SEQUENCES AND STRATIGRAPHIC HIERARCHY OF THE PARANÁ BASIN (ORDOVICIAN TO CRETACEOUS), SOUTHERN BRAZIL

E. J. Milani[a], U. F. Faccini[b], C. M. Scherer[c],
L. M. Araújo[a], J. A. Cupertino[a]

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Resumo

A Bacia do Paraná, uma vasta área de sedimentação paleozóica-mesozóica, abriga um registro estratigráfico com idades entre o Neo-Ordoviciano e o Neocretáceo, compreendendo seis superseqüências (Milani, 1997): Rio Ivaí (Ordoviciano-Siluriano), Paraná (Devoniano), Gondwana I (Carbonífero-Eotriássico), Gondwana II (Meso a Neotriássico), Gondwana III (Neojurássico-Eocretáceo) e Bauru (Neocretáceo). As três primeiras correspondem a grandes ciclos transgressivos paleozóicos, enquanto as demais são representadas por pacotes de sedimentitos continentais e rochas ígneas associadas.

Estas superseqüências constituem o registro preservado de sucessivas fases de acumulação sedimentar que se intercalaram a períodos de erosão em ampla escala. A evolução de cada unidade foi condicionada por contextos particulares em termos de clima e condições tectônicas. A Superseqüência Rio Ivaí relaciona-se à implantação da Bacia do Paraná, e a geometria de sua área de ocorrência, com depocentros alongados de orientação geral SW-NE, sugere ter ela sido controlada por algum mecanismo de rifteamento. A Superseqüência Paaná acumulou-se durante uma época de amplo afogamento marinho das áreas cratônicas do Gondwana. Condições de bacia intracratônica, implicando um efetivo isolamento no interior continental, começam a predominar durante a deposição da Superseqüência Gondwana I, o que viria a culminar no desenvolvimento de amplos campos de dunas eólicas, já ao final do Jurássico. Os magmatitos Serra Geral, do Eocretáceo, estão relacionados aos estágios iniciais de ruptura do paleocontinente, e a cobertura continental Bauru encerrou a história sedimentar da Bacia do Paraná.

O potencial petrolífero da Bacia do Paraná vincula-se a dois sistemas petrolíferos bem estabelecidos: para o primeiro, favorável a hidrocarbonetos gasosos, a geração ocorreu nos folhelhos da Formação Ponta Grossa e a acumulação nos arenitos do Grupo Itararé ou da Formação Rio Bonito; o segundo inclui geração nos folhelhos betuminosos da Formação Irati e acumulação nos arenitos Rio Bonito, sendo propício à ocorrência de óleo. Sob vários aspectos, o papel do magmatismo mesozóico na maturação dos horizontes potencialmente geradores da Bacia do Paraná parece ter sido um ponto crucial de sua história evolutiva, e um item que requer investigações adicionais.

(a)PETROBRÁS/E&P/GEREX, Av. Chile, 65 - 20035.900 - Rio de Janeiro, RJ, Brasil

(b)UNISINOS, Dpto. de Geologia, CP 275 - 93022.000 - São Leopoldo, RS, Brasil

(c)UFRGS, Inst. de Geociências, CP 15001 - 91501.970 - Porto Alegre, RS, Brasil

Abstract

The Paraná Basin, a vast sedimentation area during Paleozoic and Mesozoic times, holds a stratigraphic record ranging in age from late Ordovician to late Cretaceous and comprising six supersequences or unconformity-bounded units (Milani, 1997): Rio Ivaí (Ordovician-Silurian), Paraná (Devonian), Gondwana I (Carboniferous-early Triassic), Gondwana II (middle-late Triassic), Gondwana III (late Jurassic-early Cretaceous), and Bauru (late Cretaceous). Three of them coincide with major Paleozoic transgressive-regressive cycles, and the others are Mesozoic continental sedimentary packages with associated igneous rocks.

These supersequences are the remnant record of successive phases of sediment accumulation alternating with times of erosion. The evolution of each supersequence was constrained by a particular tectonic and climatic setting. The Rio Ivaí supersequence is closely associated with basin inception and its geometry suggests that deposition was to some extent controlled by normal faulting. The Paraná supersequence deposited during a time of widespread marine flooding over the cratonic area of southwestern Gondwana. From the deposition of the Gondwana I supersequence onward true intracratonic conditions were established. Sharing Gondwana's dessication trend the Paraná Basin sedimentation history culminated with extensive desertic conditions during the Jurassic. The Lower Cretaceous Serra Geral continental flood basalts are related to the initial moments of South Atlantic rifting, and the upper Cretaceous Bauru continental cover ended the history of the basin.

The hydrocarbon potential of the Paraná Basin is related to two well defined source beds: the Devonian shales (Ponta Grossa Formation) and the upper Permian bituminous shales and limestones (Irati Formation). Sandy reservoirs can be found in the lower Devonian Furnas Formation, in the upper Carboniferous/lower Permian Itararé Group and in the lower Permian Rio Bonito Formation. The role of intrusive bodies in the maturation of source rocks and in the trapping of hydrocarbons seems to be crucial and deserves more investigation.

INTRODUCTION

The paleocontinent of Gondwana, consolidated in late Precambrian/early Paleozoic times after successive collisional episodes and tectonic collages related to the Brasiliano/Pan-African orogenic cycle, was the site of extensive, and in many places continuous, cratonic sedimentation during Paleozoic and most of Mesozoic times. In spite of lying today in individual basins situated over continental blocks split apart by thousands of kilometers (South America, Africa, Australia, India and Antarctica) as a consequence of Gondwana's breakup in Mesozoic times, these strata still retain many characteristics in common that serve as indicators of their shared geologic evolution.

The Paraná basin is one of these areas, situated in central/southeastern South America (Fig.1). It comprises 1,100,000 square kilometers of Brazil and about 100,000 square kilometers each of Uruguay, Paraguay and Argentina. Its lithologic record is constituted by an up to 8,000 meter-thick sedimentary and igneous rocks package. The basin has a NE-SW elliptical shape and its depocenter axis is nearly coincident with the Paraná River that lends it its name. The geologic evolution of the Paraná Basin was complex. Its lithologic record witnesses several stages of its history, each controlled by climatic and tectonic factors. A multitude of depositional settings, with both marine and continental components, including glacial beds, desert sandstones and shallow marine to transitional facies, were established successively in a basin whose outlines were continually reshaped by tectonic activity. Included is the largest igneous accumulation on land areas of the planet, the continental flood basalts of the Serra Geral Formation. The whole package ranges in age from late Ordovician to late Cretaceous,comprising six supersequences discussed below.

In Brazilian geology, few themes deserved so many investigations as the stratigraphy of the Paraná Basin. Since the seminal work of White (1908), much research has been conducted to elucidate the spatial and temporal relationships of the rocks that fill the basin. Some tens of formal stratigraphic charts have already been published, each one of then incorporating at the time a particular contribution to basin's knowledge. Remarkable studies with regional approaches were made by PETROBRÁS groups (Sanford and Lange, 1960; Daemon and Quadros, 1970; Northfle et al., 1969; Schneider et al., 1974; Zalán et al., 1990), by the PAULIPETRO team (Fulfaro et al., 1980) and by university researchers (Soares, Landim and Fulfaro, 1978).

According to the dominant paradigms in those days, the stratigraphic interpretation of the Paraná Basin was for a long time dependent on the "layer cake" concept. As a consequence, the distribution of rock units was interpreted in a tabular frame work. Correlation among members, formations and groups was persistently persued over hundreds of kilometers, and a eventual lack of correlation was solved by proposing a new lithostratigraphic unit. As a rule such of "solutions" frequently complicated the understanding of basin evolution and gave rise to a profusion of lithostratigraphic denominations with only local relevance. The appearance of Sequence Stratigraphy has brought the understanding of how things work during the filling history of a sedimentary basin. The episodicity concept together with the adoption of depositional sequence as the basic unit for stratigraphic interpretation (Mitchum et al., 1977) has been proved to be very useful in Basin Analysis.

Some dificulties in applying Sequence Stratigraphy's concepts to intracratonic syneclises arise from its geometrical characteristics. They generally have uncommonly big size and a typical ramp profile with extremely low angles of basement dip; as a consequence, time lines are close to the horizontal. The development of these huge basins includes long periods of subsidence and sediment accumulation intercalated with equally long periods of uplift originating regional unconformities that may represent lacunas tens of millions years long.

During these periods of uplift the significant amounts of the previously accumulated sedimentary packages may be eroded. After each interruption the sedimentary basin is reestablished, often with characteristics (shape, subsidence rates, nature of sedimentation) very different from what they were before. Thus almost independent basins succeed each other through time, as observed by Zalán et al. (1990).

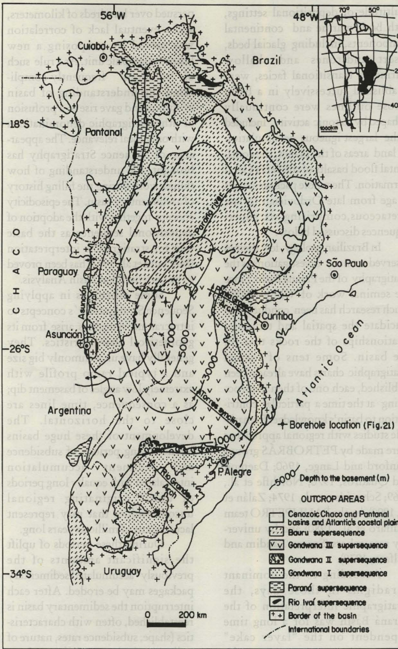


Figura 1 - Simplified geological map of the Paraná Basin, with major tectonic elements and geographic references.

The particular features of intracratonic ramp settings have already been pointed out. Lindsay et al. (1993), in an interesting synthesis, argued that "*...The problem faced in intracratonic settings is not that sequences do not exist or that eustasy does not affect sedimentation. The problem is the geometrical expression of the sequences... In an intracratonic setting ..., stratigraphic sequences are generally thin and poorly differentiated compared to their passive-margin equivalents. Slow subsidence rates, low depositional slopes and shallow water depths collectively result in diminished sediment accommodation within these basins. The sequences are extensive and thin, few have recognizable progradational geometries and erosional unconformities generally have minimal relief. During relative sea-level lowstands, little or no accomodation space may be available for sediment accumulation and lowstand deposits may be poorly developed and areally restricted. Thus intracratonic successions commonly comprise stacked transgressive-highstand deposits separated by near-planar unconformities or paracon-formities; that is, flooding surfaces commonly coincide with sequence boundaries...*"

In our work the Sequence Stratigraphy approach was used and we attempted to identify, in subsurface reference sections of the Paraná Basin, the key elements postulated by the theory. Chiefly based on oil well data a regional stratigraphic hierarchy was established. A standard section, measured in outcrops, served to calibrate some of the aspects inferred from subsurface analysis. This attempt may be viewed as an experiment carried out on a regional scale, considering the limitations imposed by the nature and low density of borehole data. Gamma ray log shape and lithologic successions were the basic tools for this research. Emphasis was given to the analysis of the major Paleozoic supersequences and some observations were made on the Mesozoic continental units.

Inside the proposed hierarchy, elements were searched which could be used to break up the sedimentary pile into stratigraphic units of progressively higher order from the (total record) first order sequence up to fifth order sequences wherever possible. Although these successively higher order sequences represent decreasing time intervals, we have not correlated them with the available global geologic time scales because of local chronostratigraphic data limitations. Therefore the stratigraphic hierarchy here presented must be viewed as particularly applicable to the Paraná Basin. Exposed intervals served as supporting sections for some of the inferences derived from subsurface observations. A detailed stratigraphic analysis was made on a portion of the Gondwana I supersequence, from the input of middle Permian deltaic sediments up to their later flooding. This section is very well exposed along the Rio do Rastro Road, a geologic monument area located in Santa Catarina State, Southern Brazil.

BASEMENT STRUCTURE

It has now been reasonably well established that Gondwana's basement which supported the development of several Phanerozoic tectono-sedimentary cycles, comprises a variety of Precambrian terranes (De Wit et al., 1988) very diversified in origin and in petrological composition. The individual fault-bounded "blocks" that had constructed the paleocontinent were aggregated to Archean cratons along foldbelts dated mostly between 800 and 450 Ma, the time span of the Brasiliano/Pan-African orogeny (Almeida & Hasui, 1983; Powell, 1993).

Some upper Proterozoic to Cambrian basins evolved concomitantly with the final coalescence of Gondwana's building blocks. They constitute a series of clastic-and carbonate-filled basins and associated magmatic rocks that predate the widespread cratonic sedimentation accumulated from Ordovician times onward. The fundamental framework of the Brasiliano/Pan-African basins and foldbelts also markedly influenced Phanerozoic basin evolution (Tankard et al., 1995).

The nature, ages and distribution of the various crustal elements that floor and surround the Paraná Basin were studied by Cordani et al. (1984). They observed that the basin is framed by belts where upper Proterozoic sedimentary sequences appear highly structured. Towards the center of the basin equivalent late Proterozoic sedimentary units are undeformed, indicating the existence of some domains with cratonic behaviour during the Brasiliano orogenic cycle. The upper Proterozoic thrust-and-fold belts define a framework of dominantly NE-SW-trending lineaments (Fig. 2) that represent crustal weakness zones reactivated under renewed compressional stress during the Paleozoic history of the Paraná Basin. Particularly during late Ordovician the transtensional reactivation of NE-SW trending features provided the initial subsidence for the basin (Milani, 1997). The northeastern border of the syneclise seems to have been controlled by a local, NW-SE-trending Brasiliano fabric. Zalán et al. (1990), in an extensive state-of-the-art summary on the tectonic evolution of the Paraná Basin, stated that transcurrent motion was the preferred way to stress dissipation along the basement fabric. Such reactivations of old lineaments influenced sedimentation by inducing depocenters to develop and controlling the drainage system, consequently the orientation of some depositional elements like deltaic lobes.

Another set of master structural elements in the Paraná Basin is oriented along the NW-SE direction, corresponding to strike slip zones along which intracontinental movements accommodated the regional stress field related to South Atlantic rifting. Its transtensional nature (De Wit et al., 1988) favoured a profusion of dikes to intrude and a huge volume of basaltic lavas to spread all over the basin. In summary, two distinct assemblages of structural elements are present in the Paraná Basin: (1) the NE-SW-trending are the older ones, directly inherited from basement structure; (2) those oriented along the NW-SE direction are younger, related to the epilogue of basin's history already in the Mesozoic.

THE BASIN FILLING: TECTONICS AND SEDIMENTATION

The complete package of the Paraná Basin is constituted by six supersequences (Fig. 3), representing cycles of subsidence and accumulation of sediments, limited by very expressive basin-scale unconformities (Milani, 1997): Rio Ivaí (RI, Ordovician-Silurian), Paraná (P, Devonian), Gondwana I (GI, Carboniferous-early Triassic), Gondwana II (GII, middle-late Triassic), Gondwana III (GIII, late Jurassic-early Cretaceous) and Bauru (B, late Cretaceous). Some of the unconformities which separate the supersequences are also recognized in areas well correlated with the Paraná Basin such as Eastern Paraguay, the North Basin of Uruguay, the subandean foreland of Bolívia and Argentina, the Chaco-Paraná Basin of Argentina, and the Cape-Karoo Basin of Southern Africa, giving them the status of the "interregional unconformities" from Sloss (1963).

The supersequences represent the remnant record of a series of sedimentation phases limited by tectonically controlled unconformity surfaces. The final result is a series of lithologic packages formally individualized as lithostratigraphic units encompassed by unconformity surfaces representing lacunas, with some time variation along the basin (Figs. 4 and 5). These breaks in sedimentation were explained by Zalán et al. (1990) as intracratonic consequences of Paleozoic orogenic peaks along the active western border of the continent (Ramos, 1988) and of South Atlantic rifting during Mesozoic time. In this work a direct correlation of supersequences with certain lithostratigraphic names was made, not to imply a rigid relationship between the two, but to allow an easy reference to well known intervals inside the stratigraphic record of the basin. The time interval corresponding to the remnant record of each supersequence (RI: 450-428 Ma; P: 410-365 Ma; GI: 310-245 Ma; GII: 237-218 Ma; GIII: 150-128 Ma; B: 115-65 Ma) classifies them as tectono-sedimentary cycles of second order (tens of Ma, Vail et al., 1977). The time framework of the Paraná Basin was basically defined by low-resolution palyno -logy (Daemon and Quadros, 1969; Grahn, 1989). Three zones based on a tetrapod fauna and positioned between late Ladinian and early Norian times (232-218 Ma) are recognized for the Triassic continental sediments (Barberena et al., 1985). There are also thick barren intervals, and in a general sense the biostratigraphic resolution in the Paraná Basin is sufficient to define second order events only. This limitation is in part compensated by the flat geometry of the sequences, with horizontal time lines, that allows easy correlation of strata over distances of several tens of kilometers. The available distribution of biostratigraphic zones is shown on Table 1.

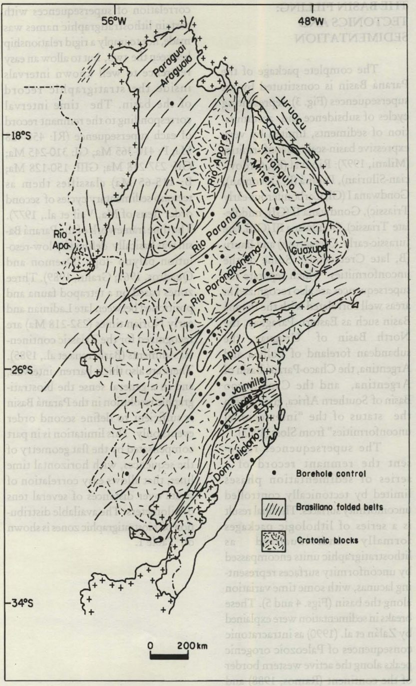


Figura 2 - Schematic map of basement structure and tectonic framework of the Paraná Basin (Milani, 1997; some features are from Cordani et al., 1984; Zalán et al., 1990, and Wiens, 1995).

System	Zones	Series/Stage (range of time)	Ma/zone
Permian-Triassic	1	Kazanian/Scytian (258-240 Ma)	18
Permian	4	Sakmarian/Kungurian (278-258 Ma)	5
Carb.-Permian	1	Stephanian/Sakmarian (296-278 Ma)	18
Carboniferous	1	Westphalian (315-296 Ma)	19
Devonian	7	Pragian/Frasnian (400-367 Ma)	4,7
Silurian	1	Llandovery (438-428 Ma)	10

Table 1 - Palynologic Zones for the Paraná Basin

As a whole the stratigraphic record of the Paraná Basin correlates in time to a part of the first Phanerozoic cycle (Vail et al., 1977), a first order global transgressive-regressive event spanning 390 Ma (Fig. 3). The RI supersequence, the basal sedimentary unit of the basin, corresponds in time to that of the maximum relative sea level in the global cycle, whereas the rest of the sedimentary fill of the basin was deposited during the regressive portion of the global cycle terminating with early Triassic red beds.

Paleozoic Supersequences (Transgressive-Regressive Cycles)

Rio Ivaí Supersequence

The oldest sedimentary package in the Parana Basin is of late Ordovician to early Silurian age and correspond to that of the Rio Ivaí Supersequence, formerly known as 'Rio Ivaí Group' (Assine et al., 1993) inside the kingdom of lithostratigraphy. This section lies above the 'Phanerozoic's first cratonic unconformity, from middle Ordovician time' (Soares, 1991) and is represented by a basal sand-conglomerate package (see Fig. 6), arkosic in its lowermost portion and quartzose at the top (Alto Garças Formation) covered by diamictites (Iapó Formation) and culminating with fossiliferous marine shales (Vila Maria Formation).The Rio Ivaí Supersequence (Fig. 7) appears over a wide area in the basin, but its occurrence is characterized by thin remnants and incomplete sections of discontinuous geometry, indicating tectonic control during its deposition and/or preservation history (Milani et al., 1996).

The Alto Garças Formation (Assine et al., 1993), is constituted by basal quartz-feldspatic conglomeratic sandstones showing medium size trough cross stratification with frequent gravel levels between the sets. The package is considered of fluvial origin. Towards the top the sandstones become finer and more mature mineralogically and textu-rally. This is well expressed in the gamma ray signature of the package with a clear upward left deflection (Assine and Soares, 1989) due to an upward decrease in feldspar content of the matrix. Sandstones of the upper interval show hummocky cross stratification indicative of a marine shoreface context. Polymictic reddish diamictites of the Iapó Formation abruptly overlie the Alto Garças Formation sandstones across the basin. The diamictites are covered by the shaly sediments of the Vila Maria Formation bearing abundant fauna and flora of macro and microfossils of early Llandovery age (Gray et al., 1985; Grahn, 1989). The Vila Maria Formation is represented by gray, brown and black shales grading to micaceous laminated siltstones that become reddish under outcrop conditions. Mud cracks are common (Faria, 1982), indicating a depositional setting submitted to periodic exposure under tidal action.

The RI supersequence occurs with thicknesses ranging from a few meters up to 362 meters in the Brazilian portion of the Paraná Basin (Fig. 8). This unit shows a clear thickening to the west, reaching up to 1,100 meters in eastern Paraguay

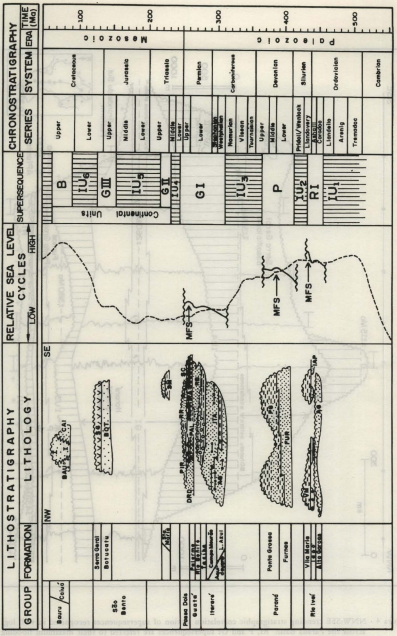


Figura 3 - Sequence-stratigraphic chart for the Paraná Basin. Relative sea level second order cycles derived from basin's stratigraphic record and referred to Vail's (1977) first order eustatic cycles (dotted line). The correlation of supersequences with absolute geologic time is approximate. Time table after Cowie & Bassett (1989). IU=interregional unconformity. Lithostratigraphic names for the Upper Permian/Lower Triassic interval: DRD - Dourados Formation, IRA - Irati Formation, RR - Rio do Rasto Formation, PIR - Pirambóia Formation, SC - Sanga do Cabral Formation.

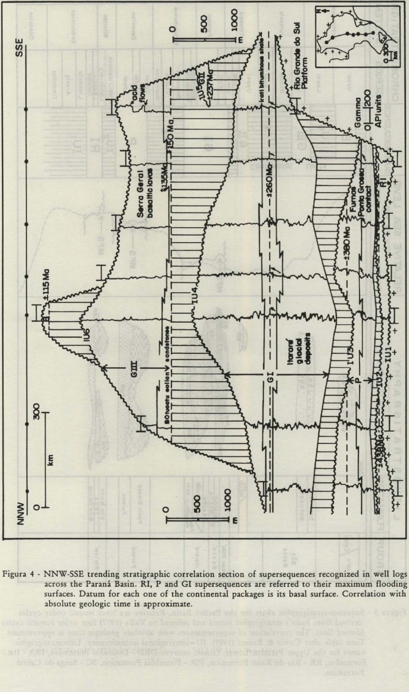


Figura 4 - NNW-SSE trending stratigraphic correlation section of supersequences recognized in well logs across the Paraná Basin. RI, P and GI supersequences are referred to their maximum flooding surfaces. Datum for each one of the continental packages is its basal surface. Correlation with absolute geologic time is approximate.

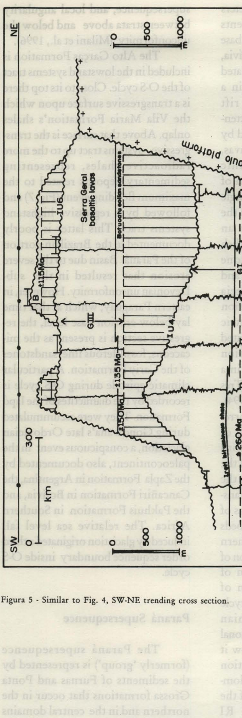


Figura 5 - Similar to Fig. 4, SW-NE trending cross section.

(Harrington, 1972), where 553 meters of Ordovician-Silurian sediments were drilled without reaching the base of the section. Westwards, in Bolívia, thousands of meters of age-correlated sediments were accumulated in a context of an open marine rift (Williams, 1995). A cratonward extension of such rifting is represented by the occurrence of a section of lavas, volcaniclastic rocks and lithic sandstones in the central domain of the Paraná Basin, reached by a single borehole that penetrated close to the 4,582 meters of its final depth an interval including oxidized, reddish basalt, medium-grained sandstone with fragments of volcanic rocks, and glass shards and volcanic breccia (Mizusaki, 1989). Intense oxidization did not allow precise radiometric dating of these igneous and related rocks but stratigraphic correlation based on well logs placed them in a pre-Devonian position. This is the Três Lagoas basalt from Milani et al. (1994).

The RI supersequence corresponds to a second order cycle of Paraná Basin's sedimentary record (Fig. 3). The fossiliferous shales of the Vila Maria Formation represent the maximum flooding event of this transgressive-regressive cycle as well as of the whole basin fill. Correlated beds occur over a wide area of southern Gondwana (Vargas Peña Formation of Paraguay, Kirusillas Formation of Bolívia, Cedarberg Formation of Southern Africa). The top of the cycle is marked by the sub-Devonian unconformity, evidenced by erosional remotion of the section below it (with clasts of Vila Maria Formation sediments in Devonian basal conglomerates), basinwide oxidization of the uppermost interval of the RI supersequence, and local angularity between strata above and below the unconformity (Milani et al., 1996).

The Alto Garças Formation is included in the lowstand systems tract of the O-S cycle. Close to its top there is a transgressive surface upon which the Vila Maria Formation's shales onlap. Above that surface is the transgressive systems tract up to the more radioactive shales, representing sedimentary deposits related to the maximum flooding event (Fig. 7) and followed by a regressive highstand systems tract. This latter is poorly documented in the Brazilian portion of the Paraná Basin due to the severe erosion that resulted in the sub-Devonian unconformity. However, in eastern Paraguay, which at that time lay below erosion base level, the regressive section is present as the micaceous, fossiliferous fine sandstones of the Cariy Formation. A particular climatic episode during O-S cycle is recorded by the diamictites of the Iapó Formation. They were accummulated during Gondwana's late Ordovician glaciation, a conspicuous event in the paleocontinent, also documented by the Zapla Formation in Argentina, the Cancañiri Formation in Bolívia, and the Pakhuis Formation in Southern Africa. The relative sea level fall induced by glaciation originated a third order sequence boundary inside O-S cycle.

Paraná Supersequence

The Paraná supersequence (formerly 'group') is represented by the sediments of Furnas and Ponta Grossa formations that occur in the northern and in the central domains

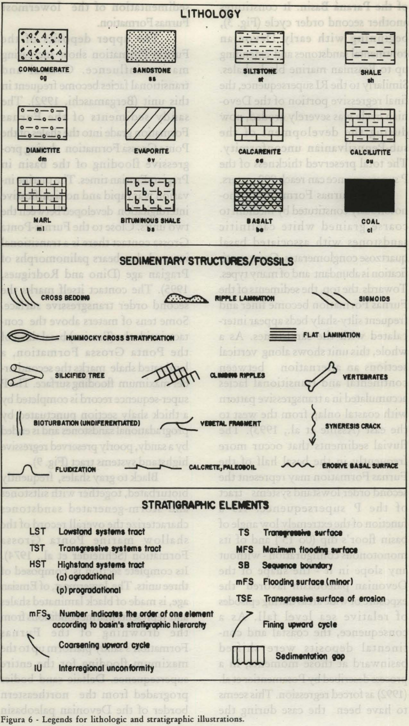


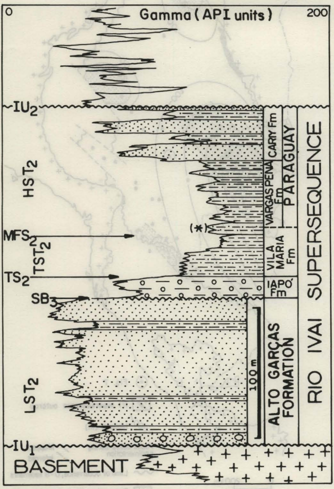
Figura 6 - Legends for lithologic and stratigraphic illustrations.

of the Paraná Basin. It constitutes another second order cycle (Fig. 3), beginning with early Devonian continental sandstones and extending up to Frasnian marine black shales. Similarly to the RI supersequence, the final regressive portion of the Devonian cycle was severely eroded, now during the development of the sub-Pennsilvanian unconformity. The total preserved thickness of the P supersequence can reach 900 meters.

The Furnas Formation is monotonously constituted by medium to coarse grained white caolinitic sandstones with associated basal quartzose conglomerates. Cross stratification is abundant and of many types. Towards the top, the sediments of the Furnas Formation become finer and frequent silty-shaly beds appear intercalated with the sandstones. As a whole, this unit shows along vertical sections an alternation between continental and transitional facies accumulated in a transgressive pattern with coastal onlap from the west to the east (Assine et al., 1993). The fluvial sediments that occur more frequently in the basal half of the Furnas Formation may represent the second order lowstand systems tract of the P supersequence. As a function of the extremely low angle of basin floor's dip (0o 15') and of its monotonous configuration - without any slope in it - the shape of the Devonian paleobasin favored the exposure of wide areas during episodes of relative sea level fall. As a consequence, the coastal and continental deposits were shifted basinward at those moments, in a process described by Posamentier et al. (1992) as forced regression. This seems to have been the case during the sedimentation of the lowermost Furnas Formation.

The upper deposits of the Furnas Formation show increasing marine influence. Coastal and transitional facies become frequent in this unit (Bergamaschi, 1992). The sandy sediments of the Furnas Formation grade into the shales of the Ponta Grossa Formation during progressive flooding of the basin in Pragian-Emsian times. The marine invasion was rapid and no significative interdigitation developed between the two units. Close to the Furnas-Ponta Grossa contact there is a transitional interval that bears palinomorphs of Pragian age (Dino and Rodrigues, 1995). The contact itself marks the second order transgressive surface. Some tens of meters above the contact, inside the (Emsian) basal third of the Ponta Grossa Formation, a laminated shale marks the second order maximum flooding surface. The P super-sequence record is completed by a thick shaly section punctuated by progradational sandstones and is ended by a sandy, poorly preserved regressive highstand systems tract (Fig. 9).

Black to gray shales, frequently bioturbated, together with siltstones and storm-generated sandstones characterize the overall record of the shallow marine Ponta Grossa Formation (Schneider et al., 1974). Its complete section is composed of three units. The lowermost, of Emsian age, is made of black laminated shales and represents marine conditions from the drowning of the Furnas Formation's sandy platform up to the maximum flooding for the entire supersequence. Deltaic sand bodies prograded from the northeastern border of the Devonian paleobasin



(*) Composite section, connection point.

Figura 7 - Gamma and lithologic profiles showing a composite, representative subsurface section of the Rio Ivaí supersequence. Location on Fig. 8 - Legends: see Fig. 6.

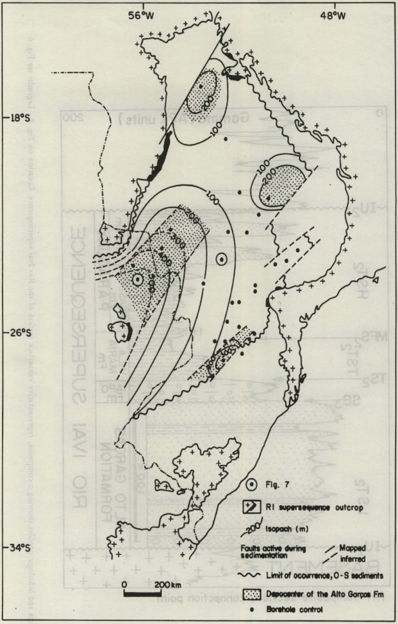


Figura 8 - Isopach map of the Rio Ivaí supersequence (from Milani et al., 1996).

during Eifelian time and compose the middle portion of the Ponta Grossa Formation. Those progradational features can be recognized in gamma ray data by its typical coarsening upward signature abruptly limited by marine shales (Fig. 9), related to higher orders of relative sea level variations or to source area reactivation, producing an increment in sediment influx. In southern Africa an equivalent section both in sedimentary nature and age was described by Theron and Loock (1988) an included in the 'Devonian deltas of Cape Supergroup'. During Givetian-Frasnian times (Melo, 1988) the thickest shaly package of the Paraná Basin's Devonian record was accumulated, reaching up to 300 meters in thickness. It represents the last flooding event of the devonian basin and forms the uppermost unit of the Ponta Grossa Formation.

The variation in basinwide distribution of the P supersequence (Fig. 10) is a function of the remnant thickness of the Ponta Grossa sediments, because the Furnas Formation is an extensive sandy blanket showing little deviations from the average thickness of 250 meters. The maximum isopach values of the Ponta Grossa Formation occur over two particular areas situated one in the northern portion and the other in the central Paraná Basin. Such areas were formerly named depocenters of Alto Garças and Apucarana, respectively. They were interpreted as highly subsiding areas, and consequently as retainers of greater depositional thicknesses of Ponta Grossa Formation sediments, relative to the surrounding areas. Between these depocenters a paleohigh was also interpreted - the Três Lagoas - Campo Grande Arch (Northfleet et al., 1969). Recent correlations (França et al., 1994) have shown that the supposed 'depocenters' are in fact areas of maximum preservation of Devonian sediments beneath the sub-Pennsilvanian unconformity. In fact, there is a remarkable continuity in lithology and facies between the two sides of the once assumed 'paleohigh'. It can then be stated that the thickness distribution of the preserved portion of the P supersequence was basically controlled by the depth of erosion during early Carboniferous time.

The P supersequence is also present in eastern Paraguay with similar thickness and facies characteristics as in the Brazilian Paraná Basin. Some wells drilled over the Asunción Arch revealed 850 meters of Devonian sediments, somewhat more than in nearby wells in Brazil. This refutes the former hypothesis of a Devonian age for the Asunción Arch (Almeida, 1980). The Paraná Basin and surrounding correlated areas had a ramp configuration, open to the west, from late Ordovician trough Devonian times.

Gondwana I Supersequence

The early Carboniferous was a time of deep changes in the Paraná Basin. A conjunction of paleogeographic, climatic (Caputo and Crowell, 1985) and tectonic (Zalán et al., 1990; De Wit and Ransome, 1992; Milani, 1992) factors active over south western Gondwana interrupted sedimentation over an extensive area: this is

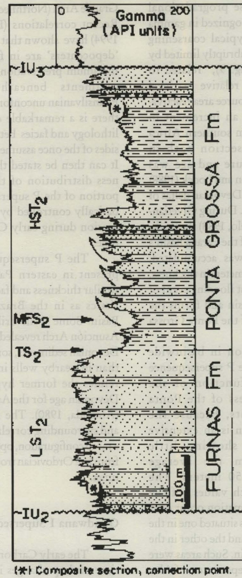


Figura 9 - Gamma and lithologic profiles illustrating the subsurface expression of the Paraná supersequence. Location on Fig. 10. Legends: see Fig. 6.

the largest lacuna in the basin's sedimentary record, lasting in some places 45 Ma (Daemon et al., 1991). Owing to the presence of ice caps in this area, associated with tectonic-induced uplift, the Mississipian is absent in the Paraná Basin.

The sub-Pennsilvanian unconformity of the Paraná Basin is of wide extent, a benchmark that separates profoundly different tectono-sedimentary histories. Recognized also in most of the correlative areas in southern Gondwana, it appears of various forms depending upon the geotectonic context of each particular area, and is attributed to the Hercynian Orogeny by various authors (López-Gamundí and Rossello, 1993; Zalán, 1991, among others). The Devonian- Carboniferous contact, marked by this unconformity, appears with strong angular discordancy in those areas where the lower package was directly influenced by the fold belt. This is the case of the 'Pacific' basins in South America (López-Gamundí and Rossello, 1993), between southern Peru and northwestern Argentina.

The erosional surface is detected as an abrupt contact between the Frasnian marine shales of the Ponta Grossa Formation, or older units, and the glacial sediments of the Itararé Group and Aquidauana Formation. Two major processes can be invoked as responsible for this erosional surface: uplift due to Hercynian movements and peneplanization in the cratonic interior; this can account for most of 50 Ma of lacuna along the interregional unconformity. The rest was caused by mechanisms of excavation by ice and by deglaciation-related sedimentary processes that produced canyons (França et al., 1994) filled with the basal layers of the GI supersequence. So during Mississipian time sedimentation in the Paraná Basin experienced the most radical break of its entire history.

With deglaciation the sedimentation was resumed during Westphalian time (Daemon and França, 1993). The GI supersequence is another second order cycle (Fig. 3) of the Paraná Basin. Because of deglaciation and the resulting rise of relative sea level, the Carboniferous-Permian sedimentation was transgressive from the base of the Itararé Group up to the Palermo Formation - the maximum flooding event for this supersequence. Above the Palermo Formation is the regressive section of the cycle that ends within early Triassic red beds (Fig. 11).

The basal portion of the GI supersequence, represented by Itararé Group's sediments in the southern and central Paraná Basin and by Aquidauana Formation's deposits in the northern Paraná Basin, is a section accumulated under a markedly glacial climate (França and Potter, 1988). An intense sedimentary influx coming from the areas laid open by deglaciation allowed depositional processes where mass flows and resedimentation have been very important. These units are constituted chiefly by diamictites intercalated with thick sandstone packages. The glacioterrestrial sediments that occur in the basal portion of the GI supersequence in some areas could be related to a lowstand systems tract. As a whole, however, the glacial sedimentary interval forms part of the second order transgressive systems tract.

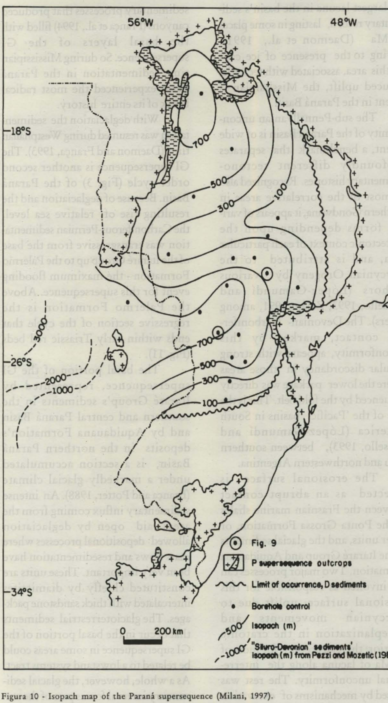


Figura 10 - Isopach map of the Paraná supersequence (Milani, 1997).

The presence of fining upward intervals (Fig. 11) suggests the transgressive tendency that dominates on a higher scale. The glacial package onlaps the sub-Pennsilvanian unconformity and extends over progressively wider areas towards its top (Figs. 4 e 5). The plentiful deglaciation water, together with an enormous volume of sediments transported to the basin, allowed the fastest episode of creation of depositional space and the highest depositional rates of basin's history. Alternatively, Santos et al. (1992) postulated crustal stretching and rifting mechanisms with differential movements of blocks along NW-SE tectonic lineaments to accommodate this package.

On a third order level a surface equivalent to a 'Type 1 unconformity' (Posamentier et al., 1988) marks the base of the Rio Bonito Formation. A sudden fall of relative sea level caused an important basinward facies shift and interrupted for a while the broad transgressive tendency of the supersequence. Sandstones associated with coal measures, siltstones and shales form a classical context of deltaic sedimentation that entered the basin at its eastern and west-northwest borders. The basal segment of the Rio Bonito Formation (Triunfo Member) represents a third order lowstand systems tract. Above it the shaly Paraguaçu Member is part of a transgressive systems tract that culminates in the Palermo Formation. This unit is dominantly represented by bioturbated shales and some storm-generated marine sandstones accumulated on a vast neritic platform (Schneider et al., 1974) and contains the maximum flooding surface of all GI supersequence.

There is a conspicuous fourth order sedimentary cyclicity along Rio Bonito-Palermo succession that is clearly visible both in subsurface data and in outcrops. Figure 12 shows the results of a stratigraphic analysis of this interval, in this case corresponding to the basal portion of the classic White Column, a reference section for Paraná Basin stratigraphy, situated along the Rio do Rastro Road in Lauro Müller County, Santa Catarina State (Fig. 1). The facies pattern identified there in the outcrops is compatible with the systems tracts that can be interpreted from gamma ray log shapes from wells situated farther basinward. The section measured in outcrops is about 220 meters thick sedimentary beds and is composed of five fourth order depositional sequences (there are two covered intervals, between 46-63 meters and between 108-134 meters, such intervals referred to the base of the measured section).

Depositional sequence I (at the base) comprises the uppermost sedimentary section of the Itararé Group and represents a highstand systems tract. An abrupt, erosional contact with a marked truncation of the section below it, with the presence of clasts of this lower section in the upper one, marks the base of depositional sequence II (lower Rio Bonito Formation). The geometry of this erosive surface shows a relatively high angle of dip (10 meters for a 100 meter-long outcrop) along the NE-SW paleocurrent direction and is interpreted as the floor of an incised valley. Above this 'Type 1 unconformity' there is a recurrent stacking pattern of fluvial, deltaic and estuarine facies shifted basinwards and

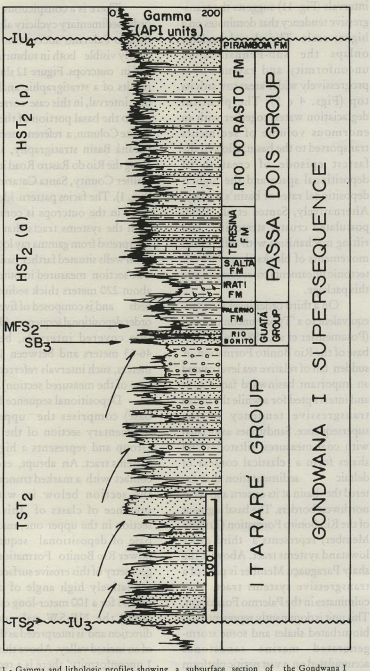


Figura 11 - Gamma and lithologic profiles showing a subsurface section of the Gondwana I supersequence. Location on Fig. 14. Legends: see Fig. 6.

with characteristic tidal features (depositional sequences II and III). This package is considered the fill of the incised valley. Depositional sequence IV also has fluvial deposits at the base, but it grades upward to more restricted environmental conditions that allowed the formation of peat swamps probably formed in lagoons protected by barriers. The depositional sequence V has also some particular features: its base is marked by a 'transgressive surface of erosion' (Bhattacharya, 1993) or 'ravinement surface' (Swift, 1968) that appears as a rough horizon covered by a pebbly lag. Above this lag there is a package of storm-generated sandstones covered by offshore shales (probably recording the maximum flooding). In depositional sequence V the lowstand systems tract is not represented so that the transgressive surface is also the sequence boundary. In lithostratigraphic terms, this transgressive surface is the base of the Palermo Formation. There is an excellent correlation between this measured section and correspondent intervals sampled by wells at various points of the Paraná Basin (Fig. 13).

The highstand systems tract of the GI depositional cycle is constituted by a shoaling upward section that culminates in sediments of the Irati Formation. Its upper portion, the Assistência Member, shows a clear lithologic diferentiation across the Paraná Basin: bituminous black shales and marls in the south give place to limestone- shale couples in the north. These couples, up to tens of centimeters thick, form a remarkable rhythmic array which can be attributed to high frequency variations of relative sea level. Each lithologic couple corresponds to a fifth order event (0,06 Ma/couple; Hachiro & Coimbra, 1993) and the package was probably accumulated under influence of the Milankovitch orbital cycles. In some areas the Assistência Member includes evaporite horizons tens of centimeters thick, reflecting a shallow, restricted basin. As a whole, the Irati Formation displays fourth order cycles that culminate in carbonates with subaerial exposure features,or in evaporites. A rich fauna of reptiles (*Mesosaurus sp*.) makes the Irati Formation a paleontologic singularity in South American's geology and allowed Du Toit (1927), early in this century, to correlate it with the Whitehill Formation of Southern Africa. The shallow Irati basin was flooded during the deposition of the Serra Alta shales during the last marine incursion in Paraná Basin. The third order aggradational highstand systems tract continues up to the upper neritic to coastal sediments of the Teresina Formation. The GI supersequence is terminated by a progradational section of red beds represented by Rio do Rasto Formation fluvial-lacustrine sandstones and shales. In the southern Paraná Basin eolian dunes were already developed and constitute the Sanga do Cabral Formation (Lavina, 1988; Faccini, 1989). In the northern domain, the Pirambóia Formation, made of medium to fine, white to reddish sandstones with planar and tangential cross stratifications of medium to large size, accumulated chiefly by eolian, and subordinately by fluvial depositional systems (Caetano- Chang, 1993), represents the final depositional context of the GI supersequence.

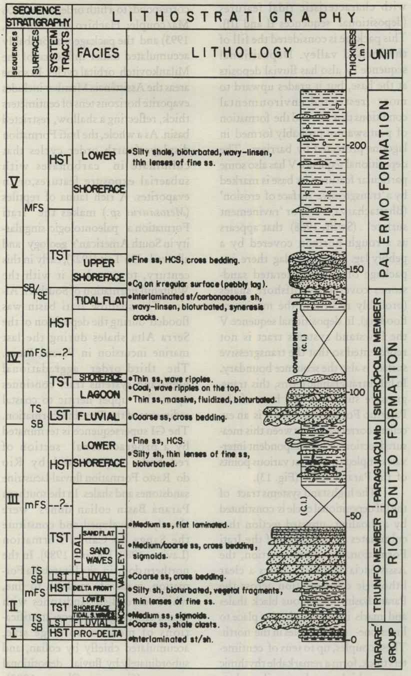


Figura 12 - Lithologic section showing facies and systems tracts of middle Permian Rio Bonito and lowermost Palermo Formations at Rio do Rastro road, southeastern Paraná Basin. Location on Fig. 14. Legends: see Fig. 6.

The final portion of the GI supersequence documents the progressive continentalization of the Paraná Basin and surrounding areas. The uplift of arches caused by active compressional tectonics along Gondwana's margin gradually interrupted the links of the continental interior basin with the surrounding oceans, completely severing the connection during late Permian-early Triassic times. With increasing regional aridity and deeply eroded source areas in a long lived, stable cratonic interior, the Paraná Basin's Mesozoic depositional history produced continental sediments and depositional sequences controlled by tectonics and climate. The GI supersequence covers the entire area of the Paraná Basin (Fig. 14) and contains the largest sedimentary volume. The maximum thickness of the supersequence coincides with the axis of today's fluvial basin, suggesting persistent stacking of the depocenter during the Paraná Basin's entire post-Devonian history.

Mesozoic Continental Supersequences

Gondwana II Supersequence

During Middle to Late Triassic times (230-215 Ma; Hälbich, 1992) southern Gondwana's margin was affected by the final paroxysm of the Cape-La Ventana orogeny (De Wit & Ransome, 1992). Stress propagation toward the continental interior (Cobbold et al., 1992) resulted in regional uplift and strike slip motions along pre-existing crustal lineaments. The unconformity above which the GII supersequence lies is probably one of the manifestations of this tectonic episode (Milani, 1992). Relaxation of the regional compressional stress field sponsored some pulses of extensional tectonics that originated grabens, at that time widespreadly distributed along southwestern Gondwana. In the domain of the Paraná Basin, Middle to Upper Triassic sediments occur only in its southernmost portion, probably confined to one of the above mentioned grabens (Milani, 1997). In the rest of the basin, the Triassic was a time of subaerial exposition and severe erosion. The GII supersequence of the Paraná Basin is represented by the Santa Maria Formation and associated units (Fig. 15). The Santa Maria Formation includes fine to medium, white sandstones, locally conglomeratic and displaying sigmoidal and tangential cross stratifications, intercalated with massive to laminated, red shales and siltstones, and subordinately with calcretes and gypsum layers. These deposits formed in a fluvial-lacustrine environment. Facies and depositional architecture analysis of Santa Maria Formation (Faccini, 1989; Scherer, 1994) revealed a strong climatic control over sedimentation expressed as frequent variations of lacustrine base level, originating a series of well defined depositional sequences of high frequency (up to sixth order). This unit contains an abundant and diversified fauna of reptiles of Late Ladinian-Early Norian age (Barberena et al., 1985) similar to those of the Cuyo and adjacent basins of Argentina. Figure 16 is a sketch that shows the occurrence of the Tr supersequence of the Paraná Basin (Milani, 1997).

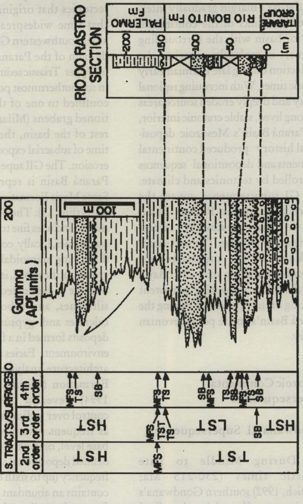


Figura 13 - Gamma and lithologic profiles of the Rio Bonito and Palermo Formations, with sequence-stratigraphic interpretation. Compare with the Rio do Rastro section (at same scale). Location on Fig. 14. Legends: see Fig. 6.

Gondwana III Supersequence

The lower portion of GIII supersequence (Fig. 17) is represented by a singular package of eolian sandstones. These fine to medium, quartzose sandstones exhibit cross stratification of large size and constitute the Botucatu Formation. They cover an exceptionally large area, in excess of 1,300,000 square kilometers, representing one of the most extensives occurrences of continental sediments all over the world. It corresponds undoubtedly to the maximum expansion of the basin during Mesozoic times, unconformably lying over older strata, expanding the former depositional areas and reaching some regions over the adjoining crystalline basement (Fig. 18).

The Botucatu Formation in the Paraná Basin is part of the widespread desertification of Gondwana, in Mesozoic pre-breakup times. This process was responsible for the appearance of large eolian deposits identified also in northern and northeastern Brazil. Correlative deposits are also found in Africa, and constitute the upper portion of Karoo System. Towards the top of the unit the sandstones are intercalated with the first lava flows that mark the initial stages of Gondwana's breakup. The igneous event culminated with a huge pile of lavas, the Serra Geral Formation. A package of volcanic and associated volcaniclastic rocks up to 2,000 meters thick overlie the sediments of Paraná Basin and an intricate network of dikes and sills intruded them. K-Ar ages of these basalts cluster in the range 115-135 Ma (Amaral et al., 1966).

Stratigraphic studies in the Paraná basaltic sequence are still in their early stages. However, geochemically distinct groups of basalts have already been determined. High Ti basalts occur dominantly in the northern half of the basin, and low Ti rocks in the southern portion. This was interpreted as suggesting the presence of large scale lateral variations in the upper mantle beneath this region (Mantovani et al., 1985) or representing magmas originated from a similar source region but differing in the extent of crustal contamination during their transit to surface (Fodor et al., 1989). Radiometric determinations using the Ar-Ar technique (Onstott et al., 1993) on sidewall cores collected during the drilling of a deep well just in the depocenter of the lavas (Milani, 1997) showed that the Serra Geral episode was a 10 million years lived one, beggining at 138 Ma and lasting up to 128 Ma. During this event, in Early Cretaceous time, the continental crust of the Paraná Basin experienced a very active rifting process and the basin it self underwent the most intense structural rearrangement of its entire history.

Bauru Supersequence

The B supersequence of the Paraná Basin is a section that corresponds lithostratigraphically to the 'Bauru and Caiuá Groups'. This package represents a post-lava cover of continental strata that was accommodated in the flexural depression originated by the load of the basalt pile. This was the last significant episode of subsidence in the basin.

The B supersequence is made of sandy-conglomeratic depos its including clasts of various lithologies

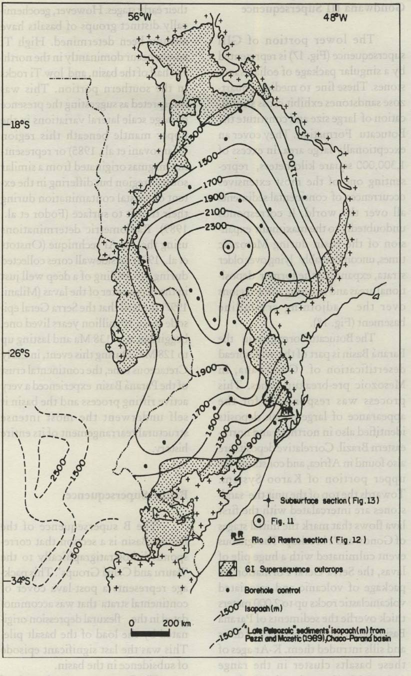


Figura 14 - Isopach map of the Gondwana I supersequence (Milani, 1997).

(volcanics, sandstones, shales and basement crystalline rocks), massive or with trough cross-stratification and cut-and-fill features. There are also subordinated silty to shaly deposits and caliche carbonates, and some local occurrences of alcaline magmatic rocks associated with the sedimentary strata. A conspicuous cyclicity marks this package (Fig. 19), observed not only in outcrop but also in subsurface data (Milani, 1997). At least two orders of cyclicity can be observed, one spanning several tens of meters of alternating shaly/sandy packages representing variations in rainfall regime at a basinal scale. The higher order cyclicity is represented by intercalations between fine sandstones up to 3 meters thick and brown shales with similar thickness (Soares et al., 1980), signifying autocyclical changes inherent to the fluvial plain.

The accummulation of B supersequence took place during Aptian to Maastrichtian times (Soares, 1991) with provenance from the northeastern border. Alluvial fans, braided fluvial and eolian facies were identified, the last one defining the central portion of the paleobasin (Fernandes, 1992).The erosive remnants of the B supersequence occur in the central-northern Paraná Basin (Fig. 20). Its depocenter appears to be situated in the same area as that of the GIII supersequence.

SUBSIDENCE HISTORY

The origin and evolution of intracratonic basins, as well as the mechanisms of subsidence in those settings, are still poorly understood (Leighton & Kolata, 1990). This is especially true of the Paraná Basin, whose huge size, coupled with a ramp profile and a depositional history marked by multiple episodes of accumulation and subsequent erosion of sedimentary successions through time, form an assemblage of particular characteristics that deserve further research. Some clues on this intriguing matter can be obtained by analysing tectonic subsidence plots, those '*sensitive indicators of the processes that cause basins to subside*' (Williams, 1995). The subsidence history of the Paraná Basin (Fig. 21) can be divided into major phases, corresponding to the time-intervals of its supersequences.

The Ordovician-Silurian phase is characterized by relatively high subsidence rates. This might be related to a transtensional mechanism of subsidence, the initial tectonic driving-force that induced the syneclise to develop and an intracratonic response to the climax of the late Ordovician Oclóyic orogeny (Ramos, 1988) at that time in progress along the border of the paleocontinent (Milani, 1997). The next phase, Devonian, started with low rates of subsidence that are indicative of a period of tectonic quiescence, in accordance with the overall sedimentological characteristics and blanket-like geometry of the Furnas Formation, the basal unit of the Paraná supersequence. From Emsian time onwards, an increasing pattern of subsidence rates was stablished as a flexural response of the lithosphere to compressional stresses sourced along Gondwana's margin (Milani, 1997). Neither the O-S nor the D subsidence phases happened in the southern domain of the basin, which formed a stable exposed platform up to early Permian times.

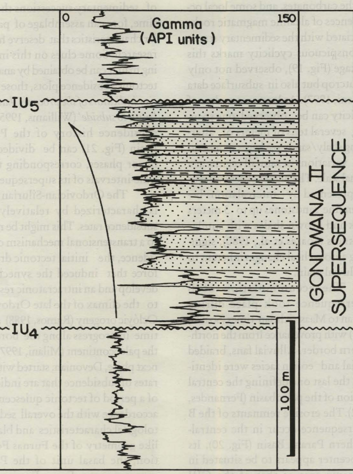


Figura 15 - Gamma and lithologic profiles from a typical subsurface section of the Gondwana II supersequence. Location on Fig. 16. Legends: see Fig. 6.

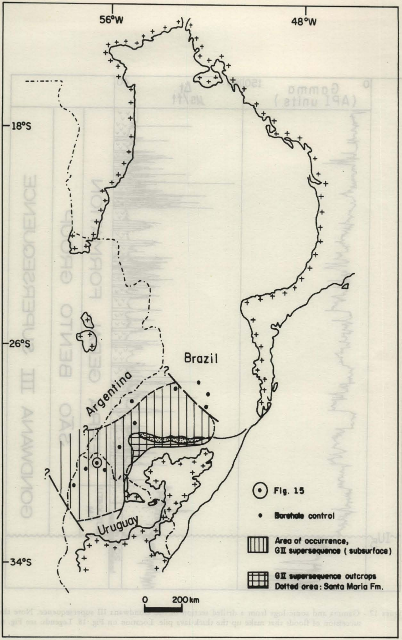


Figura 16 - Occurrence of the Gondwana II supersequence (Milani, 1997).

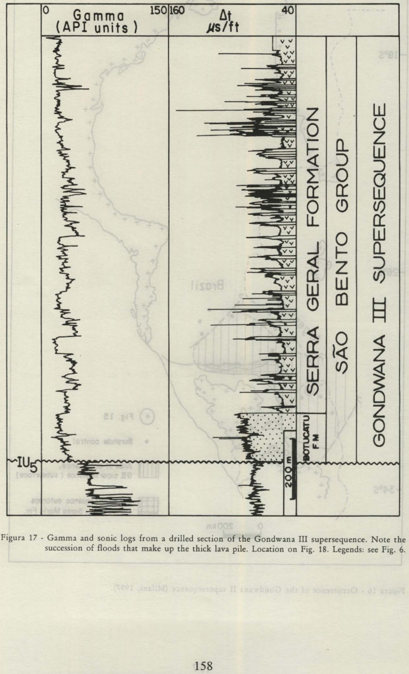


Figura 17 - Gamma and sonic logs from a drilled section of the Gondwana III supersequence. Note the succession of floods that make up the thick lava pile. Location on Fig. 18. Legends: see Fig. 6.

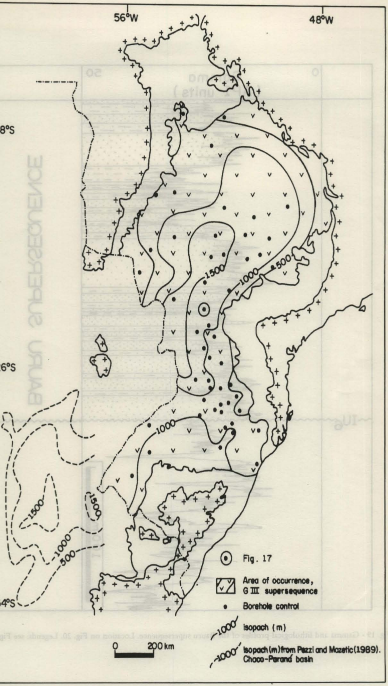


Figura 18 - Isopach map of the Gondwana III supersequence, sediments + volcanics (Milani, 1997).

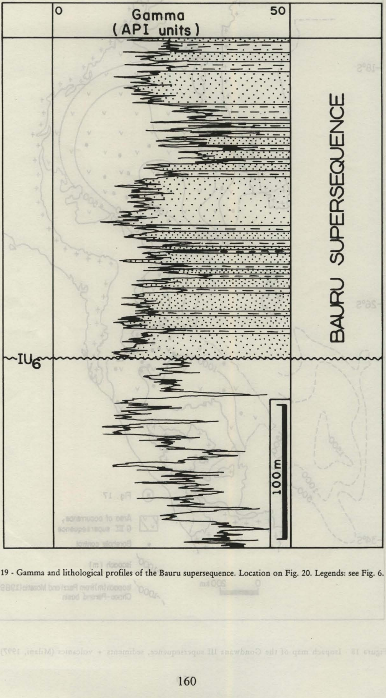


Fig. 19 - Gamma and lithological profiles of the Bauru supersequence. Location on Fig. 20. Legends: see Fig. 6.

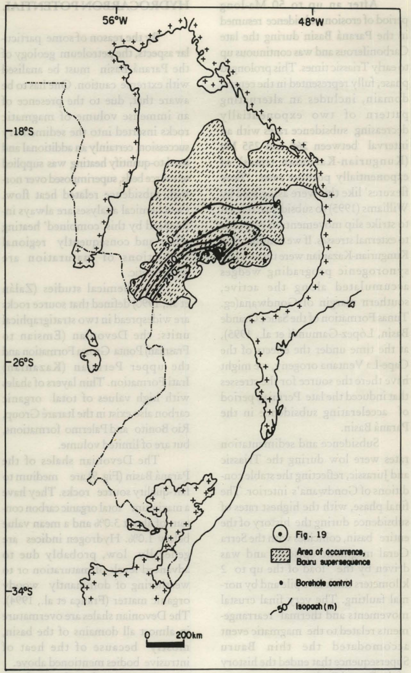


Fig. 20 - Isopach map of the Bauru supersequence (Milani, 1997).

After an up to 50 Ma-long period of erosion, subsidence resumed in the Paraná Basin during the late Carboniferous and was continuous up to early Triassic times. This prolonged phase, fully represented in the central domain, includes an alternating pattern of two exponentially decreasing subsidence rates with an interval between 265 and 255 Ma (Kungurian-Kazanian times) of exponentially positive rates. 'Slow flexures' like this were associated by Williams (1995) to subsidence related to strike slip movements in response to external stresses. If we consider that Kungurian-Kazanian were times when synorogenic prograding wedges accumulated along the active, southern margin of Gondwana(eg. Tunas Formation of the Sauce Grande Basin, López-Gamundí et al., 1995), at the time under the effects of the Cape-La Ventana orogeny, we might have there the source for the stresses that induced the late Permian period of accelerating subsidence in the Paraná Basin.

Subsidence and sedimentation rates were low during the Triassic and Jurassic, reflecting the stable conditions of Gondwana's interior. The final phase, with the highest rates of subsidence during the history of the entire basin, coincides with the Serra Geral magmatic episode, and was driven by the load of the up to 2 kilometers thick lava pile and by normal faulting. The very final crustal movements and thermal rearrangements related to the magmatic event accomodated the thin Bauru Supersequence that ended the history of the Paraná Basin.

HYDROCARBON POTENTIAL

By the reason of some particular aspects, the petroleum geology of the Paraná Basin must be analised with extreme caution. One has to be aware that, due to the presence of an immense volume of magmatic rocks inserted into the sedimentary succession, certainly an additional and hard-to-quantify heating was supplied to source beds, superimposed over normal, subsidence related heat flow. Geochemical analyses are always influenced by this 'combined' heating effect and consequently regional evaluations of maturation are problematic.

Geochemical studies (Zalán et al., 1990) defined that source rocks are widespread in two stratigraphical units: the Devonian (Emsian to Frasnian) Ponta Grossa Formation and the upper Permian (Kazanian) Irati Formation. Thin layers of shales with high values of total organic carbon also exist in the Itararé Group, Rio Bonito and Palermo formations, but are of limited volume.

The Devonian shales of the Paraná Basin (Fig. 9) are medium to fair-quality source rocks. They have a maximum total organic carbon content of about 3.0% and a mean value below 1.0%. Hydrogen indices are generally low, probably due to advanced levels of maturation or to weathering of dominantly woody organic matter (França et al., 1994). The Devonian shales are overmature in almost all domains of the basin, mostly because of the heat of intrusive bodies mentioned above.

A great number of gas and condensate shows were found in Itararé sandstones drilled in the central region of the basin and the heaviest fractions of these condensates have geochemical correlation with the Ponta Grossa shales. Recently (1996) a significant volume of gas was discovered in Itararé sandstones, trapped by a Mesozoic sill. The occurrence is under evaluation and may represent the first commercial hydrocarbon accummulation discovered in the basin. So there is an Itararé-Ponta Grossa gas-condensate play that may become important to petroleum exploration in the deep (Fig. 1), central domain of the Paraná Basin. Another possibility for reservoir-rocks to retain these light hidrocarbons is represented by the lower Devonian sandstones of the Furnas Formation that directly underlies Ponta Grossa shales.

The second play of the Paraná Basin involves sourcing from the Irati black shales to Rio Bonito coastal sandstones (Fig.11),requiring faulting with vertical displacements of some hundreds of meters to join them and allow lateral secondary migration. Oil was recovered from Rio Bonito in some wells drilled in the southern domain of the basin, and this 22° to 33° API-hydrocarbons revealed positive geochemical correlation with Irati's organic content. The Irati Formation's bituminous shales are well developed in the southern half of the Paraná Basin and exhibit total organic carbon up to 23%, with an average content of about 2% of algal, lipidic-rich, oil-prone organic matter (Zalán et al., 1990). This source bed is immature even in its deepest area of occurrence,considering the thermal effect related to subsidence and burying alone. Oils related to the Irati shales were probably generated by a mechanism of heating greatly influenced by intrusive bodies, making evaluations of effective source-rock potential of this unit a very complex task.

Tectonic studies revealed an important phase of structural movements during late Permian/early Triassic times (Zalán et al., 1990; Milani, 1992). En échelon anticlines, the unique coherent, seismically mapped structural style in the Paraná Basin up to this date, were originated by transcurrent reactivation of NE-SW-trending basement lineaments and are of the right time to trap hydrocarbons sourced by the Devonian shales during the accelerating subsidence episode of the Kungurian/Kazanian (Fig. 21). Considering the Irati-Rio Bonito play, these anticlines largely precede the time of oil expulsion from Irati's shales during early Cretaceous magmatism.

Another question concerning the hydrocarbon potential of the Paraná Basin is to define how much damage was caused by Mesozoic structural rearrangement related to Serra Geral magmatic event to pre-existing accumulations. Or, as discussed above, to characterize the role of intrusive bodies in trapping and sealing hydrocarbons. In any case, the Paraná Basin offers a wide prospective acreage to be worked, and many of these intriguing queries will probably be better answered by the bit.

FINAL REMARKS

Six major supersequences were identified in the Paraná Basin (Fig. 3). The Rio Ivaí and Paraná

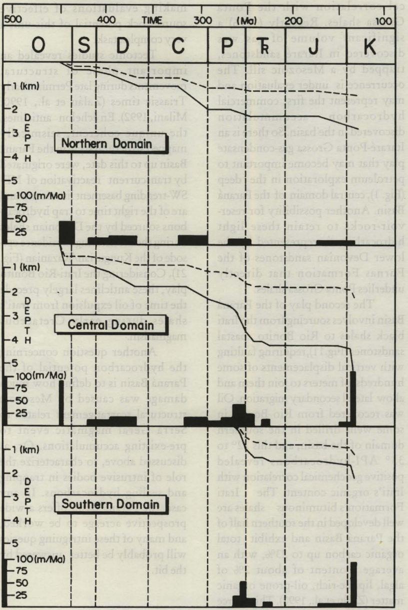


Figura 21 - Plots of total and tectonic (dashed line) subsidence for three data points representing major domains of the Paraná Basin. Bars shows tectonic subsidence rates. Time scale after Cowie & Bassett (1989). Location of boreholes is shown on Fig. 1.

supersequences represent the two major episodes of marine incursion over the craton in this portion of the paleocontinent. The Paraná Basin at that times was an immense embayment linked to a perioceanic platform at Gondwana's southern margin. The link between the Paraná Basin and the surrounding ocean was effective. Beds corresponding to the maximum flooding surfaces of the RI and the P supersequences, aged respectively Llandovery and Frasnian, can be found over various continents and constitute global markers. The development of the Paraná Basin's second order sedimentary sequences (Fig. 22) from late Ordovician to late Devonian times (*gulf stage*) was controlled by tectono-eustatic cycles related to global changes in the volume of ocean basins (Vail et al., 1977). Higher order cyclicity can be credited to climate (e.g. late Ordovician glaciation) or to changes in sedimentary input (e. g. middle Devonian progradational cycles).

The evolutive history of the Gondwana I supersequence was somewhat distinct. Long term, regionalized glacial-eustatic factors left meaningful imprints over sedimentation. In combination with tectonic changes in basin configuration, producing a water body progressively confined in the interior of the craton, the post-Devonian history of Paraná Basin seems to have an isolated intracratonic context (*syneclise stage*). The sedimentary record of this stage documents a multitude of climatic conditions between the extremes of the extensive Permian-Carboniferous glaciation and the aridity of late Permian- early Triassic times, included in a second order transgressive (deglaciation) - regressive (restriction and dessication) cycle. Higher order depositional cyclicity is equally interpreted as caused by coupled tectonic and climatic factors.

With the consolidation of Gondwana the Paraná Basin became included within the vast and arid land mass during Triassic and Jurassic times. In the early Cretaceous, Gondwana's breakup marked the end of a long sedimentation history. The sedimentary record of the Paraná Basin terminated with the accumulation of the thin post-basalt cover represented by Bauru supersequence.

The hydrocarbon potential of the Paraná Basin is still an open matter, in many aspects closely related to the effect of Mesozoic intrusive bodies upon source rock maturation and creation/destruction of traps.

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ELEMENT	SCALE	ORDER (according to basin's hierarchy)	CONTROLS (ultimate) T = Tectonics C = Climate
-Paleozoic supersequences			
RI - MFS	Global	2nd	Tectono-eustasy(T)
O glaciation	Interregional	3rd	Glacio-eustasy(C)
P - MFS	Global	2nd	Tectono-eustasy(T)
GI - MFS	Interregional	2nd	Tectono-eustasy/Glacio-eustasy (T+C)
P-C glaciation	Interregional/Basinal	2nd	Glacio-eustasy (C)
P deltas	Basinal	3rd	Tectono-eustasy (T)
Rio do Rastro road outcropping sequences	Basinal	4th	Glacio-eustasy (C)
Irati's cycles	Basinal	5th	Climate, driven by orbital cycles
Mesozoic continental supersequences			
G II	Basinal/Local	2nd	Climate, Tectonics
G III	Interregional/Basinal	2nd	
Botucatu desert	Interregional	3rd	Climate, Tectonics
Serra Geral lavas	Basinal	3rd	Tectonics
B	Basinal/Local	2nd	Climate, Tectonics

Figura 22 - Summary of stratigraphic hierarchy and controls on the development of sequences for the sedimentary record of the Paraná Basin.

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