Phanerozoic Cratonic Cores, Marginal Belts and Sedimentary Basins

"Lower Paleozoic magmatism in South America is most clearly recorded in outcrops in central and northwestern Argentina, extending into southern Bolivia, northeastern Chile and the coast of southwestern Peru. Igneous and metamorphic rocks of this age are well exposed in the geological provinces of central and northwestern Argentina, and its characteristics are considered representatives of the Paleozoic evolution of southwestern Gondwana... This distribution indicates that the basement of the southwestern sector of the South American Continent was mainly developed during the Early Paleozoic, being the Pampean and the Famatinian the best recognized orogenic episodes. These large Paleozoic regions are the basement that structurally controlled the Meso-Cenozoic Andean magmatism associated with the Pacific subduction."

(Rapela, this volume)

"Regarding the distribution of Phanerozoic sedimentary successions and particular plate-tectonic regimes, four major domains are recognized in the South American Plate: the continental interior; the western, convergent margin of the plate; the eastern side, a more than 10 000 km-long divergent margin; and the northern and southern margins of the plate, marked by a regional transcurrent tectonic regime..."

(Milani and Thomaz Filho, this volume)

PATAGONIA

Victor A. Ramos and María B. Aguirre-Urreta

Patagonia is a unique sector of southern South America that records a complex history of orogeny, continental break-up, seismic ridge collision, and foreland basin development. The geographical/physiographical limits of Patagonia are the Colorado River at about 39 °S in the N and the foothills of the Patagonian Cordillera along the western and southern margins; the crystalline Patagonian domain extends towards the E and constitute the basement for the Argentinean continental margin.

Patagonia encompasses several geological units such as the Somun Cura and Deseado massives, the San Jorge Basin, the Rio Mayo Embayment, and the Austral Basin (Fig. 1). The Patagonides foothills comprise the pre-Andean Patagonian Precordillera, the Bernárdides Mountains, and an extra-Andean region of basaltic plateaux (*mesetas*).

The Somun Cura Massif

This geological province was recognized as a stable cratonic block since the pioneer work of Windhausen (1931), who defined it as the Patagonian Massif. Its western boundary coincides with the Patagonian Precordillera, and is outlined by the Andean Thrust Front, that subdivided a western area with deformed Cenozoic rocks and a more stable area with mild or nihil deformation (Fig. 2).

Towards the SW, the Somun Cura Massif is bounded by the Cañadón Asfalto Basin, and is overlapped by the deposits of the Chubut Group, of Early Cretaceous age. The metamorphic basement consists of gneiss and micaschist metamorphosed in the amphibolite facies, associated with syn-tectonic granitoid plutons. Rb/Sr ages determinations from these rocks gave 850 ± 50 Ma (Sr^{87}/Sr^{86} initial ratio of 0.70734) according to Linares *et al.* (1990) and 620 ± 45 Ma (Sr^{87}/Sr^{86} initial ratio of 0.7038) by Varela *et al.* (1997). These rocks are related to the low-grade El Jagüelito Schist that has been considered by some authors as part of an Early Paleozoic basement. However, equivalent low-grade metamorphic rocks have been dated by Linares *et al.* (1990) at 600 ± 25 Ma (Sr^{87}/Sr^{86} initial ratio of 0.70347). New U/Pb dating on zircon from the southwestern sector of the massif indicated even older Middle Proterozoic ages.

Early Paleozoic marine deposits of Sierra Grande Formation unconformably overlie the eastern sector of the massif (Cortés *et al.*, 1984). Orthoquarzite is interbedded with important zones of oolitic iron beds up to 14 m thick. This cover, of Silurian age, forms a stable platform of clastic beds with minor tuffaceous levels, and the sedimentary rocks have a typical Malvinokaffric fauna. The fauna is characterized by the *Clarkeia antisiensis* - *Heterorthella* association of Silurian (Wenlockian) age (Manceñido and Damborenea, 1984).

Both the basement, and partially the cover, are intensely intruded by Ordovician, Carboniferous, and Permian granitoid bodies. Some authors recognize two different petrographic suites: an older suite consisting of subduction related tonalite, granodiorite and granite; and a second suite consisting of post-tectonic granite intrusives (Rapela and Caminos, 1987). New Rb/Sr ages from these assemblages gave 483 ± 22 Ma and 467 ± 16 Ma, in granodiorite and granite, and 363 ± 57 Ma and 318 ± 28 Ma in granite bodies emplaced in the Early Paleozoic cover (Varela *et al.*, 1997).

These rocks are covered by widespread acid volcanic and pyroclastic rocks that constitute an extensive rhyolitic plateau. Middle to Late Triassic ages have been recorded in the northwestern sector, associated with *Dicroidium* flora (Stipanicic *et al.*, 1968; Artabe, 1985, 1986). The rhyolitic rocks are younger towards the Atlantic coast. Rb/Sr ages obtained in several different areas of the massif yielded ages from 183 ± 2 to 178 ± 1 Ma (Rapela and Pankhurst, 1993). These ages were confirmed by Ar/Ar dating which range from 186.2 ± 1.5 to 176.9 ± 0.8 Ma in the Marifil Formation (Alric *et al.*, 1996). Both isotope studies pointed to an important short-lived melt episode that involved most of the Somuncura Massif, associated with the break-up of Gondwana (Kay *et al.*, 1993). These rocks are also closely linked with Early Jurassic granitoid with similar composition and tectonic setting (Rapela *et al.*, 1991).

Thermal sag subsidence following the Jurassic extension produced the Chubut Group continental deposits of Early Cretaceous age (Stipanicic *et al.*, 1968; Spalletti *et al.*, 1989). Several shallow marine transgressions in the Maastrichtian (Andreis *et al.*, 1989; Spalletti, 1990), Eocene, and Neogene covered most of the Atlantic side of the massif (Legarreta and Uliana, 1994). A large alkaline flood basalt province covered the Somun Cura Massif at about 27 Ma (Ardolino, 1981). These flows have been interpreted as produced by a transient hot-spot like environment by Kay *et al.* (1993), that in a few million years extruded a large volume of basalt. Late volcanic activity of alkaline basalt and rhyolite is concentrated near Telsen (Corbella, 1984) and in the Sierra de Apas, Los Chacays, Talagapa, and Pire Mahuida (Salani and Page, 1990), in volcanic domes, annular dykes, and minor flows.

The dominant structure of the massif is characterized by half-graben systems, associated with the opening of the South Atlantic Ocean. The orientation of the extension was oblique to the continental margin, and a partition of the stress in strike-slip displacements is evident (Ciciarelli, 1989). The western sector has a mild tectonic inversion produced during the Andean compression.

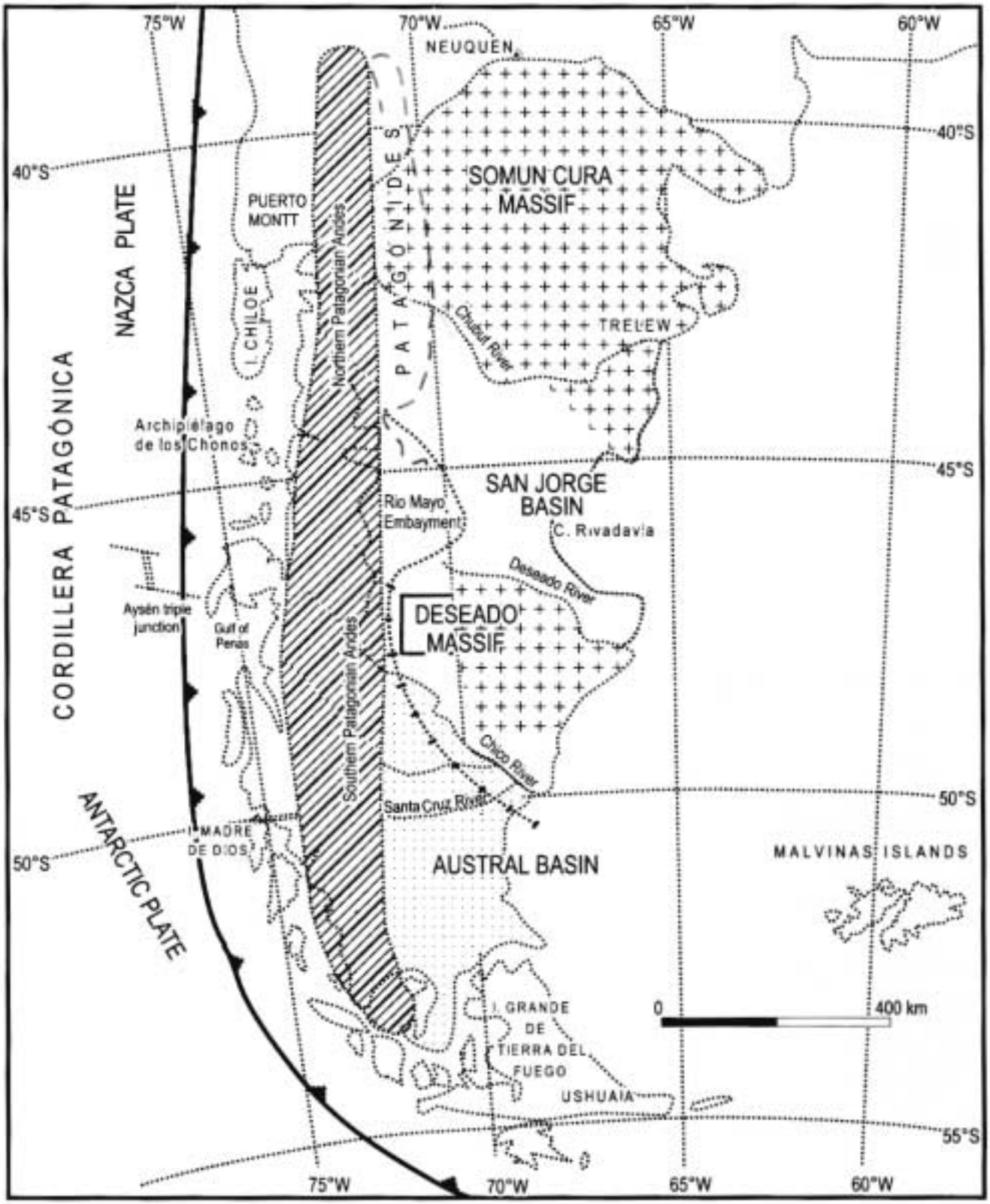


Fig. 1 - Major geological provinces of Patagonia (modified after Windhausen, 1931; Groeber, 1938).

Fig. 2 - Main geological features of the Somun Cura Massif in northern Patagonia, and adjacent geological provinces.

Fig. 3 - Main geological features of the Deseado Massif in southern Patagonia (modified after Panza et al., 1994).

70°W
68°W
Neuquén Basin
40°S
Colorado Basin
San Antonio Oeste
Gulf of San Matías
Meseta de Somun Cura
Patagonian Precordillera
42°S
Sa Pire Mahuida
Sa de Talagapa
Sa de Apas
Gan Gan
Gulf of San José
Gulf of Nuevo
Puerto Madryn
Cañadón
Rawson
Asfalto
Basin
Las Plumas
Los Altares
E. Ameghino
44°S
Chubut Group and younger sediments
Miocene trachyte
Late Cenozoic basalt
Oligocene Somuncurá basalt
Eocene basaltic plugs
Triassic to Jurassic rhyolites
Early Paleozoic rocks
Granitoid
Proterozoic basement

70°W
48°S
Puerto San Julián
Puerto Santa Cruz
68°W
50°S

The Deseado Massif

This region has been considered as an ancient and independent massif from the Somun Cura area since the work of Feruglio (1946). Leanza (1958) gave the present name to the stable basement area comprised between the Deseado and Chico de Santa Cruz rivers (Fig. 3).

The basement consists of isolated outcrops of phyllite and low-grade schist (Di Persia, 1962) that have been dated at 540 ± 20 Ma by K/Ar method (Pezzuchi, 1978). Silurian granitoid intrusives and sub-volcanic rocks are emplaced in the metamorphic rocks (Palma, 1989; Márquez *et al.*, 1994). Recent U/Pb dating on zircon gave ages of 424, 454 and 472 Ma (Middle-Late Ordovician to Silurian) in granitoid dykes of the Tres Hermanas region. Some tonalitic rocks yield ages between 407 and 402 Ma (Devonian). Detrital zircon fractions from metaquartzite samples gave a $^{206}Pb/^{238}U$ of 903 Ma (Loske *et al.*, 1999).

On this basement, minor continental basins of La Golondrina and El Tranquilo were developed in Permian and Triassic times (Stipanicic and Reig, 1956; Archangelsky, 1959; Arrondo, 1972). Red arkose, shale, and tuff of these basins have been interpreted as rift sequences by Jalfin (1987) and Jalfin and Herbst (1995). These deposits have a rich Triassic dinosaur fauna in the El Tranquilo Basin (Bonaparte and Vince, 1979) and well-preserved flora and microflora (Herbst, 1988; Zavatieri, 1993).

These deposits are intruded by Late Triassic and Early Jurassic granite of the Central Patagonian Batholith (Stipanicic *et al.*, 1972; Rapela *et al.*, 1991). The extensional regime was related to the break-up phases associated with the South Atlantic opening that developed the large Chon Aike Rhyolitic Province (Kay *et al.*, 1989). The Chon Aike rhyolite and ignimbrite, with scarce basalt, is associated with a clastic continental sequence deposited in half-graben systems (Ramos, 1996). The age of the rhyolite varies from 168 to 170 Ma in the eastern sector of the massif (Pankhurst and Rapela, 1993).

These clastic and volcanic rocks are covered by younger ignimbrite flows, volcanic and clastic sequences of Early Cretaceous age, that indicate a reactivation of the extension in the northwestern sector of the massif (Palma, 1989). Atlantic marine transgressions of Paleocene, Eocene and Oligocene-Miocene age are interbedded with continental clastic and pyroclastic sequences (Legarreta and Uliana, 1994).

The structure of the region displays an intense penetrative deformation in the metamorphic basement (Panza *et al.*, 1994); extensional structures in the Permian and Mesozoic deposits (de Giusto *et al.*, 1980); and sub-horizontal Late Cretaceous-Cenozoic sequences. The Jurassic rocks are associated with important gold low-sulfidation epithermal systems at Cerro Vanguardia and related ore-districts (Genini, 1989; Schalamuk *et al.*, 1995).

The Patagonides

The pioneer work of Keidel (1921) recognized the Patagonides, an old mountain chain situated between the Northern Patagonian Andes and the Somun Cura Massif. The present definition of the Patagonides is mainly based on the work of Groeber (1938) and Frenguelli (1946). This geological province comprises Paleozoic and Mesozoic sedimentary deposits and associated igneous rocks deformed during the latest Cretaceous (Fig. 4). The different ranges of the Patagonides can be subdivided in two distinct morphostructural units, the Patagonian Precordillera and the Bernárdides.

The Patagonian Precordillera

This region comprises a series of pre-Andean mountains developed between the Ñirihuau Basin at the foothills of the Patagonian Andes and the Somun Cura Massif (40°S to 43°30'S). The stratigraphy was established by Franchi and Page (1980), and the main structural features are shown in the Figure 4.

The basement consists of Precambrian metamorphic rocks exposed in the Gastre region that is intruded by Early Paleozoic granitoid plutons (Dalla Salda *et al.*, 1994). These Precambrian rocks are the basement of the Tepuel Late Paleozoic marine basin (Suero, 1962), later defined as a composite basin to include the Jurassic deposits by Ugarte (1966). The Late Paleozoic rocks consist of glacial, glaciomarine, marine and continental deposits several thousand metres thick, developed in a back-arc extensional setting (Ramos, 1983).

Black shale and sandstone beds bearing Late Pliensbachian to Early Toarcian ammonites and bivalves (Riccardi, 1983; Hillebrandt, 1987) are exposed between Esquel and the Sierra de Payaniyeu. These Liassic rocks interfinger with continental and volcaniclastic deposits (Cortiñas, 1984), defining an extensional intra-arc basin. The Liassic rocks are covered by the Middle to Late Jurassic Lonco Trapial volcanics (Nullo, 1983), which correspond to an extra-Andean volcanic arc. This arc is partially coeval with the Lago La Plata Formation along the axis of the Patagonian Cordillera (Ramos, 1983).

Granitoid bodies along the extra-Andean region represent the large Central Patagonian Batholith of Early to Middle Jurassic age, emplaced along extensional faults trending W-NW (Rapela *et al.*, 1991). Lacustrine limestone and black shale of the Cañadón Asfalto Group define a basin trending NW deposited in a half-graben system during Middle to Late Jurassic time (Figari and Courtade, 1993). This renewed episode of extension is obliquely positioned to the E of the Liassic intra-arc basin. An extensive cover of late Early Cretaceous continental deposits of the Chubut Group unconformably overlies the Jurassic rocks. These continental deposits are interfingered with thick tuff layers that are the piroclastic equivalent of the Early Cretaceous volcanic arc of the Divisadero Group, well exposed along the axis of the Patagonian Cordillera (Ramos and Drake, 1987).

The eastern area is also covered by Maastrichtian-Danian marine deposits related to an Atlantic short-lived transgression. The western part is covered by Late Cretaceous tholeiitic basalt flows. Paleogene alkaline basalt related to a ridge subduction are developed S of 43°S (Ramos and Kay, 1992). The structure of the

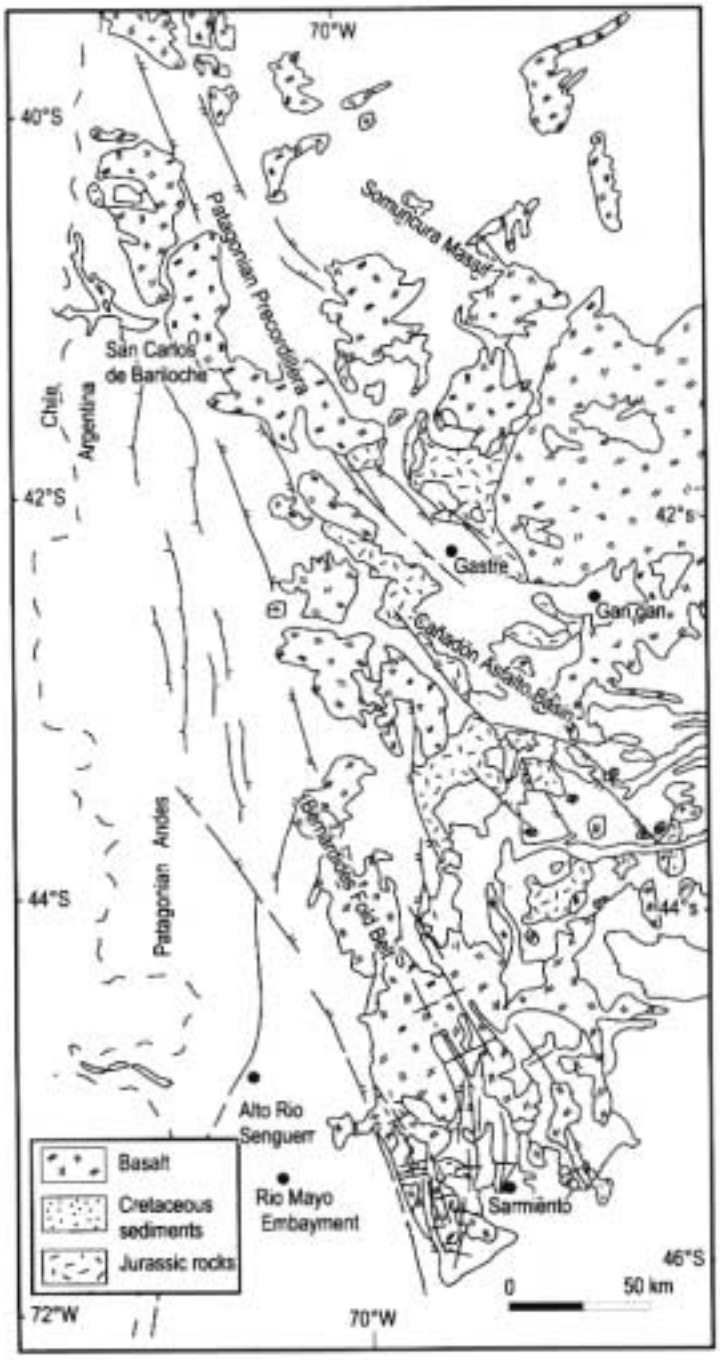
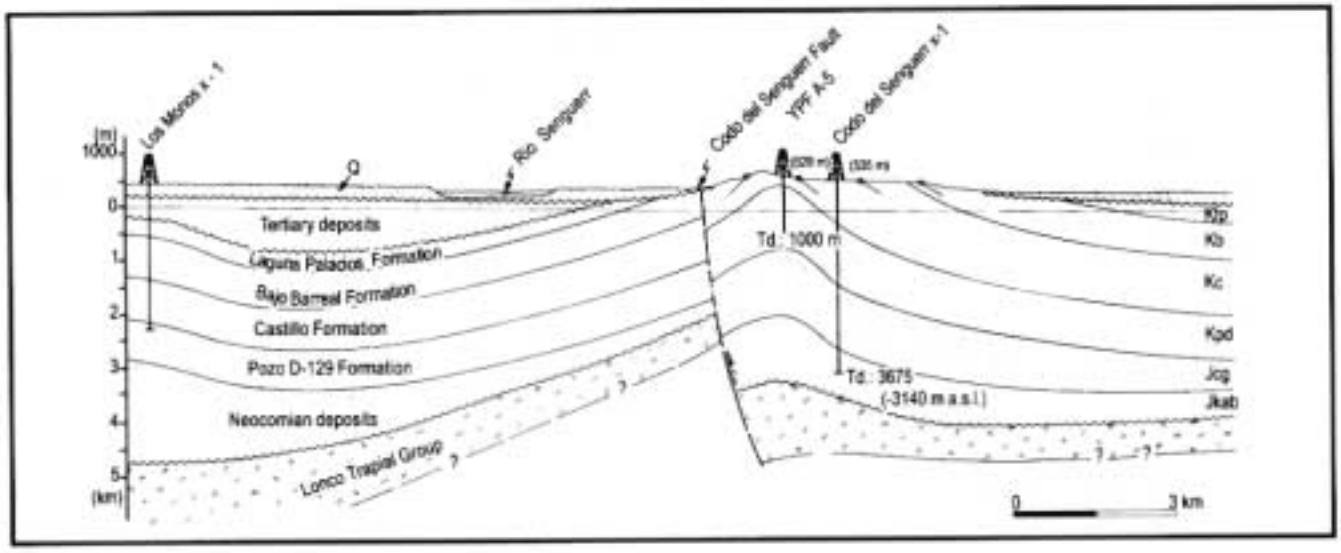


Fig. 4 - Main geological features of Patagonides with the Patagonian Precordillera and the Bernardides Fold Belt (after Barcat et al.*, 1984; Figari and Courtade, 1993).*

Fig. 5 - Structural section of Codo del Rio Senguerr Anticline produced by tectonic inversion of Mesozoic half-grabens (after Ramos, 1999). Note the contrast between the Lonco Trapial Group and Neocomian synrift deposits with the younger sag facies.



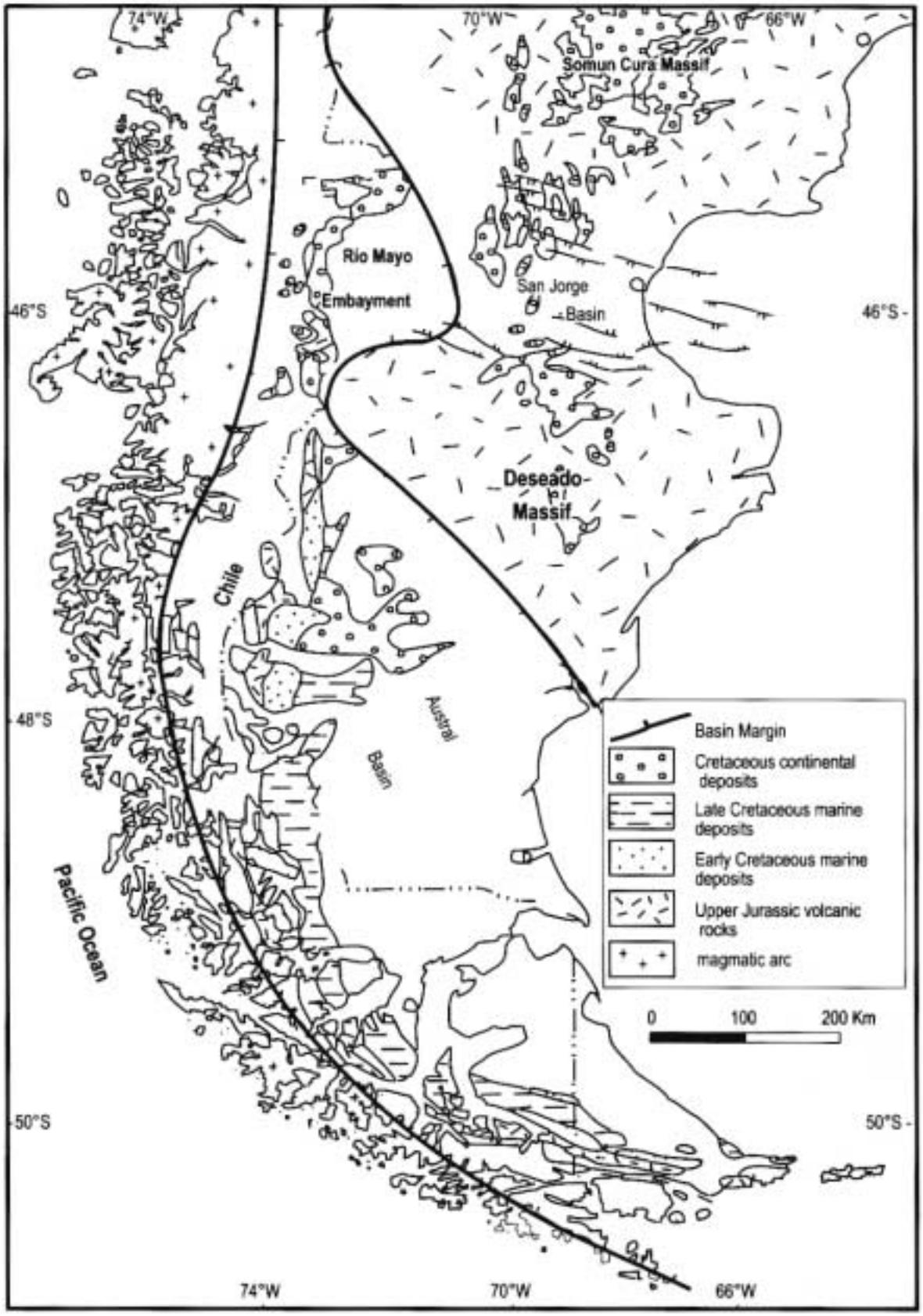


Fig. 6 - Main geological features of southern Patagonia, with main exposures of the Río Mayo Embayment and the Austral Basin (modified after Riccardi, 1988).

Patagonian Precordillera is characterized by tectonic inversion of previous normal faults with a dominant westerly vergence (Márquez and Giacosa, 1999). Due to the oblique trend of the normal faults, there are important strike-slip displacements (Coira *et al.*, 1975).

The Bernárdides

A series of ranges in the central extra-Andean Patagonia (43°30'S to 46°S) has been grouped as the Bernárdides by Ferello (1969). These ranges are separated from the Patagonian Andes by the depression of the Genoa and Senguerr River valleys. The eastern boundary coincides with Lake Colhue Huapi.

The Bernárdides fold belt is characterized by large anticlinal structures, such as the Codo del Río Senguerr (Fig. 5) and the Sierra de Castillo, bounded by N-NW-trending faults developed by tectonic inversion of early Mesozoic half-grabens (Homovc *et al.*, 1993). The anticlinal structures have vergence to the E or to the W, following the dip of the previous normal faults. The initial fill of these half-grabens is exposed to the N, in the Patagonian Precordillera. The fill consists of Liassic deposits, Middle Jurassic volcanics and lacustrine Pre-Cretaceous shale. The sag phase deposits are represented by the late Early Cretaceous Chubut Group (Sciutto, 1981). These continental and pyroclastic sequences, the oldest units exposed in the Bernárdides, are famous for their abundant dinosaur remains (Bonaparte and Gasparini, 1978). Most of the type localities of the different units of the Chubut Group, as defined by Lesta (1968), are well exposed in the region. These deposits are partially covered by extensive basalt flows, domes, and alkaline intrusives of Paleogene age described by Ferello (1969). The marine deposits are only preserved in the easternmost localities, as the region was a positive area during most of the Cenozoic.

The compressive structure of the region was produced by tectonic inversion and strike-slip displacements in the Late Cretaceous and reactivated in Cenozoic times (Barcat *et al.*, 1984). Although the exposures of these structures end at the Codo del Río Senguerr, it is possible to continue this trend farther S in the subsurface (Figari *et al.*, 1998).

The San Jorge Basin

This E-W-trending, pericratonic continental basin was developed as an aulacogenic basin during the opening of the South Atlantic (de Wit, 1977). The basin was formed between the Somun Cura and Deseado massives. The basement of the basin is exposed in its northern and southern flanks, within the Somun Cura and Deseado massives. It consists of low and high grade metamorphic rocks of Precambrian age intruded by Early Paleozoic granitoid plutons.

An extensional regime started in Early Mesozoic times, with the development of a series of W-NW-trending half-graben systems. The very initial fill of these grabens comprised Early Jurassic deposits and Middle Jurassic volcanics, similar to the previously described syn-rift deposits of the Bernárdides (Fitzgerald *et al.*, 1990; Figari *et al.*, 1996). A late syn-rift sequence is mainly composed of continental fluvial deposits of Neocomian age, that in the western side represent a short-lived marine transgression during the Valanginian (Figari *et al.*, 1999).

Most of the basin fill consists of continental fluvial deposits of the Chubut Group of Early Cretaceous age (Lesta *et al.*, 1980). These rocks correspond to the thermal sag phase of the basin. Conformably overlying the Chubut Group there are Maastrichtian-Danian shallow marine deposits, continental Paleogene tuff beds and clastic deposits of the Sarmiento Group, the late Oligocene-Miocene Patagonian marine transgression and the continental Santa Cruz Formation of early-middle Miocene age (Legarreta and Uliana, 1994). The basin is covered by thick gravel blankets, and isolated patches of basaltic rocks.

The structure consists of a series of gentle anticlines, partially bounded by high angle reverse faults, produced by tectonic inversion of previous normal faults (Fitzgerald *et al.*, 1990; Homovc *et al.*, 1993).

The Río Mayo Embayment

A Neocomian basin developed between the Patagonian Andes and the Bernárdides to the N, and the Somun Cura Massif to the S (Fig. 6). For a short time it was partially linked with the San Jorge Basin. This basin represents an embayment of the Neocomian sea in a retro-arc position, associated with the paleogeographic evolution of the arc system and partially connected with the Pacific Sea (Aguirre-Urreta and Ramos, 1981). This basin is controlled by a series of W-NW half-grabens, such as the Rio Mayo half-graben, only partially inverted during the compressive phase (Peroni *et al.*, 1995). The structural trend is perpendicular to the N-NW trending half-graben system of the Bernárdides (Figari *et al.*, 1999).

The basement consists of the Middle to Late Jurassic Lonco Trapial volcanics, that have been reactivated by the Tithonian-Neocomian rifting (Clavijo, 1986). The fill of the basin consists of conglomerate packages, sandstone and shale of the Tres Lagunas Formation, which is overlain by black shale beds of the Katterfeld Formation. These marine units bear an ammonite fauna indicative of a Valanginian to Hauterivian age (Riccardi, 1970; Aguirre-Urreta and Rawson, 1999). At the base of this marine sequence there is a stratigraphic level that records maximum eustatic conditions, a bed that can also be recognized in the western subsurface part of the San Jorge Basin. The Neocomian deposits have a maximum thickness in the western sector, pinching out to the E in the Bernárdides Fold Belt, and have been interpreted as a late syn-rift by Fitzgerald *et al.* (1990). The fill ends with the fluvial and fan delta sandstone of the Apeleg Formation, of Hauterivian to Barremian age, and the continental deposits of the Chubut Group (Hechem *et al.*, 1993). A thick sequence of Cenozoic sediments covers most of the embayment (Figari *et al.*, 1999).

The Austral Basin

The Austral Basin is a typical retro-arc basin controlled by thermal subsidence until the latest Cretaceous when tectonic flexural subsidence, associated with the initial deformation in the Patagonian Andes gave place to a foreland basin (Biddle *et al.*, 1986).

The Meso-Cenozoic deposits of the Austral Basin (Fig. 6) cover the southern part of Patagonia. The basement of the basin consists of highly deformed sedimentary and metasedimentary deposits of Late Paleozoic age. These rocks also constitute the basement of the Patagonian Andes at these latitudes. A strong angular unconformity, produced during the Gondwanan Orogeny (Du Toit, 1927), separates these rocks from the volcanic, pyroclastic, and volcaniclastic deposits of Middle-Late Jurassic age. The volcanic rocks of El Quemado Formation constitute the easternmost outcrops of the Jurassic arc exposed along the axis of the Patagonian Andes. Thick Meso-Cenozoic sedimentary sequences overlie the previous rocks and constitute the fill of the Austral Basin (Biddle *et al.*, 1986). This basin opens towards the S, where the most complete Late Jurassic and Cretaceous sections were deposited. The Neocomian deposits exposed along the foothills of the Patagonian Andes are mostly marine clastics.

The base of the sedimentary sequence is composed of coarse quartzitic sandstone units ranging from fluvial continental to littoral marine facies of Tithonian to Hauterivian age. These deposits, known as the Springhill Formation, constitute an extensive clastic platform (Robles, 1982). A thick series of black shale beds of basinal facies (Río Mayer Formation) bear fossiliferous calcareous nodules. A prograding sequence of green sandstone and shale beds (Río Belgrano Formation, Barremian), bearing zones with abundant fossils preserved in sandy concretions are covering the underlying shale. Towards the S, the Neocomian deposits are represented by deeper water facies, and thus the fauna is scarce and not well preserved. Ammonites from the Hauterivian - Barremian are widely distributed through the northern part of the basin while the Berriasian and Valanginian faunas are only locally found. They were grouped in six assemblages (Riccardi, 1984, 1988) that were recently updated with new studies (Aguirre-Urreta, 1993).

Towards the S, in the region of lakes Viedma and Argentino, turbidite deposits of Late Cretaceous age are represented by the Cerro Toro Formation (Katz, 1963). Ammonites from Cenomanian to Campanian age have been found in these beds (Riccardi, 1988). These basinal facies are covered by a series of sandstone and shale beds of Maastrichtian to Cenozoic age.

The Patagonian mesetas and adjacent plains

One of the typical geological features characteristic of the extra-Andean Patagonia is the widely exposed basaltic plateaux known as the *mesetas* (Nágera, 1939). The *mesetas* are exposed N and S of the Deseado Massif, from the Atlantic coast up to the foothills of the Patagonian Andes (Ramos *et al.*, 1982). The substratum of these features is composed of Paleogene and Neogene continental deposits bearing a rich and peculiar fauna of giant mammals. These units are interbedded with ash-fall tuffs, that have been extensively used to date the mammal age sequences (Marshall *et al.*, 1983).

The plateau basalts S of 46°S form extensive plateaux such as the Meseta Buenos Aires, Belgrano, Central, La Muerte, Strobel, Las Vizcachas, among others. There are alkaline plateau basalts (Ramos *et al.*, 1982), and more alkaline post-plateau basalts of Neogene age. This retroarc basaltic activity is related to the development of asthenosphere windows associated with the subduction of seismic ridges along the Chile trench, S of the triple junction (Ramos and Kay, 1992).

The *mesetas*, farther S and in the eastern region, are capped by the Patagonian gravels first described by Darwin (1846). These gravels are interpreted as glacial and fluvioglacial deposits of late Neogene and Quaternary age. These deposits are dissected by wide valleys with younger glacial and fluvial deposits. Tertiary molasse sediments overlie some basaltic rocks in the eastern foothills, and are in turn covered by younger basalt flows. Basalt flows are widely distributed in the extra-Andean region, and are covered by glacial and alluvial deposits of Late Tertiary and Pleistocene age. The Pali Aike Volcanic Field exposed at the southern extremity of Patagonia consists of tens of alkaline basaltic monogenic cones of Plio-Pleistocene age (Skewes and Stern, 1979). These are related to neotectonic reactivation of Mesozoic extensional rift faults (Corbella *et al.*, 1996).

Geological history

The Patagonian basement records a Precambrian history that started in the Middle Proterozoic, as detected in detrital zircon fractions from the Deseado Massif (Loske *et al.*, 1999), as well as from the western part of the Somun Cura Massif. The northern sector of this massif has evidence for a Brasiliano deformation, as dated by Linares *et al.* (1990).

Reconstruction of crustal growth of Patagonia began in the Early Paleozoic, when a magmatic arc was developed in the northern margin of the Somun Cura Massif. Age constraints for this magmatic belt are erratic. Middle to Late Ordovician Rb/Sr ages should be confirmed in order to reconstruct a period of reverse polarity of subduction in the southern margin of Gondwana. At this time the Deseado Massif was also the locus of Early Paleozoic magmatism. It has been proposed that both basement blocks were independent terranes amalgamated during the Early Paleozoic to form the Austral continent (Palma, 1989).

Paleomagnetic data are still insufficient, as the Late Paleozoic paleopoles indicate that Patagonia was already part of Gondwana, but there are not good paleopoles in Early Paleozoic rocks (Rapalini and Vilas, 1991). Potential sutures, one N of Somun Cura, and another between the two massives, indicate important Permian rifting. The Permian NW trending rifts are developed in the hanging-

wall of the potential suture as described by Melchor (1995) in the Sierra de Carapacha located in the vicinity of the Colorado River (39 °S). The offshore half-graben can be correlated with the onshore La Golondrina rift basin.

The Early Jurassic rift, associated with an intra-arc basin, has a different trend. Most of the first order structures have a N-NW trend as shown for the Patagonides Fold Belt (Barcat *et al.*, 1984). Extension shifted toward the margin where the Cañadón Asfalto Rift, in the middle of the extra-Andean Patagonia, has an unequivocal NW trend (Figari *et al.*, 1996). The Neocomian trend is shifted again to a W-NW trend, almost perpendicular to the Early Jurassic structures (Uliana *et al.*, 1989). After the Neocomian extension, the entire system went into a generalized thermal sag subsidence, as depicted by the large and extensive cover of the Chubut Group.

The first evidence of compression along the Patagonian Andes is registered in the Middle to Late Cretaceous. An angular unconformity between 77 Ma old basalt and Neocomian sediments E of Lake Fontana, marks the approximate orogenic front at that time. The nature of this deformation is still unknown and could reflect either an acceleration of the convergence rate, or a change of the convergence vector close to 80 Ma, or a collision of an oceanic ridge migrating from S to N as detected by Ramos *et al.* (1994). This last proposal is based on the finding of an adakite of 84 - 77 Ma E of Lago San Martín, associated with an important volcanic gap in the Southern Patagonian Andes.

Paleogene deformation is present S of 43°30'S, where the active Paleogene magmatic arc ends. Extensive alkaline basalt flows of Paleocene to Eocene age, together with essexite and other alkaline dyke swarms, widespread in the extra-Andean Patagonia, are associated with Paleogene ridge collision of the Posadas Basalt (Ramos and Kay, 1992). Neogene Andean deformation has two different regimes N and S of the Aysen Triple Junction (46°30'S). The northern sector has a mild deformation that partially inverted the properly oriented extensional structures. As a consequence of that the Bernárdides Fold Belt, almost perpendicular to the main stress, had the largest inversion. The remaining structures had a mild inversion, combined with strike-slip displacements. To the S of 46°30'S a successive sequence of segments of the ocean ridge has collided against the trench and has fostered the uplift of the Southern Patagonian Andes, deformed the molasse sediments in the extra-Andean Patagonia, and controlled the extensive basaltic plateaux (Ramos, 1989). Present neotectonic activity is restricted to S of Aysén Triple Junction, being most of Patagonia stable and undeformed.

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THE SIERRAS PAMPEANAS OF ARGENTINA:

PALEOZOIC BUILDING OF THE SOUTHERN PROTO-ANDES

Carlos W. Rapela

Lower Paleozoic magmatism in South America is most clearly recorded in outcrops in central and northwestern Argentina, extending into southern Bolivia, northeastern Chile and the coast of southwestern Peru. Igneous and metamorphic rocks of this age are well exposed in the geological provinces of central and northwestern Argentina (Fig.1), and its characteristics are considered representatives of the Paleozoic evolution of southwestern Gondwana. Outcrops of Lower Paleozoic rocks are much more scattered S of 33°S, where they appear as the basement rocks of the Patagonian massifs and are also recognized in drill cores as far S as the Strait of Magellan. This distribution indicates that the basement of the southwestern sector of the South American Continent was mainly developed during the Early Paleozoic, being the Pampean and the Famatinian the best recognized orogenic episodes (Pankhurst and Rapela, 1998). These large Paleozoic regions are the basement that structurally controlled the Meso-Cenozoic Andean magmatism associated with the Pacific subduction.

Within the classic geological-morphostructural provinces recognized in the Argentinean geology, there are several that include extensive sectors composed mainly of igneous and metamorphic rocks of Early and Middle Paleozoic age. The best exposed and studied are the provinces of the northwestern sector: the Sierras Pampeanas, the Famatina System, the Precordillera, the Eastern Cordillera and Puna; and in Patagonia, the North Patagonian Massif (Fig. 1). The Early Paleozoic tectonic evolution of southern South America described here is based on new geochemical, isotope and petrological data from a 500 km traverse at 31°S - 32°S across the Eastern Sierras Pampeanas, the southern extension of the Famatina System, the Western Sierras Pampeanas, and the Precordillera (Pankhurst *et al.*, 1998; Rapela *et al.*, 1998a, b, 1999). Pre-Silurian metamorphic and magmatic history in this transect (Fig. 1) has been inferred from: (1) dating by conventional U/Pb on abraded zircon, U/Pb SHRIMP analyses, and whole-rock Rb/Sr and K/Ar; (2) thermo-barometry based on microprobe mineral analyses; and (3) Nd and Sr isotopes, and major element and trace element geochemistry of the magmatic suites. Recent accounts on the Early Paleozoic history of the provinces of the northwestern Argentina, and different viewpoints on its geodynamic evolution are presented in the book The proto-Andean Margin of Gondwana, Pankhurst and Rapela (eds), 1998. Pioneering contributions and research on the geology of these provinces, back in time up to 1978, can be consulted in the Segundo Simposio de Geología Regional Argentina, volume I, Turner (ed), 1979.

Gondwana mobile belts and the Precordillera Terrane

Geological and paleontological evidence indicating that the Argentine Precordillera is a Laurentian terrane has revolutionized ideas about the proto-Andean margin of South America (Dalziel, 1997; Benedetto, 1998). Although the exotic origin of the Precordillera has been widely accepted, the timing of accretion and the associated geotectonic models remained controversial (*e.g.* Dalla Salda *et al.*, 1992, 1998; Astini *et al.*, 1995; Dalziel, 1997; Benedetto, 1998; Rapela *et al.*, 1998b). Despite the fact that several problems are still unsolved, unravelling the evolution of the Gondwana margin immediately prior to accretion of the Precordillera terrane has helped to distinguish different mobile belts and to better constrain existing geodynamic models (Rapela *et al.*, 1998b; Sims *et al.*, 1998).

Paleozoic provinces at 22° S to 33° S may be divided into those related to Early to Middle Cambrian accretion (the Pampean Mobile Belt), and those associated with Ordovician subduction (the Famatinian Mobile Belt) and later collision of an exotic terrane (the Precordillera Terrane). More precise geochronological data and detailed petrological studies lead to a more restricted definition of Pampean and Famatinian events and their duration (Rapela *et al.*, 1998b). The Pampean Mobile Belt includes the Eastern Sierras Pampeanas and Eastern Cordillera provinces (Fig. 1). From 22° S to 27° S the Pampean Belt is dominated by the Puncoviscana Formation, which is mainly composed of a thick sequence of low-grade metamorphic rocks including metapelite and turbidite beds with well preserved primary structures (Jeek, 1990), carrying trace fossils and indicating a late Precambrian (Vendian) to early Lower Cambrian (Tommotian) age (Durand, 1996). This tightly folded series is intruded by Cambrian granite and unconformably covered by Middle-to Late Cambrian platform sediments, therefore suggesting a Middle Cambrian deformation (Rossi *et al.*, 1992; Durand, 1996). From 27°S to 33°S only metamorphic equivalents of the Puncoviscana Formation are exposed. The sequences are mostly composed of medium to low pressure and temperature, high-grade metamorphic rocks and anatectic granites of Early to Middle Cambrian age, partially remobilized and intruded by Ordovician to Carboniferous granitoid plutons (Rapela *et al.*, 1998a).

The Famatinian Mobile Belt, encompassing the Puna, the Famatina System, the Sierra de los Llanos de La Rioja and Sierras de San Luis, consists of low- pressure and low-to-high temperature metamorphic rocks, back-arc sediments, and widespread Early Ordovician magmatic rocks (Fig. 2).

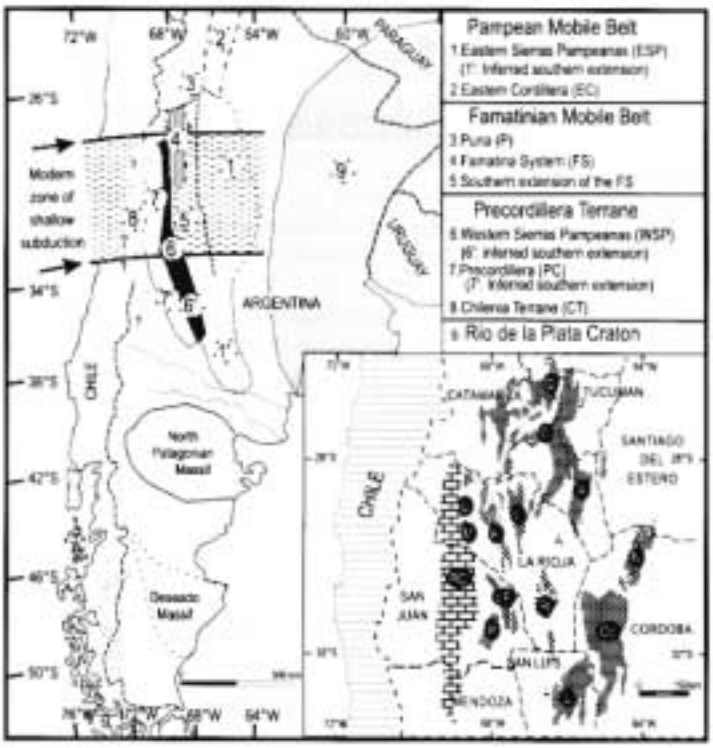

FIG. 1. Early Paleozoic geological provinces in the southern Andes, disclosed by back-thrusting above Miocene "flat-slab" subduction (modified after Rapela et al., 1998b). Principal sierras in this segment are: Q - Quilmes; C - Capillitas; A - Ancasti; F - Famatina; V - Velasco; U - Umango; M - Maz; N - Norte de Córdoba; Co - Córdoba; L - San Luis; R - Llanos de la Rioja and Chepes; VF - Valle Fértil; P - Pie de Palo; PC - Precordillera.

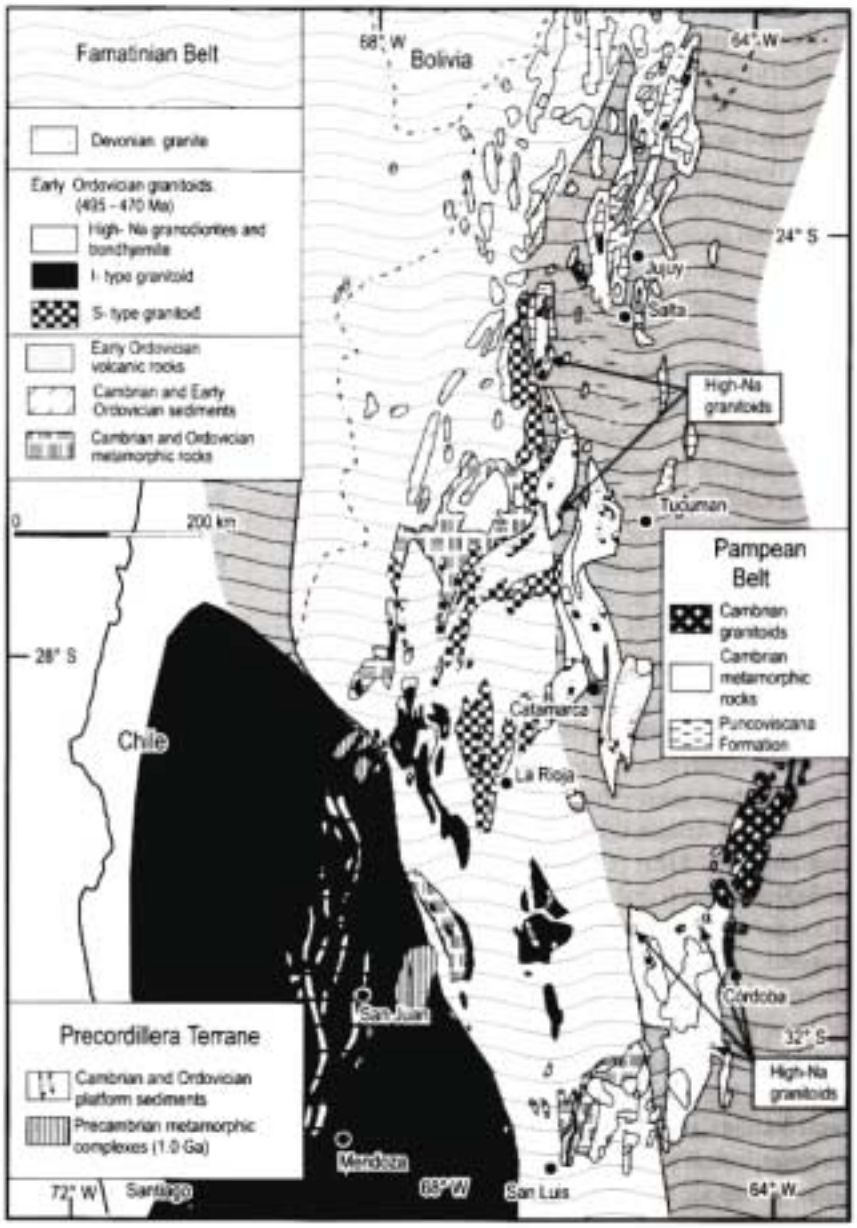

FIG. 2. Early Paleozoic reconstruction of the proto-Andean margin of southern South America after the docking of the Precordillera Terrane.

The Precordillera Terrane (Precordilleran Terrane of Astini *et al.*, 1995) is essentially equivalent to the Cuyania Terrane of Ramos *et al.* (1998) and consists of metamorphic basement partly covered by Cambrian-Ordovician carbonate rocks. In the Precordillera the latter contain typical Laurentian faunas (Benedetto, 1998) and subsequent siliciclastic units that extend into the Upper Paleozoic; a Grenville age for their unexposed basement has been inferred from xenoliths in Miocene volcanic rocks (1.102 ± 0.006 Ga, U/Pb zircon, Kay *et al.*, 1996). Exposed Grenville-age basement occurs both W and E of the Precordillera. Caminos (1973) was the first to recognize the contrasting lithology of the basement rocks occurring to the E of the Precordillera as the Sierra de Pie de Palo, Sierra de Maz and Sierra de Umango, namely the Western Sierras Pampeanas (Fig.1), that are characterized by an absence of major batholiths, abundant ultramafic, mafic and metamorphosed carbonate sequences, with metamorphic assemblages that generally indicate higher-pressure metamorphism than in the Eastern Sierras Pampeanas. The isotope ages indicating a Grenvillian age for the Western Sierras Pampeanas (McDonough *et al.*, 1993; Varela *et al.*, 1996; Pankhurst and Rapela, 1998) is further evidence favouring the allochtony of the Precordillera Terrane, and confirmed the early observations made by Caminos (1973, 1979) indicating sharply contrasting evolutionary lines and petrogenetic processes for the basement rocks of the Eastern and Western Sierras Pampeanas.

The Neoproterozoic-Devonian evolution of the Pampean and Famatinian belts is compared to that of the Precordillera Terrane in Figure 3. The geodynamic model described below follows the main features presented by Rapela *et al.* (1998b), but new U/Pb SHRIMP data have allowed better estimations of the intrusion age of the large peraluminous batholiths (Rapela *et al.*, 1999), and modifications in the interpreted sequence of events.

Supercontinent break-up: opening of the Puncoviscan and Southern Iapetus oceans

Break-up of the the latest Precambrian Pannotia Supercontinent produced continental terranes that were accreted to Laurentia and Gondwana in early Paleozoic collisions. Recently reviewed geological evidence along the conjugate margins indicates a latest Precambrian to Early Cambrian age for the rift-drift transition (Dalziel, 1997). The Puncoviscana Formation of western Argentina is seen as the South American proximal counterpart of deep-marine passive margin sequences overlying the edge of the Río de la Plata Craton (Figs. 1 and 3). Inferred sequential opening of the Puncoviscan and Southern Iapetus oceans (the result of a spreading-center shift?) left fossil oceanic crust between a detached continental block, the Pampean Terrane, and the Gondwana margin (Fig. 3).

Pampean Orogeny: Early Cambrian subduction and terrane collision

The proto-Andean margin of Gondwana changed from passive to active in Early Cambrian time, leading to closure of the Puncoviscan Ocean (Fig. 3). The youngest trace fossils in the Puncoviscana Formation are Tommotian (Durand, 1996), *c.* 534 - 530 Ma. These date the last passive margin deposits, succeeded by a thick accretionary prism. A subduction-related belt of metaluminous calc-alkaline granitoid bodies and dacite-rhyolite was emplaced along the eastern part of the Eastern Sierras Pampeanas (Lira *et al.*, 1996; Rapela *et al.*, 1998a). In the Sierras de Córdoba this is dated at 530 ± 4 Ma by U/Pb on abraded zircon from three plutonic units (Rapela *et al.*, 1998a). Intrusion was followed by crustal thickening and burial to granulite facies conditions (P = 8.6 ± 0.8 kbar, T = 810 ± 50 °C). A clockwise P-T-time path is inferred, producing regional migmatites during peak thermal conditions of P = 5.7 ± 0.4 kbar, T = 820 ± 25 °C; dated at 522 ± 8 Ma by a U/Pb SHRIMP age on monazite. Immediately following this, strongly peraluminous, cordierite- and sillimanite-bearing granite and associated cordieritite were generated by low-P anatexis of metasediments (P = 3.9 ± 0.6 kbar, T = 684 ± 60 °C); an 18 point Rb/Sr whole-rock isochron gave 523 ± 4 Ma, Sr_i = 0.7136, mean square of weighted deviates (MSWD) = 2.0; and U/Pb on abraded zircon gave 523 ± 2 Ma. This orogeny is interpreted as being due to Early to Middle Cambrian collision between the semi-autochthonous Pampean Terrane and Gondwana (Rapela *et al.*, 1998a,b). Middle Cambrian deformation of the Puncoviscana Formation N of 27 °S (Rossi *et al.*, 1992; Bahlburg and Hervé, 1997) is ascribed to the Pampean Orogeny. SHRIMP ages of 1.4 Ga to 600 Ma for inherited zircon from both high-grade metapelite and peraluminous granite suggest provenance from Middle to Neoproterozoic sources.

Ordovician subduction on the Gondwana Margin: the Famatinian Arc

After Pampean terrane accretion, the proto-Pacific margin became passive at this latitude until Early Ordovician time: there was no orogenic activity and little granitoid emplacement in the Sierras Pampeanas between 515 and 490 Ma. The Famatinian Magmatic Arc began to develop in earliest Ordovician time and affected all geological provinces in southwestern Gondwana. An inner arc of sparse high-Al trondhjemite bodies was emplaced at 496 ± 2 Ma in the Pampean foreland of the Sierras de Córdoba; a new cordilleran arc of calcic granitoid plutons began in the W at 492 ± 6 Ma in the Sierras de Los Llanos-Chepes and at 484 ± 5 Ma in the Famatina System (U/Pb SHRIMP and U/Pb conventional on abraded zircon, Rapela *et al.*, 1998a, 1999; Pankhurst *et al.*, 1998). New U/Pb SHRIMP data on the typical peraluminous facies of the large Capillitas and Velasco batholiths that were previously considered to be of Silurian-Devonian age, also revealed an Early Ordovician age (470 ± 3 Ma; 479 ± 3 Ma, Rapela *et al.*, 1999). The new results suggest that supracrustal reworking is a prominent feature of the Early Ordovician climax of the

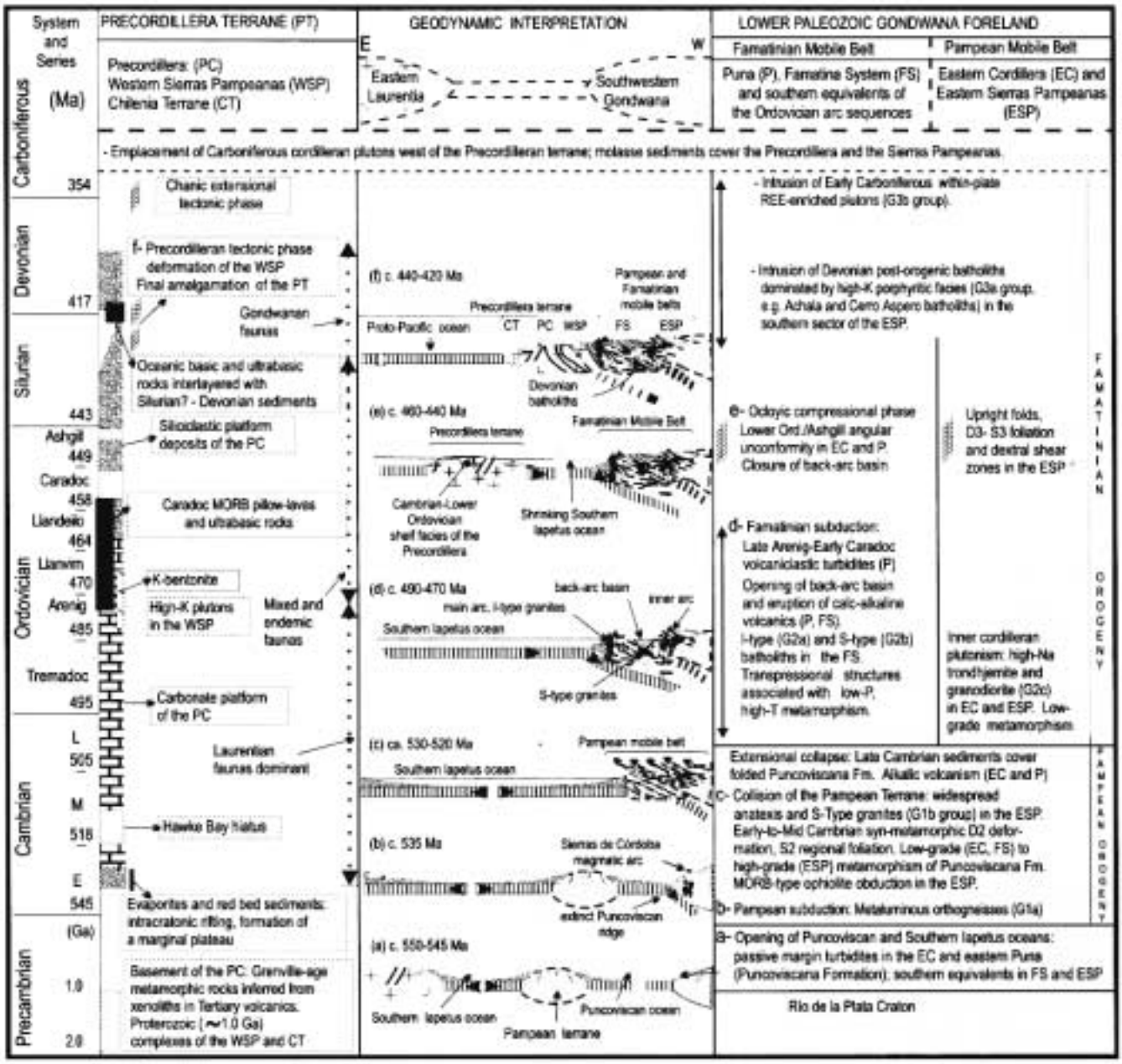

FIG. 3. Sequence and characteristics of Paleozoic orogenic events in the proto-Andean margin of South America (modified after Rapela et al.*, 1998b). Tectono-magmatic evolution and geochronological control for Gondwana are after Pankhurst* et al. *(1998) and Rapela* et al. *(1998a, 1999); time scale of Gradstein and Ogg (1996). Sedimentary sequences, faunas and tectonic phases in the Precordillera are simplified and slightly modified after Astini* et al. *(1995), Benedetto (1998), and Keller* et al. *(1998); plate tectonic stages of the Precordillera terrane are after Keller* et al. *(1998). Acronyms as in Figure 1.*

Famatinian episode. Local generation of S-type granite intrusions during high-T, low-P metamorphism in the Sierra de Chepes occurred also in Early Ordovician times (479 ± 4 Ma; 483 ± 12 Ma, Rapela *et al.*, 1999).

I-and S-type Famatinian granites intruded the westernmost passive margin sequences overlying the Pampean basement. They exhibit identical Sm/Nd crustal residence ages to those of the Cambrian plutonic rocks of the Sierras de Córdoba (1.75 - 1.55 Ga), significantly older than those of the Precordillera Terrane (Pankhurst *et al.*, 1998). The Famatinian Magmatic Arc was clearly continental, not an island arc. Although roughly coeval, the Famatinian granitoid intrusives show a regular geographical distribution of compositional types (Fig. 2): (a) medium to small size bodies of high-Na tonalite, trondhjemite and granodiorite were emplaced in the easternmost side of the orogen, along the older Pampean Belt; (b) low-Ca peraluminous batholiths and small bodies of cordierite-bearing monzogranite were emplaced *in situ* at shallow depths, in high-T, low-P metamorphic rocks cropping out along the central sector of the Famatinian Belt; and (c) I-type, calcic metaluminous suites, from gabbro to high silica leucogranite, were emplaced along the western side of the Famatinian Belt. Volcanic rocks are also conspicuous to the N of this belt.

A wide back-arc basin filled by Tremadocian–Llanvirnian shallow-marine volcaniclastic and/or volcanic rocks opened between the inner and main arcs (Fig. 3). It was underlain by oceanic crust in the southern Puna (Bahlburg and Hervé, 1997), and opened progressively southwards, reaching the Sierras de San Luis at 33° S (Sims *et al.*, 1998). The basin closed during the Late Ordovician *Ocloyic tectonic phase, producing westward thrusting and* mylonite belts in the high-grade Pampean basement of the Sierras de Córdoba (D3 deformation). Pegmatites associated with the dextral shear zones of this stage yield K/Ar ages of 447 - 435 Ma (Rapela *et al.*, 1998a).

The passive margin of the Precordillera Terrane

Evolution of the Gondwana foreland at this time sharply contrasts with that of the obviously exotic Precordillera (Fig. 3). The Precordillera has a typical passive margin, Early Cambrian-Arenigian, carbonate shelf sequence, which resembles that of the southern Appalachians and similarly overlies Grenville-age metamorphic rocks (Astini *et al.*, 1995; Dalla Salda *et al.*, 1992, 1998; Kay *et al.*, 1996). The Grenville age of Western Sierras Pampeanas orthogneiss considered part of the Precordillera Terrane basement is established by Rb/Sr whole-rock isochrons of 1.03 ± 0.03 Ga, initial Sr = 0.70258 ± 0.00028 (Sierra de Umango; Varela *et al.*, 1996) and 1.021 ± 0.012 Ga, initial Sr = 0.7045 ± 0.0003 (Sierra de Pie de Palo; Pankhurst and Rapela, 1998).

Ordovician high-K quartz monzonite and monzogranite intruding the Grenville rocks of the Sierra de Pie de Palo (481 ± 6 Ma, SHRIMP U/Pb zircon, Pankhurst and Rapela, 1998) were tentatively associated with volcanism (Rapela *et al.*, 1998b) represented by K-bentonite interbedded with the Arenig–Llanvirn carbonate units of the Precordillera (Huff *et al.*, 1998). This magmatism was coeval with an extensional collapse of the Precordillera carbonate shelf, indicated by Arenigian mass-flow turbidite deposits and giant olistoliths, and culminating with eruption of Caradocian mid-ocean ridge basalt and ultramafic rocks (Fig. 3; Astini *et al.*, 1995). Ocloyic compressive tectonism at the Gondwana margin (Fig. 3; Bahlburg and Hervé, 1997) may have been related to the Ashgillian closure of the Famatina back-arc basin and not to the accretion of the Precordillera Terrane, as often supposed.

Docking of the Precordillera Terrane

Timing of the collision of the Precordillera Terrane with Gondwana is still unresolved. Despite many other differences, most recent geodynamic models have considered that this event occurred during the Middle Ordovician Famatinian Orogeny (Dalla Salda *et al.*, 1992; Astini *et al.*, 1995; Dalziel, 1997; Ramos *et al.*, 1998). *However, there is increasing evidence for later accretion,* during Silurian time (Fig. 3): (1) there is no evidence for Late Cambrian subduction on the Gondwana margin, which started *c.* 490 Ma, leaving little time to close the southern part of the Iapetus Ocean before the Middle Ordovician; (2) reactivation of the Grenville basement in the Sierra de Pie de Palo occurred between 432 and 394 Ma (Ar/Ar ages on hornblende and muscovite, Ramos *et al.*, 1998); (3) the first contraction of the Precordillera sedimentary sequences occurred in Late Silurian-Early Devonian times (Astini, 1996), which is consistent with K/Ar data obtained in the western sedimentary sequences of the Precordillera, suggesting a thermal overprint during the 425 - 400 Ma interval (Buggisch *et al.*, 1994); (4) the first unequivocal evidence for close proximity of the Precordillera to Gondwana is the Early Wenlockian (*c.* 425 Ma) *Clarkeia* fauna (Benedetto, 1998), and; (5) intrusion of high-K batholiths in the southern sector of the Eastern Sierras Pampeanas and the formation of transpressional shear zones continued well into Devonian times (Sims *et al.*, 1998).

A Silurian accretion of the Precordillera terrane overlaps with that of the postulated Chilenia terrane (Ramos and Basei, 1997), so that the small outcrops from which Chilenia has been identified might really be slivers of the Precordillera Terrane basement, displaced westwards during the collision, rather than a separate terrane (such an origin for the Frontal Cordillera basement outcrops was considered by Ramos and Basei, 1997). If the Precordillera Terrane was sutured to Gondwana in Late Ordovician to Silurian times, this cannot be the tectonic cause of the Early Ordovician Famatinian Orogeny. A more obvious tectonic setting for the generation of Famatinian magmas is the opening and closing history of the Famatina back-arc basin.

Conclusions

The crustal framework of the Southern Andes was formed during Early Paleozoic continental collisions. The first was the Early to Middle Cambrian (530 - 520 Ma) collision of the Pampean Terrane against the newly-formed passive margin of Gondwana. Subduction restarted at *c.* 490

Ma (Tremadocian?), forming a wide continental arc and an ensialic back-arc basin floored by oceanic crust. Accretion of the Precordillera Terrane to Gondwana was complex and protracted, starting with closure of the Famatinian back-arc basin during the Late Ordovician (450 - 440 Ma) and concluding with collision in Silurian times (440 - 420 Ma), followed by intrusion of large post-orogenic Devonian batholiths in the southern Sierras Pampeanas .

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Sedimentary Basins of South America

Edison José Milani and Antonio Thomaz Filho

Sedimentary domains of the South American Plate

Regarding the distribution of Phanerozoic sedimentary successions and particular plate-tectonic regimes, four major domains are recognized in the South American Plate: the continental interior, a region of a long and complex geological history constituting a vast realm where thick sequences of Paleozoic and Mesozoic sediments accumulated; the western, convergent margin of the plate, along which the continental lithosphere of South America confronts the oceanic floor of the Pacific Ocean, creating a large orogenic belt, the Andes, with several sedimentary basins associated; the eastern side, a more than 10 000 km-long divergent margin originated by the break-up of the Gondwana paleocontinent and the separation of the South American and African plates since the Mesozoic; and the northern and southern margins of the plate, marked by a regional transcurrent tectonic regime along major transform faults that define the active contact of the South American Plate with, respectively, the Caribbean and the Scotia plates (Fig. 1). This review attempts include the most representatives sedimentary provinces that occur along these large-scale tectono-sedimentary domains of the continent; being the text on the Brazilian intracontinental sags and failed rift basins, a condensed version of Milani and Zalán (1998).

The interior region of the plate is known as the South American Platform (Almeida *et al.*, 1977; Almeida and Hasui, 1984), and is composed mainly of metamorphic and igneous complexes of Archean age. This domain forms the core of the plate, and consolidated by Late Proterozoic-Early Paleozoic times after the collage of the Brasiliano-Panafrican Cycle. This first-order tectono-magmatic cycle corresponds to an ancient amalgamation of several distinct landmasses and closure of several seaways situated among them, originating in this way the nucleus of Gondwana. Crystalline rocks of Precambrian age are extensively exposed in three major shield areas known as Guiana, Central Brazil, and Atlantic. Some of the zones of crustal weakness of the Brasiliano-Panafrican framework were used afterwards as major lines of control over the evolution of the Paleozoic intracratonic basins (Tankard *et al.*, 1995) as well as over the rupture lines during the Mesozoic rifting and opening of the South Atlantic Ocean.

Phanerozoic cratonic sequences developed extensively from Late Ordovician time until the Cretaceous, and the five major syneclises (Fig. 2) were formed: Solimões, Amazonas, Parnaíba and Paraná in Brazil, and Chaco-Paraná in Argentina, Paraguay and Uruguay. These occupy the about 3.5 M km² of South America, as large remnants of a certainly much wider original area of sedimentation. The intracratonic sequences in the South American Platform configure a series of unconformity-bounded units (Sloss, 1963; Soares *et al.*, 1978) that resulted from successive phases of subsidence and accumulation of sedimentary rocks, the record of which was interrupted during several periods of widespread erosion.

Towards the SW, a persistently active convergent setting developed during almost all the Phanerozoic era along the margin of the Gondwana, defining a deformational belt known as the Gondwanides (Keidel, 1916; De Wit *et al.*, 1988). Along this mobile belt, sedimentation, tectonics, and magmatism kept through time a similar style to that observed today in the Andean Chain and related basins. Collisional episodes due to terrane accretion along the margin were remarkable (Ramos, 1988), and originated several orogenic cycles. In other words, the present-day tectonic regime and physiographic configuration of the western margin of the continent perpetuates the long-lived convergent character of that realm.

The eastern margin of the South American Plate is younger, having evolved from Mesozoic times onward. The development of the Atlantic Ocean since the break-up of the Gondwana left a large divergent margin basin encroached on the continent. The tectono-sedimentary evolution of the passive margin (Asmus and Ponte, 1973) included a rift stage, during which lacustrine sediments were deposited. In Aptian times, a large salt basin developed and marked the transitional stage that was characterized by restricted circulation followed by a cycle of open marine sedimentation under the rapid invasion by waters of the South Atlantic Ocean. Aborted Mesozoic interior rift basins indented the eastern margin in several places, and the Atlantic rifting resulted in a pervasive intrusion of dykes and sills and extrusion of huge volumes of basic lavas in the adjacent Paleozoic syneclises.

To the N, the margin of the South American Plate lies in contact with the Caribbean Plate along a large transform boundary, the Oca-San Sebastian-El Pilar Fault, since the early Cenozoic. Sedimentation and tectonics in that region were greatly influenced by right-lateral wrenching. Similar strike-slip conditions are found along the southern border of the South American Plate, where it make contact with the Scotia Plate along the North Scotia Ridge, a left-lateral transform zone.

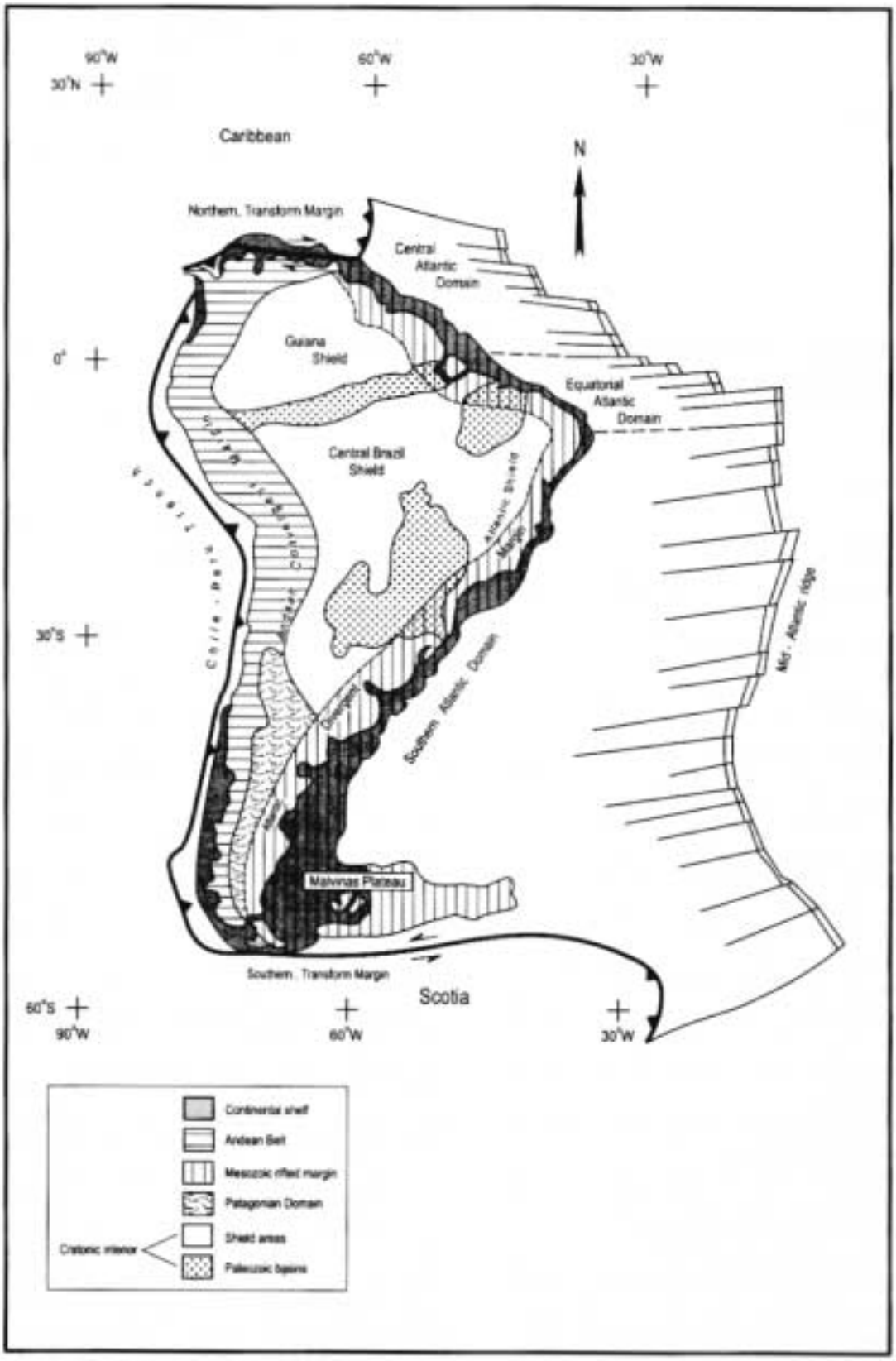
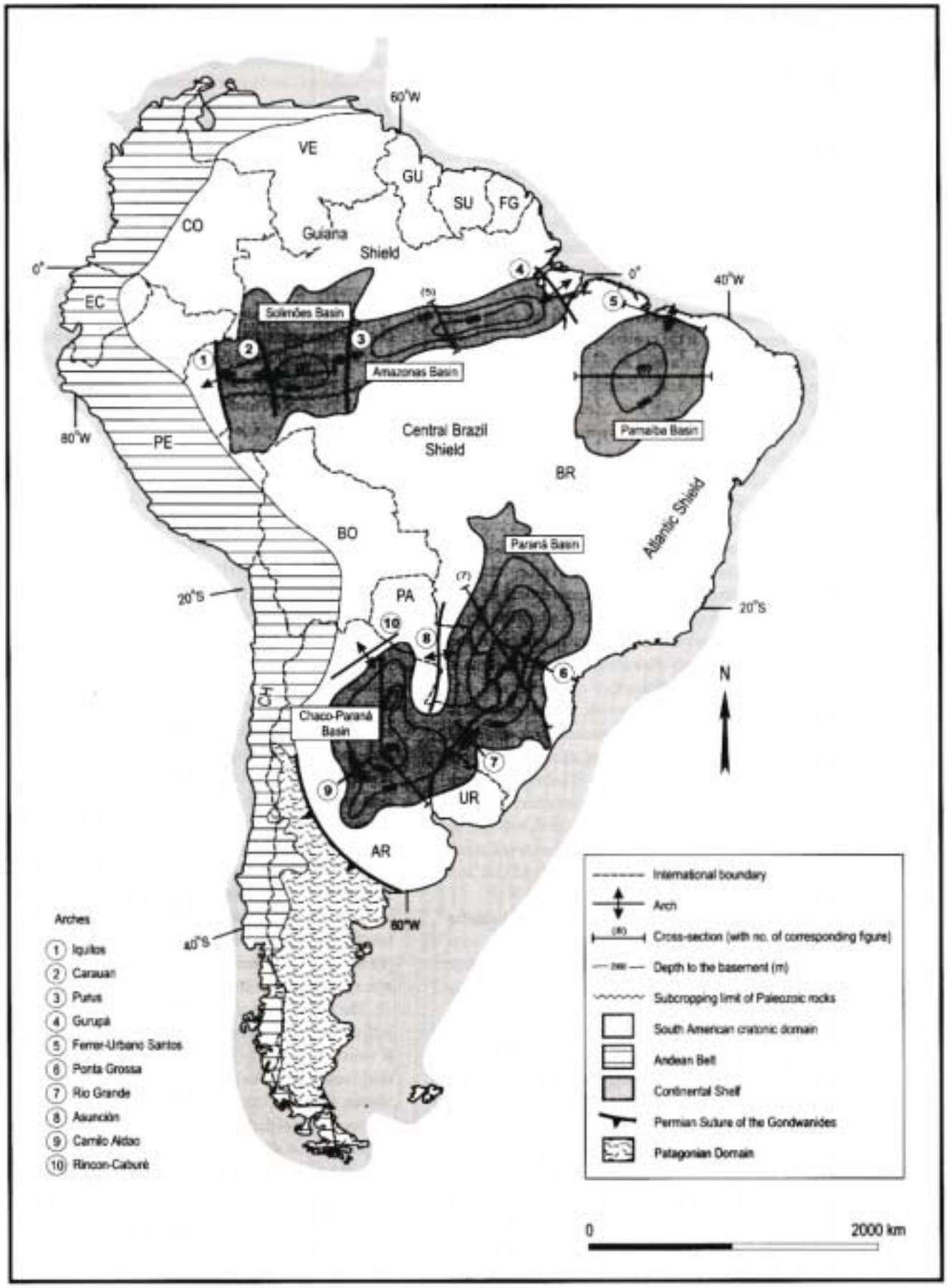


FIGURE 1 - The South American Plate and its major tectono-sedimentary domains.

FIGURE 2 - Situation map of the Paleozoic intracontinental sags of South America (compiled from various authors). The South American cratonic domain represents the core of the continent, and this large region achieved a final stable condition during the late Proterozoic to earliest Paleozoic Brasiliano Orogenic Cycle (Almeida and Hasui, 1984). Countries: FG-French Guiana, SU-Surinam, GU-Guiana, VE-Venezuela, CO-Colombia, EQ-Equator, PE-Peru, BO-Bolivia, CH-Chile, AR-Argentina, PA-Paraguay, UR-Uruguay, and BR-Brazil.


60°W
VE
GU
SU
FG
CO
Guiana
Shield
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EC
Solimões Basin
Amazonas Basin
Parnaíba Basin
40°W
80°W
PE
Central Brazil
Shield
BR
Atlantic Shield
BO
Paraná Basin
PA
20°S
Chaco-Paraná
Basin
UR
AR
40°S
60°W
N
Arches
1 Iquitos
2 Carauari
3 Purus
4 Gurupá
5 Ferrer-Urbano Santos
6 Ponta Grossa
7 Rio Grande
8 Asunción
9 Camilo Aldao
10 Rincon-Caburé
International boundary
Arch
Cross-section (with no. of corresponding figure)
Depth to the basement (m)
Subcropping limit of Paleozoic rocks
South American cratonic domain
Andean Belt
Continental Shelf
Permian Suture of the Gondwanides
Patagonian Domain
0
2000 km

Cratonic Interior

Paleozoic intracontinental sags

Paleozoic intracontinental sedimentary successions and related magmatic rocks in South America are preserved in five individual depocenters (Milani and Zalán, 1999), four of them in Brazil, and one in Argentina (Fig. 2). The Brazilian basins are the Solimões, Amazonas, Parnaíba and Paraná, the names of which are derived from the major rivers that flow along the main axis of each. The sedimentary successions of the Chaco-Paraná Basin of Argentina lie below the Cenozoic deposits in the sub-Andean flats that developed along most of the western part of the continent. The interior cratonic basins of South America have an elliptical to semi-circular shape with individual basins ranging in size from 500 000 km² to more than 1 000 000 km². In common, these basins have such features as a relatively simple structural and stratigraphic framework and the presence of enormous volumes of Mesozoic basaltic magma.

Intracratonic subsidence is still a matter of debate (Milani, 1999). To date no convincing mechanism has been proposed to explain the subsidence and to justify how these basins had their subsidence history marked by several episodes of reactivation, giving rise to a pile of sedimentary and volcanic strata that can reach a thickness of several thousands of metres. Rifts are known below some of these intracratonic basins, and some of them are certainly related to the origin of the Paleozoic syneclises. However, sometimes their much older ages, and sometimes their restricted distribution, are clear obstacles to the hypothesis of considering an extensional, fault-controlled mechanism of subsidence as the general, direct predecessor of the overlying sag. Additional cycles of subsidence in the intracratonic basins could have been achieved either by different events of lithosphere stretching (Gonzaga *et al.*, 1997), or, by lithosphere flexure due to cratonward influence of distant, plate-margin orogenies (Johnson, 1971; Milani and Ramos, 1998).

Whatever the driving mechanisms of the subsidence events, the depressions were filled essentially with siliciclastic rocks related to successive Paleozoic transgressive-regressive cycles, with the remarkable exception of an evaporite-carbonate cycle in the Pennsylvanian-Permian record of the Solimões, Amazonas and Parnaíba basins. In most of these basins, the first cycle of sediment accumulation took place during the Late Ordovician (Fig. 3), when the invasion of seas over Gondwana was widespread. Glacial influence over the sedimentary environment is recorded at various ages (Caputo and Crowell, 1985), between the latest Ordovician in the Paraná Basin and the Devonian in the Solimões and Amazonas basins. In the Paraná and Chaco-Paraná basins, the glacial influence returned, and was extreme in the Mississipian with the development of ice caps over the area. The progressive retreat of the glaciers during the Pennsylvanian allowed the development of the third transgressive-regressive cycle of sedimentation.

The last Paleozoic depositional cycle in all these five basins terminates with Late Permian to Early Triassic continental red beds, marking the drying out of the intracratonic basins, and the final disappearance of the seas from the interior areas of Western Gondwana. These arid conditions proceeded during the Mesozoic and eolian deserts dominated the Late Jurassic depositional scenery, associated with large volumes of magmatic material already related to the mechanisms that led to the break-up of Gondwana.

Solimões Basin

The Solimões Basin, comprising an area of over 600 000 km², is situated in northern Brazil and is entirely covered by the Amazonas forest. The occurrence of Paleozoic packages is restricted to two thirds of the total area of the basin, and these are not exposed, being onlapped and covered by sandy, Cretaceous to Recent continental sediments. Together the Solimões Basin and its eastern counterpart, the Amazonas Basin, constitute an E-W elongated, 2500 km-long, 500 km-wide and up to 5000 m-deep interior basin (Fig. 2).

The Solimões Basin is separated from the Acre Basin to the W and from the Amazonas Basin to the E by, respectively, the Iquitos and Purus arches (Fig. 2). The structural framework of the Solimões Basin shows a prominent NW-SE-striking positive feature, the Carauari Arch (Fig. 4), that define two sub-basins: Jandiatuba and Juruá. Mainly during pre-Pennsylvanian times, this positive feature had a decisive control on the distribution of sedimentary thickness and facies. The total sedimentary sequence in the deeper, Juruá Sub-Basin attains 3800 m.

The structural framework of the Solimões Basin is marked by the presence of the Solimões Megashear Zone (Caputo and Silva, 1990). This constitutes a classical example of an intraplate deformation belt, comprising a fault-and-fold system that strikes N70°-80°E, over a distance of about 1 000 km. The belt, caused by Jurassic to Cretaceous right-lateral wrenching, is defined by regularly spaced, right-stepping *en échelon* reverse faults trending N30°-40°E with associated hangingwall anticlines.

The stratigraphic framework of the Solimões Basin (Fig. 3) is defined by four Paleozoic supersequences covered by two units, one of Cretaceous and the other of Cenozoic age. During Late Triassic to Early Jurassic times, the Penatecaua Magmatism (Eiras *et al.*, 1994a) intruded the Paleozoic sedimentary units with a large volume of diabase sills and dykes.

The sedimentary record of the Solimões Basin starts with the Ordovician Supersequence (Eiras *et al*, 1994a), that is constituted by the continental to shallow marine siliciclastic rocks of the Benjamin Constant Formation. The Silurian-Devonian Supersequence follows and is constituted by a succession of dark grey marine shales named the Jutaí Formation, that grade eastwards into coastal sandstone units and micaceous siltstone of the Biá Member, marking the facies change due to the onlap of the sequence over the Carauari High.

The silexite and sandstone beds of the Uerê Formation, together with the black shale, rich in organic material, diamictite and sandstone of the Jandiatuba Formation, span the Emsian-Tournaisian range and constitute the Devonian-Carboniferous Supersequence. The section, up to 300 m thick, is considered of shallow marine origin, transgressive up to the Frasnian beds and remarkably regressive upwards.

From Carboniferous times onwards, the sediments

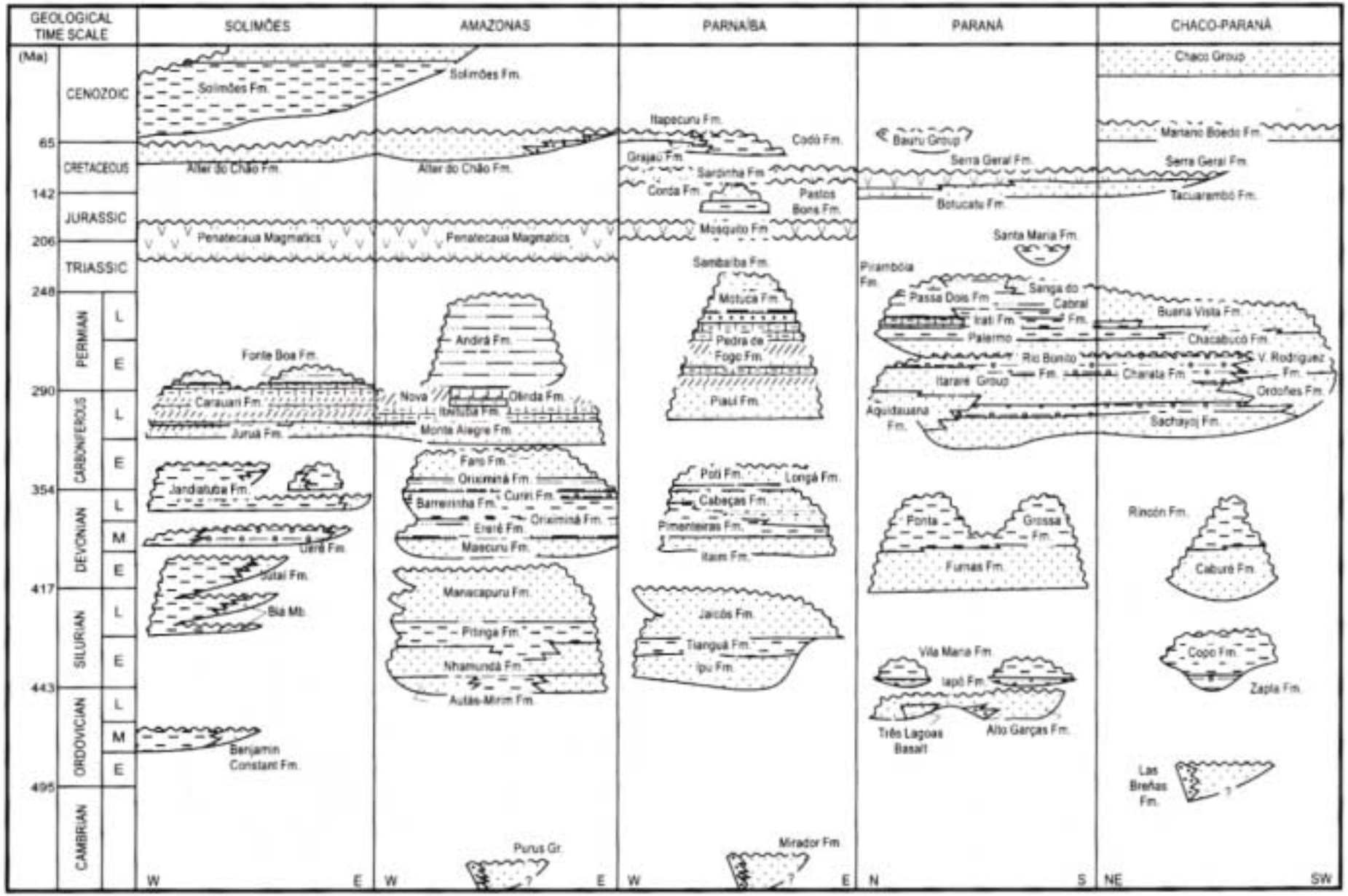


FIGURE 3 - Stratigraphic summary of the Paleozoic intracontinental sags of South America. Main sources of information were Eiras et al. *(1994a), Solimões Basin; Cunha* et al. *(1994), Amazonas Basin; Góes and Feijó (1994), Parnaíba Basin; Milani* et al. *(1994), Milani (1997), Paraná Basin; Russo* et al. *(1987), Jager (1997), Pezzi and Mozetic (1989), Chaco-Paraná Basin. Geological time scale simplified from Gradstein and Ogg (1996). Lithological representations are of common use.*

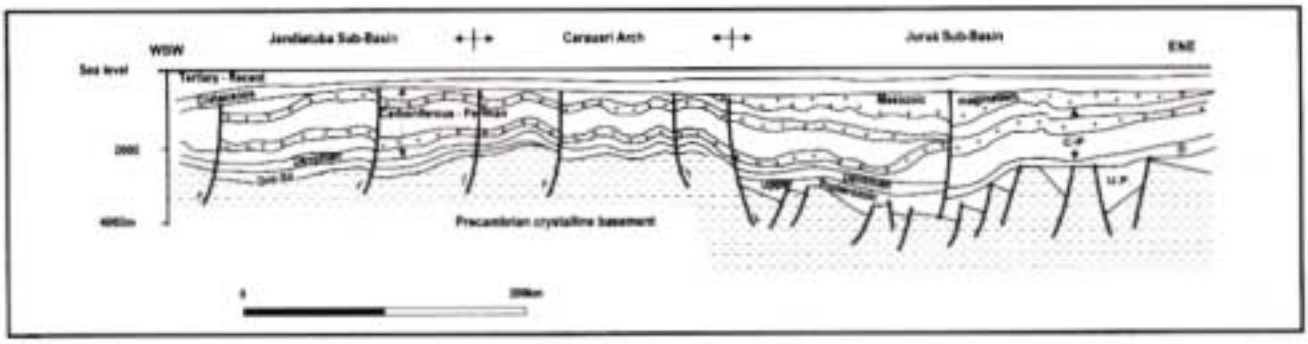


FIGURE 4 - Cross-section of the Solimões Basin (after Eiras, 1996; permission to reprint granted by the author).

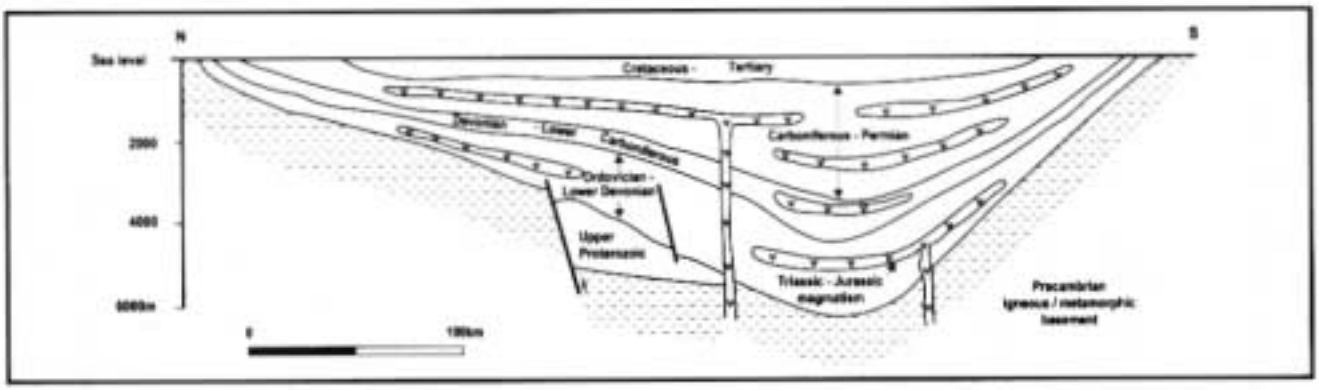


FIGURE 5 - Cross-section of the Amazonas Basin (after Gonzaga et al., 1997; permission to reprint granted by the authors).

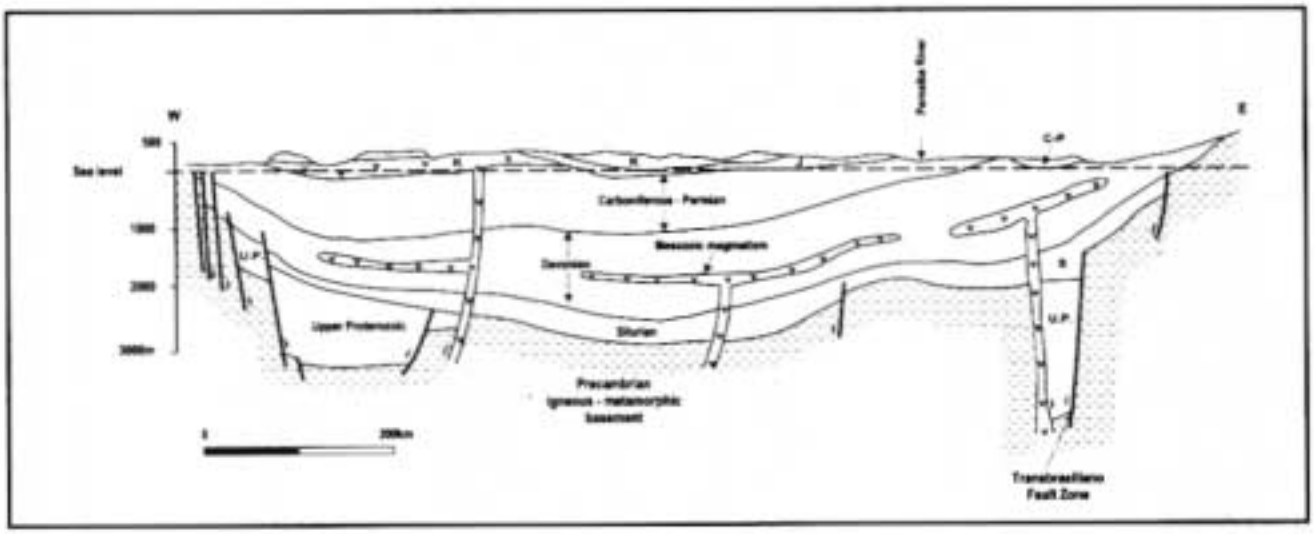


FIGURE 6 - Cross-section of the Parnaíba Basin (after Góes et al., 1990; permission to reprint granted by the authors).

covered the barrier once formed by the Purus Arch and so Amazonas and Solimões basins became united into a single depositional basin (Caputo and Silva, 1990). The accumulation of the initial units of the Carboniferous-Permian Supersequence occurred under conditions of severe aridity, with partial continentalization of the entire region, allowing deposition of a blanket of eolian sandstone beds known as the Juruá Formation. This formation grades upwards into an up to 1300 m thick package of rhythmic carbonate and evaporite units of the Carauari Formation. The sequence is terminated by a section of fluvial and lacustrine red beds named the Fonte Boa Formation.

A regional unconformity, with a mild angularity along the belt of deformation of the Solimões Megashear Zone, separates the Paleozoic record from the younger strata. The Javari Group (Eiras *et al.*, 1994a), including the Alter do Chão and Solimões formations, represents, respectively, the Cretaceous and Cenozoic Supersequences of the Solimões Basin, the former spreading into the Amazonas Basin, and the latter developing mostly towards the W and reaching the Acre Basin. The Alter do Chão Formation consists of coarse-grained ferruginous sandstone beds that accumulated in an alluvial-fluvial system. The Solimões Formation is an argillaceous unit, including beds of coquina and lignite, holding abundant fauna and flora of Miocene/Pliocene age.

Amazonas Basin

This basin covers about 500 000 km² of northern Brazil, lying completely under the Amazonas forest. The major axis trends E-W (Fig. 2), and its sedimentary strata onlap the Precambrian provinces of the Guiana Shield to the N and of the Central Brazil Shield to the S, cropping out along both these sides of the basin. To the E, a Mesozoic rift shoulder, the Gurupá Arch, isolates the Amazonas Basin from a Mesozoic failed rift, the Marajó Basin. To the W, the Amazonas Basin is separated from the Solimões Basin by the roughly N-S-trending Purus Arch. The depocenter of the basin holds a stratigraphic record up to 5000 m thick (Fig. 5).

The basement of the Amazonas Basin consists mainly of igneous and metamorphic complexes, but some Proterozoic rift successions of alluvial, fluvial and lacustrine sedimentary rocks occur in its western region, comprising the Purus Group. The existence of strong positive gravity anomalies coincident with the axis of the syneclise, suggesting shallow ultrabasic bodies (Linsser, 1974), together with the underlying aulacogenic strata, led to the interpretation of crustal stretching as the driving mechanism for the initial subsidence of the Amazonas Basin. More recent work (Gonzaga *et al.*, 1997) interpreted four extensional events during the evolution of the Amazonas Basin, spanning the ranges Ordovician-Early Devonian, Devonian-Early Carboniferous, Middle Carboniferous-Permian and Cretaceous-Cenozoic. Each of these events was manifest by relatively high sedimentary accumulation rates during the interpreted extensional phases, succeeded by periods of low sedimentary accumulation rates driven by thermal subsidence.

The stratigraphic framework of the Amazonas Basin (Fig. 3) includes three Paleozoic supersequences covered by Cretaceous to Recent continental clastic sediments (Cunha *et al.*, 1994). The Ordovician-Devonian Supersequence or Trombetas Group, is composed of marine sandstone included in the Autás-Mirim, Nhamundá and Manacapuru formations, and shale and diamictite beds of the Pitinga Formation. These sediments in part accumulated under the influence of the Late Ordovician-Early Silurian glaciation, that affected large parts of Gondwana.

A second transgressive-regressive cycle is recorded in the Amazonas Basin by the sedimentary rocks of the Urupadi and Curuá groups that together comprise the Devonian-Carboniferous Supersequence. This large stratigraphic unit includes the Maecuru and Ererê fomations (Early Devonian), consisting of coastal sandstone and shallow marine shale units at the base, followed by an up to 250 m thick sequence of laminated black shale beds named the Barreirinha Formation, of Frasnian age. The Barreirinha Formation is considered to indicate the maximum paleobathymetric conditions during the history of the basin. A controversial Famennian glacial cycle (Daemon and Contreiras, 1971) is interpreted from the record of the Curiri Formation consisting of diamictite with associated shale and siltstone units. The upper part of this sequence, Oriximiná and Faro formations, record the regressive part of the cycle. Regional erosive processes affected the basin during the final stages of the Mississipian.

A renewed cycle of subsidence and sediment accommodation took place from the Pennsylvanian onwards. The lowermost beds of the Carboniferous-Permian Supersequence, or Tapajós Group, is a blanket of eolian sandstone included in the Monte Alegre Formation, that is covered by a sequence of carbonate and evaporite units with subordinated sandstone and shale beds that define the Itaituba and Nova Olinda formations. These stratigraphic units attain a maximum thickness of 1600 m. The cycle closed by the continental red beds of the Andirá Formation, of Late Permian age. E-W regional extension allowed a pervasive intrusion of magmatic bodies during Late Triassic and Early Jurassic times; the Penatecaua Magmatism (Mizusaki *et al.*, 1992).

Parnaíba Basin

The Parnaíba Basin is located in the western portion of the northeastern region of Brazil, occupying an area as large as 600 000 km². The Parnaíba Basin is a circular sag with a total sedimentary section of about 3500 m of thickness in its depocenter, and is framed by an almost continuous belt of outcrops (Fig. 2). The Ferrer-Urbano Santos Arch, a positive flexural feature related to the Mesozoic opening of the Equatorial Atlantic Ocean, defines the northern limit for the Parnaíba Basin, where the Atlantic rifting broke the previous connection of this huge syneclise with analogous basins that lie today in northwestern Africa.

Geophysical data, together with subsurface information, revealed the existence of a basal sequence of arkose confined inside Late Proterozoic/Early Cambrian N-S-trending grabens lodged by the crystalline basement. This sandy section of poorly constrained age, known as Mirador Formation, was interpreted as being the rift sequence that initiated the Parnaíba Basin (Góes *et al.*, 1990). A flexural

sag developed afterwards (Fig. 6), but an influence of the initial rift architecture on the location of cratonic sedimentation depocenters was felt up to the Early Carboniferous.

A remarkable feature in the structural framework of the Parnaíba Basin is the Transbrasiliano Fault Zone, that cuts its eastern/southern portion and produced important structures in that domain. This fault zone, a deep-seated structural element in central Brazil, runs across the continent for 3000 km, from N to S in a NE-SW trend, starting in the Equatorial Atlantic and reaching Paraguay, crossing also the northernmost portion of the interior Paraná Basin. Within the Parnaíba Basin the fault zone is expressed as a wide band of surface and subsurface deformation that controlled the positioning of old aulacogens and Paleozoic depocenters. Outside the limits of the Transbrasiliano Fault Zone, the structural style in the Parnaíba Basin is almost featureless, being mostly represented by subtle fault-block tectonics. Intrusion of magmatic bodies during the Mesozoic was widespread and was also responsible for typical related deformation of the host sedimentary rocks.

The stratigraphic framework of the Parnaíba Basin (Fig. 3) encompasses three major Paleozoic and two Mesozoic supersequences (Góes and Feijó, 1994). The rocks of the Serra Grande Group, mainly of Silurian age, represent the older strata, accommodated by the initial subsidence of the syneclise. These rocks include sandstone with subordinate siltstone, shale and diamictite beds named the Ipu Formation; grey shale, siltstone and micaceous coastal sandstone of Wenlock age known as the Tianguá Formation; and coarse-grained sandstone typical of braided stream deposits known as the Jaicós Formation. The entire sequence represents a complete transgressive-regressive cycle of sedimentation.

The Devonian Supersequence or Canindé Group, of Eifelian-Tournaisian age, has tide and storm-related sediments in the Itaim Formation; black shale, rich in organic mater, up to 300 m thick known as the Pimenteiras Formation; fine-grained shallow marine sandstone, locally with diamictite beds, named the Cabeças Formation; fluvial sandstone and shale in the Longá Formation; and an Early Carboniferous heterolythic sequence of fine-grained sandstone and shale units known as the Poti Formation.

The beginning of the Pennsylvanian sedimentation in the Parnaíba Basin was marked by significant modifications in both environmental and tectonic characteristics (Góes and Feijó, 1994). Depocenters changed from an elongated graben-controlled geometry to a circular configuration, and the condition of a temperate, open marine basin turned into a restricted sea under progressive aridity (Caputo, 1984). The Balsas Group, or Carboniferous-Triassic Supersequence, consists of a clastic-evaporitic succession of sedimentary rocks with fine- to medium-grained sandstone, brown shale and subordinated limestone units, the Piauí Formation; rhythmite with alternating oolitic limestone units, white anhydrite and yellow sandstone beds in the Pedra de Fogo Formation; brown siltstone, medium-grained sandstone, locally with anhydrite beds named Motuca Formation; and eolian sandstone in the Sambaíba Formation.

Two main pulses of magmatic activity took place in the Parnaíba Basin during the Mesozoic. Both intrusive emplacements and volcanic flows occurred, the former being preferentially found inside the rocks of the Canindé Group. The first magmatic cycle, from the Triassic-Jurassic and correlated to the Penatecaua Magmatism of the Solimões and Amazonas basins, is known as the Mosquito Formation, and is related to the rifting of the Central Atlantic. The second pulse, aged Early Cretaceous and related to the rifting of the South Atlantic, constitutes the Sardinha Formation.

Between the two magmatic pulses, a phase of continental sedimentation developed, constituting the Mearim Group of Jurassic age. This package, of restricted area of occurrence, includes green to red argillite and siltstone in the Pastos Bons Formation and sandstone in the Corda Formation, being the section related to an eolian environment. Also related to the development of the Equatorial Atlantic are the Codó, Grajaú and Itapicuru formations, that constitute the Cretaceous Supersequence of the Parnaíba Basin. The Aptian Codó Formation is made of black shale rich in organic material, accumulated during a brief incursion of Mesozoic oceanic waters over the northern part of South America.

Paraná Basin

The Paraná Basin is located in southern Brazil, where it covers an area exceeding 1 000 000 km^2, extending into the neighbouring countries of Paraguay, Argentina and Uruguay, and there it occupies another 400 000 km^2. The basin has a NNE-SSW-trending elliptical shape with two thirds of its surface covered by basaltic lava of Mesozoic age (Fig. 2). The infilling sedimentary strata appear along a 5500 km-long belt of outcrops shaped during Mesozoic-Cenozoic times, encircling almost completely, the syneclise. The stratigraphic record of this huge basin, including sedimentary and magmatic rocks, surpasses the thickness of 7000 m in the central part of the basin, just in the region where runs the river that lends its name to the basin (Fig. 7).

The eastern flank of the Paraná Basin corresponds to a crustal region that was deeply affected by the South Atlantic rifting and the opening of the ocean. Uplift and erosion since the Early Cretaceous has been responsible for the removal of large amounts of Paleozoic sedimentary rocks from that area. The Asunción Arch defines the western border of the basin, a flexural bulge related to the loading of the Cenozoic Andean thrust sheets along the western margin of the plate. To the N and to the S, the strata of the Paraná Basin onlap crystalline rocks of Precambrian cratonic provinces of the basement.

The inception and further evolution of the Paraná Basin in the continental interior of Gondwana, since the Late Ordovician, had a close relationship to the development of the Gondwanides, an extensive Phanerozoic mobile belt marked by a succession of orogenic cycles (Ramos *et al.*, 1986). Such orogenic stresses exerted a decisive influence on the creation of accommodation space for the various supersequences that fill the Paraná Basin (Milani, 1997), as well as on the deformational history of the basin (Zalán *et al.*, 1990) by means of intraplate reactivation of NE-SW trending preexisting zones of crustal weakness, inherited from the Brasiliano Orogeny or cratonward propagation of regional flexural subsidence.

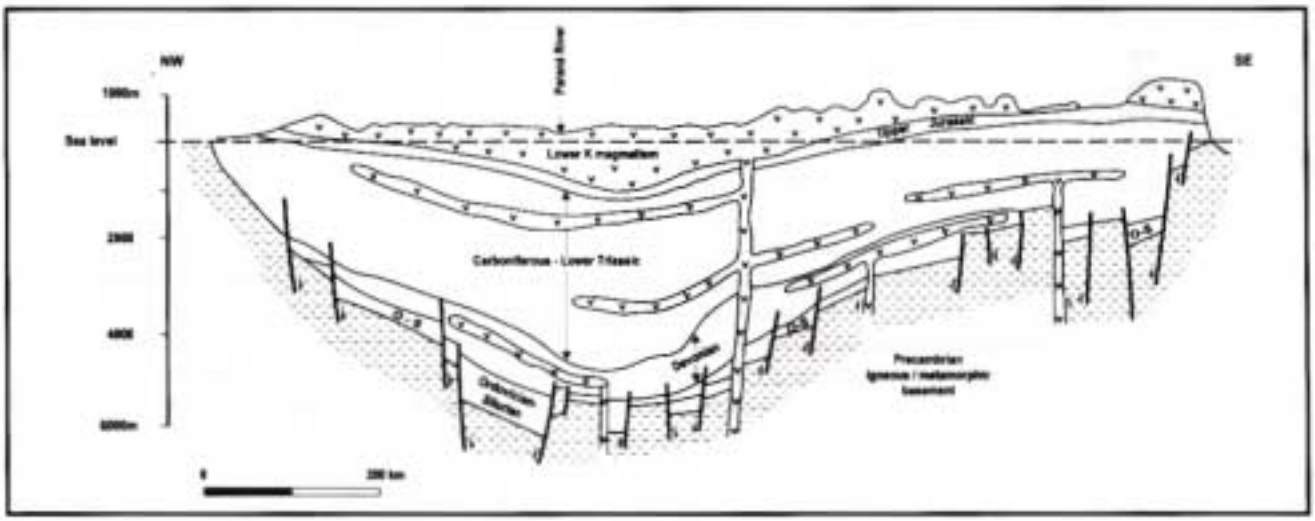


FIGURE 7 - Cross-section of the Paraná Basin (after Milani and Zalán, 1998).

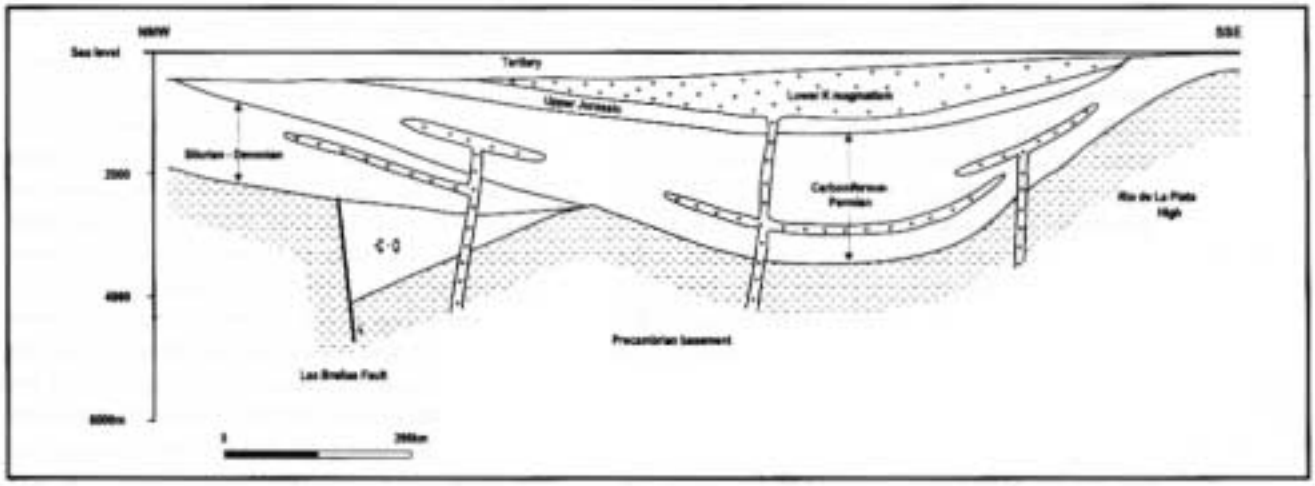


FIGURE 8 - Conceptual cross-section of the Chaco-Paraná Basin (based on information from Pezzi and Mozetic, 1989; Russo et al., 1987).

The stratigraphic record of the Paraná Basin (Fig. 3) includes six supersequences (Milani *et al.*, 1994; Milani, 1997): Rio Ivaí (Caradocian-Llandoverian), Paraná (Lochkovian-Frasnian), Gondwana I (Westphalian-Scythian), Gondwana II (Anisian-Norian), Gondwana III (Late Jurassic-Berriasian) and Bauru (Aptian-Maastrichtian). Three of these second order allostratigraphic units correspond to Paleozoic transgressive-regressive cycles, and the others are Mesozoic continental sedimentary sequences with associated igneous rocks.

The Rio Ivaí Supersequence begins with a basal sandy unit known as Alto Garças Formation, up to 300 m thick, followed by some tens of metres of diamictite beds defining the Iapó Formation that record the Late Ordovician-Early Silurian glaciation of Gondwana. The uppermost unit of the supersequence, the Vila Maria Formation, consists of micaceous shale and fine-grained sandstone containing Llandovery-age macro and microfossils. Some of the best reference sections for the Ordovician-Silurian sequence of the Paraná Basin can be found in its Paraguayan sector, where this interval is known as Caacupé and Itacurubi groups.

The Devonian sedimentary beds of the Paraná Basin, also described as the Paraná Supersequence, spans the range Pragian-Frasnian and are composed of a basal blanket of coarse-grained, kaolinite-rich sandstone beds, the Furnas Formation, covered by a shaly section with subordinate siltstone and deltaic sandstone units that constitute the Ponta Grossa Formation. The Devonian shale beds, particularly its lowermost section of Emsian-Eifelian age, hold the endemic Malvinokaffric fauna of invertebrates (Melo, 1988). Bioturbation is a dominant characteristic in these shales, but some intervals of black laminated rocks also occur, recording maximum paleobathymetric conditions of the Devonian sea. In Uruguay, the Devonian section is named Durazno Group.

The Gondwana I Supersequence is the most voluminous packet of sedimentary rocks in the Paraná Basin among all its second-order allostratigraphic units, with a thickness that reaches a maximum of about 2500 m. This is a sedimentologically heterogeneous and complex section that records the contrasting paleoenvironmental changes through time that occurred in Gondwana from the glacial period in the Pennsylvanian to the dry and arid times during the Triassic.

The lowermost section of the Gondwana I Supersequence is represented by a sequence of glaciogenic deposits included in the Itararé Group and Aquidauana Formation in Brazil, the Coronel Oviedo Formation in Paraguay, and the San Gregório Formation in Uruguay. These rocks are composed of diamictite, turbiditic sandstone units, conglomerate, subordinate varvite and tillite beds (França and Potter, 1988). The maximum thickness is about 1500 m. This section represents the thickest and stratigraphically most complete record of the Late Carboniferous-Early Permian glaciation-related sedimentary rocks known in Gondwana, spanning the Westphalian to Artinskian range.

The glaciogenic deposits were followed by a transgressive section known as Guatá Group, that includes deltaic sandstone and coal beds of Artinskian-Kungurian age, the Rio Bonito Formation; and siltstone and shale in the Palermo Formation, the latter representing the maximum flooding stage for the entire Gondwana I Supersequence (Milani, 1997). In the Kazanian, a section of bituminous shale and limestone beds with subordinated evaporite units named the Irati Formation was deposited. The Irati black shale exhibits an organic carbon content as high as 23%, a value that is among the highest of known sedimentary rocks the world over. The shales also carry the characteristic reptilian *Mesosaurus* fauna, that early in this century permitted the correlation of the Gondwana strata of southern Brazil with those in southern Africa (Du Toit, 1927), thus supporting the nascent theory of continental drift.

The Gondwana I Supersequence is terminated by the deposits included in the upper portion of the Passa Dois Group, represented by the sequence of red beds of the Rio do Rasto Formation, accumulated through the dawn of the Mesozoic. Continental facies up to several hundreds of metres thick encroached the remnants of the Rio do Rasto Basin from the northern and southern borders, constituting stratigraphic units named, respectively, Pirambóia and Sanga do Cabral formations. In Uruguay and northeastern Argentina, these continental successions are even thicker and are named Buena Vista Formation.

Lacustrine red beds of local occurrence and associated fluvial and eolian deposits constitute the Gondwana II Supersequence of the Paraná Basin. This section holds a remarkable Middle to Late Triassic tetrapod fauna (Barberena *et al.*, 1985). Huge seas of eolian dunes, the Botucatu Formation, of widespread regional distribution, dominated the Late Jurassic to Early Cretaceous scenario of the Paraná Basin, being followed by the Early Cretaceous magmatic rocks of the Serra Geral Formation. The Serra Geral Magmatism is predominantly basaltic in nature. However, rocks of intermediate and acid composition have been observed. Taken together, the Botucatu and Serra Geral formations comprise the Gondwana III Supersequence, also known as São Bento Group. The Serra Geral Magmatism peaked between 137±0.7 Ma and 126.8±2.0 Ma (Turner *et al.*, 1994), and the remnant pile of lava observed at the surface at may reach a thickness of 2000 m.

The Upper Cretaceous Bauru Supersequence is an up to 280 m thick package of alluvial, fluvial and eolian sedimentary rocks that ended the depositional history of the Paraná Basin. It occupied the flexural sag originated by the load of the volcanic pile; the depocenter of the Bauru Supersequence being coincident with the region of maximum thickness of lava. It includes conglomerate deposits with clasts of various rock-types, including sandstone, siltstone, argillite and calcrete. It contains a Senonian fauna including *Chelonia*, *Crocodilia* and *Dinosauria* (Huene, 1939, *apud* Fernandes and Coimbra, 1996).

Chaco-Paraná Basin

The Chaco-Paraná Basin is situated in northeastern Argentina, being an elliptical-shaped basin with the main axis oriented ENE-WSW, and encompassing an area of about 500 000 km² (Fig. 2). Its surface expression appears as an almost featureless flat plain covered by Quaternary to Recent fluvial deposits. In its northeastern part is remarkable the presence of Lower Cretaceous basalt flows, a lithological unit that is fully developed in its Brazilian counterpart, the Paraná Basin. To the W, the Chaco-Paraná Basin is limited by the Pampean Ranges, a system of thrusted Precambrian basement rocks uplifted in the Neogene by the Andean Orogeny. To the N the basin is separated from the Tarija Basin of southeastern Bolívia and Paraguay by the Rincón-Caburé Arch.

Subsidence and sediment accumulation in the Chaco-Paraná Basin began during Ordovician(?)-Silurian times. It seems that a deep SW-NE striking depocenter named the Las Breñas Low represented the initial site of sedimentary deposition in the region. This depocenter occurs in the central portion of the basin (Pezzi and Mozetic, 1989), and appears as an asymmetric graben with structural dip of the basement to the NW, against its master bordering normal fault (Fig. 8). The nature and age of the rocks contained within the graben are unknown. However, seismic information indicate that these are probably both sedimentary and igneous, and may be up to 5000 m thick. In spite of being the nature and thickness of the rocks inside the Las Breñas depocenter still speculative topics, a reasonable hypotesis based on seismo-stratigraphic analysis is that of a basal sequence of immature siliciclastic sediments, covered by a mixed quartzose-carbonate marine beds and culminating in deeper marine shale units (Pezzi and Mozetic, 1989). The complete sequence is probably confined to the Early Paleozoic.

Milani (1997) and Milani and Ramos (1998) suggested that there may be a relationship between the Las Breñas Low and analogous features in the Brazilian Paraná Basin, situated to the NE, where the Lower Paleozoic depocenters are related to the beggining of the sedimentation and which retain the record of the first transgressive-regressive cycle, the Ordovician-Silurian Supersequence.

The Silurian-Devonian Supersequence of the Chaco-Paraná Basin (Fig. 3) surpassed the depositional area of the previous unit, and locally includes remnants of the Late Ordovician-Early Silurian glaciation in the Zapla Formation. The Zapla Formation is followed by a sequence of micaceous, dark grey shale units of Silurian age known as the Copo Formation. There then follows the classic Devonian succession found in the basins of southwestern Gondwana consisting of a basal section of continental to shallow marine sandstone beds known as Caburé Formation that grade into the marine black shale section of the Rincón Formation. The total thickness of the Devonian sequence exceeds 1200 m.

The Permian-Carboniferous Supersequence is up to

2300 m thick in the Chaco-Paraná Basin (Russo *et al.*, 1987), and occur in two distinct sub-basins. In the western, Alhuampa Sub-Basin the lowermost unit, the Stephanian-Asselian Sachayoj Formation, consists of medium-grained sandstone units interbedded with black shale, followed by diamictite. This sequence is up to 550 m thick and is known as the Charata Formation, the characteristics of which indicate a cold and humid, glacial to periglacial environment. A similar sedimentary succession appears in the eastern sub-basin, but there the lower stratigraphic unit, known as the Ordoñez Formation, consists of about 1500 m of white sandstone beds, and grey to black shale with associated diamictite beds. The upper unit consists of some 650 m sandstone, siltstone and shale, and is known as Victoriano Rodríguez Formation.

There followed the transitional Chacabuco Formation, composed of siltstone and shale, locally bituminous, and lenticular beds of limestone. These deposits grade upwards into a thick sequence of continental sandstone beds, known as the Buena Vista Formation. These sandstone units invaded the remnants of the Permian seas and closed the Paleozoic history of sedimentation in the Chaco-Paraná Basin. Such continental sedimentation persisted up to the Early Triassic.

During the Jurassic, the Chaco-Paraná Basin was the site of a broad crustal upwarp, reflecting the initial tectono-thermal events related to South Atlantic rifting. Fluvial and eolian sediments up to 400 m thick accumulated throughout the region and constitute the Tacuarembó Formation. There then followed the intrusion and extrusion of the Early Cretaceous diabase and basalt of the Serra Geral Formation. In the Paleocene, large parts of the Chaco-Paraná Basin were invaded by waters of the South Atlantic Ocean, resulting in the accumulation of some 350 m of grey calciferous mudstone and sandstone beds, with subordinated beds of gypsum, a sequence known as the Mariano Boedo Formation. From Miocene times onwards, a continental sequence of sands encroached on the Chaco-Paraná Basin from the W, constituting a wedge of poorly consolidated post-orogenic sediments derived from the Andean Belt, known as Chaco Group. These sediments exceed 2000 m in thickness.

Atlantic, Divergent Margin

Continental margin basins

The divergent margin of South America (Fig. 1), can be followed over a distance of about 10 500 km from the Orinoco Delta in easternmost Venezuela, to Tierra del Fuego, at the southern tip of Argentina. It is a large geological province that originated by the mechanisms that caused the break-up of Western Gondwana and the resulting drift of the African and South American plates since the Mesozoic, forming in this way, the South Atlantic Ocean and related marginal sedimentary basins.

Considering the nature and orientation of the regional stress fields during rifting and the following dynamics of the divergent motion between African and South American plates during drifting, three diverse domains are recognized along this margin. These are the dominantly extensional domains from southernmost Argentina up to the northeastern corner of Brazil. Secondly, a transform segment corresponding to the margin along the Equatorial Atlantic; and thirdly the region to the N of the mouth of the Amazonas River.

In the southern extensional domain, the structural pattern of the rift phase was marked by dominantly dip-slip normal faults. This style can be observed in each individual basin along the margin (Ojeda, 1982; Chang *et al.*, 1992; Urien and Zambrano, 1996). Transfer faults occur at high angles to the regional strike of normal faults. The set of normal faults evolved and defined the regional trend of the newly growing passive margin, and the former transfer faults nucleated large transform zones in the oceanic floor, the projection of which against the continental border intercepts it in almost at right angles.

The tectonic style in the Equatorial Atlantic Domain was different (Zalán, 1985; Szatmari *et al.*, 1987; Mascle *et al.*, 1988; Matos, 2000). Right lateral wrenching was the mechanism responsible for crustal rupture, creating a pattern of high-angle oblique faults that controlled rifting and resulted in the development of large-scale parallel-to-shore fracture zones (Gorini, 1977). These fracture zones include those of Fernando de Noronha, Chain, Romanche, and Saint Paul.

A third region of the divergent margin of South America, lies to the N of the mouth of the Amazonas River (Fig. 1). This constitutes part of another extensional domain, the Central Atlantic Ocean. This is the older segment of the extensional margin of the plate, in which an early phase of rifting occurred in the Triassic.

Individual sectors or "basins" along the continuous divergent margin of South America share some fundamental characteristics, including the classic rift, transitional and open marine tectonic and sedimentological patterns (Asmus and Ponte, 1973; Asmus, 1984). However, there are differences, too, and in some cases these are significant differences, justifying their consideration as individual geological provinces.

Rifting, and the subsequent opening of the Atlantic Ocean, was a remarkably diachronous event along the divergent margin of South America. This was of Late Triassic age in the northernmost sector of the Brazilian Margin (Brandão and Feijó, 1994a); Early Jurassic in southern Argentina (Baldi and Nevistic, 1996); Neocomian along the eastern Brazilian margin (Chang *et al.*, 1992), and Aptian along the Equatorial Atlantic (Matos and Waick, 1998), a range of time that spans about 90 Ma. The existing evidence suggests that there occurred an early opening along the Guiana and in the Caciporé-Foz do Amazonas basins, related to Central Atlantic rifting. In the Jurassic, crustal fracturing started to define the southern margin of Argentina, and this event propagated northwards to northeastern Brazil during the Neocomian. By the Aptian, the final delimitation of the South American and African plates was close to an end with the breaking along the Equatorial Atlantic. The Pernambuco-Paraíba Basin is recognized as the last sector of the divergent margin of South America to undergo rifting (Matos, 1998), as late as Late Aptian times (Feijó, 1994b).

Central Atlantic Domain

Rifting in the Central Atlantic region occurred during Late Triassic to Early Jurassic times, and led to the separation of the North American and African plates. The tectonic mechanisms that created a divergent plate margin in the region were influenced to large extent by the fabric of the basement, which was printed during Late Paleozoic orogenies (Manspeizer, 1988). The Variscan-Alleghenian orogenic belt formed by the coalescence of the Gondwana and Laurasian cratons (Rast, 1988). Along both margins of the Central Atlantic Ocean the presence of remnants of the Variscan-Alleghenian deformation belts is remarkable, including the Mauritanides Orogen in Western Africa and its American counterpart, the Appalachian Belt; to the S, those ancient belts can be projected towards the northernmost region of South America.

The Newark Supergroup fills one of the several Triassic to Early Jurassic rift basins related to the Atlantic margin of the North American and African plates (Manspeizer, 1988). This might be used as representative for correlation with the equivalent units in some of the northernmost Mesozoic basins of South America (Fig. 9). The Newark Supergroup is a sequence some up to 9000 m thick of lacustrine conglomerate, arkosic and lithic sandstone units, siltstone and red-brown mudstone. Syn-rift sedimentation in the Newark Basin began during Anisian to Carnian times and extended up to the Liassic.

The first incursion of the sea in the Central Atlantic Basin occurred in the Late Triassic, probably during the Carnian (Manspeizer, 1988), when Tethyan waters invaded westward through the Gibraltar Fracture Zone or southwards from eastern Greenland. By the Early Jurassic, close to the time of the post-rift unconformity, the evolving margins of the Central Atlantic were submitted to tectonic reactivation. Basins were uplifted and eroded, the sea retreated, and tholeiitic volcanism associated with lacustine strata followed (200 Ma to 175 Ma; Sutter, 1985, *apud* Manspeizer, 1988). This distinctive evolutive phase signaled the end of syn-rift times and the onset of sea-floor spreading in the Central Atlantic Ocean.

Guiana Basin

The Guiana Marginal Basin is situated in the northernmost part of the Atlantic margin of South America, encompassing the territorial waters of easternmost Venezuela, the Guiana, Surinam and French Guiana, with a total area of more than 400 000 km^2 (Fig. 9). The basin contains an estimated 10 000 m of Mesozoic to Cenozoic sediments (Krook, 1975), assigned to the Corantijn Group (Fig. 10) in the Surinam coastal region. The initial stages of crustal rifting in that area were marked by the intrusion of the Apatoe Dolerites, of Late Triassic age (227±10 Ma).

The sediments of the Corantijn Group were deposited during a succession of transgressive-regressive sedimentary cycles, starting with the sandy Nickerie Formation of Late Cretaceous age, followed by the Calcutta Formation (Paleocene to early Miocene) and the Tambaredjo Formation (late Miocene to Pleistocene) (Noorthoorn van de Kruijff, 1970, *apud* Krook, 1975). A significant stratigraphic hiatus occurs between the Upper Cretaceous and the Paleocene, in the upper Eocene-lower Miocene interval, and in the mid-lower Miocene. Holocene clays constitute the Demerara Formation, mostly supplied by the Amazonas River and the Caribbean oceanic current.

To the NE of the continental shelf of Surinam, a particular feature exists (Fig. 9); in that area, the size of the shelf is much larger than its mean size, defining the Demerara or Guiana Marginal Plateau (Colette *et al.*, 1971, *apud* Krook, 1975). The Demerara Plateau is an almost undisturbed depositional feature with an asymmetric profile, being steep-sided to the N and NE and gentle to the W. The oldest rock already sampled from the Demerara Plateau is a sandstone of Late Jurassic age.

Caciporé-Foz do Amazonas Basin

The Caciporé-Foz do Amazonas Basin covers about 270 000 km^2 of the northernmost continental margin of Brazil, adjacent to the mouth of the Amazonas River and along the coast of the State of Amapá (Fig. 9). The offshore basin is delimited by a NNW-SSE-trending dyke swarm of Triassic age that cuts through the outcropping area of the Guiana Shield and dates the initial rifting in that region, thus related to the opening of the Central Atlantic.

The first rift phase in the Caciporé-Foz do Amazonas Basin (Fig. 10) is represented by the Calçoene Formation, a sequence of tholeiitic volcanic rocks with radiometric ages ranging from 186 to 222 Ma (Brandão and Feijó, 1994a). The volcanic rocks are intercalated with sandy red beds of alluvial, fluvial and lacustrine sediments. This rift sequence, that has an estimated thickness exceeding 1000 m, was tilted inside the half grabens where it is confined, displaying an angular unconformity with the overlying sediments. With respect to rifting in the Central Atlantic region, this sequence occupies a similar tectonic setting and chronostratigraphic position of that of the Newark Supergroup, previously described.

A second and even more important phase of rifting in the area occurred during the Valanginian-Middle Albian interval, when the Caciporé Formation, consisting of up to 7000 m of syn-tectonic grey shale with intercalated sandstone beds, locally with volcanic rocks (125 Ma) accumulated in deep grabens (Fig. 11). This formation is followed unconformably by transgressive shale and prograding marginal marine beds of sandstone, known as the Limoeiro Formation, which accumulated between the Late Albian and the early Paleocene, and marks the initial stages of the post-rift phase. The upper Paleocene to middle Miocene sequence is represented by the Marajó Formation. This formation is up to 2000 m thick and consists of coarse-grained marginal marine sandstone beds that interfinger seawards with the limestone units of the Amapá Formation. The Amapá Formation consists of a great variety of carbonate rocks, and grades towards the continental slope into the shaly facies of the Travosas Formation.

The post-middle Miocene record in the Caciporé-Foz do Amazonas Basin is represented by the siliciclastic rocks of the Pará Group, including the coarse-grained sandstone beds of the Tucunaré Formation, the fine-grained sandstone and siltstone units of the Pirarucu Formation, and the deep-water shales and turbidites of the Orange Formation. The

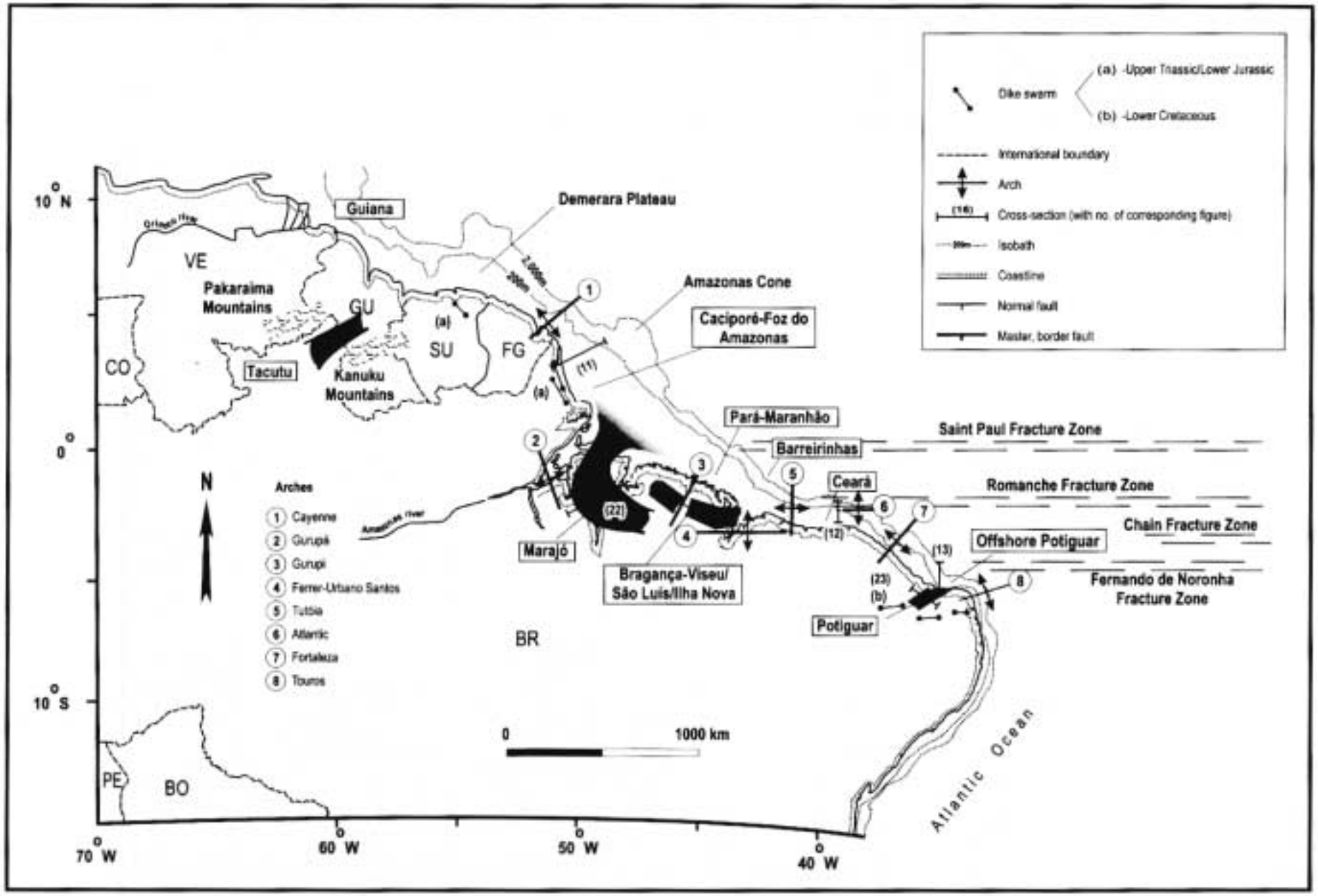


FIGURE 9 - The Central Atlantic and Equatorial segments of the divergent margin of South America (compiled from various sources). Countries: see Fig. 2.

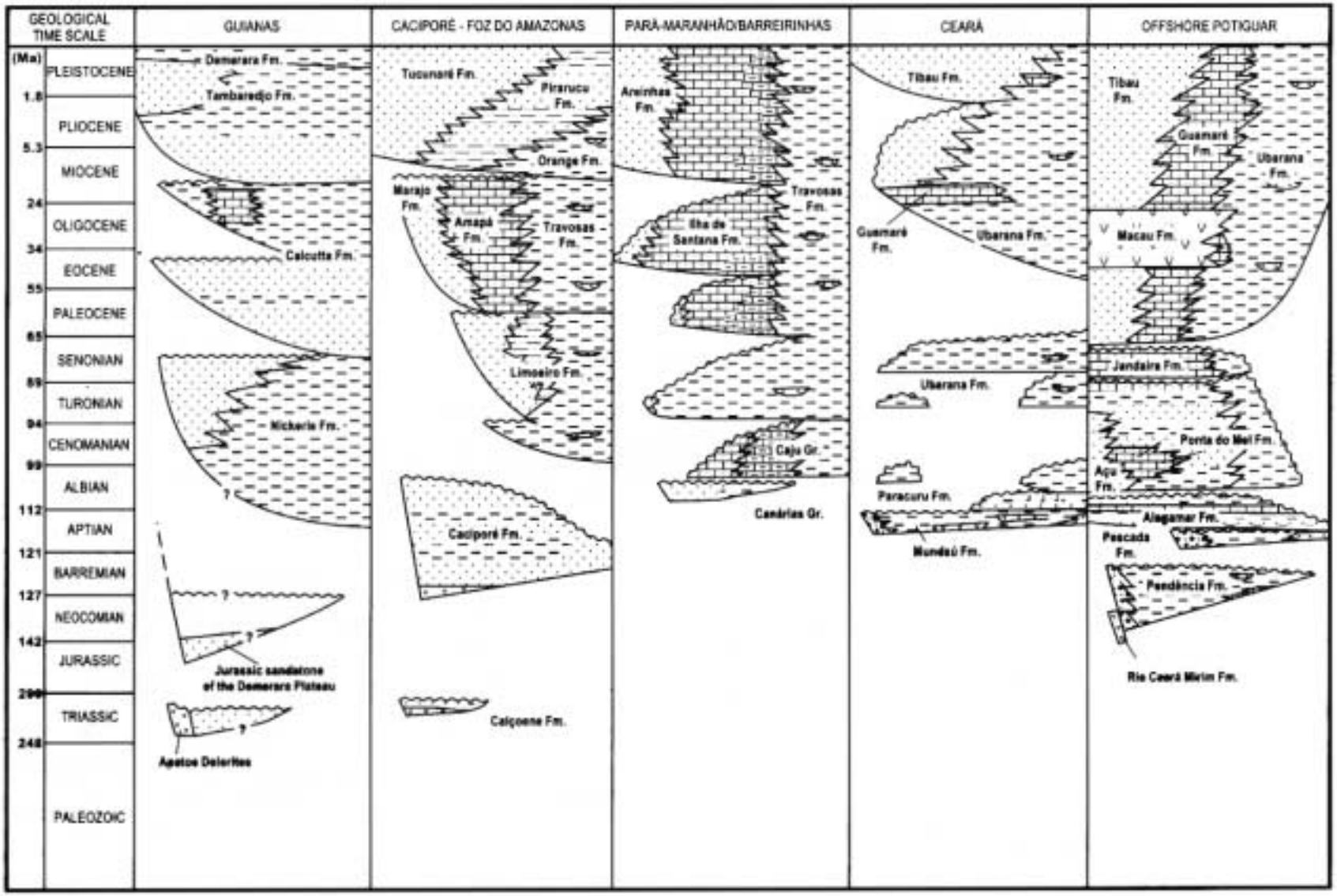


FIGURE 10 - Stratigraphic summary of the Central Atlantic and Equatorial Atlantic marginal basins of South America. On each display, continent is at the left side. Chart for the Guiana Basin is mostly conceptual, and corresponds to its coastal domain. Chart for the Ceará Basin is more representative of its central portion, the Acaraú-Icaraí Sub-Basin; to the west, in the Piauí-Camocim Sub-Basin, the Late Cretaceous to Early Cenozoic lacuna is even greater (Late Cenomanian to Late Eocene hiatus), and to the east, in the Mundaú Sub-Basin, it is of almost imperceptible amplitude. Main sources of information were Krook (1975), Guiana Basin; Brandão and Feijó (1994a), Caciporé-Foz do Amazonas Basin; Brandão and Feijó (1994b), Feijó (1994), Pará-Maranhão/ Barreirinhas basins; Beltrami et al. (1994), Ceará Basin; Araripe and Feijó (1994), Offshore Potiguar Basin. Geological time scale simplified from Gradstein and Ogg (1996). Lithological representations are of common use.

Orange Formation includes a peculiar feature: the Amazonas Cone. This gigantic deep-water fan is several-kilometres thick, and consists of partially unconsolidated shale deposited by gravity-controlled bottom flows and intercalated turbidite bodies with clay to gravel-sized particles (Damuth, 1976). Its characteristic feature is the adiastrophic structures like diapirs and growth faults (Castro *et al.*, 1978, *apud* Brandão and Feijó, 1994a).

Equatorial Atlantic Domain

Equatorial Atlantic transform tectonics imposed particular characteristics on the dynamics of rifting and the final geometry of each of the related marginal basins. The conventional architecture of rift basins, in which subsidence is controlled by a master border fault and where the basement tilts towards it, with fans of coarse clastic sediments developing adjacent to the faulted margin, is not a standard pattern that can be easily recognized along the Equatorial Atlantic marginal basins (Matos and Waick, 1998).

Specific patterns of transtensional rifting along a continental-scale transform plate boundary led to strongly segmented development along the Equatorial Atlantic (Fig. 9), with significant differences in the thermal history, facies distribution, magmatism, uplift and deformational styles from one basin to another. Some regions of the Equatorial Atlantic margin experienced almost continuous subsidence, resembling that of the purely extensional Eastern Brazilian margin, whereas other sectors underwent strong episodes of inversion and erosion that created large lacunas in their stratigraphic record.

The available data set indicates that rifting along the Equatorial Atlantic margin occurred between the Aptian and the Cenomanian. Matos and Waick (1998) suggested an almost instantaneous, widespread Aptian rift phase that fractured the entire Equatorial margin by a right-lateral strike-slip motion, a contrasting mechanism with respect to the longer, Late Jurassic to Barremian rift stage commonly observed along the extensional margin of the South Atlantic. In such a particular tectonic context of rapid overall crustal rupture and mechanical subsidence, marine incursion was facilitated and at some places influenced sedimentation already during the rift phase.

Pará-Maranhão/Barreirinhas basins

The Pará-Maranhão Basin (Fig. 9) is situated in the offshore region of the homonymous states of northern Brazil, covering an area of about 50 000 km^2. The Barreirinhas Basin is the eastward continuation of the former, covering an area of around 20 000 km^2 in the offshore regions of the State of Maranhão, a small part of this being on land. The striking characteristic in the stratigraphic record of this part of the Equatorial Atlantic margin (Fig. 10) is the persistent development of a carbonate platform, known as the Ilha de Santana Formation, ranging in age from Maastrichtian to Recent.

The Barreirinhas Basin is developed on Paleozoic to Neocomian siliciclastic and magmatic rocks that correspond to the stratigraphic sequences of the adjacent Parnaíba Interior Basin (Feijó, 1994a). These sequences are the Serra Grande Group (Silurian), the Canindé Group (Devonian), the Balsas Group (Carboniferous to Triassic), the Mearim Group (Jurassic), and Sardinha Volcanics (Neocomian). Rifting in this part of the margin occurred during the Early and Middle Albian (Brandão and Feijó, 1994b), and is represented by a sequence of immature lithic sandstone beds, siltstone and green shale, comprising the Canárias Group. These beds are interpreted as deltaic facies that were deposited in a prematurely marine rift basin. Shallow marine conditions dominated during the Late Albian, with the deposition of the Caju Group. The Caju Group consists of a basal sequence of quartzose sandstone units named the Periá Formation followed by bioclastic limestone units, the Bonfim Formation, and shales of the Preguiças Formation.

The open marine section, from Cenomanian time onwards, is represented by the Humberto de Campos Group, a classic coast-platform-slope-deep basin depositional complex. The proximal facies are the quartzose sandstone beds of the Areinhas Formation that interfinger with the high-energy carbonates of the Ilha de Santana Formation. Deeper water facies include shale and turbiditic sandstone units known as the Travosas Formation.

Ceará Basin

This basin is situated in the offshore part of the State of Ceará (Fig. 9), and covers about 35 000 km^2. Due to prominent differences in the tectonic and stratigraphic styles, three distinct domains are recognized in the Ceará Basin. From W to E these are the Piauí-Camocim, Acaraú-Icaraí and Mundaú sub-basins. The sub-basins are separated by important positive transversal features, corresponding to basement highs, large volcanic bodies or huge anticlines produced by syn-sedimentary structural inversion (Zalán, 1985). Compressional faults and folds were first described in the Piauí-Camocim Sub-Basin and in the adjacent Barreirinhas Basin by Miura and Barbosa (1972), at a time when the presence of compressional tectonics in the context of Atlantic-type marginal basins was considered anomalous and often contested.

Rifting occurred during Early to Middle Aptian times in the Ceará Basin (Beltrami *et al.*, 1994). This stage accommodated a sequence of more than 4000 m of continental sedimentary rocks, corresponding to the alluvial, fluvial and lacustrine facies of the Mundaú Formation (Fig. 10). In the Late Aptian, the transitional sequence of the Paracuru Formation accumulated, to form up to 500 m of sandstone, chalk, coarse-grained limestone and black shale in marginal marine to shallow marine environments. The top of this section is defined in the Ceará Basin by an important regional unconformity (Fig. 12).

From the Albian time onwards, a thick slope shaly facies started to develop in the entire Ceará Basin, corresponding to the Ubarana Formation, with subordinate beds of sandstone and limestone. However, the kinematics of this transform margin left important differences in the stratigraphic record preserved in its sub-basins, particularly that deposited in Late Cretaceous to early Cenozoic times. In the Piauí-Camocim sub-basin, an important lacuna was recorded spanning the interval between the Late Cenomanian-late Eocene, due to a strong episode of basin inversion. At this time, the Atlantic high, an E-W oriented positive structure related to a large, deep-seated transpressive wrench fault

(Zalán, 1985), was originated. The corresponding hiatus is of lesser extent but still important in the adjacent Acaraú-Icaraí Sub-Basin, and almost imperceptible in the easternmost, NW-SE-trending Mundaú Sub-Basin.

From the Eocene-Oligocene to Recent, coarse-grained clastic sediments accumulated in the proximal areas of a fully developed depositional system situated at the continent margin. These are the beds of the Tibau Formation that grade into the carbonate rocks of the Guamaré Formation deposited in the shallow waters and to shale beds in the more distal areas, the latter being known as Ubarana Formation. Another aspect observed in the Ceará Basin that certainly reflects the presence of an oceanic fracture zones cutting its floor, is the abundance of guyots and seamounts in the deep-water regions. Volcanic rocks also occur as flows and intrusions, affecting all stratigraphic levels.

Offshore Potiguar Basin

The Potiguar Basin is situated in the easternmost part of the Brazilian equatorial margin, in the northeastern corner of Brazil (Fig. 9), occupying some regions of the states of Ceará and Rio Grande do Norte. It includes an offshore segment having an area of about 27 000 km^2 and an onshore segment that covers 22 000 km^2; the latter being discussed in the section on Failed Rift Basins.

The Potiguar Basin underwent a complex evolution, merging elements from both the Equatorial and the Southern Atlantic tectonic zones. Rifting started in the Late Berriasian as result of a WNW-ESE regional extensional stress field (Cremonini *et al.*, 1998) that persisted up to the Early Barremian. During this stage, a sequence of shale beds, rich in organic matter, and sandstone units, including alluvial, fluvial, deltaic and lacustrine facies, named Pendência Formation (Fig. 10), filled fault-bounded depressions (Fig. 13). A second rift phase caused by E-W extension and only in the offshore regions of the basin was active during the Late Barremian to Early Aptian, and expanded the deformation to the W. During this phase the Pescada Formation was deposited. This formation consists of alluvial-fluvial sandstone beds with associated siltstone and shale units. Basic magmatism of the Rio Ceará Mirim Formation constituted a persistent association to rifting in the domain of the Potiguar Basin.

The transitional-to-marine cycle is represented by the Alagamar Formation, of Late Aptian age (Araripe and Feijó, 1994), fully developed in the offshore domain of the basin, where it contains about 600 m of sediments. This formation is composed of a basal sandy sequence, known as the Upanema Member; an intermediate section of black shale and associated limestone beds, informally named the Ponta do Tubarão Beds; and an upper sequence of black shales, included in the Galinhos Member. From Albian time onwards, sedimentation assumed the standard marginal basin configuration of proximal sandy facies, corresponding to the Açu and Tibau formations; carbonate units included in the Ponta do Mel, Jandaíra and Guamaré formations; and a distal shaly facies known as the Ubarana Formation.

In the Late Campanian, right-lateral strike-slip deformation affected the Potiguar Basin, creating a WNW-ESE-trending pattern of structures and causing the development of a regional unconformity of significance in the offshore part of the basin (Cremonini *et al.*, 1998). In the early Cenozoic, subaquous olivine-basaltic magmatism known as Macau Formation took place. Final tectonic events in the region of the Potiguar Basin are represented by Oligocene to Recent, E-W compression released along pre-existing faults trending NE-SW, making this one of the most seismically actives regions of Brazil.

Southern Atlantic Domain

Late Jurassic time marked the beginning of rifting in the southernmost part of the South Atlantic (Uliana and Biddle, 1988; Urien and Zambrano, 1996). However, since the Late Triassic to Early Jurassic, a series of geological phenomena linked to the main phase of break-up, but of more localized occurrence, preceded the overall rupture. In southern Argentina, two active phases of rifting are recognized as preceding the final, Late Jurassic rupture: the Chon Aike Phase (Late Triassic-Early Jurassic) and the Lonco Trapial-Aguada Bandera Phase (Middle Jurassic) (Keeley and Light, 1993). The remarkable 180 Ma complete isotope resetting of the Paleozoic sedimentary rocks of the Paraná Basin (Thomaz Filho *et al.*, 1976), indicating a time of anomalously high heat flow, was another phenomenon related to this Jurassic, early phase of rifting. The consequent elevated continental freeboard just before rifting may explain the dominance of continental sedimentation in the Jurassic, pre-rift sequences. The presence of magmatism and the earliest rifting in southernmost Argentina was the precursor to the imminent widespread break-up.

The pre-existing structural grain of Gondwana, including Precambrian and Paleozoic to Middle Triassic trends, played an important role during Mesozoic rifting. Large sectors of the South Atlantic rupture were accommodated as normal faults upon a much older fabric. However, the existence of prominent transversal structures created complications to this simple picture of propagating rifts, as was the case of the Gondwanides (Urien and Zambrano, 1996), in which the southern margin of the paleocontinent evolved as a collisional belt facing the Panthalassa during the Late Paleozoic.

The southernmost part of the eastern continental margin of South America that developed over the Gondwanides domain, is marked by the presence of a large offshore region of continental crust. This is a complex geological domain striking E-W known as the Malvinas Plateau that extends for more than 2000 km from the shoreline of southern Argentina (Fig. 14). The western, cratonward side of this transversal feature merges both morphologically and structurally with the normal-sized passive margin of the continent (Biddle *et al.*, 1996). To the E and SE, far away from the shoreline, the plateau developed a rifted transitional margin to oceanic crust. Important accumulation of sedimentary rocks, up to 7000 m thick, occurred on the southeastern flank of the plateau in the Malvinas Oriental Basin (Kress *et al.*, 1996).

The northern border of the Malvinas Plateau coincides with the important E-W trending Malvinas (Falklands) fracture zone, along which continental and oceanic crust abruptly keep contact and define the Malvinas (Falklands) Escarpment. This submarine escarpment is almost 3000 m

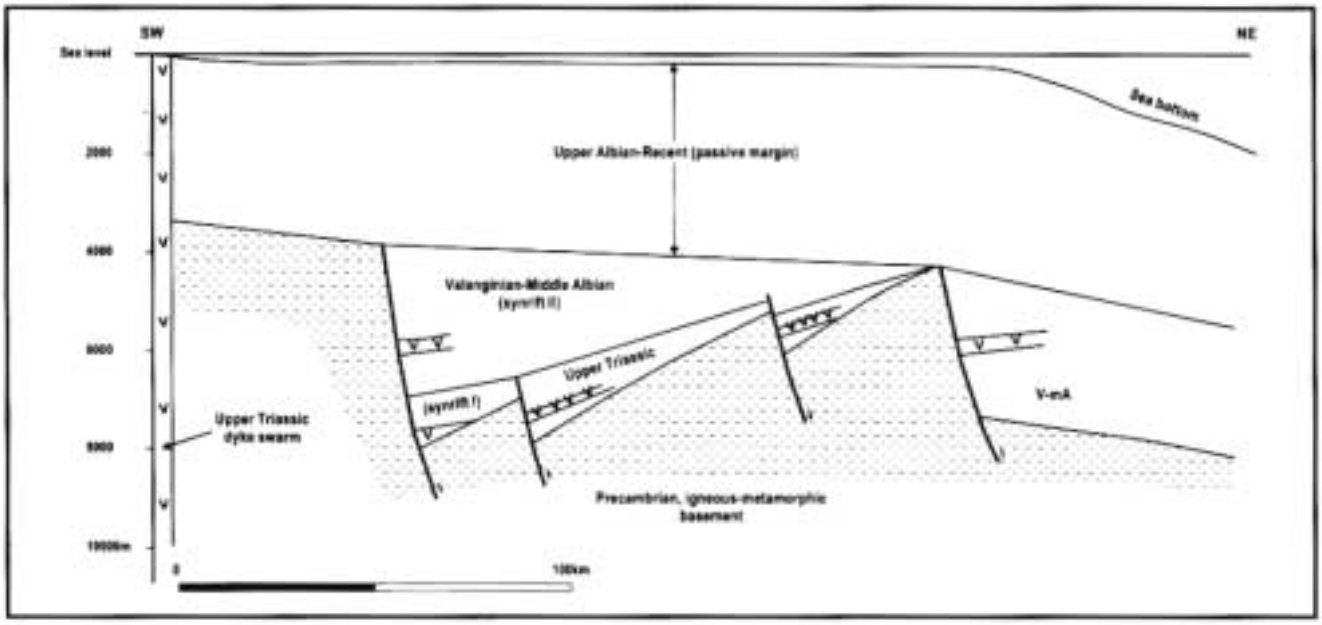


FIGURE 11 - Conceptual cross-section of the Cacipore/Foz do Amazonas Basin (based on information from Brandão and Feijó, 1994a).

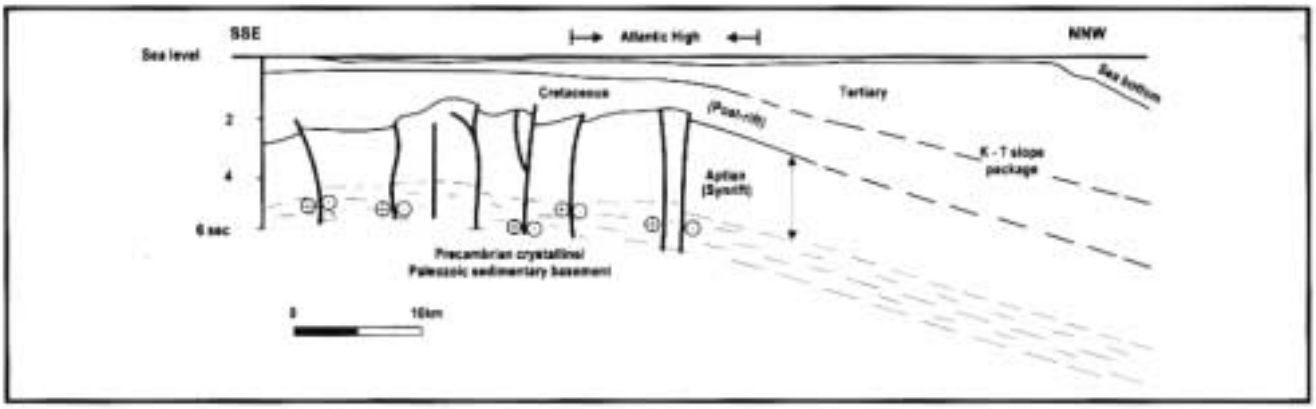


FIGURE 12 - Geoseismic cross-section of the Piauí-Camocim Sub-Basin of the Ceará Basin (after Zalán, 1985; permission to reprint granted by the author).

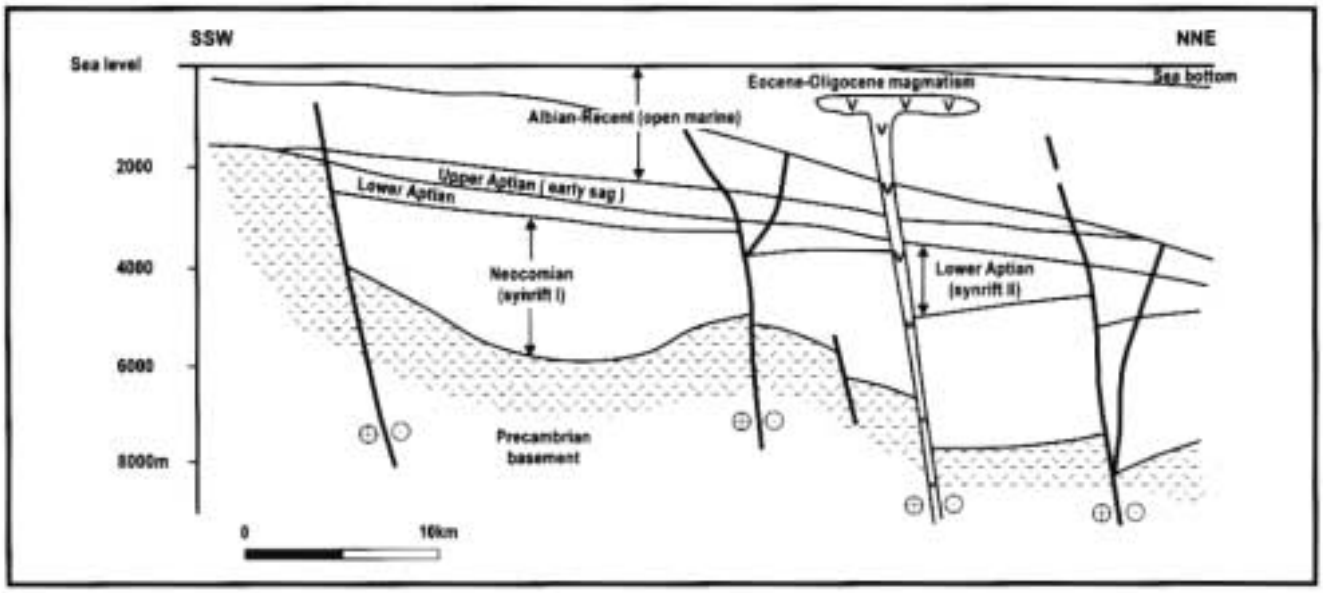


FIGURE 13 - Cross-section of the Offshore Potiguar Basin (after Cremonini et al., 1998; permission to reprint granted by the authors).

high, and the North Scotia Ridge, the active transform boundary between South American and Scotia plates, marks the southern limit of this large continental salient.

Developed on the Malvinas Plateau are a Mesozoic to Recent sedimentary package estimated to have a maximum thickness of about 4000 m (Biddle *et al.*, 1996). The western part of the plateau is marked by the Malvinas Islands, a remote archipelago where there occurs a complete succession of Paleozoic sediments overlying Precambrian basement, the Cape Meredith Complex dated at 1.124 Ga (Nullo *et al.*, 1996). The Paleozoic sequence includes elements that support its correlation with those of Gondwana in South America and Africa, showing the classic succession of a lower unit, the Gran Malvina Group of Silurian-Devonian age, and an upper section, the Isla Soledad Group of Late Carboniferous-Permian age. Between these two groups of rocks there appears a regional unconformity that corresponds to a major break, encompassing a lacuna as large as the Mississipian. The Paleozoic sediments were intruded by Early Jurassic diabase dykes (180 Ma to 192 Ma; Musset and Taylor, 1994, *apud* Nullo *et al.*, 1996).

To the N of the Malvinas Plateau, from the southern Argentinean margin, up to the Santos Basin in southeastern Brazil, the continental margin of South America is about 3000 km long and strikes SW-NE (Fig. 14). At the northeastern end of this straight part of the margin lies the São Paulo Ridge in the deep water realm, and the Florianópolis Platform in the shallower area. The continuation of these features towards the continent coincides with the Ponta Grossa Arch, a prominent NW-SE trending magmatic rift where abundant Early Cretaceous tholeiitic intrusions (128 Ma to 134 Ma; Turner *et al.*, 1994), affecting the Paleozoic successions of the Paraná Basin and surrounding basement, define the largest dyke swarm of the continent.

The São Paulo Ridge also marks the southern limit of the São Paulo Plateau, where the extended crust of the continental margin widens considerably compared to adjacent regions, reaching more than 400 km of width between the 2000 m and 3000 m isobaths (Mascle and Renard, 1976), and holding the Santos and Campos basins. On its seaward side, the São Paulo Plateau is limited by a steep scarp that marks also the eastern border of the area of salt occurrence in these marginal basins. To the NW, the São Paulo Plateau is delimited by the Serra do Mar, another prominent feature along the divergent margin of South America. The present-day configuration of these ranges is given by a chain of scarps, about 1000 km long and up to 2200 m high. Its regional NE-SW trend follows the structural grain of the Precambrian rocks of the Atlantic Shield (Almeida and Hasui, 1984). The origin and development of this uncommonly high topographic feature along the eastern margin of the continent was interpreted by Almeida and Carneiro (1998) as the result of Paleocene to Recent scarp retreat upon the uplifted block of the Santos faultline, a large synthetic normal fault that was progressively buried and today lies offshore.

The divergent margin of South America, to the N of the São Paulo Plateau, extends N-S for about 1200 km. In its northern extremity, this sector reaches the Salvador Deflection (Szatmari *et al.*, 1984), the point where the marginal rift bifurcates into an inland branch, the Recôncavo-Tucano-Jatobá Rift System, and a coastal branch that extends along the length of the Jacuípe Basin, Sergipe-Alagoas Basin, and Pernambuco-Paraíba Basin to its northernmost limit, the Touros Platform, in the northeastern corner of Brazil.

Pernambuco-Paraíba Basin

The northernmost segment of the occidental, extensional margin of the South American continent is known as the Pernambuco-Paraíba Basin. It lies mainly offshore and the total area is about 35 000 km², of which some 9000 km² lies on land (Fig. 14). With respect to the entire eastern margin, this is the region where rifting occurred last, the rupture having been prevented up to Early Aptian times by the nature and high rigidity of the cratonic rocks that constitute the Precambrian basement (Matos, 1998). The sedimentary accumulation in the offshore areas of the basin has not yet been drilled, and its nature and stratigraphy are inferred from seismic data.

Rifting occurred very quickly in this region and lasted for about 5 Ma (Matos, 1998) during the Late Aptian. A sequence at least 3000 m thick of conglomerate and sandstone units, the Cabo Formation (Fig. 15), was deposited. These sedimentary rocks are associated with alkaline and calc-alkaline volcanic rocks, named the Ipojuca Formation, and filled fault-bounded depocenters during this phase. There followed a sag phase, when the Albian to Cenomanian carbonates of the Estiva Formation were deposited in a shallow marine basin (Feijó, 1994b). Senonian times witnessed the encroachment of the marginal coarse-grained clastic sediments of the Beberibe Formation, and the fine-grained clastics of the Itamaracá Formation upon the shallow marine basin. During the Latest Cretaceous to Recent, carbonate units developed in the shallow marginal basin, a sequence that is included in the Gramame and Maria Farinha formations, that grade seawards into the shale beds of the Calumbi Formation.

An unusual aspect of the geology of the Pernambuco-Paraíba Basin is the existence of good exposures of the K/T boundary, not found elsewhere along the continental margin of Brazil. This interval was studied by Albertão (1995). Here the K/T boundary corresponds to a zone situated about 60 cm above the contact between the Gramame Formation, of Maastrichtian age, and the Maria Farinha Formation of Paleocene to Oligocene age. This contact is expressed as an erosive surface separating a lower sequence of biomicritic marlstone beds of neritic environment from a sequence of limestone units and shale beds accumulated under deeper neritic conditions. These show hummocky cross stratification, interpreted as the result of the action of a tsunami. A bed of marlstone that shows anomalously high values for iridium and total organic carbon marks the K/T boundary itself. Here, as elsewhere, worlwide, we see a remarkable level of extinction of pre-existing biota that may be due to the impact of an extraterrestrial body (Alvarez *et al.*, 1980, *apud* Albertão, 1995).

Sergipe-Alagoas Basin

The Sergipe-Alagoas Basin is situated in northeastern Brazil, and covers an area of about 35 000 km², two thirds of which lies offshore (Fig. 14). Along the entire eastern margin

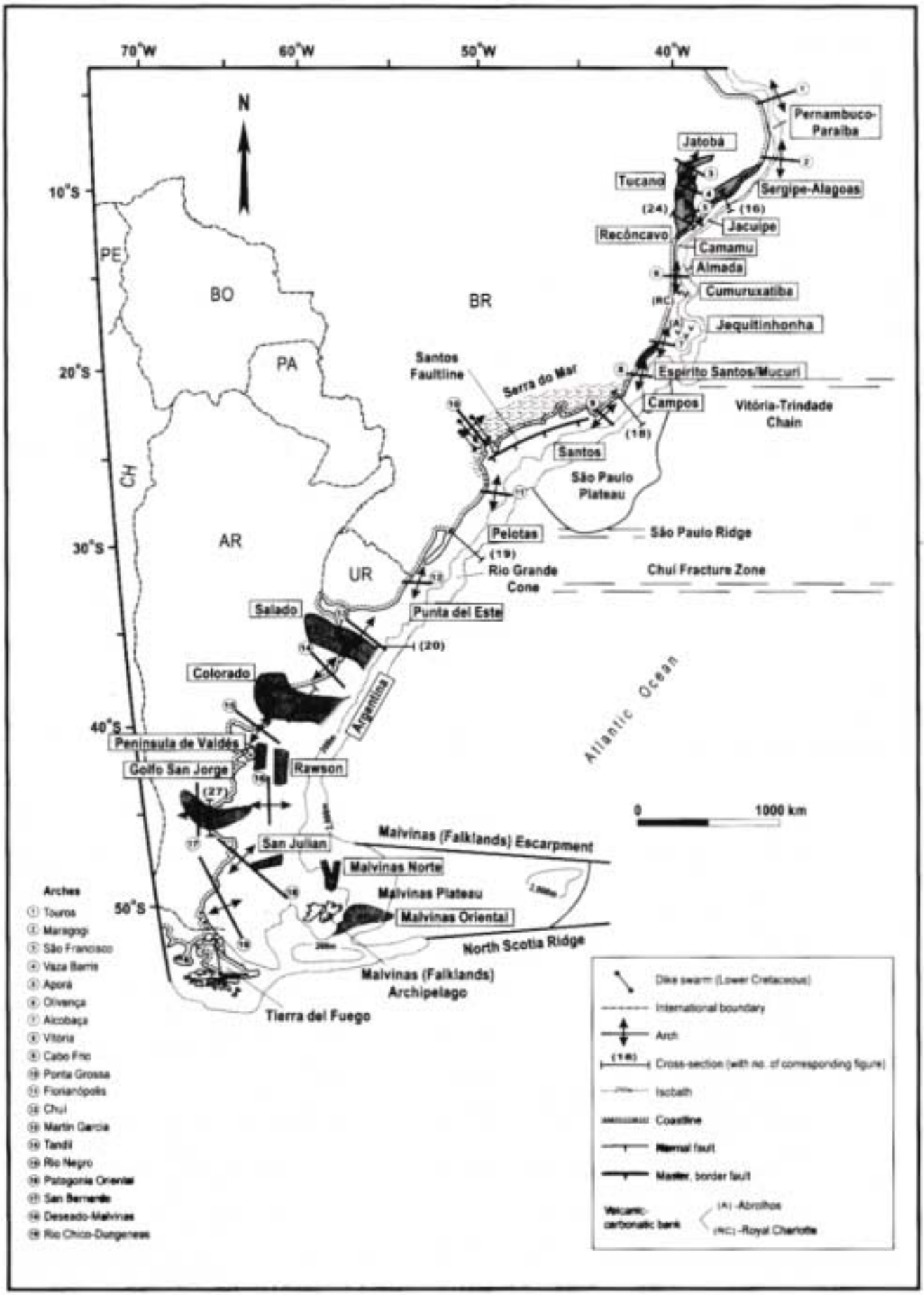
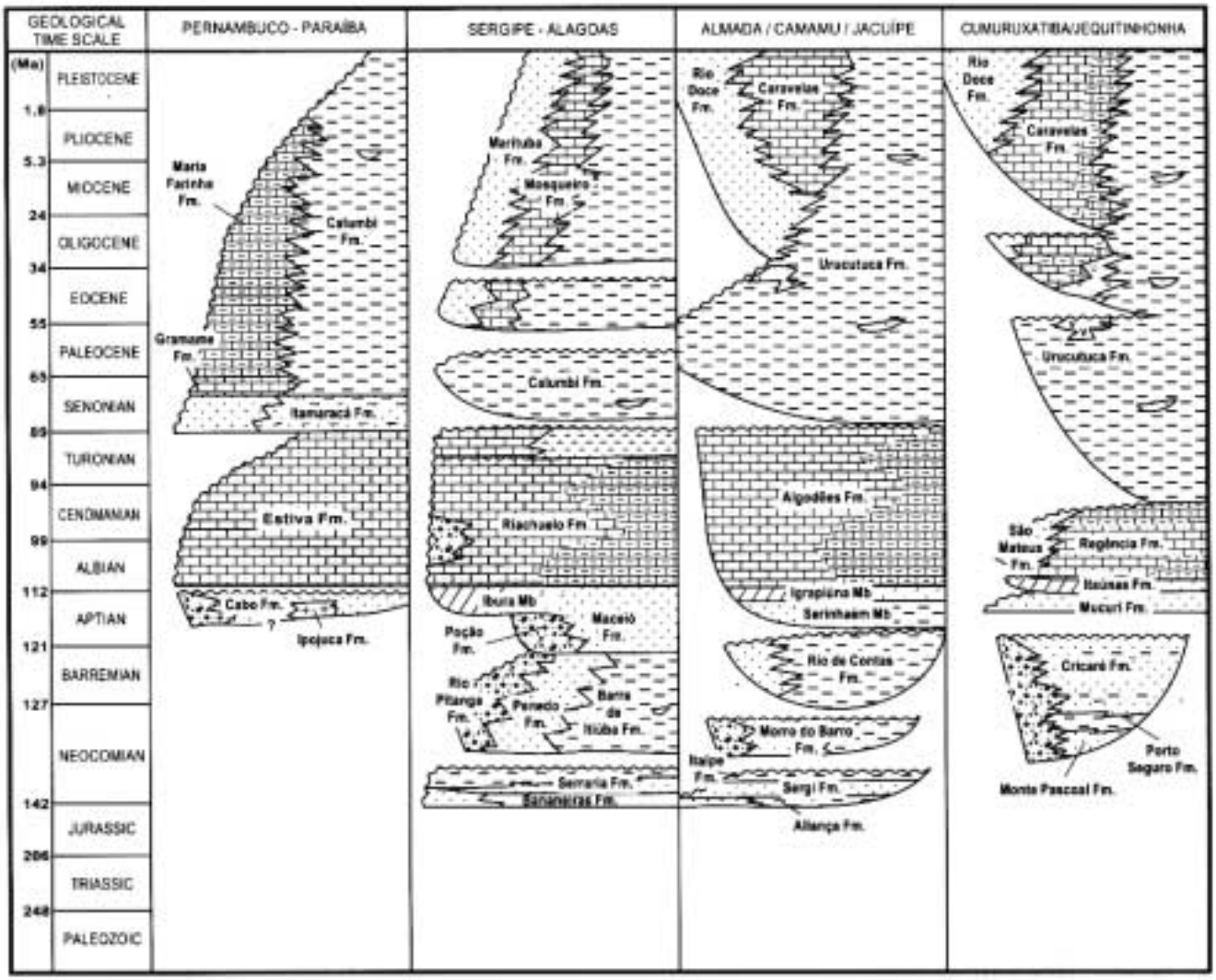


FIGURE 14 - The Southern Atlantic segment of the divergent margin of South America (compiled from various sources). Countries: see Fig. 2.



of Brazil, the Sergipe-Alagoas Basin has the most complete stratigraphic record, including remnants of Late Proterozoic and Paleozoic sedimentary successions, a fully developed Jurassic to Early Cretaceous pre-rift sequence, and the classic Mesozoic-Cenozoic rift and post-rift sequences (Fig. 15).

Northeastern Brazil was the site of extensive sedimentation during the Paleozoic and probably during the Late Proterozoic as well, a fact that is supported by the countless occurrences of these strata throughout the region. These beds are invariably preserved from erosion by local subsidence due to Mesozoic extensional tectonics. The Estância Formation is the oldest of these rock units. It consists of an undeformed, very low-metamorphic grade succession of conglomerate, sandstone, shale, limestone and dolomite beds of Late Proterozoic to Cambrian age that are exposed in the southern part of the basin.

Paleozoic remnants in the Sergipe-Alagoas Basin are included in the Igreja Nova Group (Feijó, 1994c). The Batinga Formation, of Late Carboniferous age, consists of diamictite beds, coarse-grained sandstone, and laminated siltstone deposited under glaciomarine conditions. The Aracaré Formation consists of red sandstone, shale, limestone and silexite of Early Permian age.

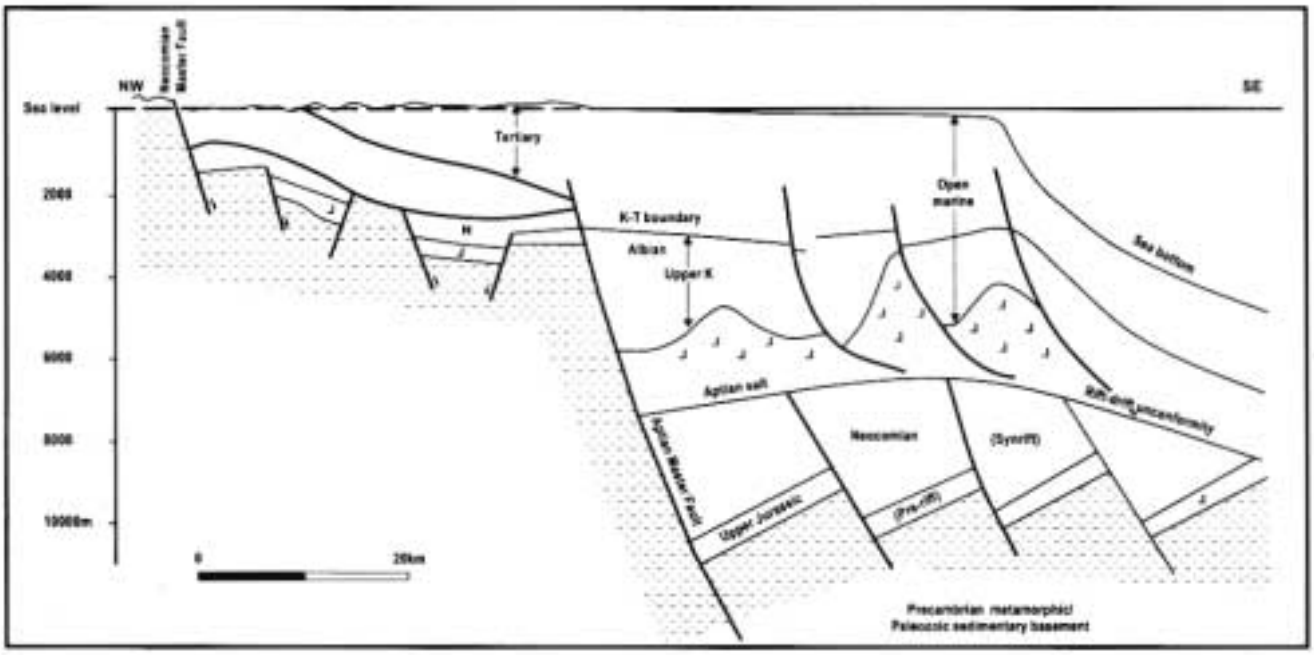
The Late Jurassic to Early Cretaceous pre-rift sequence of the Sergipe-Alagoas Basin corresponds to the Perucaba Group (Feijó, 1994b). It consists of fine-grained red sandstone beds at the base, the Candeeiro Formation; followed by red shale in the Bananeiras Formation; and medium to coarse-grained white and reddish sandstone beds with exuberant cross-bedding, the Serraria Formation.

In the Sergipe-Alagoas region the initial crustal rupture was in response to transtensional forces (Milani *et al.*, 1988; Milani and Szatmari, 1998; Szatmari and Milani, 1999), and rifting along this part of the margin was a process completely devoid of magmatism. A set of *en échelon* N-S trending grabens developed along the regional, SW-NE strike of the nascent margin, and were filled by the Neocomian continental sedimentary rocks represented by the lower part of the Coruripe Group. This group includes conglomerate accumulated as alluvial fans along the faulted margin, known as the Rio Pitanga Formation; the fluvial sandstone of the Penedo Formation; alternating shale and sandstone beds of deltaic origin, of the Coqueiro Seco Formation; and lacustrine shale of the Barra de Itiúba Formation.

A recurrent rift phase took place during the Early Aptian, promoted by a NW-SE extensional stress field. A large NE-SW trending fault-line running approximately along the present day shoreline and separating the onshore part of the basin from that offshore thus originated (Fig. 16). The onshore part of the basin displays a thin sedimentary record whereas the sequence that occurs offshore is known to attain 10 000 m. The second rift phase

FIGURE 15 - Stratigraphic summary of the Southern Atlantic marginal basins of South America, eastern and northeastern Brazilian sectors. Chart for the Sergipe-Alagoas Basin is more representative of its southern domain, the Sergipe Sub-Basin; and the Almada/Camamu/Jacuipe chart is more representative for the Camamu sector. On each display, continent is at the left side. Main souces of information were Santos et al. *(1994), Cumuruxatiba/Jequitinhonha basins; Netto* et al. *(1994), Almada/Camamu/Jacuipe basins; Feijó (1994c), Sergipe-Alagoas basin; Feijó (1994b), Pernambuco-Paraíba Basin. Geological time scale simplified from Gradstein and Ogg (1996). Lithological representations are of common use.*

FIGURE 16 - Cross-section of the Sergipe-Alagoas Basin (after Cainelli and Mohriak, 1998; permission to reprint granted by the authors).



is marked by the conglomerate beds of the Poção Formation in the Alagoas Sub-Basin and by the lower part of the Maceió Formation in the Sergipe Sub-Basin. A sag phase followed, and Late Aptian evaporite beds that constitute the Ibura Member of the upper part of the Maceió Formation filled the depositional space.

Albian carbonates, the Riachuelo Formation, are fully developed in the Sergipe Sub-Basin, and grade to a sandy-conglomeratic proximal facies known as Angico Member. The Upper Cretaceous to Recent continental margin sequence is named the Piaçabuçu Group, and corresponds to the sandstone beds of the Marituba Formation, the carbonate units of the Mosqueiro Formation and the shale of the Calumbi Formation. According to interpretations of seismic data, there occur locally some magmatic bodies of probably Late Cretaceous to early Cenozoic age in the deep water realm of the Sergipe-Alagoas Basin, constituting seamounts and intrusions into the sedimentary rocks (Santos and Castro, 1992, *apud* Feijó, 1994c).

Almada/Camamu/Jacuipe basins

These basins correspond to the offshore parts of the continental margin of Brazil that is situated adjacent to the Todos os Santos Bay, in the State of Bahia covering an area of about 110 000 km², with a small fraction of this on land (Fig. 14). The Todos os Santos Bay corresponds to the southernmost termination of the aborted Recôncavo-Tucano-Jatobá Rift System, and the region where this interior rift links with the continental margin. This important tectonic junction, situated right at the mouth of the Todos os Santos Bay, is marked by a complex tectonic pattern. During the evolution of the northern part of the Camamu Basin, both compressional and extensional regimes were active, producing an intrincate framework with a mix of structural styles.

Some intervals in the stratigraphic succession of these basins show similarities with equivalent sections in adjacent basins, from where they had also obtained their stratigraphic names (Fig. 15). This is the case of the Paleozoic Afligidos Formation and the pre-rift Aliança and Sergi formations, classical units of the interior Recôncavo Basin. Above the sandstone units of the Sergi Formation lies a section of up to 500 m of thick grey and brown shale beds of lowermost Neocomian age known as the Itaípe Formation, representing the transition between the pre-rift stage and the rift stage (Netto *et al.*, 1994).

The syn-rift lacustrine basin was filled by shale named the Jiribatuba Member that grades into proximal coarse-grained sandstone, the Tinharé Member. Together these beds constitute the Morro do Barro Formation. The Barremian to Early Aptian times correspond to a sequence of mixed clastic and carbonate sedimentary rocks known

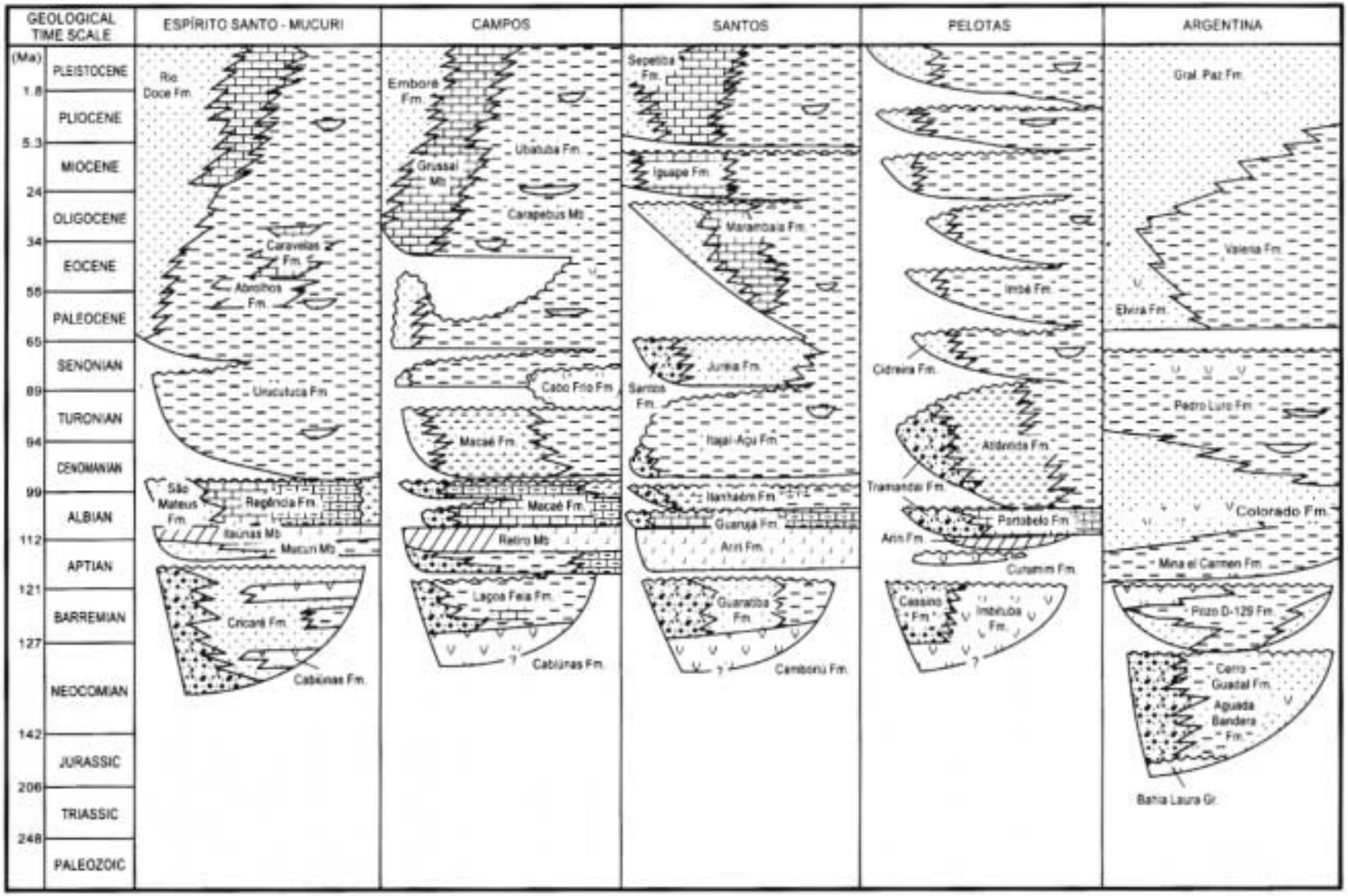


FIGURE 17 - Stratigraphic summary of the Southern Atlantic marginal basins of South America, from Argentina to southeastern Brazil. On each display, continent is at the left side. Chart for the Argentina Basin is a compilation of data from the various sub-basins of that domain. Main souces of information were Keeley and Light (1993), Urien and Zambrano (1996), Argentina Basin; Dias et al. *(1994), Pelotas Basin; Pereira and Feijó (1994), Santos Basin; Rangel* et al. *(1994), Campos Basin; Vieira* et al. *(1994), Espírito Santo-Mucuri Basin. Geological time scale simplified from Gradstein and Ogg (1996). Lithological representations are of common use.*

as Rio de Contas Formation. These consist of grey and brown shale beds and fine-grained to conglomeratic sandstone that accumulated under deltaic-lacustrine conditions. In the Jacuípe Basin the Neocomian sequence is absent, and the rift sequence is represented by the Rio de Contas Formation, in that area spanning the range Barremian-Early Albian.

A section consisting of evaporite beds and associated clastic sedimentary rocks of Late Aptian age define the Taipus-Mirim Formation. This formation consists of very fine-grained sandstone intercalated with siltstone and black shale rich in organic mater, a sequence known as the Serinhaém Member. The Igrapiúna Member consists of carbonate (including dolomite), brown shale, halite and anhydrite. Locally, the anhydrite is replaced by a layer of barite in some regions of the Camamu and Almada basins. These rocks are the result of the first marine transgression into the basin that developed under arid conditions (Netto *et al.*, 1994). The classic Albian-Cenomanian carbonate sequence is known as the Algodões Formation. It is followed by the Late Cretaceous and Cenozoic sequence that in the Almada/Camamu/Jacuípe basins is lithologically similar and holds the same stratigraphic nomenclature of the equivalent rocks existent in the Espírito Santo-Mucuri Basin, that is Urucutuca, Caravelas and Rio Doce formations.

Cumuruxatiba/Jequitinhonha basins

These dominantly offshore basins correspond to a stretch of the Eastern Brazilian Margin that strikes approximately N-S and is about 350 km long (Fig. 14). These basins occupy an area of about 45 000 km^2 along the coast of the State of Bahia. The basement in the area consists of Precambrian granitic-gneissic terrains of the São Francisco Craton (Almeida and Hasui, 1984). The structural framework of the rift phase in these basins is defined by N-S and SW-NE-trending dominantly synthetic normal faults, locally interrupted by NW-SE-oriented transfer faults and accommodation zones.

Neocomian to Early Aptian sedimentation in these basins (Fig. 15) corresponds to the Cumuruxatiba Group and the Cricaré Formation. The former includes a basal sequence of clastic sedimentary rocks, the Monte Pascoal Formation, consisting of coarse to medium-grained sandstone beds intercalated with dark grey to black shale and conglomerate that may represent the pre-rift section. The syn-rift package is represented by the lacustrine shale of the Porto Seguro Formation (Santos *et al.*, 1994) and the Cricaré Formation. The Cricaré Formation, as well as the rest of the stratigraphic record in the Cumuruxatiba/Jequitinhonha basins, including the early Cenozoic magmatism of the Abrolhos Formation, exhibit similar lithological characteristics to the equivalent section found in the adjacent Espírito Santo-Mucuri Basin, also borrowing from that basin the names of the formal stratigraphic units.

Espírito Santo-Mucuri Basin

This basin is situated in the coastal (about 20 000 km^2) and the offshore regions (200 000 km^2) of the State of Espírito Santo and the southernmost part of the State of Bahia (Fig. 14). The southern part of the basin, in the deep water realm, is connected to the Campos Basin, but is separated from the adjacent basin over the continental platform and onshore domains by a positive feature at the level of the Precambrian basement, known as the Vitória High. To the N, the Mucuri Basin displays the marginal sag successions similar to that seen in basins along the eastern coast of Brazil.

The Espírito Santo-Mucuri Basin evolved over a complex association of Precambrian igneous and metamorphic rocks (Vieira *et al.*, 1994). The oldest indications of rifting in the region are NW-SE trending Jurassic dykes, known as the Fundão Suite. This early magmatic event was followed by a Neocomian-Barremian episode of extrusion of tholeiitic basalt and volcaniclastic beds during the rift phase known as the Cabiúnas Formation, where the magmatic bodies locally interfinger with the sediments.

Syn-rift sedimentation of the Cricaré Formation in the Espírito Santo-Mucuri Basin is estimated at 5000 m of Neocomian to Early Aptian continental conglomerate, sandstone, coquina, calcilutite and dolomite beds, with associated black shale with organic matter (Fig. 17). The sequence accumulated according to a pattern of N-S to NE-SW trending, dominantly synthetic normal fault-bounded blocks, and is terminated at the top by an important erosional unconformity, separating this lowermost unit from the transitional beds of the Mariricu Formation. The Mariricu Formation is represented by Late Aptian conglomerate, feldspathic coarse-grained sandstone and shale, the Mucuri Member, that grades upwards into a sequence of evaporite beds and black shales known as the Itaúnas Member.

The open marine sediments in the Espírito Santo-Mucuri Basin form the Barra Nova Group, of Albian age, and the Espírito Santo Group, spanning the Cenomanian to the Recent. The former consists of coarse-grained sandstone of marginal marine facies, the São Mateus Formation that grades seawards into the limestone units of the Regência Formation. The Espírito Santo Group is the classic sequence that defines the prograding continental platform, constituted by a proximal sandy facies known as Rio Doce Formation interfingering with carbonate beds, the Caravelas Formation; and becoming shaly at the slope and deep basin, the realm of the Urucutuca Formation.

Cenozoic times were marked in the Espírito Santo-Mucuri Basin by the important Abrolhos magmatic event that imposed profound structural rearrangements to the basin. The Abrolhos Formation (Vieira *et al.*, 1994) corresponds to the sub-alcaline to alcaline volcanic and volcaniclastic rocks that were extruded during late Paleocene-Eocene times. The magmatism peaked between 60 Ma and 40 Ma, and the resulting bodies are intercalated with the limestone units of the Caravelas Formation and with the shale beds of the Urucutuca Formation. The outpouring of large volumes of magma in the off-shore part of the basin added local complications to the conventional gravity-driven salt tectonics; reaching such a down-dip obstacle, halokinesis developed a distinctive pattern of compressional structures around the Abrolhos Complex.

Campos Basin

The Campos Basin is situated in the territorial waters of the State of Rio de Janeiro, southeastern Brasil. The basin

covers an area of almost 100 000 km²; of which, only about 500 km² are onshore (Fig. 14). To the N, it is partially isolated from the Espírito Santo Basin onshore, and from the shallow water domain, by the Vitória High, an elevated block of Precambrian basement that coincides with the westward prolongation of the Vitória-Trindade Chain in the Atlantic seafloor. Crystalline basement has scarcely been sampled by drilling in the basin, and corresponds to the same Precambrian gneissic domain that crops out in the surrounding areas. To the S, the Campos Basin is limited with the Santos Basin along the Cabo Frio Arch, an area of persistently active magmatism during the post-break-up evolution of the margin. In that domain, Turonian to Campanian sediments are intercalated with volcaniclastic deposits, flood basalts and diabase sills of 80 Ma to 90 Ma. Recurrent magmatism formed volcanic cones during Eocene times (Mohriak *et al.*, 1995).

Rift sediments of the lower part of the Lagoa Feia Formation in the Campos Basin span the time interval Late Neocomian-Barremian, and overlie and interfinger with the basalt and volcaniclastic beds of the Cabiúnas Formation, dated at 120 Ma to 130 Ma (Dias *et al.*, 1990). The lower part of the Lagoa Feia Formation (Fig. 17) includes conglomerate with abundant clasts of basalt that form large fans along major border faults of tilted blocks, coarse to fine-grained sandstone, shale rich in organic material, siltstone and coquina, defining a complete sequence of lacustrine sedimentation. The coquinas are up to 50 m thick bioclastic accumulations of pelecypod shells, named the Coqueiros Member, constituting sedimentary rocks associated with structural syn-depositional highs, and representing a particular facies of porous rocks in this basin (Rangel *et al.*, 1994). The upper part of the Lagoa Feia Formation, lying above an expressive unconformity, is represented by a sequence of Aptian conglomerate beds and shaly red beds that grade upward into a section of Late Aptian evaporites known as the Retiro Member, with rhythmic intercalations of anhydrite and halite. The occurrence of the Aptian and older sediments is limited by a SW-NE trending synthetic, basement-involved fault-line nearly parallel and close to the coast (Fig. 18).

During Albian to Cenomanian times, marine conditions prevailed. The Macaé Formation consists of clastic and oolitic, coarse to medium-grained limestone beds, the Quissamã Member. Locally, these limestone beds are completely dolomitized. The vertical succession includes beds of calcilutite, marlstone and shale, a package known as Outeiro Member. The sandy turbiditic bodies that occur at some places are known as the Namorado Sandstone. In the proximal part of the basin, the Macaé Formation consists of conglomerate and poorly sorted sandstone beds that form the Goitacás Member. These beds grade basinward into the others facies of the Albian-Cenomanian sequence. The Campos Group unconformably overlies the Macaé Formation.

The Campos Group represents the post-Cenomanian filling-in of the marginal sag during the last thermal phase of subsidence and seaward tilting of the continental margin. It consists of two laterally interfingering units. The proximal is the conglomeratic, sandy and carbonate-bearing Emborê Formation; and the distal is the shaly Ubatuba Formation. The Ubatuba Formation consists of thousands of metres of shale and marlstone, with intercalated sandy turbiditic bodies, collectively known as Carapebus Member.

The post-rift tilting of the basin to the E also triggered adiastrophic structures caused by the voluminous salt flow (Demercian *et al.*, 1993). Salt tectonics and the resulting structural styles in the Campos Basin configure two particular cases: close to the coastline, an upper extensional, 100 to 200 km wide domain caused by horizontal extension above the Aptian salt layer; and a lower compressional domain, in the deep water regions, originated by downdip contraction of the thin-skinned, gliding package. Listric normal faults, including a basal synthetic shear for the entire rafted section, are features overall associated with salt tectonics.

Santos Basin

The Santos Basin is a large, NE-SW trending concave coastal basin that occupies about 200 000 km² of the continental margin of southeastern Brazil (Fig. 14). To the N, the basin is limited by the Cabo Frio Arch, and to the S by the Florianópolis Platform, both features lying as the westward prolongation of ocean fracture zones (Cainelli and Mohriak, 1998) and related to important magmatic activity associated with sedimentation. The Santos Basin overlies the São Paulo Plateau that along the Brazilian eastern margin is a unique feature of anomalous highly extended continental lithosphere.

To the W, the basin is limited by a belt of coastal ranges up to 2200 m high where Precambrian rocks crop out, the Serra do Mar, a physiographical feature that confines the marginal sag to the offshore domain. The border of the pre-Aptian package is marked by a synthetic normal fault, the trace of which runs parallel to the shoreline about 50 km seaward. This feature remained active up to Late Cretaceous times, and was onlapped by the Cenozoic sediments during the thermal subsidence phase. The maximum thickness of the Neocomian to Recent sediments is estimated at about 11 000 m.

Rifting in the Santos Basin occurred in the Neocomian-Early Aptian, when lacustrine sediments accumulated (Fig. 17). The rift sequence, named the Guaratiba Formation and hardly sampled in the basin, includes proximal reddish coarse siliciclastic wedges with fragments of basalt and quartz, and coquina deposited over, and probably interfingering with, the Lower Cretaceous basalt of the Camboriú Formation. Anoxic lacustrine deposits including shaly beds, rich in organic material, are supposed to exist in the deep-water region of the basin (Pereira and Feijó, 1994). The rift sequence is covered by the Aptian evaporites of the Ariri Formation, consisting of intercalations of anhydrite and halite. The downdip flow of the evaporites during the late evolution of the basin provided abundant halokinetic structures in the deep-water region of the Santos Basin. Large salt diapirs and walls are observed, attaining several kilometres in hight.

The Albian succession, known as Florianópolis, Guarujá and Itanhaém formations, consist of, respectively, fine-to coarse-grained red sandstone, carbonate and grey shale, a suite of rocks deposited under open marine conditions during progressive deepening of the basin. Maximum flooding conditions were reached during Cenomanian-

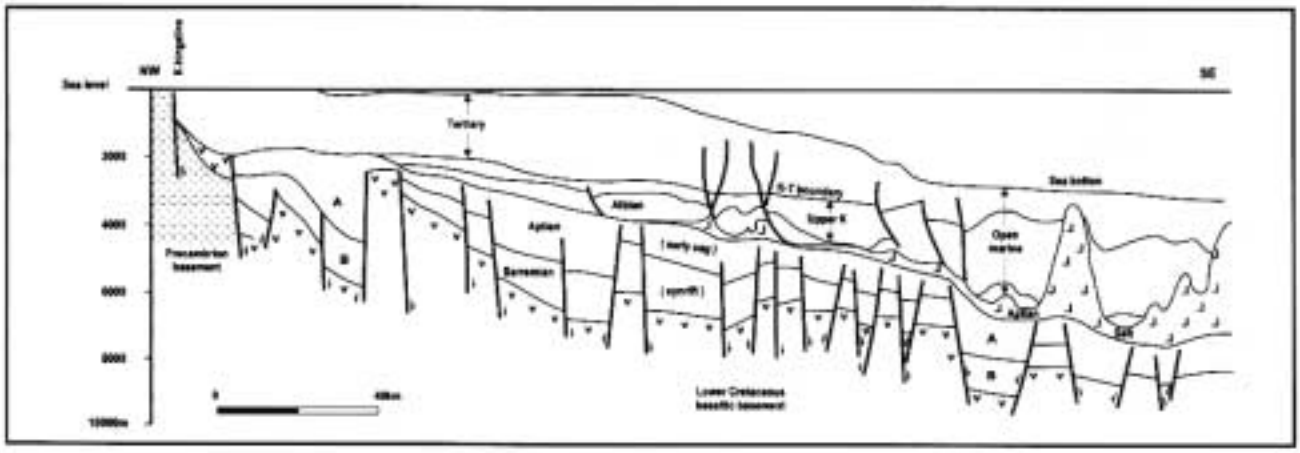


FIGURE 18 - Cross-section of the Campos Basin (after Cainelli and Mohriak, 1998; permission to reprint granted by the authors).

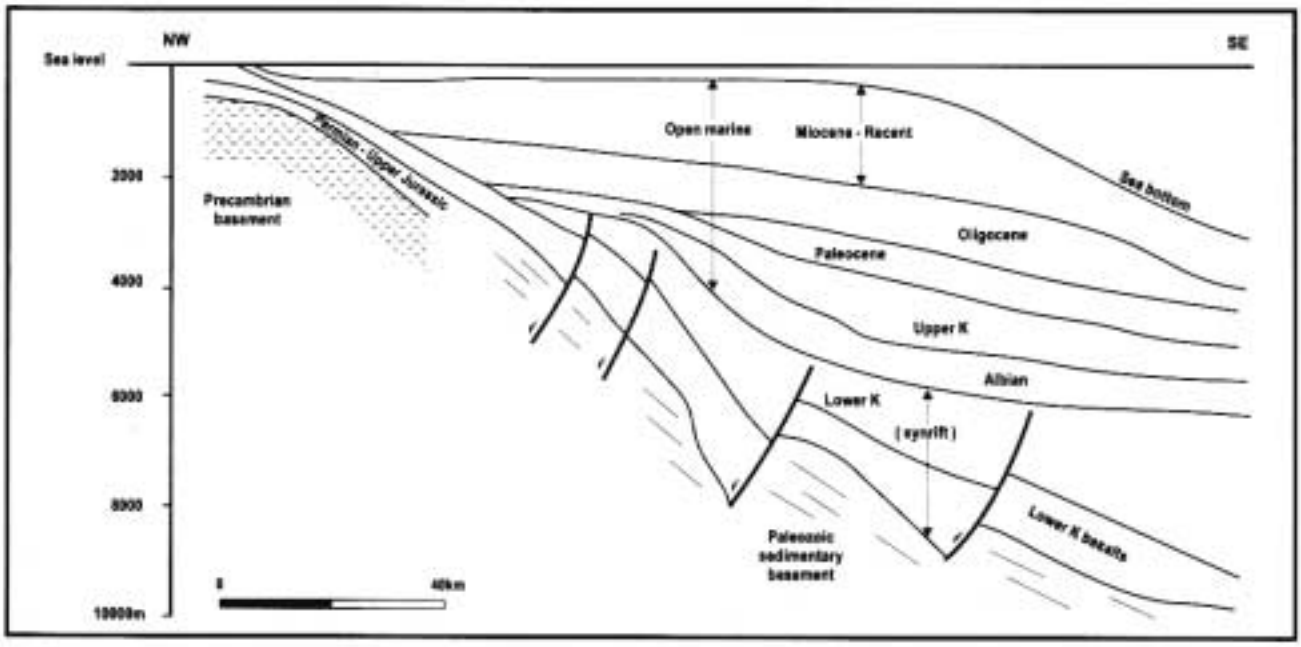


FIGURE 19 - Cross-section of the Pelotas Basin (after Dias et al., 1994, in Cainelli and Mohriak, 1998; permission to reprint granted by the authors).

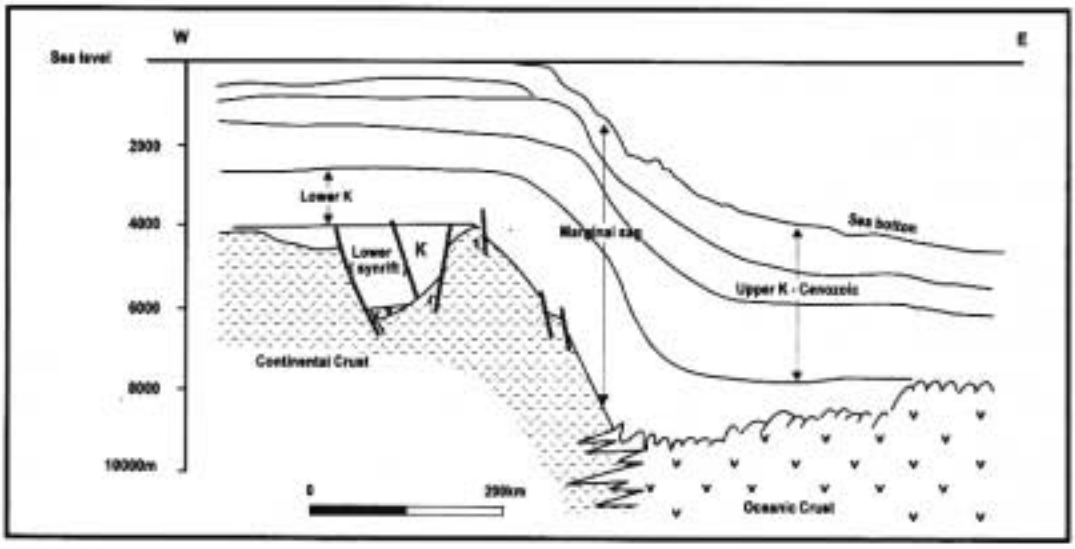


FIGURE 20 - Cross-section of the northern portion of the Argentina Basin (after Urien and Zambrano, 1996; permission to reproduce granted by Asociación Geológica Argentina).

Turonian times, when the dark grey shales of the Itajaí-Açu Formation were deposited. In the proximal regions, a thick wedge of conglomerate beds, the Santos Formation, and shallow marine sandstone beds, the Juréia Formation, spanning the Santonian-Maastrichtian interval, encroached on the basin in response to the uplift of the coastal Serra do Mar. This event is dated at 100 Ma to 80 Ma by apatite fission track analysis (Lelarge, 1993). Further evolution of the Santos Basin, during the Cenozoic, was marked by a basinward siliciclastic progradation, corresponding to the deposits of the Iguape and Sepetiba formations, against a large shaly platform/slope system included in the Marambaia Formation.

Pelotas Basin

The Pelotas Basin (Fig. 14) extends for about 160 000 km^2 in the offshore region of the southernmost Brazilian state, the State of Rio Grande do Sul. This basin also underlies about 40 000 km^2 of the coastal region of that province. In the onshore part, the basin is filled by a sequence of Cenozoic sandy siliciclastics sedimentary rocks as thick as 1800 m (Dias *et al.*, 1994). The post-Neocomian rocks that fill the Pelotas Basin directly overlie the crystalline Precambrian basement or over Paleozoic sequences that correspond to those of the Paraná Basin. The southern limit of the basin is the Chuy Fracture Zone, situated close to the international boundary with the Uruguay. To the N the Florianópolis Platform separates the Pelotas Basin from the Santos Basin.

Rifting occurred during Neocomian times (Fig. 17), when the basaltic flows of the Imbituba Formation and the coarse-grained siliciclastic rocks of the Cassino Formation were deposited. In the shallow-water region, where the rift structure is imaged by seismic data (Fig. 19), the half-grabens that define the rift blocks are controlled by high-angle antithetic faults (Cainelli and Mohriak, 1998). The basalt of the Imbituba Formation, with a characteristic array of seaward dipping wedges (Fontana, 1990), is 124±8.6 Ma old (K/Ar method, Dias *et al.*, 1994), an age that is close to the time when the voluminous intracontinental Serra Geral magmatism was terminating (126.6±2.9 Ma, Ar/Ar method, Milani, 1997; 126.8±2.0 Ma, Ar/Ar method, Turner *et al.*, 1994). This relationship seems to indicate a major shift in the volcanic centre from the interior of the plate towards its nascent margin.

The record of the continental-to-marine, evaporitic transitional phase is known only in the Florianópolis Platform, where there occurs a sequence, up to 50 m thick, consisting of halite, anhydrite, and carbonate beds included in the Ariri Formation, of Late Aptian age. These beds overlie the Curumim Formation, in which there occur trachy-andesites of Aptian age (113.2±0.1 Ma, Ar/Ar method, Dias *et al.*, 1994). The Florianópolis Platform also defines the southern limit of the great Aptian saline basin of the Southern Atlantic (Dias, 1998). The absence of evaporite beds gives the Pelotas Basin a monotonous, unfaulted and almost undeformed profile of a gently tilted monocline for its post-Aptian sequence, in sharp contrast with the standard configuration observed along the rest of the eastern Brazilian marginal basins.

From the Albian to the Recent, thermal subsidence and an essentially transgresive pattern of sedimentation dominated. The Early Albian is represented by the carbonate sequence of the Portobelo Formation that is covered by Late Albian to Recent proximal sandstone beds known as Tramandaí and Cidreira formations. These units grade to siltstone and fine-grained limestone of the Atlântida Formation, and to shale of the Imbé Formation towards the deep parts of the basin. The entire supra-Portobelo sequence is cut by a series of erosional surfaces that correspond to times of major regression. In the southern part of the Pelotas Basin, there occurs a sequence of post-Paleocene sediments up to 6000 m thick that define the Rio Grande Cone, a region with abundant structures related to gravitational movement of shale and that holds significant occurrences of gas hydrates in its upper levels (Fontana, 1989).

Argentina Basin

The Argentina continental margin basin is a 2300 km long, NE-SW trending straight segment of the South American eastern border (Fig. 14). It has an average width of 350 km to the 200 m isobath, and has a total area of about 800 000 km^2. Towards the N, in the Uruguaian continental waters, this segment of the margin is named Punta del Este Basin. Local depocenters, corresponding to Jurassic to Early Cretaceous aborted rift basins, and the intervening platform areas, all were draped by a sequence of Late Cretaceous to Cenozoic marine sedimentary rocks that may reach a thickness of 4000 m (Fig. 17).

The large offshore marginal sag of Argentina is divided into three domains (Ramos, 1996): the northern domain is characterized by the predominance of a transverse-to-shore structural pattern inherited from the Mesozoic rifting from the NW-SE pre-existing fabric in the area. In this northern sector the aborted rift structures of the Salado and Colorado basins developed, indenting cratonward from the margin (Fig. 20). Contrasting with the above, normal faults run parallel to the continental margin and define the framework of the rift phase in the central domain of the Argentina Basin, that includes the Rawson, Península Valdés, San Julian, and North Malvinas grabens. The southernmost domain is defined by the presence of the transverse structural feature of the Malvinas (Falklands) Islands Platform and its eastward prolongation, the Malvinas Plateau. This is a a large province of submarine continental crust bordered to the N by the prominent scarp of the Malvinas (Falklands) Fault Zone and to the S by the transform zone of the North Scotia Ridge.

The onset of extensional conditions and fault-driven subsidence in this area occurred during the Early Jurassic and marked the beginning of the development of the South Atlantic (Fig. 17). Magmatism was important during the initial stages of rupture (for example, dykes of basic rocks peaking between 180 Ma and 192 Ma in the Malvinas (Falklands) Islands (Musset and Taylor, 1994, *apud* Nullo *et al.*, 1996), and heralding large-scale break-up of Gondwana. The framework of rifting was to a large extent controlled by the pre-existing structural grain, and the rift phase accommodated continental deposits of lacustrine facies, including black shale, sandstone and limestone units, locally intercalated with abundant volcanic and volcaniclastic rocks.

As early as the Valanginian, the creation of oceanic crust began in the area (McLachlan and McMillan, 1979, *apud*

Light *et al.*, 1993), and sedimentation developed under incipient marine conditions associated with a phase of thermally-driven subsidence. However, up to Middle Cretaceous times the occurrence of widespread marine sedimentation in the Argentina Basin was made difficult by the presence of structural positive elements (Urien and Zambrano, 1996). Aptian times were marked by anoxic conditions and the local development of sediments rich in organic matter (Dias, 1998). A final stratigraphic pattern was established with the invasion of the Atlantic, transgressive from Late Cretaceous times to the Neogene. This was followed by a regressive tendency, when deltaic systems spreaded all over the shelf (Keeley and Light, 1993), offlapping the continental margin and prograding over the slope sequences, with abundant submarine erosion associated.

Failed rift basins

Extensional processes related to South Atlantic rifting led to the development of a series of grabens striking towards the craton from the continental margin (Figs. 9 and 14); most of which are restricted to the onshore domain of the continent in a function of the present-day freeboard along the margin. These rift basins have variable sizes, from few thousand to several ten thousand square kilometres; shapes, most usually being crescent or linear; position with respect to the margin, from parallel to normal-to-shore; and nature of its floor correspondent to different structural provinces of the South American Platform, lying directly over Precambrian crystalline basement or over older cratonic sedimentary cover.

The control exerted upon their positioning and evolution by basement weakness zones was also a variable factor: some were strongly controlled by pre-existing grain and others created their own. Rifting ages observed in these grabens reflect the age of that sector of the continental margin. This varied enormously and covered a time span of about 90 Ma. It is late Late Triassic along the northernmost sector of the Brazilian Margin (Marajó Basin; Milani and Zalán, 1998) and Early Jurassic in southern Argentina (Golfo San Jorge Basin; Baldi and Nevistic, 1996); Neocomian along the eastern Brazilian Margin (Recôncavo-Tucano-Jatobá basins; Caixeta *et al.*, 1994); and Aptian along the Equatorial Atlantic (São Luís/Bragança-Viseu/Ilha Nova basins; Lima *et al.*, 1994).

Each of these rift basins shows an evolutionary picture with a particular degree of completeness with respect to the full development of the continental margin of South America. Some of these rift basins became inland, aborted grabens still during the Cretaceous, and only contain lacustrine rocks. Others were partially or completely involved in the overall post-rift subsidence of the continental margin, and over their syn-tectonic sequences were deposited transitional and marine sedimentary beds.

Tacutu Basin

The Tacutu Basin (Fig. 9) includes areas of the State of Roraima (4500 km^2), in northernmost Brazil, and of the neighbouring country of Guiana (7000 km^2), where it is named the North Savannas Rift Valley (Berrangé, 1977). It is a NE-SW trending rift system about 300 km long and 30 to 50 km wide. It contains a sedimentary-volcanic fill of Jurassic to Recent age with a thickness that surpasses 7000 m (Fig. 21). The surface expression of this trough is essentially flat and dominated by tropical savanna. The faulted margins of the rift define highlands, the Pakaraima Mountains in the N and the Kanuku Mountains in the S.

The basement of the Tacutu Basin consists of Precambrian rocks of the Guiana Shield. Rifting was to a large extent controlled by NE-SW structural lines, pervasive in the ancient basement (Eiras and Kinoshita, 1990). The origin of the Tacutu Graben can be credited to differential rotation within the Guiana Shield during the opening of the Central Atlantic. The basin is limited by normal faults on both sides, but with an asymmetric transversal profile since that larger downthrows can be observed along the master faults of the southern border. An inversion in the sense of dip of the basement occurs when reaching the Guianan sector, where the master fault shifts to the northwestern side. An important E-W transfer zone known as the North Savannas Arch defines the region where the sense of dip of the basement inverts.

An interpreted pre-rift sequence, consisting of up to 1200 m of Jurassic basalts, the Apoteri Formation, and subordinate lacustrine red siltstone of the Manari Formation, underlies the Tacutu Basin (Eiras *et al.*, 1994b). The basalt was extruded mainly under subaerial conditions, but the existence of some pillows also indicates local subaquous volcanism. K/Ar dating indicates ages between 180 Ma and 150 Ma (Eiras and Kinoshita, 1990), a range consistent with the time of the opening of the southern part of the Central Atlantic Ocean.

During the initial stages of its evolution, the rift depression in the Tacutu Basin was filled by some 950 m of Tithonian evaporite beds and intercalated grey to brown shale and sandstone known as Pirara Formation. These beds interfinger towards the margins with a coarse-grained sandy and conglomeratic clastic wedge. The bromine content of these halites suggests marine influence, probably some short-lived incursions of the adjacent Central Atlantic waters.

Most of the rift sequence is aged Berriasian to Middle Albian, and is mainly composed of a thick succession of redbeds. The basal unit, the Tacutu Formation, up to 2700 m thick, consists of lacustrine siltstone and subordinated sandstone. The upper unit, the Tucano Formation, consists of fluvial and deltaic sandstone with a maximum thickness of 2200 m. Both syn-rift units interfinger with conglomerate and coarse-grained sandstone derived from footwall erosion along the southeastern faulted margin.

During the Cenozoic, the Tacutu Basin was submitted to a vigorous phase of inversion and structural rearrangement (Eiras and Kinoshita, 1988). The compressional stress field originated by the convergent motion between the South American Plate and the oceanic plates of Cocos, Nazca and the young-lived Caribbean Plate was released in the Tacutu area by transpressional motion along the major bounding faults of the graben. This gave rise to a series of positive features, including reverse faults, large anticlines and prominent flower structures. From the Pliocene onwards, a renewed phase of subsidence has affected the Tacutu Basin (Cordani *et al.*, 1984), that is

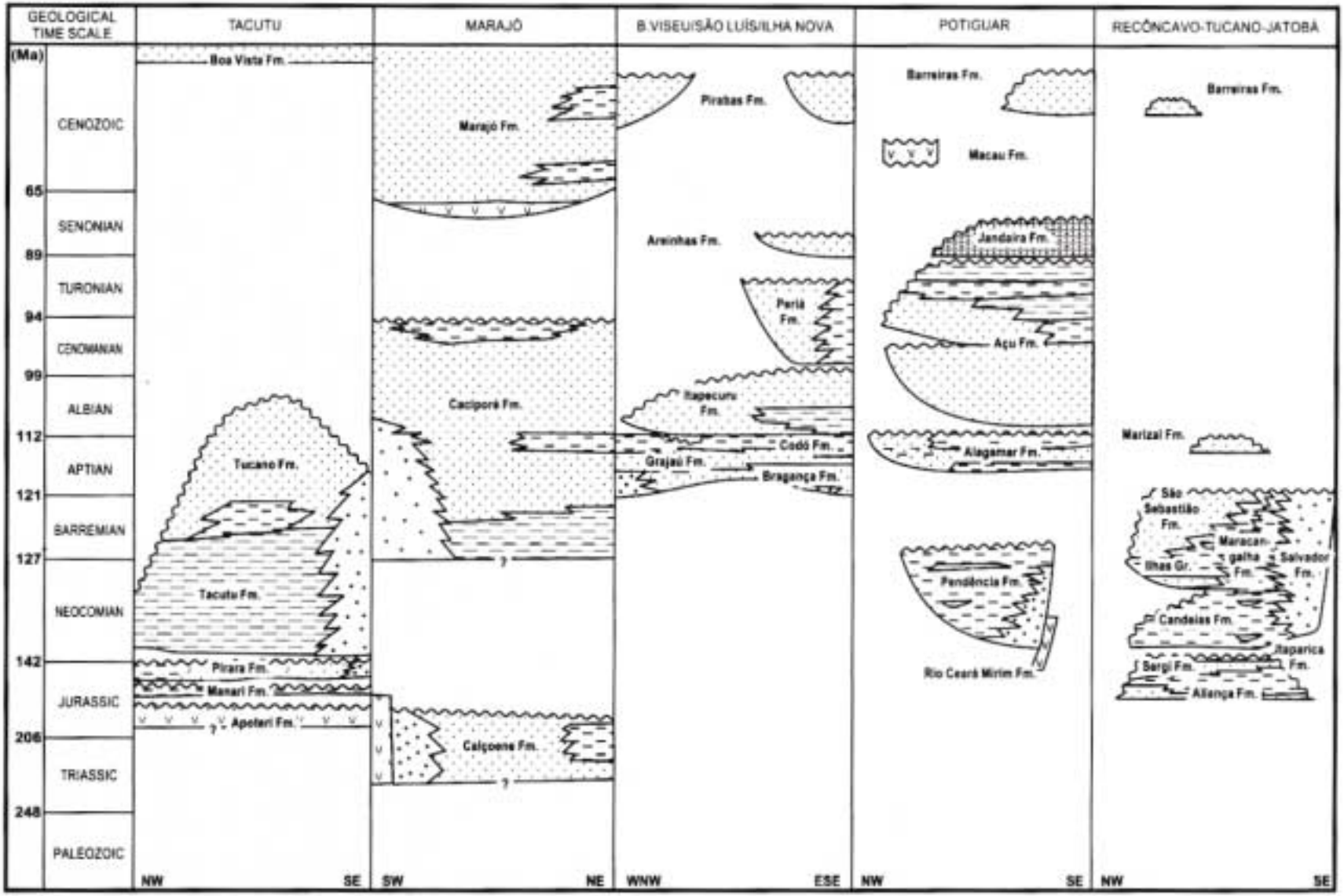


FIGURE 21 - Stratigraphic summary of the failed rift basins in the Brazilian sector of the divergent margin of South America. Chart for the Recôncavo-Tucano-Jatobá basins is representative of the southernmost portion of this rift system, the Recôncavo Basin. Chart for the Marajó Basins is mostly conceptual. Main sources of information were Eiras et al. *(1994b), Tacutu Basin; Lima* et al. *(1994), Bragança-Viseu/São Luís/Ilha Nova Basins; Araripe and Feijó (1994), onshore Potiguar Basin; Caixeta* et al. *(1994), Recôncavo-Tucano-Jatobá basins. Geological time scale simplified after Gradstein and Ogg (1996). Lithological representations are of common use.*

nowadays accommodating the fluvial-lacustrine system of the Boa Vista Formation.

Marajó Basin

The Marajó Basin is situated in the northern-equatorial region of Brazil, in the State of Pará. It is a boomerang-shaped, dominantly inland rift basin with a northeasternmost extension continuing below the Atlantic Ocean (Fig. 9). Its on-shore area is about 52 000 km², mostly in the tropical flooded areas and swamps adjacent to the mouth of the Amazonas River.

The tectonic framework of the Marajó Basin includes three major structural domains or depocenters: the Mexiana, Limoeiro, and Cametá grabens. The Mexiana Graben trends SW-NE and links the onshore basin with the equatorial continental margin of Brazil, exhibiting a full graben profile and a complex pattern of normal and strike-slip faults, folds, and magmatism during the rift phase.

The SE-NW striking Limoeiro Graben is the largest sub-basin of the system, showing a SW dipping half-graben profile with a maximum depth to the basement of about 12 000 m. Large listric normal faults trending parallel to the margins of the basin define its structural framework. These normal faults exhibit large displacements between the adjacent blocks. Such downthrows associated with the low angle of the fault planes create huge gaps in map view, with separations that may surpass 10 km. In its central part, the Limoeiro Graben is marked by strong positive Bouguer anomalies and a regional basement high, both features parallel to the axis of the basin. The Cametá Sub-Basin is the southeastern end of the Marajó Basin, and it lies over a thick sequence of Paleozoic rocks corresponding to the same stratigraphic units that fill up the adjacent Parnaíba interior sag.

The Marajó Basin represents the southernmost extension of the Central Atlantic Rift, and its beginning occurred during the Triassic (Fig. 21), when an extensional tectonic regime dominated the region. However, no biostratigraphic information exists to support this statement, which is based solely on the presence of Late Triassic magmatic rocks as sills and dikes in the region. The initial phase of rifting accommodated a thick sequence of barren, dominantly fluvial and deltaic continental sandy sediments named the Calçoene Formation. A second, and in fact the most important, phase of rifting occurred during the Hauterivian(?)-Aptian interval, imposing a significant rearrangement in the pre-existing framework of the basin. This phase accommodated about 5000 m of sandy sediments in a large fault-bounded trough, a sequence known as the Caciporé Formation. Fault activity decreased with time, and an early sag configuration was achieved during the Cenomanian, when dominantly shaly sediments were deposited. This late rift section lies just below a regional unconformity that marks the change from the second rift stage to fully post-rift tectono-sedimentary conditions (Fig. 22).

The post-rift record, named the Marajó Formation, started in the Maastrichtian, and is also a sandy section of marginal marine fluvial and deltaic sedimentary rocks that filled up a large sag basin. Most of this sequence corresponds to the discharge of the Amazonas River drainage basin during the Cenozoic. Locally, this section exhibits indications of marine influence over sedimentation, such as the presence of planktonic foraminifera and glauconitic sandstone beds.

Bragança-Viseu/São Luís/Ilha Nova basins

The Bragança-Viseu/São Luís basins are located in northeastern Brazil (Fig. 9), in the states of Pará and Maranhão, covering an area of 25 000 km². They constitute an onshore aborted rift system that strikes NW-SE, accompanying the orientation of major structural discontinuities of the Precambrian basement (Aranha *et al.*, 1990). In part, they lodge Paleozoic rocks correlated with those of the adjacent Parnaíba Basin. In the offshore region of the State of Maranhão, the São Luís Basin continues into the Ilha Nova Graben, a WNW-ESE trending basin having an area of about 5000 km². Towards the E the Ilha Nova Basin merges with the Barreirinhas Basin, a segment of the open continental margin of Equatorial Atlantic.

The development of this rift system occurred as a result of an extensional stress field active during Aptian time, related to the opening of the Equatorial Atlantic continental margin. The maximum total depth of the basin is about 5000 m. Tectonics and sedimentation terminated at the end of rifting, and the onshore domain of these basins does not exhibits thermal subsidence phase-related deposits. Right-lateral wrenching, related to the regional sense of displacement between the African and South American plates, affected the Bragança-Viseu/São Luís/Ilha Nova basins during the Albian (Aranha *et al.*, 1990).

The rift phase of the Bragança-Viseu/São Luís/Ilha Nova basins is represented by a succession of clastic sedimentary rocks starting with Aptian grey, medium-grained sandstone with subordinate siltstone and conglomerate beds known as the Bragança Formation (Fig. 21), of alluvial and fluvial depositional systems (Lima *et al.*, 1994). This sequence has a maximum thickness of about 300 m, and is followed by a clastic-evaporitic section of Late Aptian age named the Grajaú and Codó formations, that includes fine-grained sandstone, bituminous black shale, anhydrite and calcilutite beds. The organic content of this section shows indications of an anoxic, transitional marine environment. A sequence of marginal marine, fluvial to deltaic reddish sandstone beds, the Itapecuru Formation, ends most of the stratigraphic record of the Bragança-Viseu/São Luís basins. In the Ilha Nova Basin, sedimentation continued up to the end of the Cretaceous through the Periá and Areinhas formations. This final phase of deposition was related to thermal subsidence. Sandy sediments recurred during the Miocene and constitute the Pirabas Formation.

Potiguar Basin

The onshore Potiguar Basin is situated in the north-easternmost corner of Brazil (Fig. 9). It covers an area of about 22 000 km² and it includes a non-outcropping, confined, aborted graben that strikes NE-SW, and is filled with Neocomian to Aptian sedimentary rocks. These rocks are completely covered by a sequence of sub-horizontal Aptian-Campanian strata of regional extent. The sediments are related to a post-rift sag phase, of which only the Albian-Campanian rocks crop out. Thickness in the centre of the buried rift basin attains 6000 m.

The structural framework of the onshore Potiguar Basin includes depocenters or grabens, internal highs and platforms. The grabens are asymmetric features developed along NE-SW normal faults (Fig. 23), with the basement dipping to the SE against the major boundary faults, the Carnaubais Fault being the most important of these. Block rotation along listric faults created some internal highs between adjacent grabens. Shallow platforms border the deep, confined Potiguar Basin on both its eastern and western sides, and do not include an Early Cretaceous record. E-W trending strike-slip faults affected the basin during the Barremian to Early Aptian. Persistent magmatic activity took place during the rift phase in the Potiguar Basin, creating a diabase dyke swarm along the margins of the basin. These igneous rocks, known as the Rio Ceará-Mirim Formation, span the range of 140 Ma - 120 Ma (Araripe and Feijó, 1994). Magmatic activity in the region of the Potiguar Basin is closely related to the active rifting mechanism and left a characteristic signature of local positive Bouguer anomalies (Milani and Latgé, 1987; Milani, 1991). These anomalies reflect deep-seated intrusive bodies, the E-W orientation of which defines a trend that in a pre-drift reconstruction continues into the Benué Trough in Nigeria (Adighije, 1981).

The rift sequence in the Potiguar Basin, up to 6000 m thick (Fig. 21), is represented by the Pendência Formation, consisting of lacustrine shale, fluvial, deltaic and turbiditic sandstone and conglomerate of Berriasian to Early Aptian age. These beds are confined inside the limits of the central graben, with no outcrops. The top of the sequence is marked by a regional unconformity, and the rift sequence is structurally tilted to the SE.

The Alagamar Formation, of Late Aptian age, covers the rift sequence. It represents the transitional, restricted marine phase of evolution of the basin, and consits of black shale, marlstone and calcilutite beds. This section is covered by fine to coarse-grained sandstone beds and subordinate green shale and red siltstone of Albian-Cenomanian age known as the Açu Formation. The stratigraphic record of the onshore Potiguar Basin includes also the Turonian to Campanian high-energy carbonate beds of the Jandaíra Formation. Eocene-Oligocene magmatic rocks constitute the Macau Formation. The last sedimentary deposits in the basin consist of alluvial sand known as Barreiras Formation, of Miocene age.

Recôncavo/Tucano/Jatobá basins

The Recôncavo-Tucano-Jatobá Rift System is situated in the State of Bahia in the northeastern region of Brazil (Fig. 14). This interior rift system strikes N-S, it is about 500 km long and covers an area of about 46 000 km². The Recôncavo-Tucano-Jatobá Rift System developed together with the initial stages of opening of the South Atlantic during the Neocomian. By the Aptian it became an aborted interior basin when the extensional stress field was concentrated in the adjacent continental margin of northeastern Brazil, and the South American and African plates started to move apart in that area (Lana and Milani, 1986).

The Recôncavo Basin covers an area of about 1 . 500 km² in the southern part of the interior rift system. It is a single graben that strikes in NE-SW, parallel to the Salvador Fault, the major tectonic element that forms the faulted southeastern margin of the rift. The Salvador Horst, situated to the E of the Salvador Fault, is a prominent block where Precambrian granulite is exposed, and separates the interior basin from the offshore Jacuípe Basin. The tectonic framework of the basin includes a set of both synthetic and antithetic NE-SW-trending normal faults that run parallel to the main border, in addition to some NW-SE-striking transfer zones that accommodate the lateral displacement between disrupted crustal blocks (Milani, 1985). The network of faults separates the more stable areas such as the platforms from the subsiding regions. The regional dip of the basement is to the SE. In the main depocenter, the Recôncavo Basin contains about 7000 m of sediments.

Neocomian syn-rift sedimentation in the Recôncavo Basin was preceded by the accumulation of a pre-rift succession of rocks (Fig. 21), indicating the initial, unfaulted stage of crustal stretching. This Late Jurassic pre-rift sequence, or Brotas Group, includes the fluvial-lacustrine red beds of the Aliança Formation and a blanket of grey and reddish fluvial-eolian sandstone, the Sergi Formation. The syn-rift sequence is composed of a dominantly lacustrine shaly section with sediments rich in organic matter and turbiditic sandstone beds in the basal part, included in the Candeias and Maracangalha formations. These beds are followed by prograding sediments forming deltas, the Ilhas Group, and fluvial sandstone beds, the São Sebastião Formation. The Salvador Formation is a thick wedge of conglomerate that occurs adjacent to the Salvador Border Fault (Fig. 24) and interfingers with the other stratigraphic units of the syn-rift sequence. A 250m thick succession of Late Aptian alluvial sedimentary rocks, the Marizal Formation, constitutes the limited vestige of a post-rift record related to thermal subsidence in this basin (Caixeta *et al.*,, 1994).

The Tucano and Jatobá basins cover an area of about 35 000 km², mostly in the arid, flat and dusty region of the *caatinga*, a characteristic biotic and climatic domain in the interior of this region of Brazil. These basins are completely surrounded and underlain by Precambrian rocks of the Atlantic Shield, the lines of structural weakness of which were followed during the Neocomian rifting.

The Tucano Basin is the major N-S striking segment of the rift (Fig. 14). It consists of three sub-basins: Southern, Central and Northern sub-basins, each separated by important transfer zones. Large normal boundary faults, striking in NE-SW, controlled the subsidence of the individual grabens of Southern Tucano and Central Tucano sub-basins, where the basement dips to the SE. The depocenter of Central Tucano Sub-Basin, expressed on gravity data as an impressive -140 mGal anomaly, is the deepest part of the rift system, being filled with over 12 000 m of sediments (Milani, 1987). An important inversion occurs between the Central and Northern Tucano sub-basins, along the Vaza-Barris Arch, and in the Northern Tucano Sub-Basin the basement dips to the W (Santos *et al.*, 1990). The Jatobá Basin is the northernmost, E-W-striking element of this rift system, and there the Ibimirim Fault controlled the subsidence, also due to Mesozoic reactivation of an ancient Precambrian shear zone.

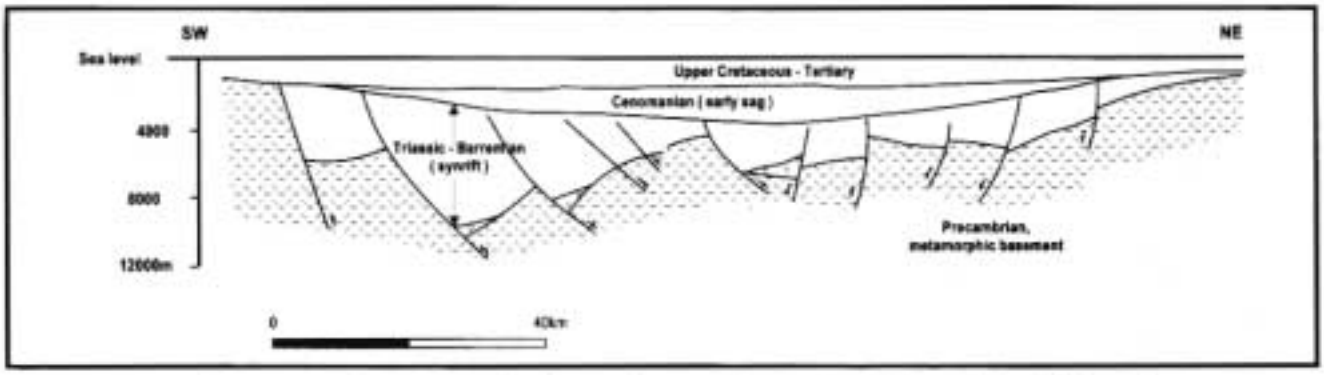


FIGURE 22 - Conceptual cross-section of the Limoeiro Graben, the main depocenter in the Marajó Basin (after Milani and Zalán, 1998).

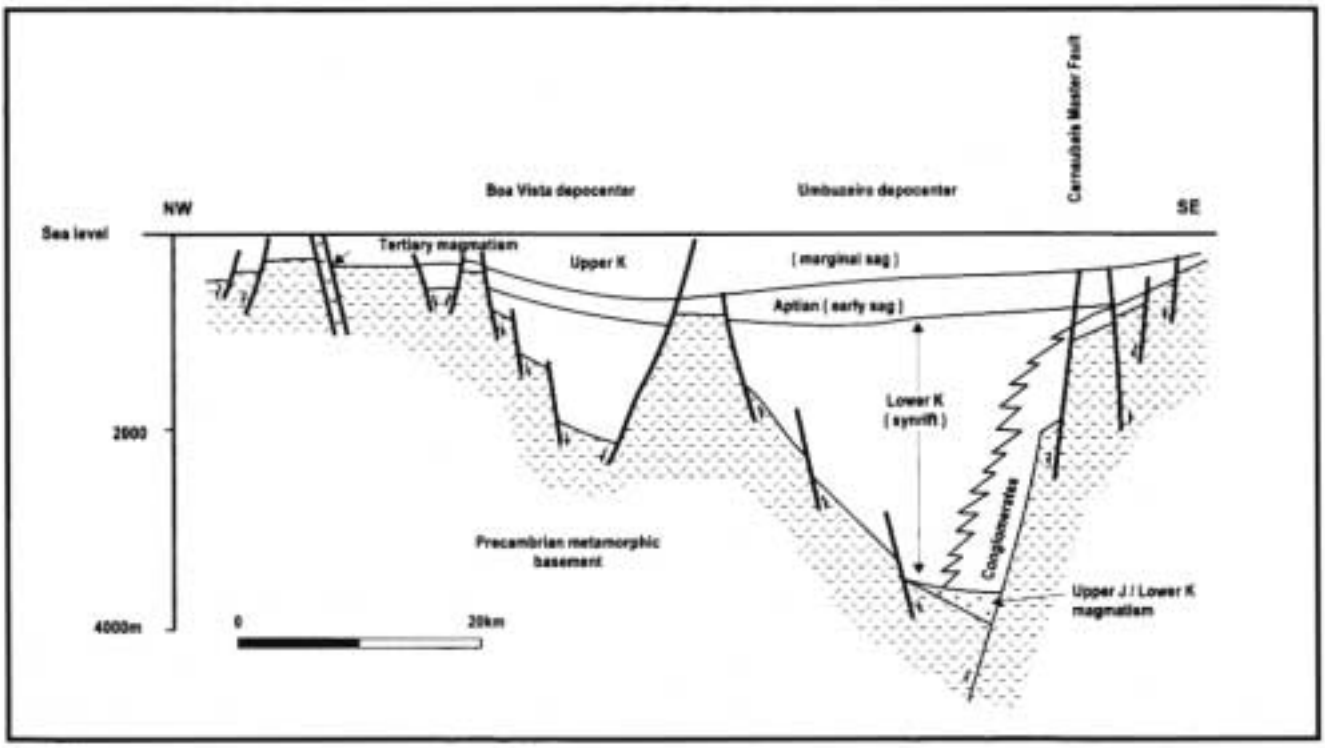


FIGURE 23 - Cross-section of the onshore portion of the Potiguar Basin (after Bertani et al., 1990; permission to reprint granted by the authors).

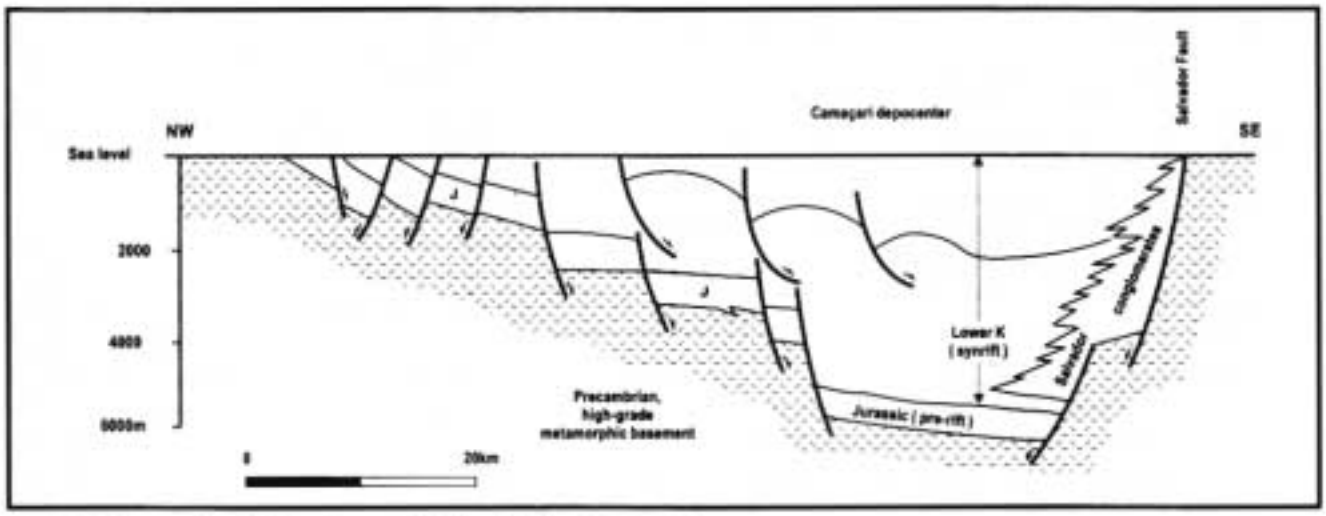


FIGURE 24 - Cross-section of the Recôncavo Basin (after Milani and Zalán, 1998).

Remnants of a previous, widely distributed Paleozoic cratonic sedimentation can be locally found below the Late Jurassic to Early Cretaceous sediments of the Tucano and Jatobá basins (Caixeta *et al.*, 1994), as well as elsewhere in the northeastern region of Brazil. In the Northern Tucano Sub-Basin and Jatobá Basin, Paleozoic strata are thicker and include Silurian to Devonian fluvial sandstone beds of the Tacaratu and Inajá formations, and Carboniferous to Permian sandstone, limestone, and evaporite units and bituminous black shale beds comprising the Curituba, Santa Brígida and Afligidos formations.

Pre-rift and syn-rift sedimentation in the Tucano and Jatobá basins resembles that of the Recôncavo Basin, including the same lithostratigraphic nomenclature. However, remarkable differences exist and are related basically to the overall character of the deposits, with a sandy component being dominant in the northern basins. This regional picture seems to represent the north-to-south sense of progradation of the axial fluvial-deltaic system that filled up the huge Recôncavo-Tucano-Jatobá interior rift system.

Salado Basin

The Salado Basin is located in the Province of Buenos Aires in Argentina, and occupies an area of 85 000 km², about half of it being in the onshore domain. The main axis of the basin is linear, and trends NW-SE, parallel and adjacent to the Rio de La Plata Estuary (Fig. 14).

Seismic information suggests that the basin overlies a sequence of siliciclastic sedimentary rocks of probable Paleozoic age (Tavella and Wright, 1996), equivalent to the sequences found in the inland Chaco-Paraná Basin. The rift stage is interpreted as having started in the Late Jurassic and peaked during the Neocomian, taking advantage of ancient weakness zones in the basement (Stoakes *et al.*, 1991). Volcanic rocks occur associated with the lacustrine sediments of the rift phase and are named the Rio Salado Formation (Fig. 25). These are essentially beds of red sandstone, conglomerate and argillite. A regional, angular unconformity separates the 1200 m thick rift sequence from the following, post-rift section.

The early post-rift sequence, with ages spanning the range Aptian-Senonian, is represented by a sequence of 2000 m of transitional sediments related to a phase of sagging, including alluvial, fluvial and deltaic depositional systems known as the Gral. Belgrano Formation, that interfingers with the shallow marine deposits of the Chilcas Formation. Fully passive margin conditions were reached by the Cenozoic, when the subsidence rate decreased, and the eustatically-controlled sedimentary successions of the Paz and Valeria formations were accumulated. These included platform shales, beds of deltaic sandstone and subordinate carbonate units.

Colorado Basin

The Colorado Basin is situated in the southeastern corner of the Province of Buenos Aires in Argentina, covering an area of about 90 000 km², mostly in the offshore domain (Fig. 14). The axis of the basin trends in E-W and the trough is confined between important positive features, the Rawson High-North Patagonian Massif to the S-SE and the Sierras Australes (or La Ventana Fold and Thrust Belt) to the NW (Fryklund *et al.*, 1996).

The rifting stage in the Colorado Basin started during Late Jurassic to Early Cretaceous times (Lesta *et al.*, 1980), over a basement of Paleozoic sedimentary strata and granitic rocks. The sedimentary basement corresponds to the offshore extension of the Claromecó Basin, a Permian foreland province related to the evolution of the Cape-La Ventana Fold Belt (López-Gamundí *et al.*, 1995).

A classical conglomeratic-sandy-shaly sequence up to 2000 m thick, the Fortín Formation, represents the rift phase in the Colorado Basin (Fig. 25). Its occurrence is confined to half-grabens, the development of which followed the WNW-ESE grain of the La Ventana Fold and Thrust Belt, especially along the northern border of the basin (Juan *et al.*, 1996). Uplift and erosion were important mechanisms during the final stages of the rift phase (Juan *et al.*, 1996).

Albian to Cenomanian siliciclastic sedimentary rocks several thousands of metres thick represent the sag phase, and are named the Colorado Formation, lying unconformably over the rift sequence. Open marine conditions prevailed onwards, starting with the deposition of the shaly sediments of the Pedro Luro Formation, of Cenomanian to Paleocene age. Recurrent tectonic activity is suggested by the presence of the Ranquel flood basalts that are associated with the Pedro Luro beds (Keeley and Light, 1993). A section of intercalating glauconitic sandstone beds and shale accumulated during Eocene times and constitutes the Elvira Formation. These rocks are overlain by the dominantly shaly Barranca Final Formation. Both formations are related to the passive margin stage of evolution of the continental margin of Argentina (Fig. 26).

Rawson/Península de Valdés basins

The Rawson/Península de Valdés basins are two parallel-to-coastline, fully offshore troughs with areas of, respectively, 35 000 km² and 20 000 km², linked along their northern boundaries by a system of E-W trending small grabens (Fig. 14). The Rawson Basin contains some 5000 m of sediments, and the Península de Valdés Basin contains a sequence around 3300 m thick. In like manner to observations made in some of the aborted rift basins of eastern Argentina, the Rawson and Península de Valdés basins overlie Paleozoic sedimentary rocks. In this case these are Silurian and Devonian strata of the Sierra Grand Formation (Yrigoyen, 1989) that dip at about 30° and exhibit the same Jurassic to Neocomian age of rifting observed in correlative basins.

The sedimentary record of the rift stage is made by fining upwards cycles that include basal fluvial sandstone beds grading to argillite (Marinelli and Franzin, 1996). Volcanic rocks of Jurassic age (181±10 Ma, Linares, 1977) are associated with the sequence of red beds that filled the rift basin (Fig. 25). The rift deposits were suceeded by the sag phase sequence, a package of transgressive glauconitic sandstone beds that passes upwards to marine shale, the deposition of which ended by Late Cretaceous times. The Cenozoic section consists of argillite, thin beds of glauconitic sandstone and fossiliferous limestone units. Effusive basaltic bodies of Paleocene age (Yrigoyen, 1989) are also found in the Rawson Basin, and occur along some unconformity surfaces that break the open marine section.

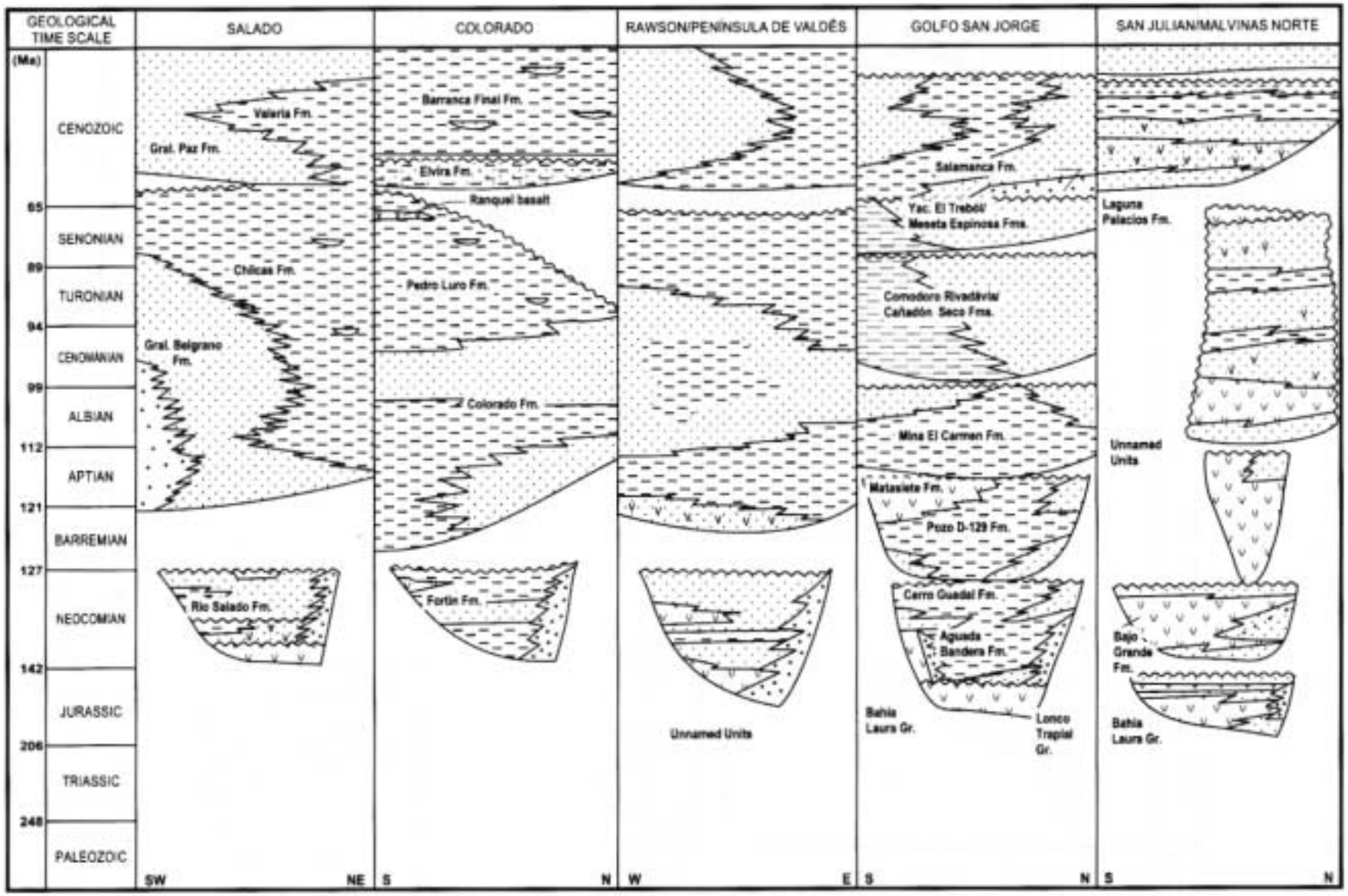


FIGURE 25 - Stratigraphic summary of the failed rift basins in the Argentinean sector of the divergent margin of South America. Main sources of information were Tavella and Wright (1996), Salado Basin; Juan et al. (1996) Fryklund et al. (1996), Colorado Basin; Marinelli and Franzin (1996) Yrigoyen (1989), Rawson/Peninsula de Valdés Basins; Baldi and Nevistic (1996), Golfo San Jorge Basin; Figueiredo et al. (1996) Ross et al. (1996), San Julian/Malvinas Norte Basins. Geological time scale simplified from Gradstein and Ogg (1996). Lithological representations are of common use.

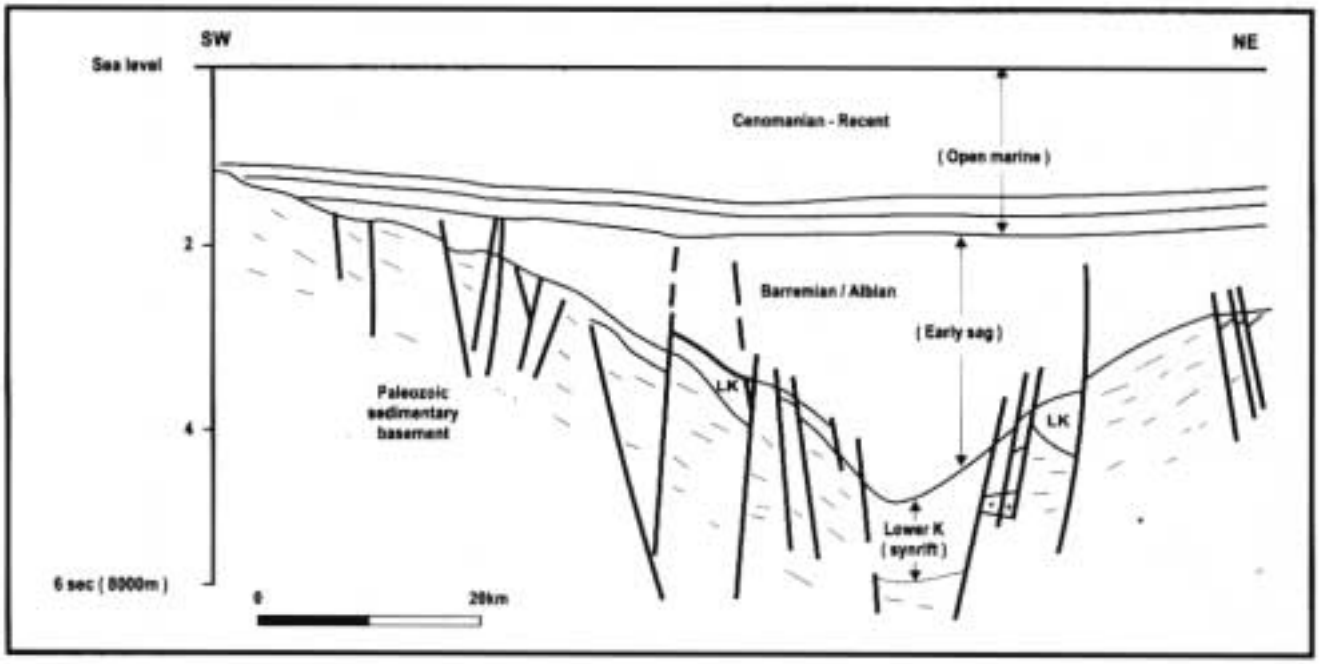


FIGURE 26 - Geoseismic cross-section of the Colorado Basin (based on seismic information and interpretation from Fryklund et al.*, 1996; permission to reproduce granted by Asociación Geológica Argentina).*

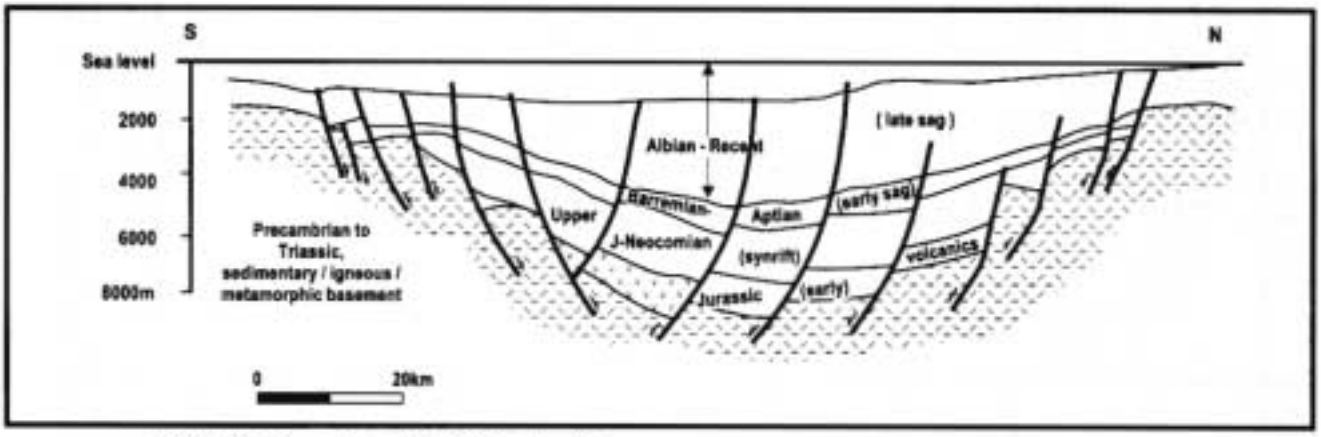


FIGURE 27 - Cross-section of the Golfo San Jorge Basin (after Baldi and Nevistic, 1996; permission to reproduce granted by Asociación Geológica Argentina).

Golfo San Jorge Basin

The Golfo San Jorge Basin has an area of about 170 000 km², being two thirds onshore, and is situated in the central sector of the Argentinean Patagonia (Fig. 14). The limits of the basin are defined by important tectonic elements of southern South America: the Andean Belt to the W, and the N-S-trending Patagonia Oriental High in offshore regions to the E (Urien and Zambrano, 1996). To the S and N, respectively, there occur the cratonic blocks of Deseado and Nord Patagonico. The basin mainly contains Late Jurassic-Cretaceous sediments that attain a maximun thickness of 7000 m, the depocenter being situated in the onshore domain of the basin.

The main extensional structures in the framework of the Golfo San Jorge Basin run E-W. Its tectonic development started during Jurassic time (Baldi and Nevistic, 1996) with the beginning of rifting that created a series of normal fault-controlled depocenters. Magmatism was associated with this initial rift phase. Furthermore, during the Late Jurassic and Early Cretaceous, the rate of mechanical subsidence decreased and the initial isolated depocenters were joined into a single sag basin. From early Cenozoic times onward, the basin experienced a compressional phase related to the Andean Orogeny that produced structural inversion along a series of pre-existing normal faults and a regional positive area in the western part of the basin. This structure is the N-S striking San Bernardo Range. Several changes in sedimentary facies development and distribution also occurred during this phase of structural inversion.

The Golfo San Jorge Basin is filled with siliciclastic, volcanic and volcaniclastic deposits (Barcat *et al.*, 1989). During the Jurassic early syn-rift phase mainly igneous rocks accumulated there, included in the Lonco Trapial Group, in the northern region, and Bahía Laura Group in the southern area (Fig. 25). The 800 m thick lowermost sedimentary sequence, related to the late syn-rift stage, consists of lacustrine shale, rich in organic matter, and fluvial-deltaic sandstone beds named the Pozo D-129, Anticlinal Aguada Bandera, and Cerro Guadal formations (Lesta *et al.*, 1980). The early sag phase accommodated lacustrine black shale beds in the centre of the basin, the Pozo D-129 Formation, that grades laterally into sandstone and volcaniclastic units of the Matasiete Formation.

From Albian times onward, the Golfo San Jorge Basin experienced its late sag phase of evolution, dominated by thermal subsidence (Fig. 27). The Chubut Group represents this stage, and consists of a basal sequence of shale beds grading upward to sandstone deposits, the Mina El Carmen Formation. These beds are followed by a dominantly sandy, fluvial to deltaic section included in the Comodoro Rivadávia and Cañadón Seco formations that developed from N to S (Baldi and Nevistic, 1996). During the final stages of the Cretaceous, the remnants of the sag depositional space were filled up by a progradational succession of sedimentary rocks known as Yacimiento El Treból and Meseta Espinosa formations.

Due to particularly high freeboard conditions towards the domain of the Atlantic Ocean the Golfo San Jorge Basin received its first marine sediments only during the early Cenozoic, and such a marine record is represented by the conglomerate, argillite and sandstone beds of the Salamanca Formation. The rest of the stratigraphic record of the Golfo San Jorge Basin, dominantly of Oligocene to Miocene age, consists of alternating continental sedimentary rocks and transgressive marine beds.

San Julian/Malvinas Norte basins

The San Julian Basin is an offshore trough situated to the SE of the Golfo San Jorge Basin (Fig. 14), on the Atlantic margin of Argentina. It has an area of about 5 000 km², and trends in E-W. The maximum thickness of its volcaniclastic-sedimentary sequence is about 6000 m. The basin developed over the northern border of the Deseado Massif, that is considered an exotic terrane docked against the border of Gondwana during the Late Paleozoic (Figueiredo *et al.*, 1996).

The tectono-sedimentary evolution of the San Julian Basin started with a rift phase of Middle Jurassic age (Fig. 25), when an up to 1400 m of massive tuff beds, brecciated argillite and sandstone with tuffaceous matrix were accumulated. These beds are known as the Bahia Laura Group, and they are exposed in the inland Patagonia area. They have been dated at 168±2 Ma to 170±4 Ma by Rb/Sr method (Rapela and Pankhurst, 1994).

The Bajo Grande Formation that follows is still dominated by volcaniclastic rocks and is of Late Jurassic-Neocomian age. According to Figueiredo *et al.* (1996), it corresponds to a phase of sagging with some remnant activity of the major boundary faults. Tuff beds derived from subaerial ash flows, including glass shards and exhibiting fine vitric textures mainly represent sedimentation during this phase. This unit and the previous one were involved in post-depositional compressional deformation of Cretaceous age, caused by stresses developed along the Malvinas (Falklands) Fault Zone during the early stages of drifting of South America to the W. This resulted in an angular unconformity separating the Neocomian sequence from the flat-lying Maastrichtian sediments. The Maastrichtian sediments, named Laguna Palacios Formation, are likewise tuffaceous and about 100 m thick.

Prograding, siliciclastic sedimentation started in the Paleocene with the first marine incursion, and covered almost completely the San Julian Basin during the Cenozoic. The tectonic environment became very quiet, but some minor reactivation of border faults occurred. These were probably related to the Miocene Andean movements along the western border of the continent.

The Malvinas Norte Basin occupies an area of about 30 000 km² and is situated to the N of the Malvinas (Falklands) Islands, in the off-shore region of southern Argentina (Fig. 14). It is a Y-shaped, NNW-SSE-trending system of grabens accommodating a still undrilled sequence having a maximum thickness, estimated by seismic data, of about 9000 m. Based on lithological information from the San Julian Basin, located some 350 km to the NW, the sediments of the Malvinas Norte Basin are interpreted to be of siliciclastic-volcaniclastic nature, and the main aspects of its tectono-sedimentary-magmatic evolution seem to closely resemble those of the adjacent trough.

Andean, Convergent Margin

Back-arc flexural basins

Phanerozoic foreland basin evolution in South America has been closely related to the development of its western, active margin. A convergent relationship between the former western Gondwana continent and the oceanic floor of Panthalassa is recognized back in time as far as the Late Proterozoic (Ramos, 1988; Bahlburgh and Breitkreuz, 1991; Gohrbandt, 1993). Flexural subsidence in different sectors of this compressional domain remained active during almost all the time, providing the space for accumulation of sediments at various time-intervals during its Phanerozoic geological history.

The sub-Andean foreland basins, related to the climax of Andean orogenic deformation and adjacent flexural subsidence, developed in the late Cenozoic. The sub-Andean setting is a continent-size geological domain spanning from Venezuela in the N, to Tierra del Fuego, in the southernmost tip of Argentina. Regional arches, trending perpendicular to the Andean Belt and defining individual basins locally interrupt the continuity of this foreland trough. However, specific and local names of basins and sub-basins do not always represent naturally individualized provinces; in some cases, they correspond to particular denominations adopted by only one of the various Andean countries that share this large province.

Considering the existing main tectonic limits, the sub-Andean domain is divided into four large provinces (Fig. 28). The northernmost extends from Venezuela to Colombia and corresponds to the Llanos-Barinas-Apure Basin. It is limited to the S by the Macarena Arch. The second province includes regions from southern Colombia, Ecuador, Peru and westernmost Brazil, and is known by the local names including the Putumayo, Oriente, Marañon, Ucayali and Acre basins. This province terminates to the S at the Fitzcarrald High. The third province is the Central Andean domain, and corresponds to southernmost Peru, Bolivia, northwestern Argentina and a small fraction of Brazil. The Madre de Dios-Beni-Chaco Basin dominates this region. The fourth province developed mostly in the Argentinean-Chilean Patagonian region includes the Neuquén and Austral basins, as well as smaller depocentres such as the Ñirihuau Basin (Cazau *et al.*, 1989).

The Phanerozoic, pre-Andean history of the Panthalassan margin of Gondwana also recorded several episodes of basin formation, occupying certain periods of time. Permian-Carboniferous foreland basins including Tarija, Calingasta-Uspallata, Paganzo, San Rafael and Claromecó (López-Gamundí *et al.*, 1994), and older basins such as the Silurian-Devonian depocenter in the Precordillera of Argentina (Ramos, 1993), had their evolution linked to tectonic loading and lithosphere flexure of specific sectors of the southwestern margin of Gondwana (Milani and Ramos, 1998).

Pre-Andean Foreland basins

Tarija-Noroeste Basin

The Tarija-Noroeste Basin is a large sedimentary basin containing a thick sequence of Paleozoic sediments, and covering an area exceeding 200 000 km^2. It covers parts of southeastern Bolivia and northwestern Argentina, and the Paraguayan Chaco. (Wiens, 1995). The stratigraphic succession of this region of South America represents an almost complete record of the Phanerozoic history of the western margin of Gondwana (Sempere, 1995). During most of this time, and in spite of being positioned adjacent to the active margin of the plate, the region behaved as a relatively stable platform having gentle dips towards Panthalassa, with minor compressional deformation associated. The existence of a very rigid basement, of cratonic nature, might be a reasonable explanation for the resistance of this particular realm.

Some of the Paleozoic tectonic episodes that affected the borders of the region and determined the main characteristics for each tectono-sedimentary cycle of deposition were remarkable. During Cambrian and Ordovician times, this domain behaved as a large back-arc margin open to the W (Starck, 1995), but this phase was interrupted by the Ocloyic Orogeny, of Late Ordovician age (Ramos, 1988). There followed a Silurian-Devonian foreland phase of sedimentation that ended by an episode of folding and basin inversion during the Late Devonian-Early Carboniferous that is known as the Chanic Orogeny.

The Permian phase of deposition accompanied the evolution of the Aymara Tectonic Cycle (França *et al.*, 1995), when the growth of the Choiyoi Magmatic Arc to the W progressively constrained the marine incursions upon the foreland domain. The Mesozoic was a time of widespread development of extensional basins (Starck, 1995), up to the early Cenozoic, when the transition to a renewed compressional regime and inversion of previous rift structures marked the beginning of the Andean Foreland Cycle in this domain. The remnants of the still undeformed Tarija-Noroeste Basin lie today in the sub-Andean flats of Bolívia and north western Argentina.

The Phanerozoic stratigraphic record of this region (Fig. 29) was summarized by Sempere (1995), for the Bolivian sector; by Wiens (1995), for the Paraguayan Chaco; and by Starck (1995), for the Argentinean Noroeste region. The sedimentary sequence in most of the Bolivian Tarija domain begins with a marine transgression, represented by the Upper Cambrian to Lower Ordovician strata of the Tacsara Supersequence that accumulated in a back-arc, NW-SE trending extensional trough (Sempere, 1995). These beds are followed by the Chuquisaca Supersequence, spanning the Late Ordovician to Middle Famennian. The lower part of this supersequence contains marine black shale in the Tokochi Formation, diamictite beds in the Cancañiri Formation, and a turbidite sequence about 1500 m thick, included in the Llallagua Formation. The upper part of the Chuquisaca Supersequence, of Silurian-Devonian age, consists of a blanket-like body of sediments and is represented by three major coarsening upwards cycles. Maximum flooding levels are represented by the shaly intervals of the Kirusillas, Chululuyoj, Icla and Los Monos formations. Remarkable regressive sequences are those of

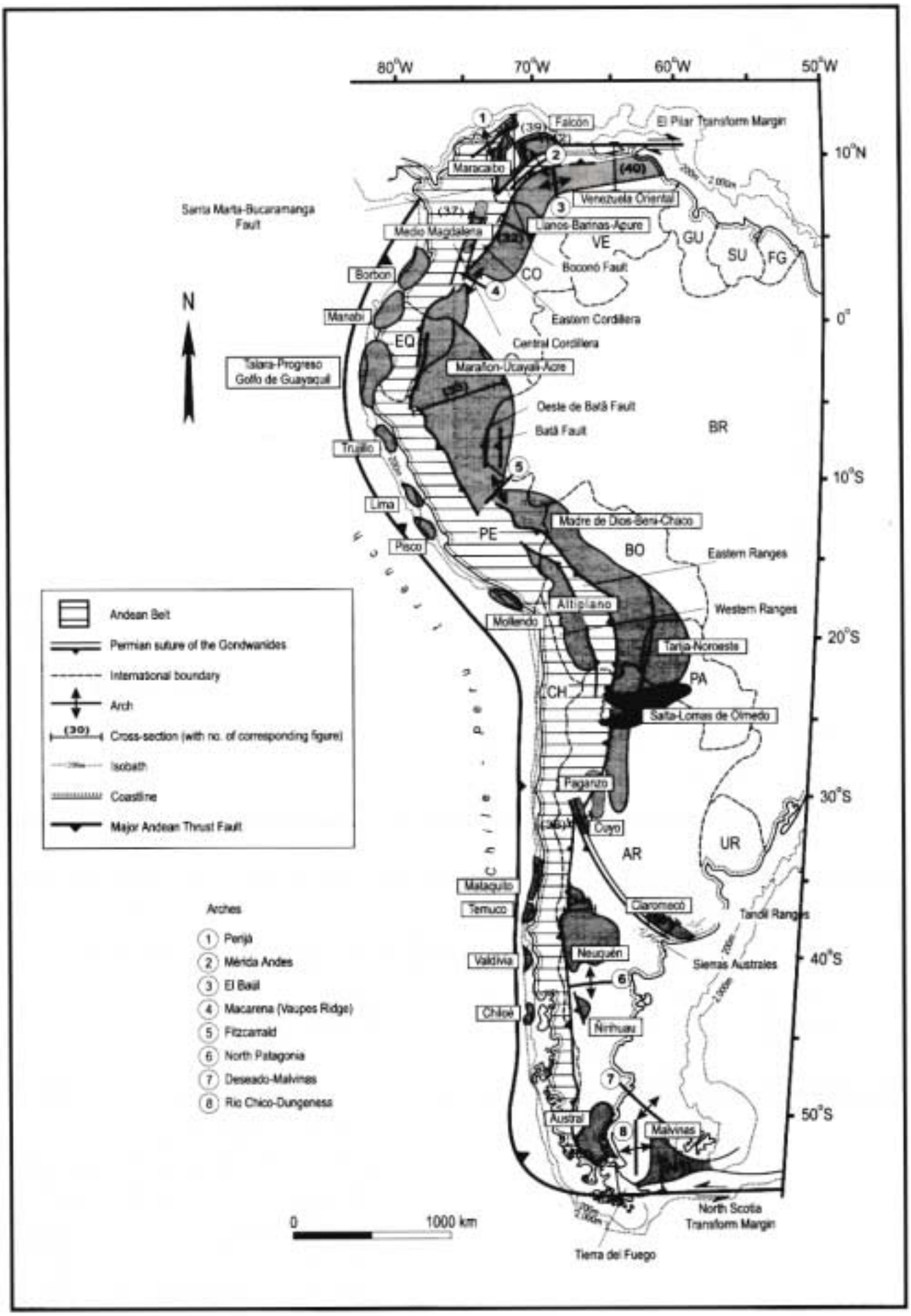
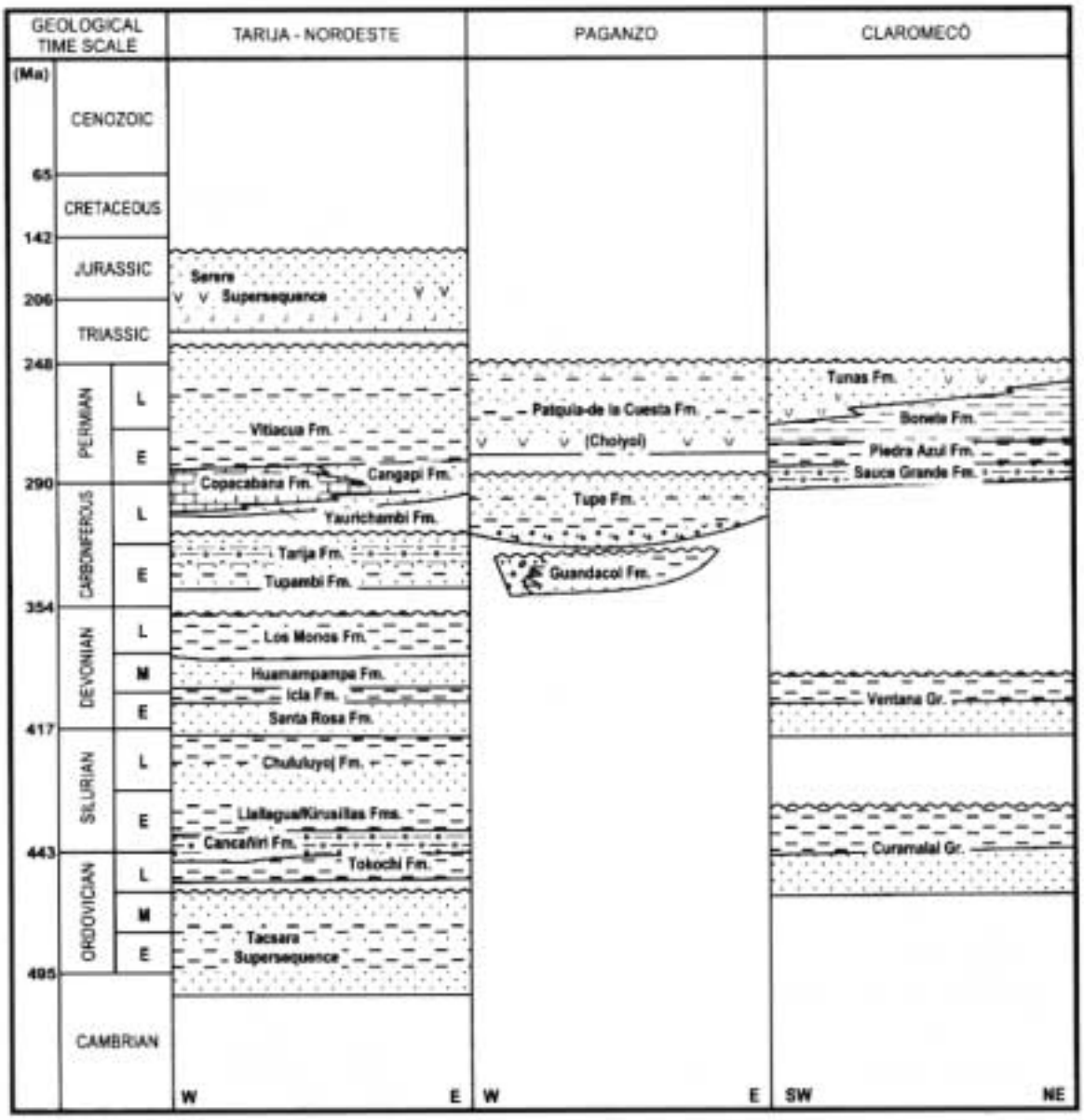


FIGURE 28 - The Andean Convergent Margin, and the Northern and Southern transform margins of South America (compiled from various sources). Countries: see Fig. 2.



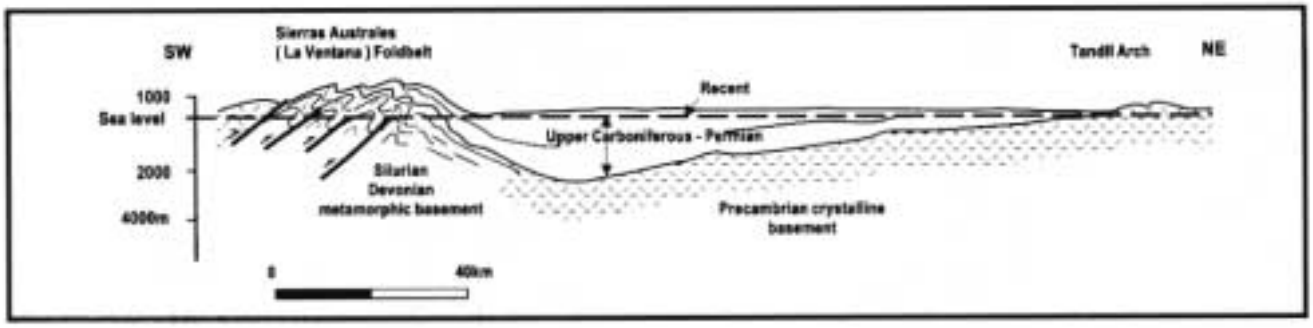


FIGURE 29 - Stratigraphic summary of some of the pre-Andean foreland basins in South America. On each chart, the folded belt margin is to the left. Main sources of information were Sempere (1995), Wiens (1995), Starck (1995), Tarija-Noroeste Basin; Fernández-Seveso and Tankard (1995), Paganzo Basin, López-Gamundí et al. (1994, 1995), Claromecó Basin. Geological time scale simplified from Gradstein and Ogg (1996). Lithological representations are of common use.

FIGURE 30 - Cross-section of the Claromecó Basin (after López-Gamundí et al., 1994; permission to reproduce granted by the Geological Society of America).

the Santa Rosa and Huamampampa formations.

The accumulation of the basal beds of the Gondwana succession during the Carboniferous marked the beginning of a clear tendency for development of continental environments. This continued throughout the Paleozoic and into the Mesozoic. Resedimentation and some factors related to the great Gondwanan glaciation, together with tectonic activity, were important mechanisms in the accumulation of the Carboniferous sediments. These are represented by the Tupambi and Tarija formations. In contrast, subtropical climate and tectonic quiescence led to the deposition of the carbonate platform sediments of the Copacabana Group during the Pennsylvanian. These limestones grade southeastwards into the sandy continental sediments of the Yaurichambi and Cangapi formations. Kungurian black shale of the Vitiacua Formation mark the last marine incursion in this area during the Paleozoic. The Carboniferous-Permian section is also known as the Cuevo Supersequence (Sempere, 1995).

From Triassic times onward, continental red beds, evaporites and associated basaltic flows and intrusions of the Serere Supersequence marked the regional stratigraphic scenario, a succession that culminated in the extensive Jurassic eolian deposits of the Ichoa Formation. This section corresponds, in part, to the Tacuru Supersequence of Starck (1995). In latest Jurassic time, this area was affected by large-scale rifting related to the initial stages of the Andean Orogeny. The Cenozoic development of the region includes the development of subsidence in the Chaco Basin. This subsidence is closely related to the growth of the Andean Chain as the result of progressive compressional deformation along the western side of the Tarija Basin and the consequent creation of a foredeep for the accumulation of several thousands of metres of terrestrial beds up to Recent times.

Paganzo Basin

The Paganzo Basin occupies about 30 000 km^2 of west-central Argentina (Fig. 28), and contains some 4500 m of Carboniferous to Permian sedimentary rocks. The basin developed over a pre-Carboniferous sedimentary basement that was deposited upon a mosaic of crustal blocks welded together during the Late Proterozoic-Cambrian Brasiliano Orogeny (Ramos, 1988). This framework of sutures in the basement provided the main lines of weakness along which the Paganzo Basin formed during the Mississipian.

The main characteristics of Lower Paleozoic sedimentary basins along southwestern Gondwana, including their dominantly marine nature, were modified by the Late Devonian-Early Carboniferous Chanic Orogeny. This intense tectonic episode is marked throughout the continent by an important hiatus, and was succeeded by the accumulation of dominantly continental deposits (Fernández-Seveso and Tankard, 1995). In the region of the Paganzo Basin, the Chanic movements were responsible for major folding and faulting of the pre-Carboniferous sedimentary basement (López-Gamundí *et al.*, 1994).

To a certain extent, the Paganzo Basin owed its origin to the Chanic stress field, by means of transtensional reactivation of weakness zones deeply-seated in the fabric of the basement. Towards the W, the Paganzo depocenter was linked to a persistently marine N-S trending trough known as the Calingasta-Uspallata and San Rafael basins (López-Gamundí *et al.*, 1994), a foredeep flexural domain adjacent to the Chanic Orogen.

The lowermost stratigraphic record of the Paganzo Basin consists of syntectonic deposits containing a Visean flora (Fig. 29). This unit, the Guandacol Supersequence (Fernández-Seveso and Tankard, 1995) is about 2000 m thick, and includes coarse-grained sedimentary rocks adjacent to basin-boundary faults and classical distal turbiditic systems; rhythmic lacustrine shale and siltstone beds with local dropstones also occur and are suggestive of a periglacial environment during Visean-Namurian times.

The initial geometry of isolated depocenters evolved to a widespread, uniformly subsiding flexural depression during the deposition of the second unit, the Tupe Supersequence, and this change in subsidence style is marked by an important unconformity. These Westphalian-Stephanian sediments are some 1300 m thick and are composed of four progradational sequences representing fluvial, lacustrine and marginal marine depositional environments, reflecting a pattern of transgressive-regressive cycles of sedimentation. A third pattern of subsidence in the Paganzo Basin is recorded by the Patquía-de la Cuesta Supersequence, mainly of Late Permian age, when the depositional area expanded even more than during Tupe deposition. The basin assumed a style of shallow epeiric sag, almost without relief, and this configuration persisted up to the beginning of the Triassic.

The Patquía-de la Cuesta Supersequence consists of continental red beds including fluvial and playa lake facies up to 1300 m thick deposited in a shallow marine basin, the remnants of the "Tupe Sea" (Fernández-Seveso and Tankard, 1995). Pyroclastics and magmatic flows related to the Choiyoi episode occur at the base of the unit. Some beds with bituminous black shale occur in the Late Kungurian-Kazanian section, indicating a time of rising of sea level. This sequence, as well as the record of the whole Paganzo Basin, terminates with a major unconformity that cuts deeply into the pre-existing deposits. This erosional surface is related to the extensional tectonics that created the successor, Triassic back-arc rift basins of western Argentina.

Claromecó Basin

The Claromecó Basin, also known as Sauce Grande Basin or Ventania Paleozoic Basin, is situated in the Province of Buenos Aires, Argentina. The basin covers an area of about 40 000 km^2 (Fig. 28). This onshore Carboniferous-Permian basin occurs between two prominent structural highs, the Sierras Australes Fold and Thrust Belt to the SW and the Tandilia Arch to the NE. To the SE it sinks below the younger sequences of the offshore Colorado Basin.

The pre-Carboniferous units in the Claromecó Basin area are represented by Precambrian igneous and metamorphic basement rocks and by Early Paleozoic sedimentary successions. The sedimentary rocks are included in two major units (Fig. 29). The first is the Curamalal Group of probable Ordovician-Silurian age, and the second is the Ventania Group of Devonian age (Harrington, 1947, *apud* López-Gamundí *et al.*, 1994). The sediments of both these groups have a total thickness of

about 2000 m. They were deposited along the pre-Carboniferous margin of Gondwana open to Panthalassa. The top of this sequence is marked by a gentle regional angular unconformity (Massabie and Rossello, 1984).

The Latest Carboniferous to Late Permian Pillahuincó Group is up to 4500 m thick, and represents the sedimentary accumulation in the Claromecó Basin. These sediments consist of a quartzose, dominantly diamictitic unit at the base, the Sauce Grande Formation, that may reach a thickness of 1100 m, and which exhibits paleocurrents that indicate a provenance from the cratonic areas to the NE. The unit grades to a shaly sequence, the Piedra Azul Formation that continues into the bioturbated shale and sandstone beds of the Bonete Formation. The Bonete Formation is an important stratigraphic marker of regional significance due to the presence of the *Eurydesma* fauna of Early Sakmarian (Tastubian) age.

The following unit, Tunas Formation, shows some contrasting characteristics with respect to the underlying sediments. The sediments are less quartzose and the southwestern provenance indicated by paleocurrents (López-Gamundí *et al.*, 1994), together with the presence of tuffaceous beds, intercalated with the Permian red beds, indicate magmatic activity in the surrounding areas as well as uplift of Sierras Australes to the SW. These sediments provided the detritus to fill this syn-tectonic foreland trough (Fig. 30). Rapid subsidence accommodated the 1500 m of the Tunas Formation close to the orogenic front. A final compressional phase of deformation in the area occurred already in the Triassic, that also involved the sediments of the Tunas Formation.

Andean Foreland basins

Llanos-Barinas-Apure Basin

The Llanos Basin is situated in northeastern Colombia, and it lies to the E of the Andean frontal thrust (Fig. 28). In the neighbouring Venezuela it is named Barinas-Apure Basin, and has a total area of about 200 000 km^2. The Llanos Basin is a classical example of a complex, foreland multi-cycle basin, the development of which started in the Triassic-Jurassic. The main tectonic events that influenced its evolution are related to the convergent plate setting of the western margin of South America.

Cooper *et al.* (1995) defined the major stages in the evolution of the Llanos Basin, including a Triassic-Jurassic rift phase followed by a phase of periodic extension in a back-arc setting during Barremian to Maastrichtian times. The onset of the pre-Andean foreland subsidence occurred in the early Paleocene and continued up to the early Miocene, but was interrupted by a phase of compressional deformation in the middle Eocene. The middle Miocene marked the settlement of the Andean-related foreland subsidence, and from the late Miocene onwards, the Llanos Basin underwent compression and inversion related to the development of the frontal fold and thrust belt of the Eastern Cordillera.

Sediment accumulation in the Llanos Basin followed a progressive eastward migration of the depocenter during the Cenozoic (Fig. 31), with the strata onlapping the Guiana Shield. As a consequence, the stratigraphic record is more complete in the western Llanos region. In most of the area, Upper Cretaceous strata directly overlie Paleozoic sedimentary and metamorphic basement.

The sediments of the Llanos Basin include a marine sequence of Cenomanian-Campanian age. The succession starts with shallow marine and shoreline sandstone beds at the base that form the Une Formation. Black shale beds, rich in organic matter, of Turonian-Early Coniacian age cover these basal units. There then follow beds of black shale, chert and phosphate layers, the Gacheta Formation. Regressive sandstone and shale beds of the Guadalupe Formation represent the end of this first transgressive marine sequence.

A second stratigraphic sequence was deposited during the late Paleocene, overlying the wide unconformity surface that marks the top of the underlying sequence (Cooper *et al*, 1995). This cycle is represented by beds of transgressive sandstone of the Barco Formation that grade to muddy coastal plain deposits known as the Los Cuervos Formation. The following transgressive cycle that started in the middle-late Eocene accumulated another succession with sedimentological style similar to the previous one, known as Mirador Formation, and including coastal, highly mature quartzarenite deposits.

From Oligocene times onward, four major cycles of marine-influenced coastal plain deposits were deposited, included in the Carbonera Formation (Cooper *et al.*, 1995), each bounded by surfaces of regional marine flooding. Onlap towards the Guiana Shield, the source area to the SE, made the units progressively sandier in that direction.

During middle Miocene time, compressional deformation in the orogenic belt increased, resulting in higher subsidence rates and in a rise of relative sea level, providing conditions for deposition of mudstone beds of the León Formation, and marking the Andean foreland basin phase (Fig. 32). In the late Miocene, a second source area was developed to the W, with the emergence of the Eastern Cordillera. The final phase of sedimentation in the Llanos Basin was the accumulation of molasse deposits. The deposition of some 3000 m of coarse grained continental clastic sediments, the Guayabo Formation, accompanied the positioning of the Andean front to its present situation.

Marañon-Ucayali-Acre Basin

The Marañon-Ucayali-Acre Basin, also known by the local names of the Putumayo, Napo, Santiago, Huallaga, Ene, and the Oriente Basin of Ecuador, is a very large foreland sedimentary province, comprising an area exceeding 900 000 km^2 (Fig. 28) and recording a long history of basin development that spans almost all the Phanerozoic Eon. A thick sequence of Paleozoic sedimentary rocks is included in the stratigraphic record of this area. The present day asymmetric geometry of the basin reflects late Cenozoic deformation. The western margin of the basin is marked by a line of thrust faults affecting Mesozoic sedimentary rocks that defines the eastern limit of the Andean Mountain Chain. Uplift of the Andean Belt has provided about 4000 m of continental clastics sediments to the basin. To the E, the Cretaceous to Cenozoic sedimentary sequence, as well as almost all the older sequences, wedge out over the Central Brazil Shield.

The Brazilian extension of this foreland domain, the Acre Basin, shows a structural framework defined by a set of N-S reverse faults and inverted normal faults (Oliveira,

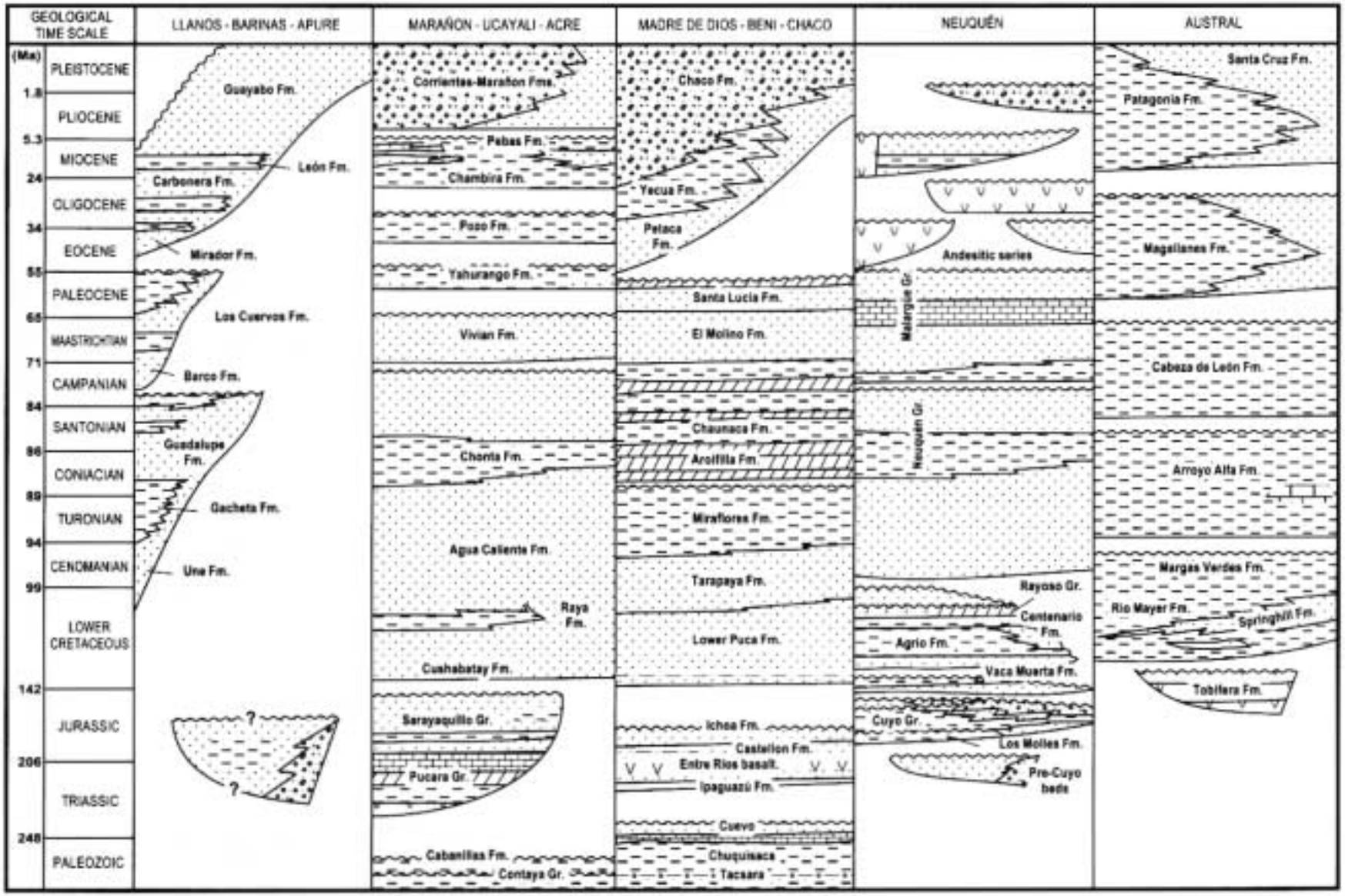


FIGURE 31 - Stratigraphic summary of the Andean foreland basins in South America. On each chart, the folded belt margin is to the left. Chart for the Marañon-Ucayali-Acre is representative of the western domain; towards the east, in the Acre Basin, most of the units pinch out over the Brazilian Shield. Main sources of information were Cooper et al. *(1995), Llanos-Barinas-Apure Basin; Mathalone and Montoya (1995), Marañon-Ucayali-Acre Basin; Sempere (1995), Madre de Dios-Beni-Chaco Basin; Vergani* et al. *(1995), Neuquén Basin; Robbiano* et al. *(1995), Austral Basin. Geological time scale simplified from Gradstein and Ogg (1996). Lithological representations are of common use.*

1994). The most prominent of these, the Batã Fault defines a hingeline that is the eastern termination of the Paleozoic-to-Jurassic sedimentary sequence. The other important fault, the Oeste de Batã Fault, marks the western border of the depressed Acre Basin and extends to the foot of the Serra do Divisor to the W, the uplifted footwall of this west-dipping reverse fault. These hills attain significant topographical expression locally and form the international frontier between Peru and Brazil. In the depocenter of the Acre Basin the crystalline basement lies some 6000 m below the surface.

The Precambrian basement provided the major lines for Phanerozoic basin evolution in this area. Along the western margin of Gondwana, accretion of continental fragments designed a fabric of sutures that has been repeatedly reactivated through time. In the region of the Marañon Basin, a NW-SE trend of Precambrian structures defines the grain on which the basin evolved (Mathalone and Montoya, 1995). The oldest Paleozoic rocks that overlie the basement are the marine Ordovician strata up to 1000 m thick. These beds are known as the Contaya Group (Fig. 31), and include sandstone and shale beds, rich in organic matter. Silurian times were basically erosive. Sedimentation continued during the Devonian with the deposition of the dominantly shaly Cabanillas Formation, about 1600 m thick. The Chanic Orogeny of Late Devonian-Early Carboniferous age defined a regional lacuna in the stratigraphic succession of the Marañon Basin, as well as in several basins of South America (Urien *et al.*, 1995). To some extent the ancient lines of crustal weakness were reactivated during the Chanic Orogeny to cause subsidence and sediment accumulation.

The Carboniferous sequence started with the fluvial clastic deposits of the Ambo Group, including conglomerate, sandstone and shale beds with associated coal seams and volcaniclastic deposits. This is followed by the transgressive, mixed siliciclastic-carbonate sediments the Tarma Formation (Westphalian). The sediments evolved from the Westphalian trough Early Permian times into the large carbonate platform of the Copacabana Group, the sediments of which grade laterally to evaporite beds. The sea retreated during the Late Permian, and a sequence up to 600 m thick of shale, rich in organic matter, was deposited. These shale beds are assigned to the Ene Formation, and they accumulated under hypersaline conditions. By the end of the Permian, regional uplift provided abundant source areas for the continental clastic sediments of the Mitu Group, including volcaniclastic beds, that occupied extensional, fault-bounded depocenters (Mathalone and Montoya, 1995). Regional erosion and abundant volcanic activity took place in the area of the actual Andean Belt during Late Permian and Early Triassic.

Particularly in the Acre Basin of Brazil, the Paleozoic record includes a major unit, known as the Carboniferous-Permian Sequence (Feijó and Souza, 1994). The existence of a Devonian section in the Acre Basin is inferred from seismic data. The Carboniferous-Permian Sequence begins with the coarse-grained clastic wedge of the Apuí Formation, succeeded by beds of bioclastic calcarenite, white anhydrite, shale and calcilutite, known as the Cruzeiro do Sul Formation. These beds carry a palynological content of Early Permian age. A Late Permian section of grey sandstone and shale beds named the Rio do Moura Formation, closes the stratigraphical record of this sequence.

The Mesozoic history of sedimentation in the Marañon-Ucayali-Acre Domain started with the transgressive marine Pucara Group, spanning the range Late Triassic to Early Jurassic. A package of evaporite and carbonate beds with shale beds, rich in organic matter, accumulated in an asymmetric, deepening-to-the-west basin. These marine beds are covered by a section of continental red beds known as the Sarayaquillo Formation, of Jurassic age and, contrary to the geometry observed for the Pucara Basin, the Jurassic beds thin to the W indicating the uplift of Proto-Andean Mountains. In the Acre Basin, some 3000 m of sediments accumulated during the Jurassic, including fine-grained yellow sandstone units and red beds intercalated with beds of white anhydrite, halite and basalt flows, known as the Juruá-Mirim Formation. The pre-Cretaceous sedimentation ended with a regional unconformity related to the Nevadan event (Mathalone and Montoya, 1995).

The Cretaceous development in this area was recorded as a westward-thickening wedge of siliciclastic rocks including two major transgressive-regressive cycles of deposition. The Cretaceous sequence begins with the marine sandstone beds of the Cushabatay Formation. This basal unit is overlain by an Albian shaly package rich in organic matter, assigned to the Raya Formation and about 300 m thick. The Albian to Early Turonian Agua Caliente Formation consists of coarse-grained and fine-grained sandstone bed and fossiliferous black shales.

Major Cretaceous transgressive conditions were attained during Coniacian-Early Santonian times, when the shaly Chonta Formation was deposited. This unit is well developed in the northern part of the Marañon Basin of Peru and its prolongation in Ecuador, the Oriente Basin, where the black shale beds are called the Napo Formation. To the S and the E, the entire Cretaceous record consists of continental deposits. The Vivian Formation, a regressive unit of Campanian fluvial to coastal sandstone, closed the Cretaceous cycle of deposition. Maastrichtian, transgressive marine beds are of local occurrence, particularly in the Ucayali depocenter, and this is believed to have been controlled by regional erosion during the Peruvian Tectonic Cycle of Late Cretaceous age.

The Cenozoic history of this region accompanied the evolution of the Andean Fold and Thrust Belt, and received about 4000 m of continental sedimentary rocks (Fig. 33). These sediments are distributed as a westward-thickening wedge including the Yahuarango Formation (Paleocene), the Pozo Formation (upper Eocene-lower Oligocene), the Chambira Formation (upper Oligocene-lower Miocene), the Pebas Formation (upper Miocene) and the coarse-grained sediments of the Corrientes/Marañon formations (Pliocene). In the Acre Basin, Cretaceous to Cenozoic times added about 3000 m of continental clastic sediments to its stratigraphic record (Milani and Zalán, 1998).

Madre de Dios-Beni-Chaco Basin

This large part of the Andean foreland domain extends between the latitudes of 10°S and 30°S, including two segments about 1300 km long each. The northernmost segment strikes in NW-SE and the other, situated to the S, strikes N-S. They join at Santa Cruz deflection at the Bolivian

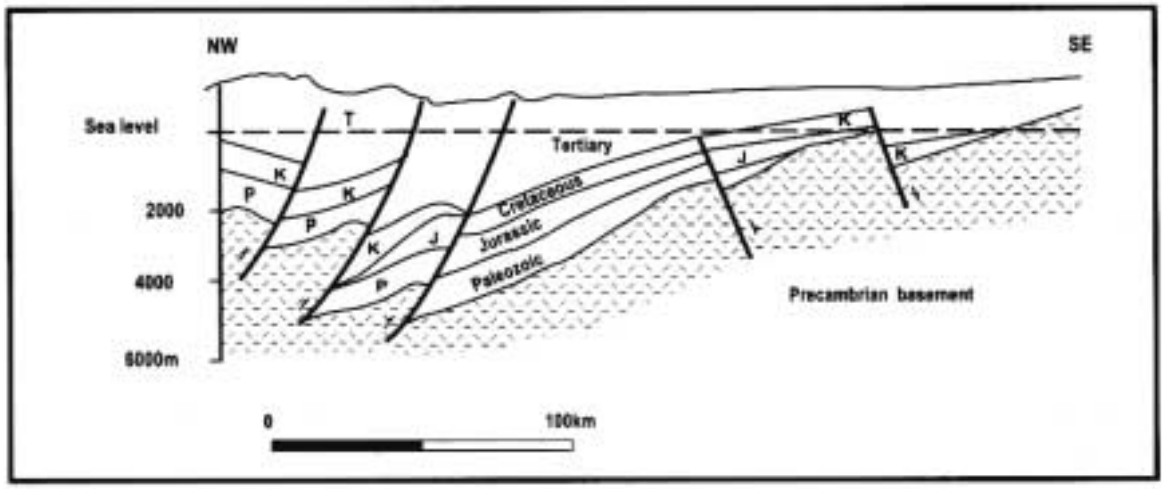


FIGURE 32 - Cross-section of the Llanos-Barinas-Apure Basin (after Alves, 1989).

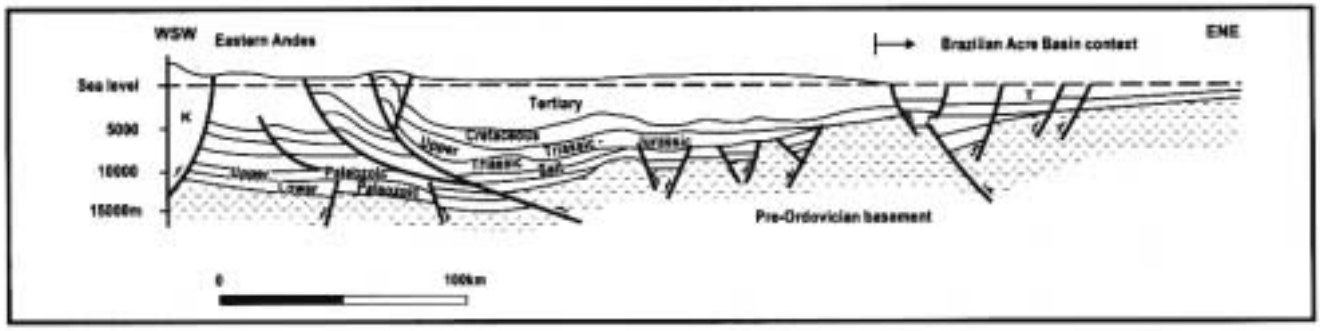


FIGURE 33 - Cross-section of the Marañon Basin (after J.M.P. Mathalone and M. Montoya R., 1995, AAPG Memoir Series No. 62, AAPG© 1995, reprinted by permission of the American Association of Petroleum Geologists whose permission is required for future use).

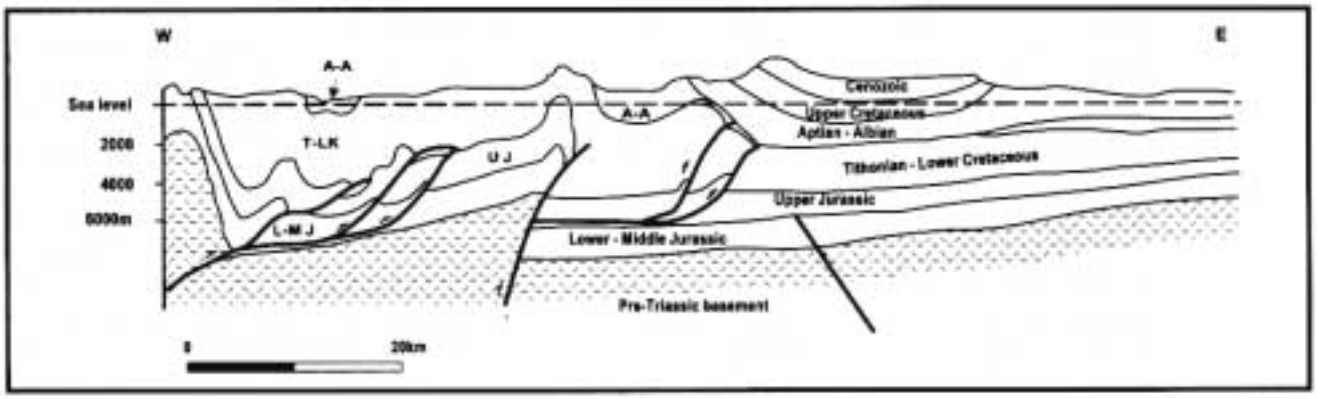


FIGURE 34 - Cross-section of the Neuquén Basin (after Uliana and Legarreta, 1993; permission to reproduce granted by the Journal of Petroleum Geology).

bend of the Andean front (Fig. 28). The total area of this province is about 700 000 km². In like manner to the Marañon Basin it includes a thick sequence of Phanerozoic sedimentary rocks showing a long history of subsidence that marked the southwestern margin of Gondwana.

The easternmost end of the Madre de Dios Basin occupies 10 000 km² of Brazilian territory, a region covered by Cenozoic continental clastic sediments and tropical forest. In that area, the maximum depth to the crystalline basement is around 1600 m, and the various sedimentary sequences, that are fully developed in the Bolivian sector, pinch out against the Central Brazil Shield (Milani and Zalán, 1998). The sedimentological record of the Madre de Dios Basin, both in lithology and in stratigraphic nomenclature, resembles that of the neighbouring Marañon-Ucayali-Acre Basin.

Towards the S, the Beni-Chaco Domain lies in a flat-lying sub-Andean region; the Jurassic to Cenozoic flexural depression developed over a basement of Paleozoic to Triassic rocks corresponding to the sequences that filled the Tarija Basin. Latest Jurassic was the time when large-scale rifting related to the beginning of the Andean system affected the region (Sempere, 1995). Continental red beds accumulated, constituting the lowermost part of the Puca Group (Fig. 31). This sedimentation was followed by a sag phase of subsidence up to the Turonian, when bioturbated shallow marine limestone units, rich in organic matter, were deposited in a flat basin during tectonic quiescence, constituting the Miraflores Formation. During the Late Cretaceous, the evaporitic-sandy-shaly sediments of the upper Puca Group accumulated, including the Aroifilla, Chaunaca, El Molino and Santa Lucia formations, the deposition of which was accompanied by relatively widespread alkaline basaltic volcanism.

The Cenozoic to Recent development of the Beni-Chaco region has been closely controlled by the evolution of the Andean Belt, the growth of which has provided the foredeep flexural subsidence to accommodate an up to 5000m of terrestrial beds up to Recent times. This section includes the sandy Petaca Formation, the shaly Yecua Formation and the thick sandy-conglomeratic molassic deposits of the Chaco Formation (Welsink *et al.*, 1995a).

Neuquén Basin

The Neuquén Basin covers an area of more than 160 000 km² of the western-central Argentina, and contains some 7000 m of sediments. It has a triangular shape (Fig. 28) and is limited to the W by the Andean Belt. This western side represented the region of linkage with adjacent Panthalassa during some of the several cycles of subsidence and evolution of the basin. The Neuquén Basin was in fact a local, cratonward reentrant in the large, N-S trending foreland domain along the active margin of Gondwana. During most of its history, the Neuquén Basin was situated between an evolving magmatic arc to the W and the cratonic regions of Gondwana to the E.

The develoment of the Neuquén Basin involved four major tectonic stages (Legarreta and Gulisano, 1989; Uliana and Legarreta, 1993). This started with a Late Triassic-Early Jurassic extensional collapse of a Late Paleozoic orogenic belt, followed by a thermal subsidence phase up to Late Cretaceous times. There then occurred a flexural subsidence stage caused by the load of the magmatic arc from Late Cretaceous to Early Cenozoic. Several episodes of basin inversion occurred, that modified to variable degrees the geometry of the depocenter and the relationship of the basin with the surrounding source areas. By Neogene times, compressional deformation resulting from the evolution of the Andes created the present day configuration of the basin.

The Neuquén Basin developed over a basement of magmatic, metamorphic and sedimentary rocks of Paleozoic to Triassic age. Early rifting occurred during Late Triassic times (Vergani *et al.*, 1995), and created a series of half-grabens that lodge the pre-Cuyo strata (Fig. 31), a thick sequence of continental coarse-grained sedimentary rocks and associated volcanic and volcaniclastic suites. Extensional conditions and normal fault controls over the sedimentation (Fig. 34) continued up to Early Jurassic and accommodated the lower beds of the Cuyo Group, represented by the marine shale beds, rich in organic matter, of the Los Molles Formation. Up to the beginning of Late Jurassic, a regressive sequence developed with provenance of fluvial-deltaic sediments from the E-SE, the post-Aalenian Cuyo section. This cycle culminated in an important tectonic event known as the Araucanian Inversion, during Late Oxfordian-Early Kimmeridgian.

During the Callovian, a N-S trending compressional belt developed in the western Neuquén Basin, known as the Dorsal de Huincul, and this was a preferential site for inversion of pre-existing rift-related structures. The Araucanian event was manifest as regional uplift and erosion, with deposition of syn-orogenic continental "molassic" beds of the lower Lotena Group in the adjacent depressions. At the end of the inversion episode, marine to evaporitic facies of the La Manga, Barda Negra and Auquilco formations accumulated in a wide sag basin formed by compressional release (Vergani *et al.*, 1995). A second event occurred during the Late Oxfordian-Earliest Kimmeridgian, reactivating older structures with intensity decreasing to the E. By the end of the Araucanian cycle of inversion, some 2000 m of strata had been removed by erosion from some parts of the Neuquén Basin.

The accumulation of the Mendoza Group followed the regional inversion phase. Sedimentation began with fluvial deposits associated with pyroclastic material, the Tordillo Formation. These fluvial clastic sediments grade to the eolian and fine-grained lacustrine rocks of the Catriel and Sierras Blancas formations. During the Tithonian, basin expansion and marine invasion provided accommodation space for a progradational unit that includes the Vaca Muerta Formation, a sequence of black shale beds, rich in organic matter (Mitchum and Uliana, 1985, *apud* Vergani *et al.*, 1995). The lower Mendoza Group terminates in Berriasian carbonate units known as Quintuco Formation.

Marine sedimentation that marked the previous cycle was partially arrested during Valanginian times, due to recurrent basin inversion. Mixed carbonate-siliciclastic sedimentation developed, comprising the Mulichinco and Chachao formations (Gulisano *et al.*, 1984). After the Valanginian, a phase of tectonic quiescence facilitated marine encroachment and the deposition of platform sediments, the Agrio Formation, that interfingers with the marginal, prograding fluvial siliciclastic sediments of the

Centenario Formation. This cycle of sedimentation continued up to Albian times, in a trend of progressive basin shallowing that allowed the accumulation of evaporite units and continental red beds of the Rayoso Group. The movements related to the Mirano inversion abruptly interrupted sedimentation.

This earliest Cenomanian phase of structural rearrangement reactivated surrounding source areas, resulting in the deposition of 1000 m of continental beds up to the end of the Cretaceous. The Neuquén Group is a Cenomanian to Campanian succession of fining and thinning upward units being mainly composed of fluvial deposits with provenance from the E. In the western part of the basin, volcaniclastic material is also present (Legarreta and Gulisano, 1989). The Late Campanian to Paleocene strata of the Malargüe Group completes the Riográndico Sedimentary Cycle. The sediments consist of marine and continental strata deposited in an epicontinental sea, with a maximum flooding event represented by the carbonate deposits of the Roca Formation (Late Maastrichtian to early Paleocene). Sedimentary provenance changed with respect to previous sequences. During the accumulation of the Malargüe Formation, the volcanic arc to the W became the major source of clastic material for the basin (Legarreta and Gulisano, 1989).

The post-Paleocene history of subsidence of the Neuquén Basin was driven by the load of the rising Andean Orogen, and was marked by the advance of the magmatic arc upon the foreland domain, with recurrent episodes of strong basement reactivation resulting in basin inversion. Thin-skinned tectonics also developed at this stage, with detachment levels within marine shale units of the Cuyo and Mendoza groups and within evaporite beds of the Rayoso Group (Vergani *et al.*, 1995).

Austral Basin

The Austral Basin, also named Magallanes Basin, corresponds to the southernmost part of the Andean foreland realm, and it covers an area of about 170 000 km^2 (Fig. 28). It is limited to the N by the Deseado High, a block of basement that separates the Austral Basin from the Golfo San Jorge Basin. To the E, the N-S trending Rio Chico High, or Dungeness Arch, defines the limit between the Austral and the Malvinas basins; towards the W, the Austral Basin faces the Andean Belt.

The basin developed from a Late Jurassic rift phase (Fig. 31), when NW-SE trending asymmetric grabens were opened and filled mainly with volcaniclastic sediments and associated lacustrine siliciclastic deposits of the Tobífera Formation. These grabens were concentrated around the Rio Chico High, the positive area of dissected Paleozoic basement that provided sediments for the basins. The rising of sea level, due to the climax of volcanic activity in the young marginal basin, allowed the deposition of transgressive sequences during Oxfordian-Kimmeridgian times, the sandy facies of which is named the Springhill Formation (Robbiano *et al.*, 1996). This succession is covered by a regressive sequence of fluvial and coastal sandstone beds of the Hidra Formation (Berriasian-Early Valanginian).

The cycle that followed showed progressively reduced magmatism. In the Austral Basin this is manifest as a period of sagging, with lower subsidence rates and the accumulation of a transgressive sequence known as Rio Mayer and Springhill formations (Late Valanginian-Early Aptian). During this cycle, a section of marine shale rich in organic matter was deposited, corresponding to the *Inoceramus* Inferior Formation of Hauterivian age.

Aptian times marked an important phase of structural modifications in the Austral Basin. The initial cycle of foreland subsidence, during the Cretaceous, was promoted by the Patagonides movements (Plozkiewicz and Ramos, 1978, *apud* Arbe, 1989). This brought about the closure of the marginal basin to the W of the depositional centre of the Austral Basin. Volcanic ash appears and this becomes more frequent in the stratigraphic record of this cycle, a sequence known as Margas Verdes Formation, that extended in time up to the Late Cenomanian.

During the rest of the Cretaceous, a complete transgressive-regressive cycle was deposited, including the dominantly shaly Arroyo Alfa and Cabeza de Léon formations. These formations include zones of marine shale beds, rich in organic matter. The top of this cycle is marked by a major unconformity that corresponds to the beginning of the subsidence of the Cenozoic foreland. From early Cenozoic times onward, the development of the North Scotia Ridge along the southern margin of the sag as part of the newly-formed active margin of the South American and Scotia plates, imposed a strong structural rearrangement on the Austral Basin. During these movements, in the early Paleocene, the southern part of the Austral Basin underwent strong E-W transpressive deformation (Robbiano *et al.*, 1996).

The Cenozoic record shows two transgressive-regressive cycles. The first form the Paleocene to Oligocene, and the second from the Miocene to Recent. A prominent pre-Miocene unconformity, related to the beginning of the Andean Orogeny, divides these two tectono-sedimentary cycles. The last stage of sedimentation corresponds mainly to the progradation of clastic sediments with provenance from the W and SW that may attain a thickness of 5000 m in the sub-Andean foredeep. On the northern flank of the basin, continental to shallow marine deposits mark the late Cenozoic progradation over the foreland ramp, constituting the Santa Cruz and Patagonia formations.

Back-arc extensional basins

This class of basins refers to the particular case of Mesozoic extensional troughs situated in the western, Andean Domain of South America. The development of back-arc rifts is attributed to periods of relaxation of compressional stresses of long duration, a conspicuous characteristic of the convergent margin of the continent. Compressional stresses along the western margin of South America have been active through most of the Phanerozoic (Urien *et al.*, 1995). Particularly important periods of relaxation were the Triassic (López-Gamundí *et al.*, 1994) and the Early Cretaceous (Ramos, 1988). Gust *et al.* (1985) included the Mesozoic events of extension observed in western South America into a single cycle that led to the opening of the South Atlantic.

Back-arc rifts were sites of local extensional subsidence that took advantage of the pre-existing compressional

structural grain. This seems to have been the case for the Mesozoic basins of western Argentina. However, other authors explain the origin of some of these troughs by transtension along pre-existing structural features under persistent Mesozoic regional compression (Kokogian *et al.*, 1993).

In a regional context, the convergent setting in which these grabens developed is sharply contrasting with the fully extensional domain found on the Atlantic side of the plate, where the initial crustal rupture by rifting led to the evolution of a large passive margin and the growth of oceanic floor. The Mesozoic back-arc rifts were arrested by the Neogene compressional deformation and crustal shortening, and in fact, some of these became included in the Andean Chain.

Cuyo Basin

The Cuyo Basin is a NW-SE trending graben with an area of about 35 000 km^2 and containing about 7000 m thick of Triassic to Cenozoic sediments (Fig. 28). The Cuyo Basin is situated in the Mendoza and San Juan provinces of western Argentina, to the E of the Precordillera block, a region that holds evidences of a series of Phanerozoic orogenic episodes due to terrane accretion along the active margin of Gondwana (Ramos, 1990). Several other rift basins exist in the same domain, and some of them are the Ischigualasto, Marayes and San Luis basins, sharing with the Cuyo, the largest of these, the same general characteristics. To the W and NW, the development of the Triassic sequence of the Cuyo Basin was arrested by the Cenozoic structural compressional framework of the Andean Belt (Kokogian *et al.*, 1993).

Six sub-basins or depocenters were identified along the strike of the Cuyo Rift, each one corresponding to a segment of large downthrow in the adjacent border fault. The sub-basins are separated one from the others by transfer zones that define prominent basement highs (Ramos, 1992).

The Triassic record of the Cuyo Basin is a 3500 m thick sequence of continental sedimentary deposits with some intercalations of volcanic rocks (Fig. 35). The syn-rift sequence begins with a section of conglomerate and sandstone beds known as the Rio Mendoza Formation. These beds grade upward into the interval of fluvial-lacustrine sandstone and shale units of the Las Cabras Formation. Basaltic rocks, dated at 235 Ma (Ramos and Kay, 1991) occur intercalated with the upper sedimentary strata of the Las Cabras Formation. The syn-rift sequence terminates with a fining-upwards cycle of fluvial to lacustrine deposits, included in the Potrerillos and Cacheuta formations. The Cacheuta Formation represents a phase of severe starvation in the lacustrine system, and consists of black shale, rich in organic material of Late Carnian age (Moratello, 1993). The entire syn-rift section contains a well-developed tetrapod fauna (Báez *et al.*, 1993) that spans the range Scythian-Carnian.

With the decrease of normal fault activity, a phase of sagging took place and the post-rift sedimentation onlapped the previous deposits, expanding the depositional area of the Cuyo Basin (Fig. 36). The Norian to Rhaetian fluvial and lacustrine deposits of the Río Blanco Formation represent this stage (Kokogian *et al.*, 1993).

The accumulation of continental successions proceeded in the Cuyo area during post-Triassic times, reaching a thickness of about 3500 m of Jurassic to Cenozoic rocks. However, this uppermost sequence was no longer related to the former rifting, but rather to regional flexural subsidence in the Andean foreland domain. This last cycle of evolution includes basalt extrusions dated as Early Cretaceous, known as the Punta de las Bardas Formation (124 to 131 Ma, Legarreta *et al.*, 1993). These flows occur above the reddish conglomerate and sandstone beds of the Barrancas Formation, and the lavas are overlain by a conglomeratic-sandy-shaly sequence of Eocene age, corresponding to the Papagayos and Divisadero Largo formations (Kokogian and Mancilla, 1989).

Salta-Lomas de Olmedo Basin

The Salta-Lomas de Olmedo Basin is situated in the sub-Andean region of northwestern Argentina (Fig. 28), and covers an area exceeding 100 000 km^2. This rift system continues into Paraguay, where it is known as the Pirity Basin (Wiens, 1995). The extensional trough developed during Early Cretaceous to early Cenozoic times, and accommodated a package surpassing 5000 m of sedimentary and associated igneous rocks; being afterwards partially arrested by the eastward-advancing, thrusted front of the Andes.

Pre-existing, Late Proterozoic-Early Cambrian sutures along which the ancient plates were welded together influenced the positioning of the faulted basin. According to Ramos and Vujovich (1994), *apud* Comínguez and Ramos (1995), in the region of the Salta-Lomas de Olmedo Basin there exists a ENE-WSW trending, northward-dipping suture zone that controlled the dip of the main detachment fault of the Mesozoic rift. Thus the Salta-Lomas de Olmedo rift is an asymmetric trough displaying a similar dip of its basement towards the N.

The Cretaceous-Tertiary basin overlies a section of older sedimentary rocks (Fig. 35), including the Upper Proterozoic-Lower Cambrian turbidite deposits of the Puncoviscana Formation; the Cambrian-Ordovician siliciclastic platform strata of the Las Breñas Formation; and the Silurian-Devonian marine sequence of the Kirusillas, Copo, Santa Rosa and Icla formations, a section having a widespread occurrence along the western region of South America.

The Salta Group fills the Salta-Lomas de Olmedo Basin, and the syn-rift sequence is named the Pirgua Subgroup (Gómez Omil *et al.*, 1989), with ages ranging between the Valanginian and the Santonian. This sequence consists of fluvial deposits conglomerate, red sandstone and shale associated with alkaline basaltic rocks. Three major cycles of volcanism concurrent with the rift phase are described (Comínguez and Ramos, 1995). These are the Lower Cretaceous Cachipunco basalt (128-112 Ma); the Upper Cretaceous Las Conchas basalt (78-76 Ma), volumetrically the most important; and a third event, of Paleocene age (63-55 Ma). The volcanic centre migrated eastwards through time.

The lower part of the Pirgua Subgroup consists of alluvial fan facies of the La Yesera Formation, accumulated along the faulted margin of the rift system and interfingering with the fluvial, eolian, and playa lake facies of the Las Curtiembres Formation. Fault activity decreased with time,

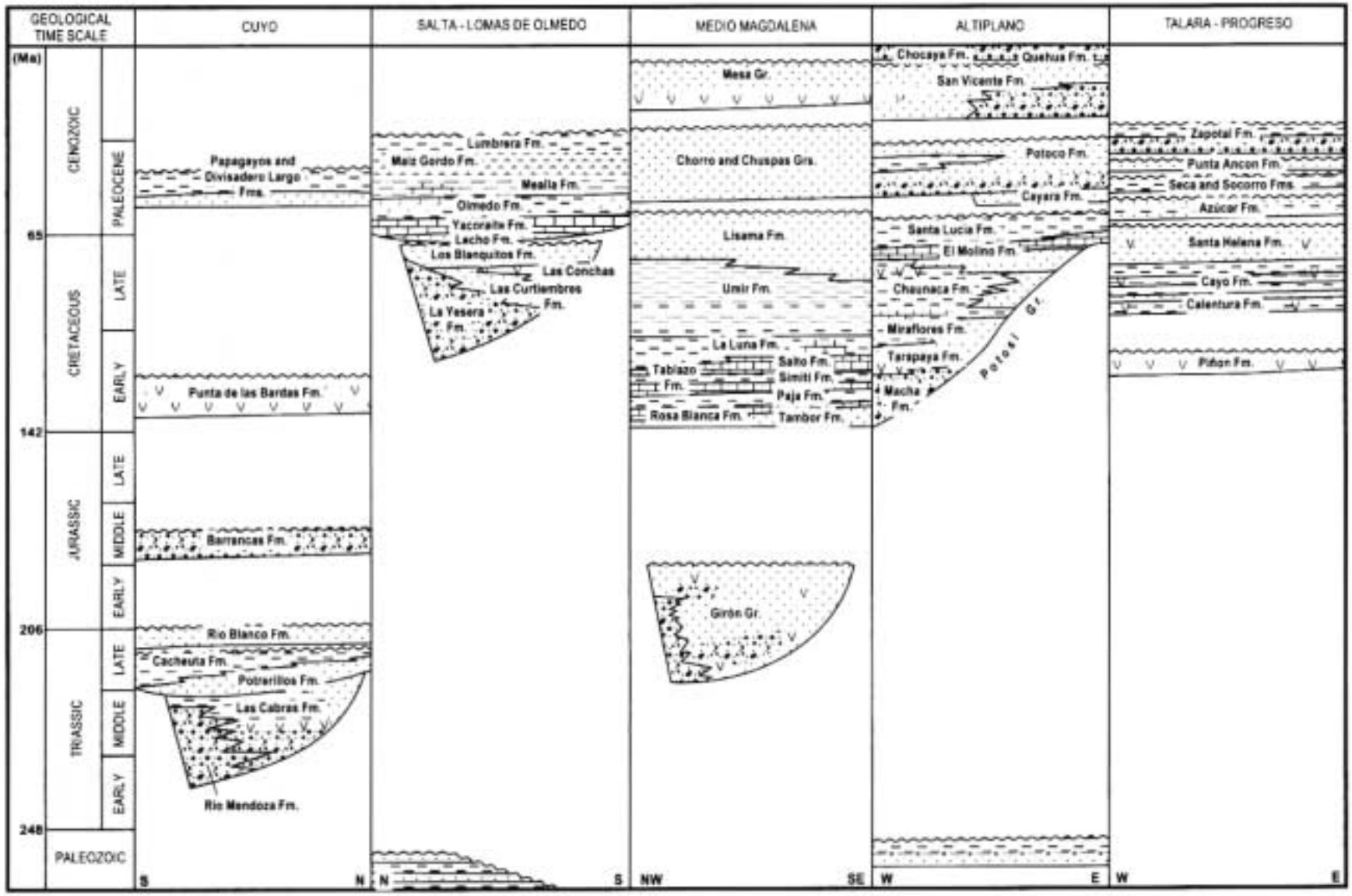


FIGURE 35 - Stratigraphic summary of the back-arc extensional basins, intermontane and fore-arc basins of South America. Main sources of information were Kokogian and Mancilla (1989), Cuyo Basin; Cominguez and Ramos (1995) Gómez Omil et al. (1989), Salta-Lomas de Olmedo Basin; Schamel (1991), Medio Magdalena Basin; Welsink et al. (1995b), Altiplano Basin; Jaillard et al. (1995), Talara-Progreso Basin. Geological time scale simplified from Gradstein and Ogg (1996). Lithological representations are of common use.

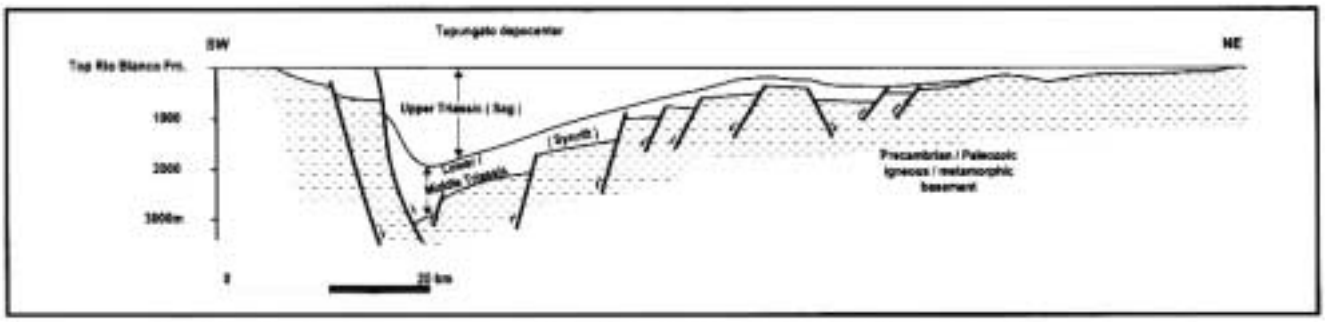


FIGURE 36 - Stratigraphic cross-section of the Cuyo Basin (after Kokogian et al.*, 1993; permission to reproduce granted by Asociación Geológica Argentina).*

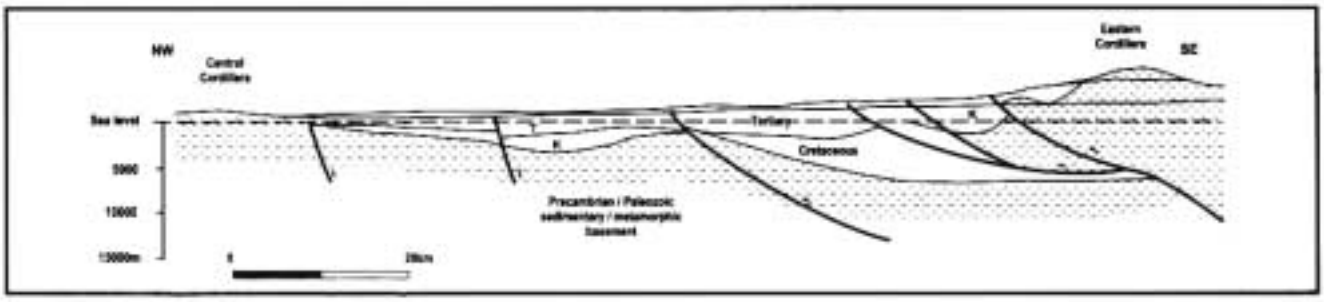


FIGURE 37 - Cross-section of the Medio Magdalena Basin (after S. Schamel, 1991, AAPG Memoir Series No. 52, AAPG® 1991, reprinted by permission of the American Association of Petroleum Geologists whose permission is required for future use).

and fine-grained deposits developed in the upper part of the rift fill, corresponding to the Los Blanquitos Formation.

The sag deposits of the Balbuena and Santa Barbara subgroups of Late Cretaceous to Eocene age succeeded the syn-rift sequence. These deposits have a total maximum thickness of about 2200 m. The post-rift section begins with the eolian beds of the Lecho Formation, covered by the mixed carbonate-clastic sediments of the Yacoraite Formation, of Campanian-Maastrichtian age. The reactivation of normal faults led to the emplacement of volcanic rocks associated with the Yacoraite beds, a magmatic cycle known as Palmar Largo. The uppermost unit of the Balbuena Subgroup is the Olmedo Formation, consisting of black shale and evaporite beds deposited in a hypersaline lacustrine environment.

The uppermost sequence of the sag phase is that of the Santa Barbara Subgroup, including, from base to top, the Mealla, Maiz Gordo and Lumbrera formations. These formations consist of shale, marlstone and subordinated carbonate beds, representing depositional systems related to ephemeral lakes, with fluvial sandy beds at their margins (Gómez Omil *et al.*, 1989).

Intermontane basins

De development of intermontane basins is a conspicuous characteristic of the Neogene history of the Andes Chain. They occur at several places along the mountain belt, from Venezuela to southern Argentina, and they formed according to two main types of mechanism, depending on the orientation of their bordering structures in relation to the regional stress field (Marocco *et al.*, 1995). The first was as strike-slip basins, undergoing cycles of syn-sedimentary deformation compatible with regional transcurrent motions. The second was by reverse faulting in response to compression.

The presence of sets of normal faults led to the interpretation of some of these basins as extensional half-grabens (Taborda, 1965, *apud* Schamel, 1991). However, according to Schamel (1991), extension was not the tectonic mechanism responsible for the development of these basins. The normal faults, as observed in some areas of the Magdalena Basin, are in fact the subordinate product of complex interactions between crustal loading by rising thrust sheets and transcurrent motions between adjacent blocks. In any case, the Andean intermontane basins underwent a continuous history of compressional deformation by progressive mountain building.

Medio Magdalena Basin

The Medio Magdalena Basin occupies an area of about 30 000 km^2 in northern Colombia (Fig. 28). In that area the Andean Belt is more than 600 km wide, or about twice of its mean size to the S, and inside this widened area there developed a Neogene successor basin along the valley that runs between the Eastern and the Central Cordillera. However, the previous history of the area witnessed much more extensive sedimentary domains, such as an extensional setting during the Triassic-Jurassic, a pericratonic trough during the Cretaceous and earliest Cenozoic, and a foreland basin during the middle Cenozoic (Schamel, 1991). Some of these pre-orogenic strata lie today in the highlands of the Eastern Cordillera, flanking the Neogene sequence that fills the NNE-SSW-trending intermontane basin.

The Mesozoic-Cenozoic sequence in the region of the

Medio Magdalena Basin (Fig. 35) was deposited over a complex of Paleozoic and Late Proterozoic metamorphic and sedimentary rocks, some of them pertaining to the domain of the Guiana Shield. A pronounced angular unconformity separates these older strata from the Mesozoic-Cenozoic successions. The basin exhibits an asymmetric transversal profile. Its eastern border is defined by a set of post-Miocene, west-vergent thrust faults that form the western border of the Eastern Cordillera (Schamel, 1991). The Central Cordillera block dips to the E and not only defines the western margin of the trough, but also underlies the Medio Magdalena Basin.

Triassic-Jurassic continental red beds with associated acid to intermediate volcanic rocks constitute the Girón Group, the basal unit of the Mesozoic section. These strata are widespread in the area. They occur filling NE-SW trending grabens, and may attain a thickness of 5 000 m. They record the phase of rift-drift in north-western South America (Pindell, 1985, *apud* Schamel, 1991) and the subsequent transition of the region to a subduction-related marginal basin (Maze, 1984, *apud* Schamel, 1991).

The Cretaceous sequence that represents a marine depositional megacycle, begins with Neocomian transgressive sandstone and conglomerate beds that rest unconformably over the Triassic-Jurassic sequence. These beds are known as the Tambor Formation. They are succeeded by a sequence of open marine limestone units and black shale beds up to 4000 m thick, included in the Rosa Blanca, Paja, Tablazo, Simiti and Salto formations. Maximum flooding was reached during Turonian-Coniacian times, and is recorded by the La Luna Formation, consisting of black shale, rich in organic material and limestone members. The drop of sea level during the Late Cretaceous and early Paleocene provided a renewed regressive cycle of sedimentation, with the deposition of the Umir and Lisama formations.

The marine Cretaceous beds were covered by a succession of three molasse sequences mainly consisting of alluvial, fluvial, and lacustrine facies that were accumulated in continental environments bounded by rising mountain chains. The basal sequence, corresponding to the Chorro and Chuspas groups, is more than 4 000 m thick (Schamel, 1991) and was fed by the rise of the Central Cordillera. The Real Group, of Miocene age succeeds it. Volcaniclastic deposits derived from the same, western uplifted area dominate the Real Group. The third molasse sequence, known as Mesa Group, was supplied with sediments from both sides of the valley, because the Eastern Cordillera was uplifted during Pliocene time (Fig. 37).

Altiplano Basin

The Altiplano Basin of Bolivia constitutes an endorheic fluvial, fluvioglacial and lacustrine depositional area of Cenozoic age situated about 4 000 m above the mean sea level, between the Western and Eastern ranges of the Chilean-Bolivian Andes (Fig. 28). It comprises an area of about 100 000 km^2, in part occupied by the Lake Titicaca, the largest body of water in the world at such a high altitude. The Altiplano Basin trends in a NW-SE orientation, and includes thick sequences of pre-Andean, Paleozoic and Mesozoic sedimentary rocks. Indeed, these sediments represent the remnants of a much larger preexisting sedimentary domain. In a tectonic perspective, the Altiplano is a contractional province originated during the Andean Orogeny (Welsink *et al.*, 1995b).

The western limit of the Cordillera Occidental, is a magmatic arc of Neogene to Recent age that developed on continental crust, the geology of which is poorly known (Roeder, 1988), but probably represents an eastward extension of the coastal Arequipa Massif (Ramos *et al.*, 1986). On the opposite side, the Cordillera Oriental is a fold-and-thrust belt involving Paleozoic sedimentary rocks that was affected by widespread granitic plutonism, with ages concentrated around the Late Triassic-Early Jurassic and the Miocene (Kontak *et al.*, 1984, *apud* Díaz-Martínez, 1995).

Precambrian rocks of the basement do not crop out in the Altiplano area, but they are known to exist in the subsurface because a reddish Late Proterozoic metagranite was sampled at a depth of 2800 m (Pareja *et al.*, 1978). The older known Paleozoic sedimentary rocks in the Altiplano Basin are Ordovician sandstone units of local occurrence (Fig. 35). Otherwise, Silurian rocks are widespread in the area and correspond to the diamictite and sandstone beds of the Cancañiri Formation. These beds are followed by a sequence of micaceous sandstone beds known as the Huanuni Formation; quartzose sandstone of the Llallagua Formation; shale in the Uncía Formation and terminating in a sandy-shaly sequence named the Catavi Formation.

The Devonian sequence includes two major transgressive-regressive cycles, starting with the basal Vila Vila Formation, consisting of quartzose sandstone, followed by a dominantly shaly section of the Belén Formation. The second cycle has a lower sandy unit found in the Huamampampa Formation, and an upper silty-shaly unit, the Colpacucho Formation. The Carboniferous system in the Altiplano area is represented by the Cumaná Formation, consisting of white sandstone and grey argillite beds related to a periglacial marine environment known as the Kasa Formation. These beds are followed by the Siripaca and Yaurichambi formations, of transitional environment, consisting of a sand and shale sequence up to 1000 m thick. The Copacabana Formation, that spans up to the Early Permian, consists of mixed carbonate-siliciclastic marine sediments (Díaz-Martínez, 1995).

The Cretaceous sequence is more than 3300 m thick in the southern part of the Altiplano Basin (Pareja *et al.*, 1978), and it unconformably overlies different Paleozoic units. It is represented by the Potosí Group, a unit characterized by rapid facies changes due to an uneven morphology of the depositional site. The Cretaceous sequence is interpreted as representing the in-fill of a rift trough and succeeding thermal sag (Welsink *et al.*, 1995b). It consists of sandstone, shale, limestone and evaporite beds that, in some places, exhibit diapiric structures. Magmatic events interrupted the Cretaceous sedimentation during the Barremian and Early Campanian.

During the Cenozoic, true intermontane conditions were attained in the Altiplano Basin following the uplift of the adjacent ranges, and the deposition of a sequence exceeding 6000 m of syn-orogenic sandstone, shale, limestone, and evaporite beds, intercalated with volcaniclastic and volcanic

rocks. These rocks are included in the Cayara, Potoco, San Vicente, Quehua and Chocaya formations. Quaternary deposition in the Altiplano Basin filled the basin to its present limits. The sedimentation is represented by some 600 m of volcaniclastic beds, lava flows, conglomerate and sandstone beds, lying sub-horizontally. Cenozoic magmatism is abundant and expressed as intrusions, lava flows and ignimbrite.

Fore-arc basins

Fore-arc basins formation and sediment accumulation occur in several places along the convergent margin of South America. Such basins developed by rapid extensional subsidence between the trench slope break of the accretionary wedge and the magmatic front of the arc, being generally overlying trapped fragments of oceanic crust older than both the magmatic arc and the accretionary complex. To some extent, such rigid basement also prevented these basins from undergoing further intense compressional deformation as that observed in the concurrent sedimentary accretionary prism. Adjacent volcanic arches provided important amounts of detritus to these basins.

Among the main fore-arc sedimentary basins along the Andean margin of South America there are the Chiloé, Valdívia, Temuco, and Mataquito basins in Chile; Mollendo, Pisco, Lima, Trujillo, and Talara in Peru; Progreso, Golfo de Guayaquil, and Manabi in Equator; and Borbon in Colombia. The region of Talara-Progreso was selected here to represent this class of basin.

Talara-Progreso Basin

The Talara-Progreso Basin is situated in the coastal region of southern Ecuador and northern Peru (Fig. 28), covering an area of about 35 000 km^2 around the Gulf of Guayaquil. It is a Miocene fore-arc trough developed on a complex Cenozoic collisional tectonic setting. The region is underlain by a piece of oceanic basement (Mégard, 1987, *apud* Jaillard *et al.*, 1995), consisting of massive tholeiitic basalt and basalt-andesite lava of the Piñon Formation. These rocks have radiometric ages around 110 Ma (Goossens and Rose, 1973), and were accreted to the South American Plate in late Paleocene-early Eocene times.

The initial tectono-sedimentary history of the region includes an accumulation of the Cenomanian to Early Coniacian pelagic marine deposits of the Calentura Formation (Fig. 35). These deposits are mainly volcaniclastic and accumulated in a marginal basin overlying the oceanic crust of Aptian-Albian age. The following tectono-sedimentary cycle was marked by the presence of an adjacent island arc providing coarse-grained detritus to the marginal depression, a sequence of Santonian-Campanian age known as Cayo Formation. The activity of the Cayo Volcanic Arc diminished with time, and the sedimentary sequences become finer towards the top.

The subsequent development of the Talara-Progreso area is marked by recurrent episodes of collision and uplift followed by extensional subsidence in the fore-arc domain, creating a pattern of short-lived fore-arc basins interrupted by periods of erosion (Jaillard *et al.*, 1995). This genetic relationship between compressional phases succeeded by extensional subsidence was explained by tectonic erosion along the plane of subduction, responsible for a loss of mass along the continental margin that is believed to be enough to trigger the subsidence of the fore-arc domain when the compression stresses decreased (Von Huene and Lallemand, 1990; Von Huene and Scholl, 1991).

It was probably that, in the late Paleocene-early Eocene times, the remnants of the Cayo Arc collided with the margin of the continent, resulting in the emergence of the region and a large influx of coarse-grained, quartz-rich sediments to the adjacent slope basin, a sequence named the Azúcar Group. By the end of this compressional phase in the middle Eocene, fore-arc extensional subsidence took place, accommodating the marine strata of the Socorro and Seca formations, deposited in an outer shelf environment. The Socorro Formation consists of laminated shale beds, siltstone, and fine-grained sandstone. Near the base of the formation, slumped beds are common, and these define the Clay Pebble facies. Upwards, the Socorro Formation grades into a sequence of laminated shale beds, siltstone, marlstone, and thin-bedded sandstone units known as the Seca Formation. The upper part of the Eocene sequence includes a section of continental to shallow marine greywacke and lithic sandstone units known as Punta Ancón Formation. Alluvial coarse-grained sandstone and conglomerate assigned to the lower part of the Zapotal Formation succeed these beds.

From Oligocene time onwards, several fore-arc basins developed in the area, including the individual troughs of Talara-Progreso and the Golfo de Guayaquil basins. These originated from the recurrent compression-to-extension changes in the regional stress field. These basins were filled with fine-grained shallow marine sandstone and shale that in part correspond to the upper part of the Zapotal Formation, dated by its planktonic foraminifera content as Oligocene-early Miocene (Jaillard *et al.*, 1995). In Quaternary times most of coastal Ecuador-Peru area emerged.

Northern and Southern, Transform Margins

Along the Andean margin of South America, persistent convergence between the continental plate and the Pacific oceanic lithosphere originated a tectonic environment that has been under net compression; being a mountain belt framed cratonward by an almost continuous foreland depression one of the most obvious result of this convergent zone of widespread crustal shortening.

The tectonic behaviour along the Caribbean and Scotian sides of South America (Fig. 1) is different. Towards the N and the S, the subduction zone on the western border of the continent changes into transpressional systems. The consequence is that oblique convergence has been the dominant way of interaction between the South American and adjacent Caribbean and Scotia plates from Paleocene time onwards, defining large-scale transform boundaries, and, in this way, allowing a complex changing pattern of strike-slip motion, local crustal shortening, and lithosphere

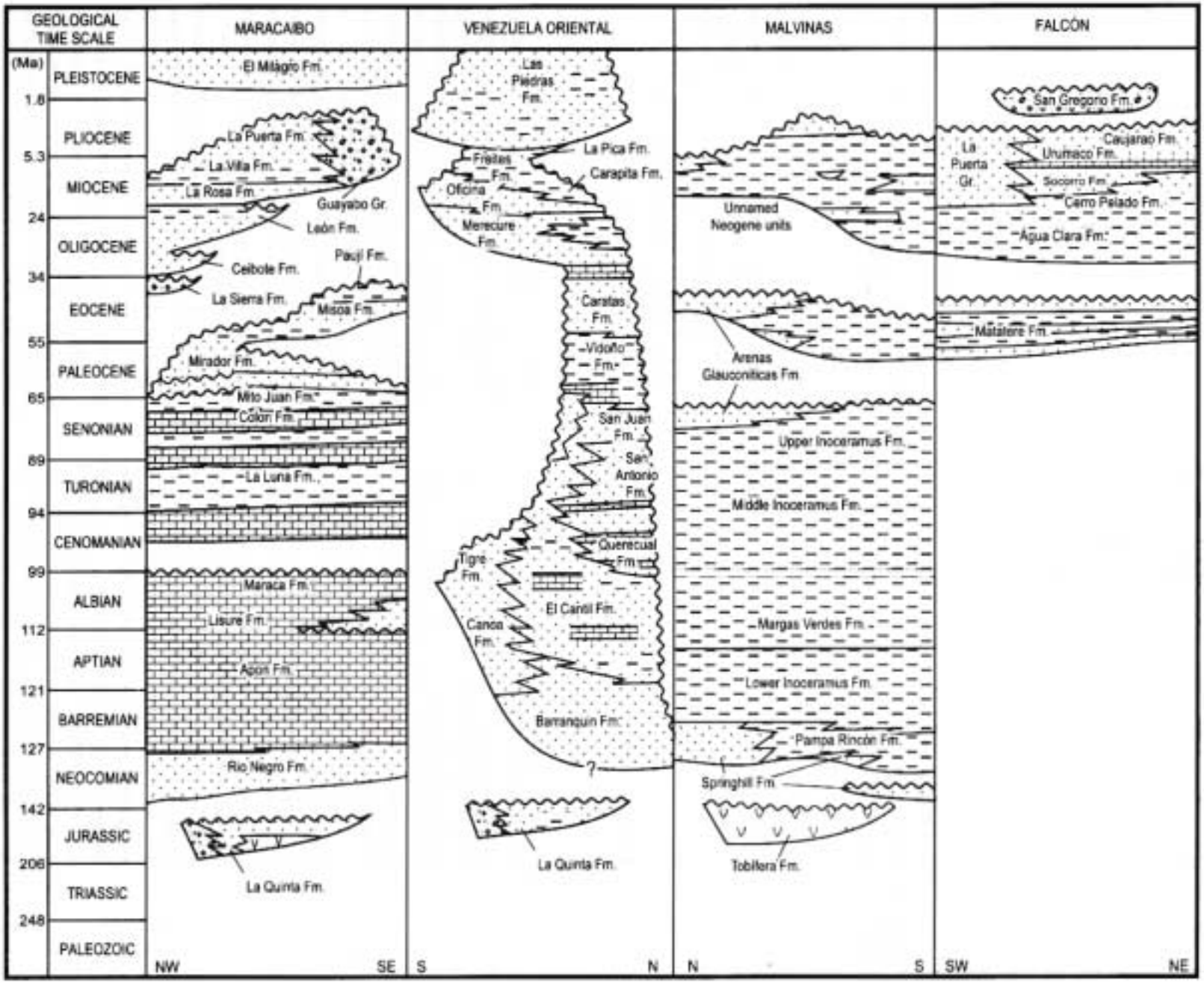


FIGURE 38 - Stratigraphic summary of the basins situated along the northern and southern transform margins of South America. Main sources of information were Parnaud et al. (1995b), Maracaibo Basin; Parnaud et al. (1995a), Venezuela Oriental Basin; Galeazzi (1996), Malvinas Basin; Macellari (1995), Falcón Basin. Geological time scale simplified from Gradstein and Ogg (1996). Lithological representations are of common use.

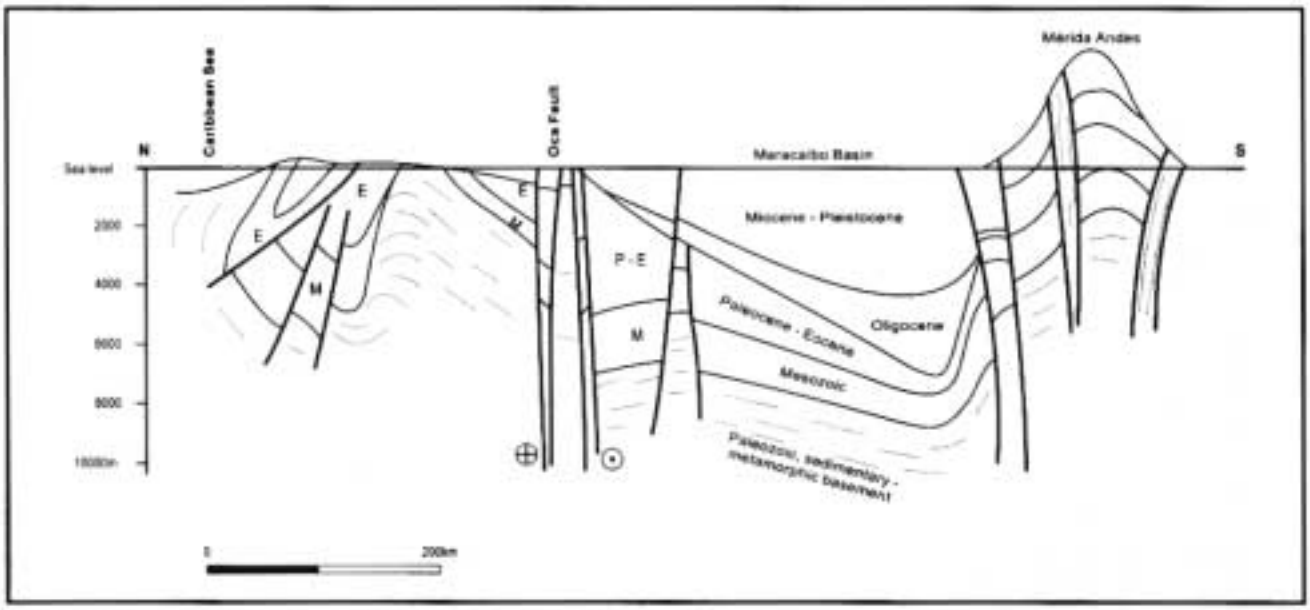


FIGURE 39 - Cross-section of the Maracaibo Basin (after Perez de Mejía et al., *1980; reproduced by courtesy of Schlumberger).*

flexure by tectonic loading as the basic mechanisms of basin formation and inversion. Also classic pull-apart grabens developed at some places, related to releasing bends of these transform margins, Oca-San Sebastian-El Pilar to the N and North Scotia to the S.

Oblique flexural basins

Maracaibo Basin

The Maracaibo Basin covers an area of about 50 000 km^2 in the northwestern region of Venezuela (Fig. 28). In its northernmost part, the Andean Belt deflects to the E to become about three times wider than its mean width in the southern region. This is a very complex region that displays thin-skinned tectonics (Kellogg, 1984) and microplate movement that depicts an intricate pattern of individual movements and interaction of blocks.

The Maracaibo Basin developed in the center of a triangular lithosphere wedge, the Maracaibo-Santa Marta Block that is being pushed away from South America by compressional stresses. The movement of the Maracaibo Block towards the N is bounded by two major strike-slip zones, the right lateral Boconó Fault and the left lateral Santa Marta-Bucaramanga Fault (Lugo and Mann, 1995). To the SE the Mérida Andes mountain range separates the Maracaibo region from the sub-Andean foreland domain of the Barinas-Apure Basin. Towards the NW the Maracaibo Basin is limited by the Perijá Mountains.

Three major tectono-sedimentary stages are recognized in the geological history of the Maracaibo Basin (Fig. 38): Jurassic rifting, related to the separation between the North and South American plates, followed by a Cretaceous phase of passive margin opening to the N-NE. This stage was interrupted by the collision between the Caribbean and the South American plates during Paleocene/Eocene times that started a cycle of foreland basin development. Flexural subsidence continued from Eocene time onwards, driven by the oblique collision and development of the transpressional northern boundary of the South American Plate (Lugo and Mann, 1995). About 7000 m of Jurassic to Recent sedimentary rocks have been deposited in the basin, and of these the uppermost 3000 m correspond to Neogene coarse-grained rocks derived from surrounding Andean relief.

The Maracaibo Basin overlies Paleozoic sedimentary and metamorphic rocks (Fig. 39). Rifting took place during the Jurassic, and accommodated continental, alluvial to lacustrine red beds, the La Quinta Formation, and associated alkaline volcanic rocks within SW-NE to N-S trending troughs. Dominantly carbonate sedimentation developed during the Cretaceous passive margin stage (Eva *et al.*, 1989), over the basal transgressive clastic deposits of the Rio Negro Formation of Neocomian-Aptian age. Carbonate accumulation started with the Aptian shallow marine shelf sedimentation of the Apon Formation, and followed with the Lisure and Maraca formations, a section of mixed siliciclastic-carbonate rocks, and continued with the deposition of Cenomanian fossiliferous limestone members. The Mérida Arch, probably originated as an uplifted faulted block during the rift stage, and persisted as a positive feature controlling, to some extent, the nature of facies that filled the passive margin basin (Macellari, 1988).

During the Turonian and Santonian, at the time of maximum eustatic sea level of the Cretaceous (Vail *et al.*, 1977), a sequence of black shale beds, rich in organic matter, marlstone and limestone units accumulated in the Maracaibo Basin and surrounding areas. The La Luna Formation, together with their stratigraphically equivalent units in adjacent basins, constitute the most important known source rock on the continent, accounting for about 80% of the already discovered hydrocarbons (Mathalone, 1996). Volcanic ash beds occur at the base of the La Luna Formation, indicating the existence of an active volcanic arc to the W (Parnaud *et al.*, 1995b), along the subduction-related Pacific margin of the continent. The passive margin megasequence of the Maracaibo Basin ended with the

deposition of Campanian to Maastrichtian micritic limestone beds and shale known as Colon Formation.

During the Late Cretaceous to early Paleocene, renewed tectonic activity due to the collision of the Pacific Volcanic Arc against the South American Plate gave origin to the foreland basin phase in the Maracaibo area. This change occurred in a diachronous mode over the former passive margin, from W to E, accompanied by a regressive phase of sedimentation. The Mito Juan Formation, reflecting highstand progradational depositional systems had its provenance in the W, and accumulated during this passive margin to foreland basin transitional phase. The progressive emplacement of nappes to the N of the Maracaibo Basin accelerated the flexural subsidence in the area, from late Paleocene time onwards. Marine sequences continued to accumulate in the Maracaibo Basin up to middle Eocene, when the basin underwent a phase of regional erosion. The sea regressed by late Oligocene times, and inundated widely up to the Miocene. The resulting deposits are known as the León Formation.

The Plio-Pleistocene marked the uplift of the Mérida Andes ranges, and the isolation of the Maracaibo Basin from the southeastern sedimentary domain, the Barinas-Apure Basin. The sea progressively retreated after the transgressive phase of the middle Miocene that resulted in the accumulation of the La Rosa Formation. Molasse sedimentation of the Guayabo Group invaded the basin from the Mérida High, indicating rapid subsidence along the orogenic front (Parnaud *et al.*, 1995b), accompanying the Neogene development of the Maracaibo Basin.

Venezuela Oriental Basin

The Venezuela Oriental Basin is situated in northernmost South America, covering an area of around 280 000 km², including the Maturín and Guárico sub-basins. Further subsidence developed during Neogene times as a foreland depression developed. This foreland depression is related to the evolution of the E-W trending Serrania del Interior Fold and Thrust Belt, and it is limited to the N by the orogenic belt itself, and by the right-lateral transcurrent El Pilar Fault. The El Pilar Fault marks the active limit between South America and the Caribbean plates (Fig. 28).

Four major stages are recognized in the Phanerozoic tectonic evolution of the area of the Venezuela Oriental Basin (Eva *et al.*, 1989). These are a Paleozoic pre-rift phase; a cycle of rifting-drifting during Jurassic and earliest Cretaceous; a passive margin phase spanning the Cretaceous-Paleogene interval; and the Neogene foreland basin stage. Pre-existing sedimentary sequences, up to 5000 m thick, form the so-called pre-rift phase. These are coastal to neritic marine Devonian and Carboniferous sediments (Stover, 1967, *apud* Parnaud *et al.*, 1995a), probably representing remnants of the widespread cratonic sequences that covered large areas of South America and constitute, in fact, the sedimentary basement for the rift sequences in this area (Fig. 38).

Rifting in the Venezuela Oriental Basin took place during Late Jurassic to Early Cretaceous times, and is represented mainly by the continental red beds and diabase sills of the La Quinta Formation. This package, an onlapping megasequence that fills a series of half-grabens, may reach a thickness of about 3600 m (Parnaud *et al.*, 1995a). Passive margin conditions were established in the Barremian, and prevailed up to the Paleogene. The sediments show three major transgressive phases. The passive margin megasequence that started with the deposition of coastal sandstone beds known as the Barranquin Formation was followed by the shallow marine beds of the El Cantil Formation and ended in a major transgression during the Turonian. Two other marine transgressions peaked in the Paleocene-early Eocene times. The first is represented by the Vidoño Formation, and the second by Areo Formation of Oligocene age. Marine shale beds, rich in organic material, were deposited during the Cenomanian to Campanian incursion of the sea, and correspond to the Querecual and San Antonio formations (Alberdi and Lafargue, 1993). To the S, the marine basin was delimited the continental sandy successions of the Canoa and Tigre formations.

The convergence of the Caribbean Plate against South America during the Oligocene terminated the passive margin phase in the Venezuela Oriental Basin, and started its foreland cycle (Fig. 40). The oblique collision megasequence (Parnaud *et al.*, 1995a) is a syn-orogenic wedge up to 6000 m thick. Deposition accompanied the eastward migration of the foredeep and the diachronous evolution of the transpressional orogenic belt related to the El Pilar transform margin and adjacent Serrania del Interior Thrust and Fold Belt, the major source of sediments during the foreland cycle. Thin-skinned tectonics developed using as detachment surfaces the Jurassic-Cretaceous interface and the boundary between the Mesozoic-Paleogene and the Neogene.

The foreland megasequence consist of Oligocene-Miocene sandy sediments that prograded from the S, included in the Merecure and Oficina formations. In the deep basin, a thick sequence of shales with turbiditic sandstone beds at the base was deposited. This sequence is knows as the Carapita Formation (Parnaud *et al.*, 1995a). Shallow marine and continental deposits filled the foredeep trough during the Pliocene and Pleistocene, defining the La Pica and Las Piedras fomations.

Malvinas Basin

The Malvinas Basin is a tectonic province developed in the southernmost region of the continent, adjacent to the E-W trending, left-lateral transpressional North Scotia Ridge, the active element of contact between South American and Scotia plates. The basin has a triangular shape with an area of more than 100 000 km² entirely in the offshore domain of southern Argentina. It contains a sequence some 7000 m thick of Mesozoic-Cenozoic rocks. It is separated from the Austral Basin, to the W by the N-S trending Dungeness Arch, and its strata onlap the Malvinas (Falklands) Platform to the E-NE (Fig. 28). The regional tectonic pattern of the basin is given by a relatively simple northern domain, where normal faults dominate, and a complex, transpressional southern border, related to the transcurrent limit of plates.

The Malvinas Basin evolved as a non-conventional foreland basin (Galeazzi, 1996) in a particularly complex tectonic domain, right where the thrust and fold belt of the Andes meets the southern transform margin of South

America. This condition provided a changing pattern of flexural subsidence during time that alternated with episodes of transpressional deformation and basin inversion.

The pre-Jurassic basement for the sedimentary successions in the Malvinas Basin is of continental nature and mainly represented by low grade metamorphic rocks and granite, the lithological context of the Panthalassan margin of Gondwana deformed by compression during the Permian to Early Triassic Cape-La Ventana Orogeny (Veevers *et al.*, 1994). Rifting in the Malvinas Basin occurred during the Jurassic (Fig. 38), in a back-arc tectonic setting, followed by thermal subsidence that spanned the range Late Jurassic-Maastrichtian. The presence of the Dungeness Arch as a positive feature, associated with depocenters adjacent to normal faults, exerted important control upon the distribution of strata during these initial phases of evolution. The rift section consists of tuffs intercalated with lavas (Yrigoyen, 1989), a package that may reach a thickness of 800 m and is known as Tobífera Formation (Thomas, 1949, *apud* Galeazzi, 1996).

During Paleocene and Eocene times, transtensional deformation took place in the southwestern sector of the basin and, from late Eocene time onwards, the basin underwent foreland flexural subsidence driven by the development of the transpressional North Scotia Ridge to the S and the Patagonic Orocline to the SW (Fig. 41). A thrust and fold belt appeared right to the S of the basin, imposing extreme changes on its shape, subsidence history and sedimentary patterns.

The post-Tobífera stratigraphic record of the Malvinas Basin begins with a Late Jurassic-Neocomian transgressive sequence related to the northwards flooding of the basin by the waters of the Weddell Sea. This retrogradational to aggradational section, included in the Springhill and Pampa Rincón formations, consists of deltaic to coastal sandstone beds, argillite and coal seams of coastal plain environments; and middle to distal platform carbonate units and shale. These units filled a wide sag related to the thermal subsidence phase that continued up to the end of the Cretaceous (Galeazzi, 1996). Drowning of the depositional platform continued, and an open marine sedimentation represents the Aptian to Maastrichtian section, a dominantly shaly succession named the *Inoceramus* and Margas Verdes formations.

Glauconitic sandstone and shale of the Arenas Glauconíticas Formation, accumulated in a distal shelf environment marks the uppermost Cretaceous to lower Eocene interval. By the end of the Eocene, the Malvinas Basin underwent a regional transpressional tectonic regime and assumed definitively its oblique foreland character. The post-Eocene stratigraphic record of the Malvinas Basin includes a southward thickening wedge of Oligocene deep marine deposits followed by a prograding, fluvio-deltaic siliciclastic sequence of Neogene age.

Pull-apart basins

Falcón Basin

The Falcón Basin is situated in northwestern Venezuela, where it covers an area of 15 000 km². This trough originated and developed as a pull-apart basin related to the dextral strike-slip motion between the Caribbean and South American plates along the large E-W trending Oca-San Sebastian-El Pilar Transform Zone (Fig. 28). The basin started to develop as a pull-apart trough in the early Cenozoic (Muessig, 1984, *apud* Boesi and Goddard, 1991), over a basement of igneous, metamorphic rocks and, locally, remnants of Mesozoic and Paleozoic sedimentary successions.

Late Paleocene to middle Eocene times were marked by the accumulation of Caribbean Plate-derived turbidite beds known as the Matatere Formation (Fig. 38) in a large depression that soon would turn into the pull-apart Falcón Basin. During the late Eocene, right-lateral transcurrent movement along the northern, transform margin of South America probably activated a transtensional depocenter along a releasing bend in northwestern region of Venezuela. As a consequence, a series of horsts and grabens, bounded by NW-SE trending normal faults appeared. These faults were arranged in a right-stepping *en échelon* pattern and defined the depocenters of the nascent pull-apart Falcón Trough.

In the Miocene-Pliocene interval, the basin underwent a strong transpressive phase of inversion (Fig. 42), with the creation of a belt of SW-NE trending anticlines along the southeastern border of the basin (Boesi and Goddard, 1991). The continued tectonic evolution of the region included diffuse right-lateral transcurrent displacement along an E-W striking fault system. Such movement progressively concentrated in the Oca Fault, defining a segment of the present-day active northern margin of the South American Plate. Due to mountain building, large volumes of sediments previously deposited in the Falcón Basin were removed during this late phase of structural inversion, and transported to the Caribbean Sea.

Sedimentation in the Falcón Basin reflects two main stages (Díaz de Gamero, 1977, *apud* Boesi and Goddard, 1991): an initial transgressive phase from late Eocene to middle Miocene, in which the sea invaded from the NE with the resulting accumulation of shale beds, rich in organic material, included in the Água Clara and Cerro Pelado formations; and a regressive phase, from late Miocene onward, as a consequence of basin inversion that caused a marine regression toward the northeastern border of the basin. Sedimentation during the regressive phase was dominantly sandy with the deposition of carbonate units in the western and southwestern parts of the basin, where the La Puerta Group developed, and sandy in the central domain, the realm of the Urumaco and Codore formations. The marginal deposits grade to finer facies towards the central and eastern parts of the basin, where developed a calmer depositional site. These distal deposits are known as the Socorro and Caujarao formations. Pliocene molasse known as San Gregorio Formation, covered large sectors of the Falcón Basin.

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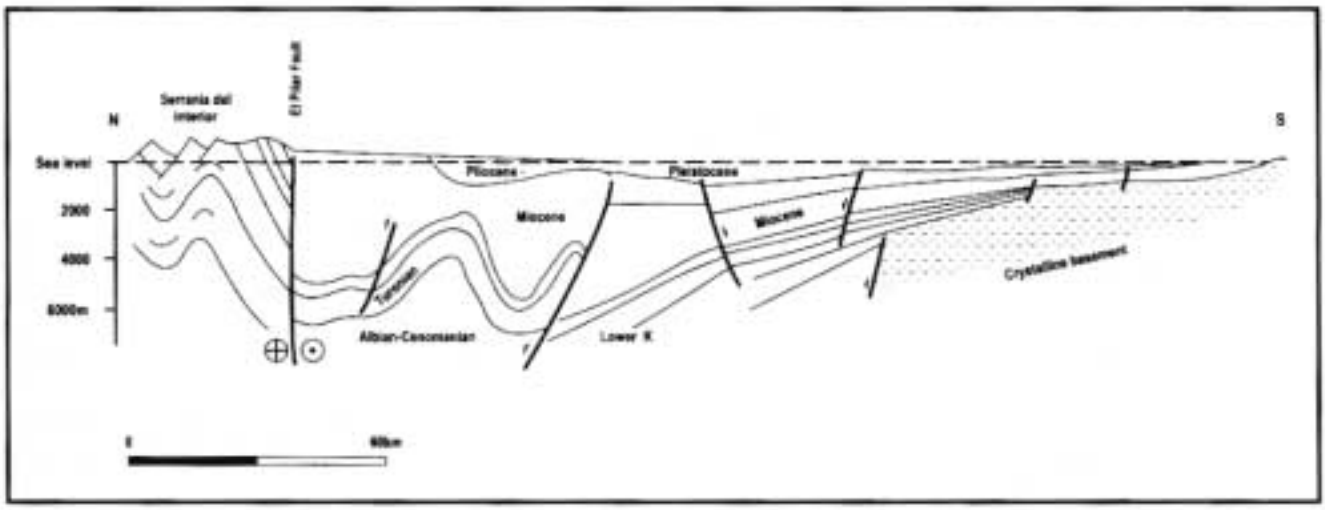

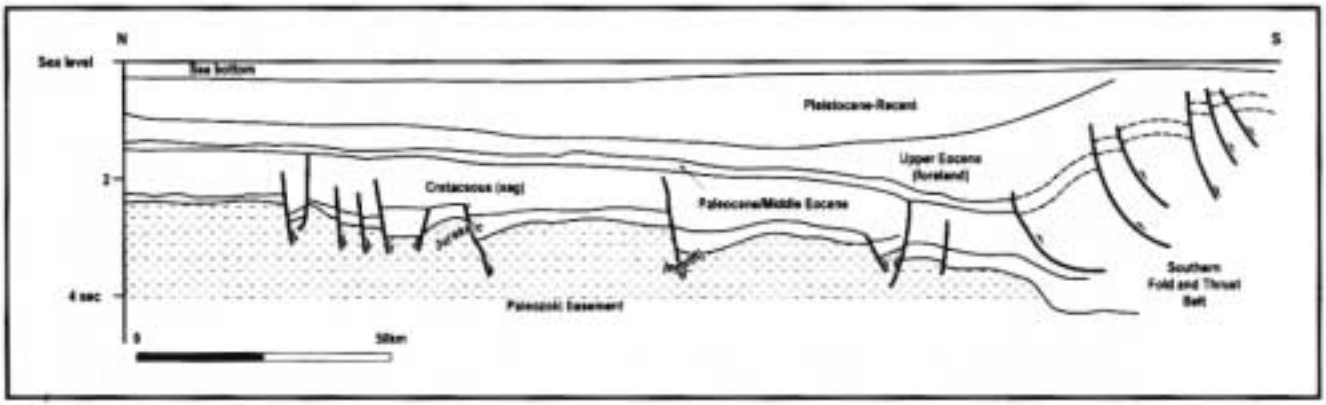

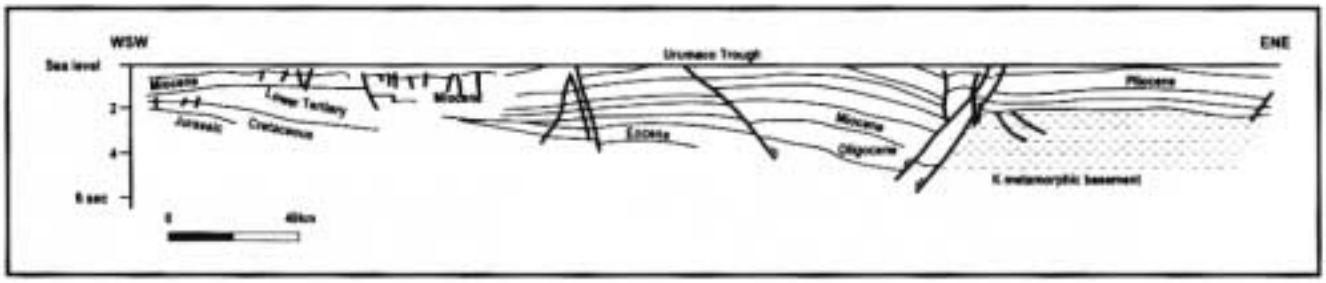

FIGURE 40 - Cross-section of the Venezuela Oriental Basin (after Perez de Mejía et al., 1980; reproduced by courtesy of Schlumberger).

FIGURE 41 - Geoseismic cross-section of the Malvinas Basin (after Galeazzi, 1996; permission to reproduce granted by Asociación Geológica Argentina).

FIGURE 42 - Geoseismic cross-section of the northwestern part of the Falcón Basin (after C.E. Macellari, 1995, AAPG Memoir Series No. 62, AAPG® 1995, reprinted by permission of the American Association of Petroleum Geologists whose permission is required for future use).

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