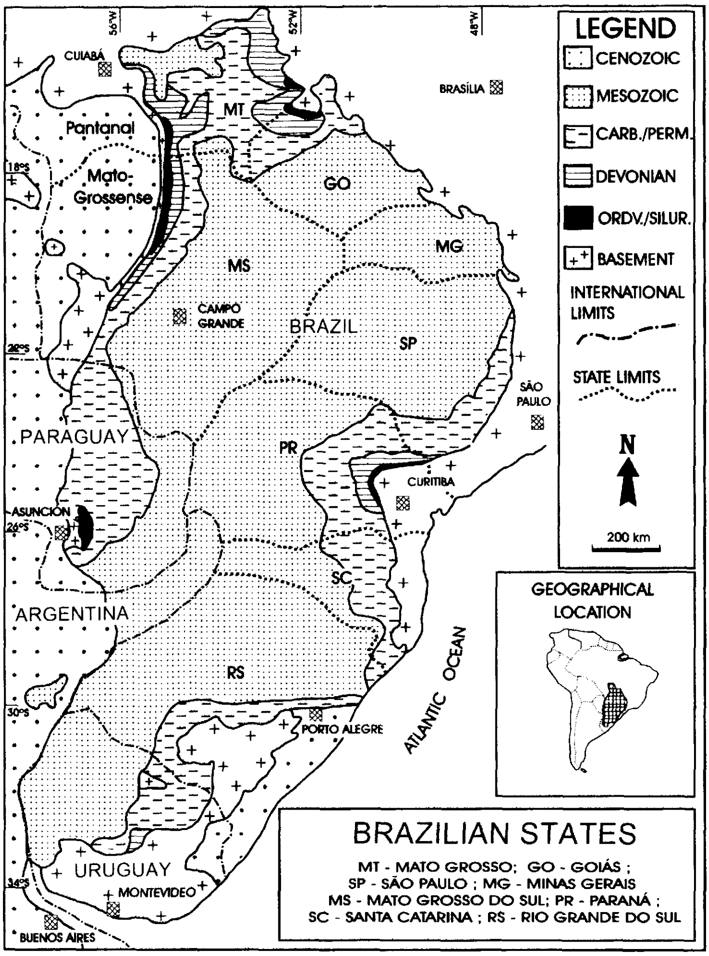

FIG. 1. Simplified geological map of the Paraná Basin.

meters, including 2000 meters of Mesozoic lava flows. This depositional site belongs to the so-called Western Gondwana Province.

The lithostratigraphic column of the basin for the three countries studied is shown in Figure 2. Because of a lack of precise paleontological indicators, a high-level correlation between the units of these three columns is almost impossible. As a result, good regional paleogeographic maps are difficult to construct.

Ordovician-Silurian

Sediments of Ordovician-Silurian age occur predominantly along the western basin margin in Paraguay and Brazil. In Brazil, deposits of this age also are recognized in the outcrop zone around the Ponta Grossa Arch, but are unknown in Uruguay. These deposits constitute the Caacupê and Itacurubi groups in Paraguay and the Rio Ivaí Group in Brazil. The Caacupê Group consists of conglomerates at its base (Paraguari Formation), fluvial to nearshore sandstones in the middle (Cerro Jhú Formation), and clean, well-sorted sands at the top (Tobati Formation). This unit interfingers with the more shaly Itacurubi Group, which is characterized by a rhythmic succession of sandstones and siltstones or shales (Eusebio Ayala Formation), shales (Vargas Peña Formation), and fine sandstones (Cariy Formation). This latter group has a rich marine fossiliferous assemblage of Early Silurian age (Llandoverian), so it is believed that sedimentation of at least part of the underlying Caacupê Group started in Late Ordovician time (Fulfaro, 1995). In Brazil, correlative units constitute the Rio Ivaí Group (Fig. 2). This group is divided into conglomeratic sandstones of the Alto Garças Formation at the base, followed upward by the diamictite deposits of the Iapó Formation and the shales of the Vila Maria Formation, the latter also containing a rich marine fauna of Early Silurian (Llandoverian) age. Assine (1996) interpreted this to be a transgressive sequence that began in the Late Ordovician.

Devonian

Sediments of Devonian age are widely represented in the Paraná Basin not only in outcrop but also in the subsurface in Brazil and Uruguay (Veroslavsky, 1994; Assine, 1996). In Paraguay, Devonian deposits occur only in the subsurface in an aulacogen named the Bajo de San Pedro, located in the east-central region of the country (Fulfaro, 1995). In Brazil, rocks of this age are represented by the Paraná Group. This group is divided into the basal sandy Furnas Formation and the upper shaly Ponta Grossa Formation. The basal unit starts with conglomerates of fluvial origin, passing upward to marine sandstone bars. Paleocurrents indicate a conection to the west with the proto-Pacific ocean. This unit interfingers with the fossiliferous marine Ponta Grossa Shales, with ages ranging from Emsian to Frasnian. In Uruguay, correlative sedimentation is represented by the Durazno Group, with the basal Cerrezuelo Formation being correlated with the Furnas Formation and the shaly Cordobés and the sandy La Paloma formations with the basal part of the Ponta Grossa Formation. Recent interpretations of the sedimentation in the Ponta Grossa posit that this event began with several separate basins, each having its own depocenter (separated by cratonic arches) and receiving sedimentation individually during the Emsian. The intervening cratonic arches were flooded as a result of the maximum Frasnian transgression, which affected most of the South American craton. As in the previous Ordovician–Silurian sequence, a cold climate still prevailed because of the high paleolatitude of this craton.

Permian–Carboniferous

The Late Carboniferous (Stephanian) marked a new stage of Paraná Basin deposition. A post-Devonian structural reorganization of the entire basin was followed in the above epoch by a new depositional episode heavily influenced by continental glaciation typical of the Gondwana continent. A glacial ice center located in West Africa (Windhoek ice center) had spread its glaciers as far as the interior neritic sea of the Paraná Basin, thus starting the glacio-marine sedimentation of the Tubarão Supergroup (Itararé Group) on the eastern margin of the basin. Along the western margin, mountain-type glaciation centers located in northern Paraguay and Bolívia extended into the same interior sea, resulting in sedimentation represented by the Aquidauana Group. Both groups—the Itararé and Aquidauana—are interfingered within the basin interior. This episode is represented in Uruguay by the San Gregório Formation (Cerro Largo Group) and in Paraguay by the Coronel Oviedo and the Aquidabán formations. Beginning in the Early Permian, deglaciation, with the eastern ice center moving to the eastern margin of Gondwana, caused a profound change in the basin's sedimentary characteristics. The sediments of this post-glacial stage in Brazil are represented by the Guatá Group.

The Guatá Group in Brazil is divided into the Rio Bonito and Palermo formations. The first was produced by deltaic sedimentation mainly caused by basement isostatic rebound after the retreat of the ice cap and is important for its coal layers and uranium deposits. The second unit marks the flooding of the basin by marine waters caused by the collision of the Patagonian and the South American plates (Perinotto, 1992). The same event is represented in Uruguay by the Tres Islas and Fraile Muerto formations (Cerro Largo Group) and in Paraguay by the San Miguel Formation (Independencia Group).

Following the Palermo transgression, a still-stand dominates the basin, resulting in the sedimentation of the Irati Formation black shales (Passa Dois Group). These shales are intercalated with limestone layers in a rhythmic succession associated by Hachiro and Coimbra (1993) with Milankovitch cycles. Nevertheless, the limestones provide good evidence that climate was warmer during Middle to Late Permian time. These sediments are termed the Mangrullo Formation (Cerro Largo Group)

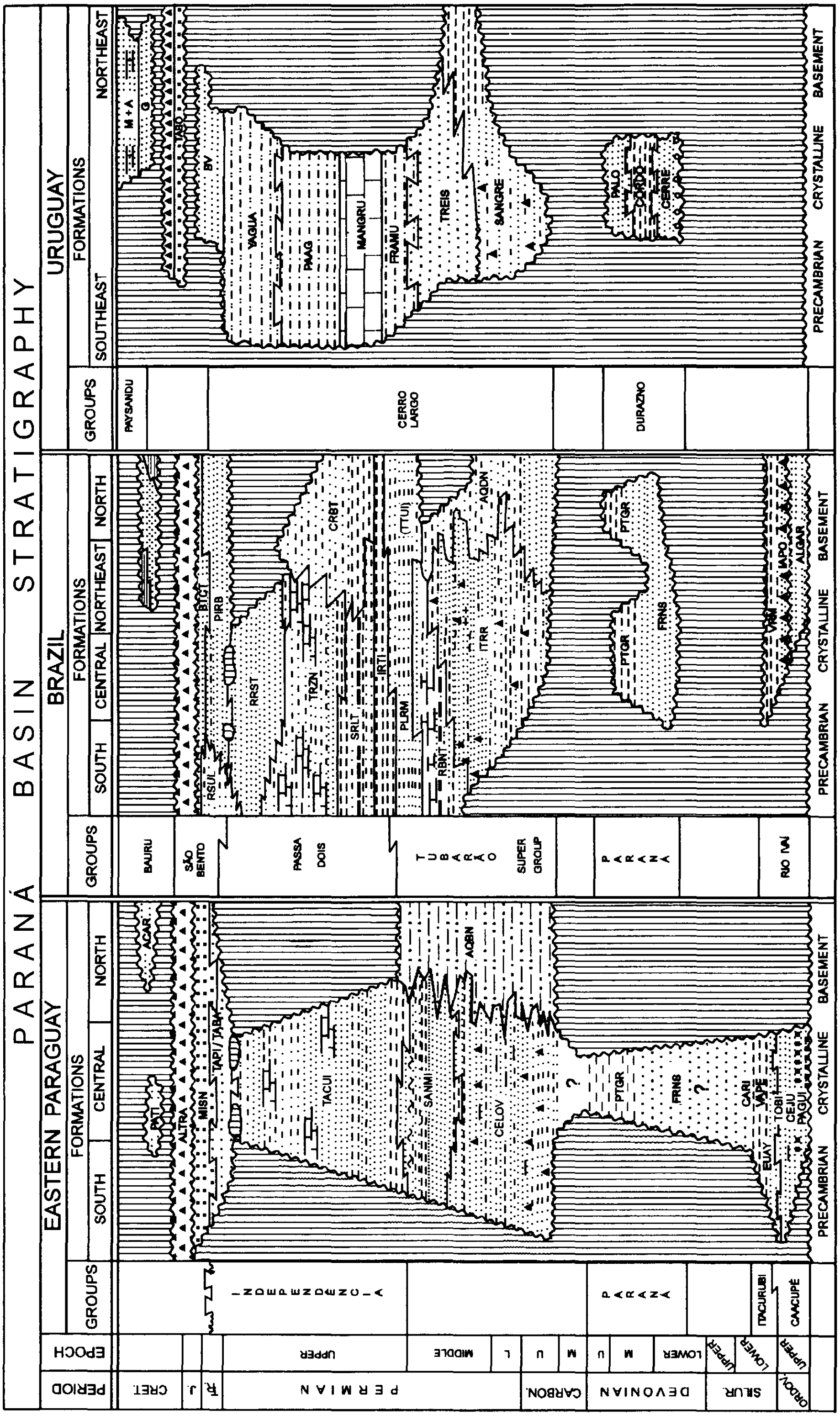
PARANÁ BASIN STRATIGRAPHY
EASTERN PARAGUAY
BRAZIL
URUGUAY
PERIOD
EPOCH
GROUPS
FORMATIONS
SOUTH
CENTRAL
NORTH
NORTHEAST
SOUTHEAST
PRECAMBRIAN CRYSTALLINE BASEMENT
BAURU
SÃO BENTO
PASSA DOIS
TUBARÃO SUPER GROUP
PARANÁ
RIO IVAÍ
PAYSANDU
CERRO LARGO
DURAZNO
INDEPENDENCIA
TACURUBI
CAACUPÉ
CRET.
PERMIAN
CARBON.
DEVONIAN
SILUR.
ORDOV.
UPPER
MIDDLE
LOWER

FIG. 2. Lithostratigraphic column of the Paraná Basin. Eastern Paraguay: PAGUI = Paraguarí Formation; CEJU = Cerro Jhú Formation; TOBI = Tobatí Formation; EUAY = Eusebio Ayala Formation; VAPE = Vargas Peña Formation; CARI = Cariy Formation; CELOV = Coronel Oviedo Formation; AQBN = Aquidabán Formation; SANMI = San Miguel Formation; TACUI = Tacuary Formation; TAPI = Tapytá Formation; MISN = Misiones Formation; ALTRA = Alto Paraná Formation; PATI = Patiño Formation; ACAR = Acaray Formation (from Fulfaro, 1995). Brazil: IAPO = Iapó Formation; VRM = Vila Maria Formation; ALGAR = Alto Garças Formation; FRNS = Furnas Formation; PTGR = Ponta Grossa Formation; AQDN = Aquidauana Formation; ITRR = Itararé Group or Subgroup; RBNT = Rio Bonito Formation; PLRM = Palermo Formation; TTUI = Tatuí Formation; IRTI = Irati Formation; SRLT = Serra Alta Formation; CRBT = Corumbataí Formation; TRZN = Terezina Formation; RRST = Rio do Rasto Formation; RSUL = Rosário do Sul Formation; PIRB = Pirambóia Formation; BTCT = Botucatu Formation; SRGL = Serra Geral Formation (modified from Stevaux and Perinotto, 1989). Uruguay: CERRE = Cerrezuelo Formation; CORDO = Cordobés Formation; PALO = La Paloma Formation; SANGRE = San Gregório Formation; TREIS = Tres Iscas Formation; FRAMU = Fraile Muerto Formation; MANGRU = Mangrullo Formation; PAAG = Paso Aguiar Formation; YAGUA = Yaguari Formation; BV = Buena Vista Formation; TABÓ = Tacuarembó Formation; ARA = Arapey Formation; G = Guichón Formation; M + A = Mercedes and Asencio Formation (modified from Goso and de Santa Ana, 1994).

in Uruguay; they are not known in Paraguay either at the surface or in the subsurface. According to Perinotto (1992), deltaic sandy sedimentation was occurring at this time along the western margin of the basin.

The sedimentation of the Irati unit marks a major change in the basin's structural behavior. A regressive stage began with the deposits of the Terezina Formation (= Estrada Nova or Corumbataí formations) in a shallow marine–tidal environment, immediately followed by the sediments of the Rio do Rasto Formation in a mixed fluvial to marine depositional system. The Terezina and Rio do Rasto formations belong to the Passa Dois Group in Brazil. In Uruguay, the correlative deposits (Cerro Largo Group) are represented by the Paso Aguiar, Yaguari, and Buena Vista formations, with similar depositional environments. In Paraguay, the entire cycle is represented by the Tacuary Formation. These units, having basically a Late Permian age, accumulated until the beginning of the Triassic.

The Tubarão Supergroup, together with the Passa Dois Group in Brazil (where they are best preserved in the basin sedimentary pile), form a perfect *facies cycle wedge*. The wedge starts and ends with fluvial deposits and exhibits a maximum marine transgression (the Palermo Formation) in its middle portion.

Triassic–Jurassic

During these periods, the basin experienced several changes, not only in depositional environments but also in structural framework, as a response to the initial break-up of Pangea, especially between Laurasia and Gondwana. Nevertheless, the Gondwana plates were still together; the cratonic basins' marginal arches began to uplift, leading to basin closure and a change from the previous exorheic character to an endorheic one. A thick sandstone sequence was deposited initially in a fluvial environment and then as desert sand dunes. This sandstone unit, which occupies four countries (Brazil, Uruguay, Argentina, and Paraguay), constitutes part of one of the largest aquifer systems in the world. The stratigraphic units are known as the Pirambóia/Botucatu Formation (São Bento Group) in Brazil, the Tacuarembó Formation in Uruguay, and the Misiones Formation in Argentina and Paraguay. Recently, these countries

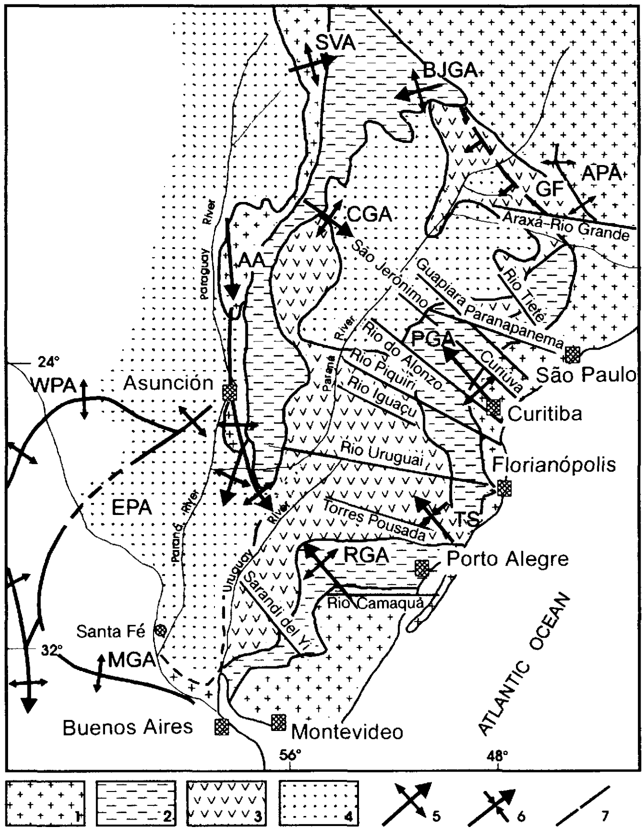

FIG. 3. Geological sketch map of the Paraná Basin (simplified after Melfi et al., 1988). Legend: 1 = pre-Devonian crystalline basement; 2 = pre-volcanic sediments (mainly Paleozoic); 3 = flood volcanics of the Serra Geral Formation (Lower Cretaceous); 4 = post-volcanic sediments (mainly upper Cretaceous); 5 = arch-type structure; 6 = syncline-type lineament; 7 = tectonic and/or magnetic lineament. Abbreviations: EPA = Eastern Pampean arch; WPA = western Pampean arch; AA = Asunción arch; CGA = Campo Grande arch; SVA = São Vicente arch; BJGA = Bom Jardim de Goiás arch; APA = Alto Paranaíba arch; GF = Goiânia flexure; PGA = Ponta Grossa arch; TS = Torres syncline; RGA = Rio Grande arch; MGA = Martin Garcia arch.

agreed to designate this unique aquifer as the Guarani Aquifer (see Table 2).

Early Cretaceous

Volcanism flooded the entire basin to a maximum thickness of 2000 meters of lava flows. Above the almost 4000 meters of the previous Paleozoic/Lower Mesozoic sediments, the addition of this volcanic unit elevated the total thickness to 6000 meters. This accretion in the sedimentary pile exerted an important influence on hydrocarbon generation within the basin. The volcanic rocks are mainly tholeiitic basalts, but large areas of more intermediate and acidic types also occur. The last type is the principal host of gem amethyst. Following these lava flows, a great number of diabase sills and dikes were intruded into the sedimentary pile locally, as in the Ponta Grossa arch margins, characterizing dike swarms. The lavas are represented by the Serra Geral Formation (São Bento Group) in Brazil, Arapey Formation in Uruguay, and Alto Paraná Formation in Paraguay. This volcanic event had its climax at ~120 Ma.

After this event, the Gondwana continent began to break up. South America and Africa were in a rift-and-drift process. The so-called Atlantic marginal basins (with only a few originating in the Late Jurassic) began to receive sediments. The Paraná Basin's eastern margin initiated vertical movements that strongly influenced the basin interior, resulting in faulting of the basalts and reorganization of the previous structural framework as a result of the superimposition of this rift phase. This structural event was described in detail by Fulfaro et al. (1982).

Late Cretaceous

New depocenters were established in the north-central and southern margins of the basin, in Brazil and Uruguay, respectively. The central portion of the basin remained as a positive feature, with the volcanic layers undergoing gentle erosion. To the north, continental sedimentation started in the Bauru Basin with aeolian deposits of the Caiuá Formation, fluvial and lacustrine deposits in a humid climate of the Adamantina Formation, and the semi-arid sandstones and limestones of the Marília Formation. These units of the Bauru Group occur in an area of 350,000 km^2 in the Brazilian states of Mato Grosso, Mato Grosso do Sul, Goiás, Minas Gerais, São Paulo, and Paraná. The entire sedimentary sequence of this group, with no more than 700 meters maximum thickness, expresses a rapid climate change from bottom to top. The upper unit, the Marília Formation, has a rich fossil reptilian assemblage with the Titanosauridae attesting to its Late Cretaceous age.These last layers also include important commercial limestone deposits (Ponte Alta Member of the Marília Formation).

In Uruguay, Late Cretaceous sedimentation is found in the "Cuenca Norte," a Uruguayan name for the meridional portion of the Paraná Basin. The sediments in this basin are represented by the Paysandu Group, consisting of the Guichón, Mercedes, and Asêncio formations. The Guichón unit is a sandy succession of fluvial bars, the Mercedes deposits are quite similar to those of the Marília Formation in Brazil, and the commercial limestone deposits—the "Queguay limestones"—are correlative with the Ponte Alta Member in Brazil. The Asêncio Formation apparently is a misinterpretation of a stratigraphic unit, because it actually is the result of Tertiary laterization of the top of the Cretaceous deposits and other units. The faunal assemblage in these units is not as rich as in Brazil.

Cenozoic

The Tertiary and Quaternary deposits in the Paraná depositional site are quite heterogeneous and are difficult to describe briefly. However, the entire Cenozoic geomorphology and sedimentation is a result of the development of the present hydrological basins. Important mineral resources are found in these deposits, such as aggregates for building construction and clays for the ceramic industry.

The basin's structural framework is shown in Figure 3. The only regional geophysical and geological structural synthesis performed on a semi-continental basis in the basin's area was completed by Hasui et al. (1993). The Archean and Proterozoic basement shows strong N-S and NE megashear zones derived from ancient collision zones. NE-striking alignments also are a constant in the basin's eastern margin and in the outcrop zone of the crystalline basement. Although several authors place strong emphasis on NE structures in basin development and evolution, the structures do not appear to be very important when an entire tectonic-sedimentary analysis of the basin is made. NW and E-W alignments, some of them truly megashear zones, are the structural features that effectively controlled the entire depositional history of the Paraná Basin. The NW and E-W alignments sectorized the basin area, creating individualized sub-basins in some periods, such as the previously mentioned Alto Garças and Apucarana sub-basins separated by the Guapiara alignment (Fig. 3); the latter represents the most important structural feature during the Paleozoic sedimentary evolution.

Other structural alignments shown in Figure 3 had their importance in the basin evolution at different times in the Paleozoic and Mesozoic. Recent data have shown that most if not all were reactivated during the Cenozoic, especially in the Tertiary, when a rapid 30° rotation of the South American plate took place in its drift away from Africa.

Non-Energy Mineral Resources

In order to describe its mineral resource potential, the Paraná Basin was divided into three provinces (Figs. 4, 5, and 6), termed the Northern (the Brazilian states of Mato Grosso, Mato Grosso do Sul, Goiás, Minas Gerais, and São Paulo), the Central (the Brazilian states of Paraná and Santa Catarina and also the Republic of Paraguay), and the Meridional (the

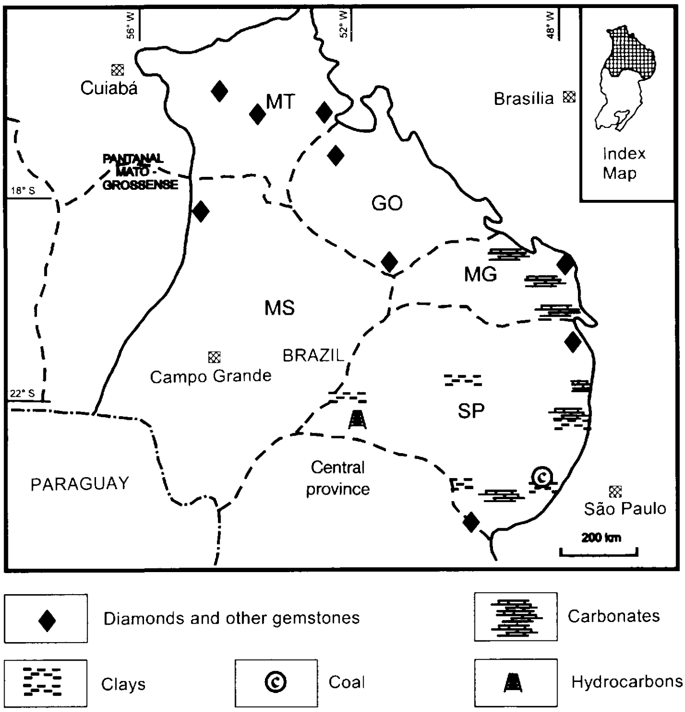

FIG. 4. Principal mineral occurrences in the Northern province of the Paraná Basin.

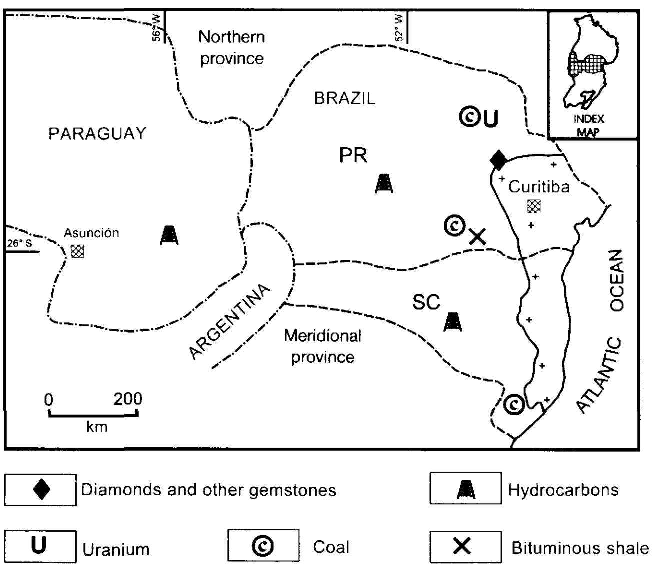

FIG. 5. Principal mineral occurrences in the Central province of the Paraná Basin.

Brazilian state of Rio Grande do Sul and the Republic of Uruguay). A synoptic view of mineral resource distribution is presented in Figure 7, which lists the distribution of mineral occurrences throughout the stratigraphic column and throughout the provinces.

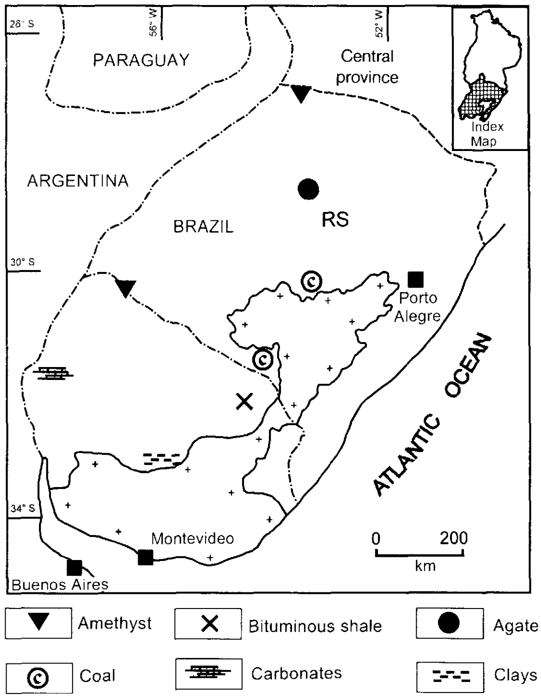

FIG. 6. Principal mineral occurrences in the Meridional province of the Paraná Basin.

Groundwater

Groundwater is one of the most important resources of the Paraná Basin as a whole, because the main aquifer systems underlie one of the most thoroughly developed regions of South America. The stored volume for the Paraná Basin is estimated at 50,000 km^3. The principal aquifer systems belong to rocks that range in age from Triassic to Jurassic to Late Cretaceous (Rebouças, 1976, 1978, 1988).

The Triassic-Jurassic deposits are represented by the sandy Piramboia and Botucatu formations in Brazil, Tacuarembo Formation in Uruguay, and the Misiones Formation in Paraguay. These units form an aquifer of continental dimensions (950,000 km^2) with an average thickness of 300-400 meters, although toward the center of the basin they may reach 800 meters.

The yield of the producing wells, which range from 100 to >2000 m in depth, is very high, ranging from 100 to more than 1000 m^3/hr (Rebouças, 1988). The usually great depths of its occurrence and the thick basaltic cover result in relatively hot and predominantly uncontaminated stored water (50 to 90°C). Results of aquifer exploration suggest potential uses as a water supply for cities (domestic and industrial) and as a source of hot geothermal water for recreational uses.

Aquifers occur in the basaltic layers of the Lower Cretaceous Serra Geral Formation in Brazil, the Arapey Formation in Uruguay, and the Alto Paraná Formation in Paraguay, mainly in the interflow zones that present cooling joints and other fracture zones of tectonic origin. Interbedded sandstone lenses in the basaltic pile increase the average porosity of these producing zones in the basaltic units. These three stratigraphic units cover an area of 1,000,000 km^2 in the Paraná Basin. Combined with the aquifer of the Botucatu and Bauru formations (and correlated stratigraphic units), more than 5000 wells provide water supply for important cities in southern South America.

The Upper Cretaceous Caiuá/Bauru groups in Brazil and the Paysandu Group (Mercedes Formation) in Uruguay cover an area of more than 360,000 km^2 in the Paraná Basin. These units, consisting mainly of sandstones, have an average thickness of 100 m and usually provide

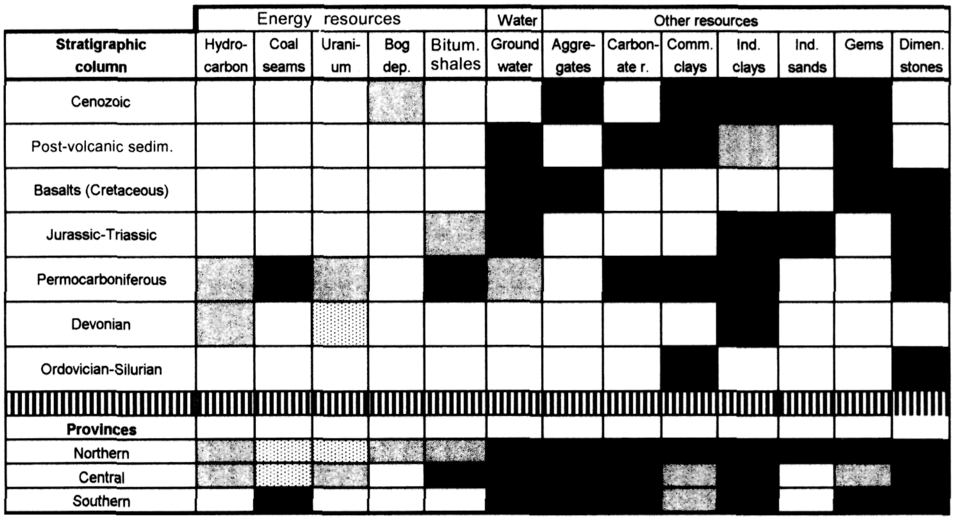

FIG. 7. Distribution of the main mineral deposits and occurrences through the stratigraphic column and provinces in the Paraná Basin. Legend: Black cells = active mining; medium grey cells = deposits or very important mineral occurrences; dotted cells = occurrences of minor importance. Abbreviations: sedim. = sediments; dep. = deposits; r. = rocks; comm. = common; ind. = industrial; dimen. = dimension.

water of good quality, almost all for domestic supply and secondarily for use by small industries.

The groundwater reserves and the hydrological parameters of these Mezosoic aquifers of the Paraná Basin are shown in Table 1. Paleozoic aquifers are significant only on the margins of the Paraná Basin, where drillhole yields range from 10 to 50 m^3/h (Rebouças, 1976, 1978). The best units for water resources are the Silurian units of the Alto Garças Formation in Brazil and the Caacupé Group in Paraguay, the Devonian sedimentary rocks of the Furnas Formation in Brazil, the Permian-Carboniferous rocks of the Tubarão Group in Brazil, the San Gregorio and Tres Islas formations in Uruguay, and the Coronel Oviedo and San Miguel formations in Paraguay. Moreover, the Rio do Rasto Formation in Brazil, which is believed to range into the Triassic locally, constitutes a groundwater source.

The Pirambóia/Botucatu and the Serra Geral formations occur in the Northern, Central, and Meridional provinces. The Misiones Formation occurs in the Central province. The Caiuá/Bauru Group crops out in the Northern province, whereas the Tacurembo Formation and the Mercedes Formation occur exclusively within the Meridional province.

Aggregates

Sand, gravel, and crushed stone have important applications in the construction industry and governmental projects (concrete, paving, structural and non-structural fill, etc.) in south-central Brazil and neighboring countries. Some sands also find industrial applications in the making of glass, crystal, etc. (see industrial sands below). The most important sources of sand production are stream channels, fluvial terraces, and floodplain deposits. Because of the very dense hydrographic network of Brazil and central-southern South America, it is possible to say that every municipality has its own sand source. Gravel deposits are restricted to stream channels and terraces, the latter mainly resulting from the erosion of rudaceous deposits of certain lithostratigraphic units of the Paraná Basin. These sand units contain 75% of the known reserves, estimated at 900 million tons (DNPM, 1991).

Crushed stone in the basin is available from rocks of the basaltic flows and diabase dikes and sills of the Serra Geral magmatic event (Early Cretaceous). Annual production of crushed basalt is 1,250,000 tons, of which 84% is produced in São Paulo state, Brazil. This production accounts for approximately US $18 million annually.

TABLE 1. Groundwater Reserves in the Paraná Basin and Some of Their Hydrological Parameters

Main aquifer systems	Main lithology	Yield, m^3/h	TDS,[2] mg/L	Specific capacity, $m^3/h/m$	References
Cretaceous sedimentary sequences	Sandstones	1.3–80.0	<200	n.a.	Rebouças (1988)
Basalts	Tholeiitic basalts	n.a.	<300	3.5×10^{-3}–37.7	———
Guarani[1]	Sandstones	10–150 (unconfined) 300–1000 (confined)	n.a.	0.03–6	Rebouças (1988) DINAMIGE (1986)

[1]The Guarani aquifer is a name proposed in the final document of the Jornada Técnico-Científica sobre Gestão Sustentável do Aquífero Internacional Botucatu (Technical-Scientific Expedition on the Sustainable Management of the International Botucatu Aquifer) for the Botucatu (Brazil), Tacuarembó (Uruguay), and Misiones (Paraguay) aquifers (Curitiba, Paraná, Brazil, 1994).
[2]TDS = total dissolved solids.

Carbonate rocks

The Paraná Basin has important reserves of limestones not only for agricultural use as a soil conditioner (predominantly Permian limestones), but also for the Portland cement industry (usually Upper Cretaceous limestones). The Permian carbonates belong to the Passa Dois Group (Irati and Terezina-Corumbataí formations) in Brazil, and to the Independencia Group (Tacuary Formation) in Paraguay. The Mangrullo Formation in Uruguay, correlated with the Irati Formation of Brazil, has no exploitable limestone reserves. The Irati Formation represents the main source for the development of these carbonates. These limestones are dolomitic and their main use in agriculture is for the alkalinization of acidic soils. They are mined in outcrops along the basin margins in the northern province in the states of São Paulo (Rio Claro, Piracicaba, Limeira, Laranjal Paulista, Conchas, and Itapetininga formations), Goiás (Montividiu, Mineiros, and Perolândia), and Mato Grosso (Alto Garça). The main area of mining is in the state of São Paulo, where a 5-m-thick layer of limestone, locally named the "banco" (bench), underlies a rhythmic sequence of 20 m of bituminous black shales intercalated with limestone layers, named the Assistência Member. Toward the Central and Meridional provinces (Paraná, Santa Catarina, and Rio Grande do Sul states), this exploitable limestone bench loses expression, and the Irati Formation is mainly constituted by clays and black bituminous shales, reaching such a richness in hydrocarbons that oil is extracted from these shales in an industrial plant at São Mateus do Sul (Paraná state). Along the northern and northwestern basin margins (Goiás and Mato Grosso states) in the northern province, the Irati bench is not well defined and limestones are worked only in two layers of minor expression.

In at least two cases, non-dolomitic limestones of the Passa Dois Group are exploited for agricultural use. They occur as limestone layers of the Terezina-Corumbataí Formation in Taguai and the Santa Rosa do Viterbo Formation in the state of São Paulo (Northern province) and in the Tacuary Formation (Independencia Group) near the city of Caaguazu in Paraguay (Central province). In a chrono-correlated stratigraphic unit in Uruguay (Meridional province), the Yaguari Formation also contains carbonate lenses intercalated with sandstones and conglomeratic sandstones. The carbonate grade of these lenses is no higher than 70% (Bossi, 1978) and they are mined only in the vicinity of La Calera.

Exploration data for 1996 indicate a production of 1,500,000 tons/year for the Irati Formation limestones in São Paulo and at least 247,000 tons/year for Goiás; both areas are in the Northern province. There are no production statistics for other regions.

The Upper Cretaceous carbonate rocks are predominantly non-dolomitic and usually bear only traces of MgO. They are widely used in their regions of occurrence by the Portland cement industry, although locally, they also are used by agriculture as a soil conditioner. There are two main zones of occurrence, one in southwestern Minas Gerais state, known as "Triângulo Mineiro" (Northern province) in Brazil, and a second far south in northwestern Uruguay (Meridional province) near Paysandu, on the border with Argentina.

In the Northern province, these limestones belong to the Marília Formation (Ponte Alta Member) of the Bauru Group. The origin of these limestones is supposed to be related to non-pedogenic groundwater calcretes in a post-depositional calcretization that acted on siliciclastic facies deposited as alluvial fans in a semi-arid environment (Silva et al., 1994). Quarries and outcrops show massive beds 8 to 15 m thick, usually with sand grains, silica concretions, and quartz to quartzite pebbles. Reserve figures are scarce, but individual deposits have potentials from tens to a hundred million tons of ore, in which the carbonate grade may be as high as 95%. These carbonates are being explored by the cement industry.

In the Meridional province, carbonate rocks are found in the Mercedes Formation (Paysandu Group), also known as the "Calizas de Queguay." Their origin is believed to be similar to that for carbonates of the northern province (Veroslavsky et al., 1996). The quarries and outcrops present a bedding geometry of lenses or tabular forms 12 to 15 m thick and a carbonate grade of 85% (locally up to 90%). In the "Queguay" area, total reserves are estimated at 30,000,000 tons of carbonates; deposits are exploited by the Administración Nacional de Combustibles, Alcoholes y Portland (ANCAP) for the cement industry.

Clays

In this paper the term clays encompasses two main categories of mineral resources—common clays (brick, tiles, etc.) and industrial clays (bentonite, kaolin, refractory, ball clays, etc.). The former represents a widespread material in the basin, mainly associated with Cenozoic alluvial plains of the principal rivers and to alterites of Permo-Carboniferous and Permian units (Tubarão and Passa Dois groups). They occur in all three provinces, where common clays for tiles represent an important resource for economic development, as in São Paulo, Paraná, Mato Grosso do Sul, and Santa Catarina states. These clays, locally referred to as "taguás" in São Paulo, are derived from rhythmites (varved clays) of the Itararé Group by weathering.

Bentonite has been found in certain layers of the Permo-Carboniferous Itararé Group and in the Bauru Group in the Northern province. In this latter occurrence, the deposits presumably are associated with tuffaceous material. Reserve figures for the latter occurrence are believed to be several million tons, although commercial exploration is not under way. In the Meridional province, the bentonite and bentonitic clays are restricted to a tabular bed with horizontal continuity in the Permian–Triassic Yaguari Formation (Uruguay). They also are associated with volcanic tuffs intercalated in this unit. Reserves of 275,000 tons are estimated for the Bañado de Medina locality (Cerro Largo department). In the Central province, there are no known occurrences, although layers of bentonite should be expected in Paraguay.

Ball clay deposits are known only in the Northern province, specifically in the state of São Paulo (São Simão and Cravinhos). These Cenozoic deposits occur as beds or lenses, with an average thickness of 50 cm, associated with bog and sand facies. Reserves are estimated at ~ one-half million tons (Branco, 1984).

Kaolin occurrences are known at the southern limit of the Northern province in the state of Paraná (Balsa Nova region), associated with the Devonian Furnas Formation and with the Permo-Carboniferous Itararé Subgroup. In the Meridional province, kaolin deposits occur in the Devonian sequence of Uruguay at the base of Cerrezuelo Formation and in the Cordobés Formation, both within the Durazno Group. The major exploration activity, especially for china, is developed in the Blanquillo region in clay layers of the Cordobés Formation. No estimated reserve figures are available. In the central province it is possible to say that clay exploration for the ceramic industry around Itauguá city, in Paraguay, consists mostly of kaolin occurrences within the Silurian

(Eusebio Ayala and Vargas Peña formations of the Itacurubi Group). As in the previous case, reserves are not known.

Industrial sands

Industrial sand production and its main commercial market are located in São Paulo state (Northern province). The consumer market is represented by glass, ceramic, and foundry casting for metallurgical industries, the latter including castings for engines in the automotive industry. The glass and foundry industries consume 81% of the industrial sand produced in São Paulo. This production is expected to approach 3.8×10^6 tons by the year 2000. In the state of São Paulo, 11 mining companies and 24 industries (11 for glass and 13 for foundry production) are active. The main source rocks are sand layers of the Pirambóia/Botucatu Formation of Mesozoic age and the Rio Claro Formation of Cenozoic age (Ferreira, 1995).

Gems and dimension stones

There are two types of economic gemstone deposits in the Paraná Basin: (1) amethyst and agate geodes associated with basaltic flows of the Serra Geral Formation in Brazil (northwestern Rio Grande do Sul state) and the Arapey Formation in Uruguay (Artigas department), both in the Meridional province; and (2) diamonds in several stratigraphic units of the basin and as detrital diamonds scattered along alluvial plains of Cenozoic age, mainly in the Northern province (along the northern margin of the basin) and in the Central province (along the Ponta Grossa Arch hinge zone).

Agate, a variety of chalcedonic quartz, is distinguished by its concentric color banding in two or more tones of brownish red, grey, blue, or white. Additionally, the different porosities of the bands allow artificial dyeing of the pieces. Amethyst is a transparent purple to violet form of quartz. Both agate and amethyst occur in the basaltic flows that form the bedrock of the Uruguay River valley. Although the two minerals have a similar genetic origin, they are not found associated in the same flow.

In Brazil, the main amethyst exploration zone is located in a 50-m-thick flow that may be followed for a distance of 25 km in the state of Rio Grande do Sul (Planalto, Frederico Westphalen, Rodeio Bonito, and Alpestre municipalities). The economic zone is situated in the upper 2–3 m of this layer immediately below the vesicular zone. The geodes present irregular to cylindrical shapes with axes of decimeter to meter sizes; the origin of amethyst is interpreted to be the result of hydrothermal action (Scopel and Gomes, 1994). Mining activity is widespread but disorganized, occupying 6000 diggers (*garimpeiros*) working 1200 mines (*garimpos*). Estimated production is ~150 to 250 tons per month, resulting in an annual income of US $20,000,000 (Koppe et al., 1994). No data exist for Uruguayan production of this gemstone.

Agate exploration is carried out in the weathered portion of basaltic flows near their vitreous facies, where there is a higher frequency of better-quality pieces. Kellerman (1994) estimated a production rate of 45 tons per month (polished material) for the Salto do Jacui and Arroio dos Tigres municipalities in Rio Grande do Sul state in Brazil. For the exploration zone in the Artigas department in Uruguay, agate and amethyst production over the past decade has averaged ~133 tons/year and 73 tons/year, respectively (DINAMIGE, 1995).

Diamonds occur in several stratigraphic units in the Paraná Basin, from the Devonian Furnas Formation through the Permo-Carboniferous Itararé and Aquidauana formations, the Mesozoic Botucatu Formation and Bauru Group, to unnamed Cenozoic deposits. In spite of this large stratigraphic spectrum, deposits of economic value are concentrated in placers of Cenozoic sediments. These placers occur both in Holocene alluvial plains and in much older fluvial terraces.

In the Northern province, diamond occurrences are located in Cenozoic sediments along the main fluvial valleys of Mato Grosso do Sul state (the Taquari-Mirim, Coxim, Taquari, and Piqueri rivers), Goiás state (the Verde, Paranaíba, Rio Claro, Araguaia, and Caiapó rivers), and Mato Grosso state in the alluvium of several small rivers that drain the Poxoréu and Chapada dos Guimarães plateaus, mainly consisting of Devonian and Mesozoic sediments. All of these diamondiferous deposits are considered to be of secondary origin. Also in this province, there are diamond occurrences in Minas Gerais and São Paulo states. In Minas Gerais, diamonds occur in the area referred to as the "Triângulo Mineiro," both in alluvial Cenozoic sediments and in Mesozoic Bauru Group conglomeratic layers (Romaria) not far from Coromandel, a famous zone of large stone production. In this latter site, 30% of the diamonds are of gem quality and associated with strong kimberlite satellite mineral assemblages. Alluvial diamonds occur (Canoas, Sapucai, Grande, and Santa Barbara rivers) in the northeastern region of São Paulo state. In this region, 70 to 80% of the diamonds are of gem quality, with the stones being mostly smaller than 35 points. Grades are presumed to vary from 0.02 to 0.18 ct/m^3 (Etchebehere et al., 1991).

In the Central province, diamondiferous deposits also occur in sediments linked to Cenozoic alluvial plains (Tibagi, Peixe, das Cinzas, Jaguariaíva, and Verde river valleys), especially where these rivers cut areas of Paleozoic rocks (Devonian Furnas Formation or Permo-Carboniferous Itararé Subgroup). The secondary character of these diamondiferous deposits is reinforced by the good quality of the gems, their small sizes (mainly under 1 carat), and the absence of indicator minerals of a primary origin (Gonzaga and Tompkins, 1991).

Consolidated economic data with respect to diamond production are not available, mainly because of the informal character of the production and the trade of these gems. From a geological point of view, theories about the origin of these diamonds usually present large gaps, although several kimberlite as well as lamproite intrusions have been recognized along the northern Paraná Basin margin and in certain localities of the basin interior (Lajes cluster and Jaguari-Rosário do Sul diatremes).

Diamond occurrences in Uruguay and Paraguay are unknown, although some lamproites were found within the ultrapotassic Guairá-Paraguarí province (80 km southeast of Assunción, Paraguay). These lamproites make this province a potentially diamondiferous area (Preser, 1991).

Sedimentary and volcanic rocks of several stratigraphic units are quarried and cut in required dimensions for use in building ornamentation and street pavements. They occur in all of the three basin provinces. They are chiefly represented by sandstones, "slates," and basalts. Silicified sandstone layers are quarried in the Botucatu Formation in Brazil, Tacuarembó Formation in Uruguay, and Misiones Formation—all of a Mesozoic age—and the Silurian Cerro Jhú Formation in Paraguay. In the latter country, columnar sandstones in joints induced by basic igneous rocks of Tertiary age in the Patiño Formation deposits are widely used for pavement and ornamentation.

Slate is the commercial name for rhythmic layers of Permian age (usually varved clays) that occur in the Itararé Subgroup and the Terezina Formation (= Corumbataí). Locally, Mesozoic intrusive diabases and basaltic layers are quarried as blocks for paving streets.

Energy Resources

Coal

During 1970–1985, the Departamento Nacional da Produção Mineral (DNPM)—a federal-level Brazilian government department for the development of mineral production—and the Companhia de Pesquisas de Recursos Minerais (CPRM)—the Brazilian Geological Survey—developed a program for the exploration and evaluation of coal, lignite, and peat occurrences throughout the country. The results of this program established what was already known—that all the economic coal deposits were located in southern Brazil, in Santa Catarina and Rio Grande do Sul states, with 91% of the national coal reserves being found in the latter state. Santa Catarina possesses 8.59% of Brazil's coal reserves and Paraná and São Paulo states together 0.52% (Lenz and Ramos, 1985). Thus it is possible to say that economic coal reserves are only encountered in the Meridional province.

The coal is normally bituminous to subbituminous and highly volatile. Ash content of raw coal (ROM) is high, with values of ~50 to 65%. Sulfur content exhibits great variability. Raw coal is mined mainly for the production of steam coal, and secondarily for cooking (only in the coal basins of Santa Catarina).

The main coal fields are in Permian deltaic deposits of the the Rio Bonito Formation (Tubarão Group), which contain 10 coal seams with an aggregate total thickness of 10 m. The largest single coal field—the great Candiota in Rio Grande do Sul state near the Uruguayan border—has coal reserves estimated at 8×10^9 tons. Total coal reserves estimated for Brazil are 23×10^9 tons (Marques-Toigo and Corrêa da Silva, 1983; Nahuys and Piatnicki, 1983; Lenz and Ramos, 1985). Mining is by open pit or underground techniques, depending on the sedimentary cover above the coal layers.

Peat deposits

Peat deposits occur predominantly in São Paulo and Minas Gerais states (Northern province) and in Paraná (Central province). In São Paulo and Paraná states, the occurrence of these usually lenticular deposits is associated with sediments of modern river floodplains—principally the Mogi-Guaçu and Jacaré-Guaçu/Jacaré-Pepira river systems in São Paulo state and the Iguaçu, Negro, Iapó, Tibagi, Ivaí, Piqueri, and Paraná rivers in Paraná state (Motta et al., 1982; Lenz and Ramos, 1985). Peat deposits amount to 75.6×10^6 m^3 *in situ* in São Paulo and 83.0×10^6 tons for Paraná (Mineropar, 1982). The results of technological assays on peat samples indicate that they represent a good energy resource for agricultural activities.

A special type of peat deposit is located in the Triângulo Mineiro area in Minas Gerais state. These deposits occur at the top of 800- to 1000-m-high plateaus, locally named "Chapadões," and have an average thickness of 2 m. Technological analysis of this material suggests that it represents a potential energy resource (e.g., for gasification, etc.). The deposits occur in 40 different points in the plateau region; total reserves are estimated at 210,000,000 m^3 (Pratini de Moraes, 1982). They are believed to be the result of sedimentation in several ancient high-altitude ponds.

Spongilites (a related non-energy resource) were discovered in association with some Holocene peat-bog ponds in southwestern Minas Gerais, southern Goiás, and northeastern Mato Grosso do Sul states. These fresh-water sponge species already were known to exist in São Paulo state in the same type of deposit. Ribeiro-Volkmer and Mota (1985) defined this entire region as being part of only one province, whose conditions had favored the occurrence of this type of species. The main uses for this material are in filtration processes, as thermal insolation, and in the abrasives industry. The total reserves in these deposits is still unknown.

Data do not exist in Uruguay regarding peat deposits. In Paraguay, the occurrence of peat should be strongly expected along the principal river valleys, such as the Tebicuary and Paraguay rivers. The modern structural framework of this country, closely related to neotectonic events, represents a mosaic of uplifted and downfaulted blocks, the latter with an almost endorheic aspect that favors the occurrence of this type of material.

Hydrocarbons

Exploration for oil or gas in the Paraná Basin began in the last decade of the 19th century, not only through governmental efforts, but also by private companies. As is the case in other Third World countries, the absence of a clear government policy for hydrocarbon exploration resulted in a serious delay in research on this energy resource. In the Brazilian portion of the Paraná Basin, several exploration campaigns and their main characteristics can be divided into five phases, as shown in Figure 8 (Milani et al., 1990).

Research carried out in the Paraná Basin has generated the following information.

(1) About 110 wells in Brazil, 25 wells in Uruguay, and at least 2 important wells in Paraguay have been drilled, mainly for stratigraphic tests.
(2) 22,000 km of seismic lines in Brazil (Milani et al., 1990), 1650 km in Uruguay (ANCAP, 1979), and 180 km in Paraguay (Redmond, 1985) have been laid, in addition to other geological and geophysical studies (e.g., morphostructural analysis, geological mapping, MT soundings, aeromagnetometric surveys, etc.).
(3) Several laboratory assays (paleontological, petrographic, geochemical, reservoir, etc.) have been conducted.

The main source rocks belong to the following stratigraphic units: (1) the shaly layers of the Vila Maria Formation (2% organic matter) in Brazil, and the Itacurubi Group in Paraguay, both of Silurian age; (2) the shales of the Ponta Grossa Formation (2% organic matter) in Brazil and Paraguay, and the shales of the El Cordobés Formation in Uruguay, both of Devonian age; and (3) the black shales of the Permian Irati Formation (average of 8% organic matter, locally reaching up to 23%) in Brazil and the Mangrullo Formation in Uruguay, of the same Devonian age.

The main reservoir rocks belong to the following stratigraphic units: (1) The Silurian

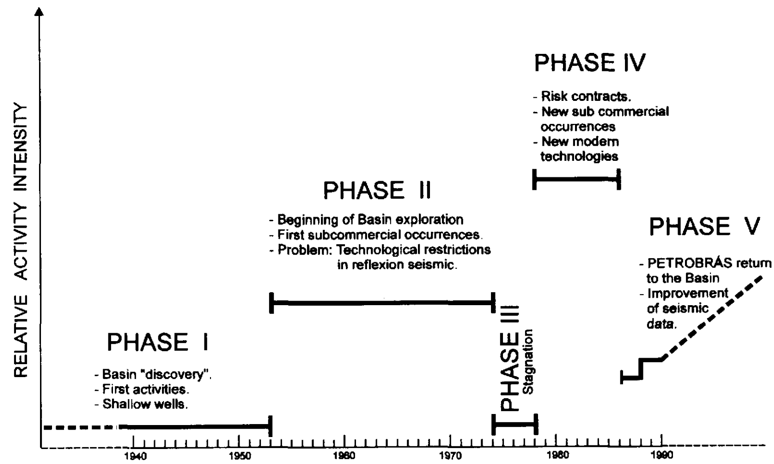

FIG. 8. Phases of hydrocarbon exploration in the Paraná Basin (after Milani et al., 1990).

Alto Garças Formation (6 to 16% porosity) in Brazil and the sandy layers of the Caacupé Group of same age in Paraguay; (2) the Devonian Furnas Formation (6 to 16% porosity) in Brazil; (3) the Permo-Carboniferous Itararé Group (6 to 16% porosity) in Brazil, the San Gregorio Formation in Uruguay, and the Coronel Oviedo Formation in Paraguay; (4) the Permian units of the Rio Bonito Formation (16 to 20% porosity) in Brazil, the Tres Islas, Fraile Muerto, Paso Aguiar, and Yaguari formations in Uruguay; and the San Miguel Formation in Paraguay; (5) the Triassic-Jurassic Piramboia/Botucatu formations in Brazil, the Tacuarembó Formation in Uruguay, and the Misiones Formation in Paraguay.

The structural framework of the Paraná Basin includes many shear zones, usually expressed as mega-alignments and clearly observed as a result of geological and geophysical surveys. The usual strikes of these structures are NW, NE, N-S, and E-W, forming a huge structural mosaic, dividing the entire basin into "boxes" in which the stratigraphic column can vary quite widely from one area to another. In Brazil, this structural framework is reasonably well known and used in petroleum evaluations of this basin (Fulfaro et al., 1982). The same can be said regarding the situation in Uruguay, where anticlines (bird-wing structures) and pinchouts against the shoulders of the central arches are explored for a prospective oil play (Goso and de Santa Ana, 1994). Regardless of the scarce existing data in Paraguay obscuring the petroleum evaluation picture, it is in this country that one of the most important structural features of the Paraná Basin is found—an aulacogen. The San Pedro downfaulted block (Bajo de San Pedro) in east-central Paraguay contains more than 6000 m of sediments ranging from at least Early Silurian to Jurassic in age, and was the former sea connection between the proto-Pacific ocean and the cratonic Paraná Basin interior (Fulfaro et al., 1982; Fulfaro, 1995).

The time-temperature-depth relationship (Lopatin's method) applied to the Paraná Basin reveals an incredible result. Lower Mesozoic volcanism, with its locally high thermal gradient and thick pile of lava flows (in some places 2000 m thick), appears to have generated ideal conditions for oil and gas generation. Nevertheless, a great number of problems are present in the determination of the most promising plays, such as flushing zones at the basin margins, where meteoric waters favor biodegradation, and the presence of hypersaline waters in the basin depocenter.

The principal oil and gas occurrences in the basin are: (1) the Cuiabá Paulista area in São Paulo state (Northern province); (2) the Chapéu do Sol, Pitanga, Cândido de Abreu, and Rio Piqueri areas in Paraná state and the Mallorquin area in Paraguay (Central province); and (3) the Três Pinheiros, Matos Costa, Taquara Verde, and Herval Velho areas in Santa Catarina state (Central province). Although commercial oil or gas occurrences have not yet been found in the Paraná Basin, the common oil shows in several layers in the stratigraphic pile, in practically all the existing drillholes, the scarce number of these wells (no more than 140 wells for an area of 1,200,000 km^2), and the low geophysical net (23,830 km of seismic lines for the same area) do not, under any circumstances, limit the potential of hydrocarbon exploration. In addition to the thick basaltic cover, the superposition of the Mesozoic rift phase above the previous volcanic-sedimentary pile, allowing the basin to be classified as a cratonic 2A complex (Fulfaro et al., 1982), increases the possibility of a future commercial oil or gas occurrence. Furthermore, the predominance of Type-III organic matter in the possible source rocks suggests that this basin is highly prospective for gas exploration.

Oil shale

Oil shales occur in the so-called pyrobituminous black shales of the Permian Irati Formation. These shales are quite continuous for more than 1000 km, across all of the outcrop belt of the eastern margin of the basin from the state of Goiás in the north to the Republic of Uruguay in the south (Fig. 1). Nevertheless, the entire area is not suitable for commercial exploration.

Economic studies developed by Petrobras (the Brazilian state oil company) in these shales began in 1955, and the final results were so promising that this company created a subsidiary in São Mateus do Sul in Paraná state (Central province), known as the Superintendência da Industrialização do Xisto (SIX). SIX was created to supervise the extraction and processing of oil from shales and operates a plant (PETROSIX) for oil extraction from the Irati Shales (referred to locally as "schists") in this area.

In the São Mateus do Sul quarries, the Irati Formation has two distinct layers suitable for oil exploration, separated by a bed of nonbituminous shales with intercalated limestone layers. The upper shale bed has an average thickness of 6.5 m, whereas the lower one is 5.2 m thick. Reserves in aggregate are 100 million m^3 (630 million barrels). The beds have a combined thickness of 10.7 m with a 7.4% oil yield (Padula, 1968).

Farther south, in Rio Grande do Sul state (Meridional province), another area of these shales was considered as favorable for commercial exploration near the city of São Gabriel. The unit exhibits an even greater thickness for the same two beds than previously described. The upper layer has an average thickness of 9.0 m and the lower one 4.5 m. Nevertheless, only the lower one, with 7% oil yield, is considered siutable for oil exploration (Padula, 1968; Alves and Padula, 1972).

In northeastern Uruguay (Meridional province), near the Brazilian border, the same stratigraphic unit is called the Mangrullo Formation. The Uruguayan State Oil Company made a regional study, both at the surface and subsurface, of the entire area of the unit's occurrence, and estimated total reserves of 60 million barrels (ANCAP, 1979). In Paraguay there is no occurrence of oil shales, at least in the basin outcrop belt.

Tar sands (oil sands)

Tar (or oil) sands in the Paraná Basin occur only in the northern flank of the Ponta Grossa arch in São Paulo state of the Northern province (Figs. 1 and 3). Tar-sand occurrences (IPT, 1980, 1986; Kramers, 1982) are divided stratigraphically into three zones: (1) near the base of the Pirambóia/Botucatu Formation (Guarei I and II, Sobar, and Bofete); (2) 60 to 80 m above the base of the Pirambóia/Botucatu Formation (Fazenda da Mina, Piapara, and Fazenda Betumita); and (3) a small occurrence at the top of the Permian Tatui Formation (= Palermo Formation) at Jacutinga.

In general, it is possible to state that tar-sand occurrences in the Pirambóia/Botucatu Formation are in layers of trough cross-bedded sandstones with lateral variations in bitumen saturation. Lateral variations are associated with the sedimentary facies and related to porosity/permeability. The vertical succession of laminae of these cross-bedded strata also present a variation in oil saturation resulting in a color alternation from black to pale yellow, leading to their designation locally as "Tiger" layers (Roncaratti, 1971; Gonçalves and Schneider, 1971; Franzinelli, 1972; Thomaz Filho, 1972; IPT, 1986).

Tar-sand occurrences are always associated with faults, diabase dikes, or with the flanks of structural highs adjacent to faults and dikes. The oil generation is related to Early Cretaceous volcanism and its source rock is the bituminous shale of the Irati Formation. Oil migration followed the aforementioned structural pattern. Trapped in the reservoir sedimentary facies (Tatui or Pirambóia/Botucatu formations), this oil was biogenically degraded to its present viscous stage (IPT, 1980, 1986). These degraded ancient oil fields were explored during World War II for gasoline production.

Uranium

The only possible commercial deposit of uranium in the basin is in the Figueira area, located in the north-central part of Paraná state (Central province). It was discovered in 1969 as a result of a systematic survey of coal basin evaluation, carried out by Nuclebras, the state-owned company in charge of the Brazilian nuclear program.

The uranium deposits are located in the basal layers of the Permian Rio Bonito Formation, whose deltaic deposits are mainly represented by sandstones, coal, and carbonaceous sediments. Saad (1973) and Morrone and Daemon (1985) described this mineralization as the result of both syngenetic and epigenetic processes. The uranium occurs as uraninite in a lenticular ore body 3 km long and 600 m wide on average. Total reserves amount to ~8000 tons of U_3O_8.

Other Possible Prospects

Over the last decade other possible prospects for mineral exploration have been identified as a result of several research programs in the Paraná Basin. A good synthesis of such prospects is found in IPT (1988).

These possible mineral resources include:

Marine evaporites. Well 2-PN-1-SP near the city of Paranapanema, São Paulo state, drilled through 10 meters of anhydrite in the Permian Irati Formation.

Continental evaporites. Some authors point to the possibility for the existence of continental evaporites in the Mesozoic sequence, especially in the Bauru Group (e.g., Silva and Delmonte, 1987; Cabral, 1991). In a re-evaluation of the mineral potential of the basin for continental evaporites, Etchebehere et al. (1993) concluded that flushing phenomena would dissolve and allow extraction of the saline facies.

Phosphate. Phosphorite layers were identified in some layers of the Permian Passa Dois Group and also in some levels of the Devonian Paraná Group. No further data are available concerning these occurrences.

Base metals. Occurrences of lead, copper, and zinc of very low potential were observed in some of the Permo-Carboniferous and Cretaceous sedimentary beds. A few occurrences of metallic copper have been reported in voids and diaclases of Serra Geral basalts.

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