Chapter 2
Results and Discussion

2.1 The Chacoparanense and Salado Basins

2.1.1 The Laguna Paiva Transgression

2.1.1.1 Distribution

The TLP (Figs. 2.1, 2.2, and 2.3) has a geographical distribution that is similar to but slightly larger than the TEP (Figs. 2.4, 2.5, and 2.6). As shown in the stratigraphic sections (Figs. 1.2 and 2.7, 2.8 and 2.9), the TLP was deposited over rocks of very different ages. They are lying directly over the Precambrian basement rocks (La Maruja), Las Breñas Formation (Silurian, YPF Pirané x−1), the Sachayoj Formation (Carboniferous-Permian, Caburé 1), the Early Cretaceous basalts of the Serra Geral Formation (Laguna Paiva 1), or the Palermo Member of the Chaco Formation (Sect. 2.1.4.2). This suggests that almost the entire region of the Chacoparanense Basin was a highland from the Early Cretaceous to the Oligocene, at the end of which would have started a period of subsidence, the beginning of large-scale continental deposition, and the ingression of the TLP (Figs. 2.1, 2.10, and 2.11).

2.1.1.2 Microfossils and Paleoenvironments

Foraminifera, ostracods, and calcareous nannoplankton were found in the deposits known as *capas de Paiva* (Stappenbeck 1926) or Mariano Boedo formation (Padula and Mingramm 1963) in several locations in the provinces of Formosa, Santa Fe, Santiago del Estero, Córdoba, and Buenos Aires. These findings confirm the mainly marine nature of these sediments. This is the first finding of foraminifera and ostracods of the TLP in the Chacoparanense Basin and of foraminifera, ostracods and calcareous nannoplankton of the TLP in the Salado Basin. The foraminifera of

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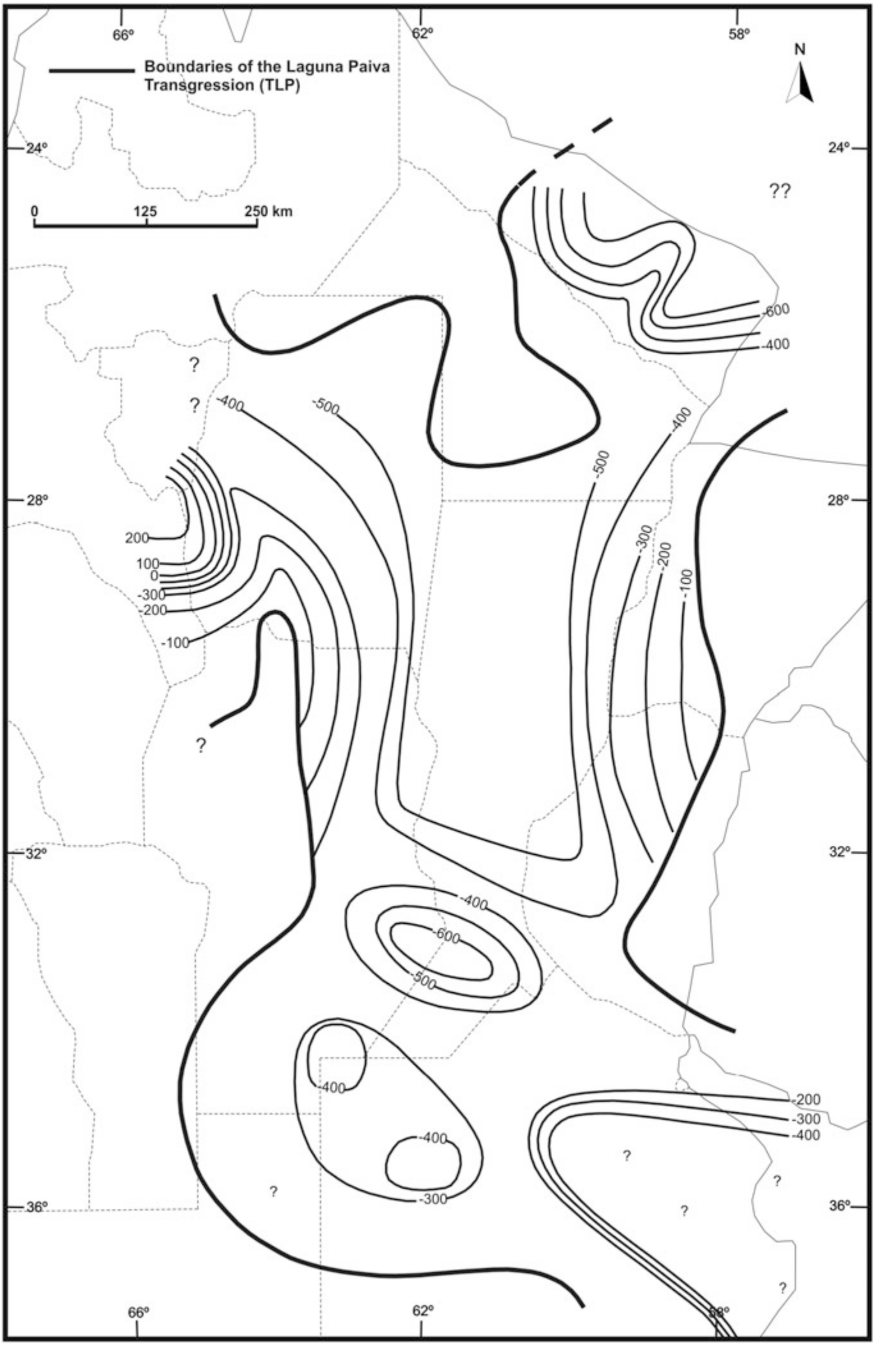

Fig. 2.1 TLP structural base in the Chacoparanense and Salado Basins

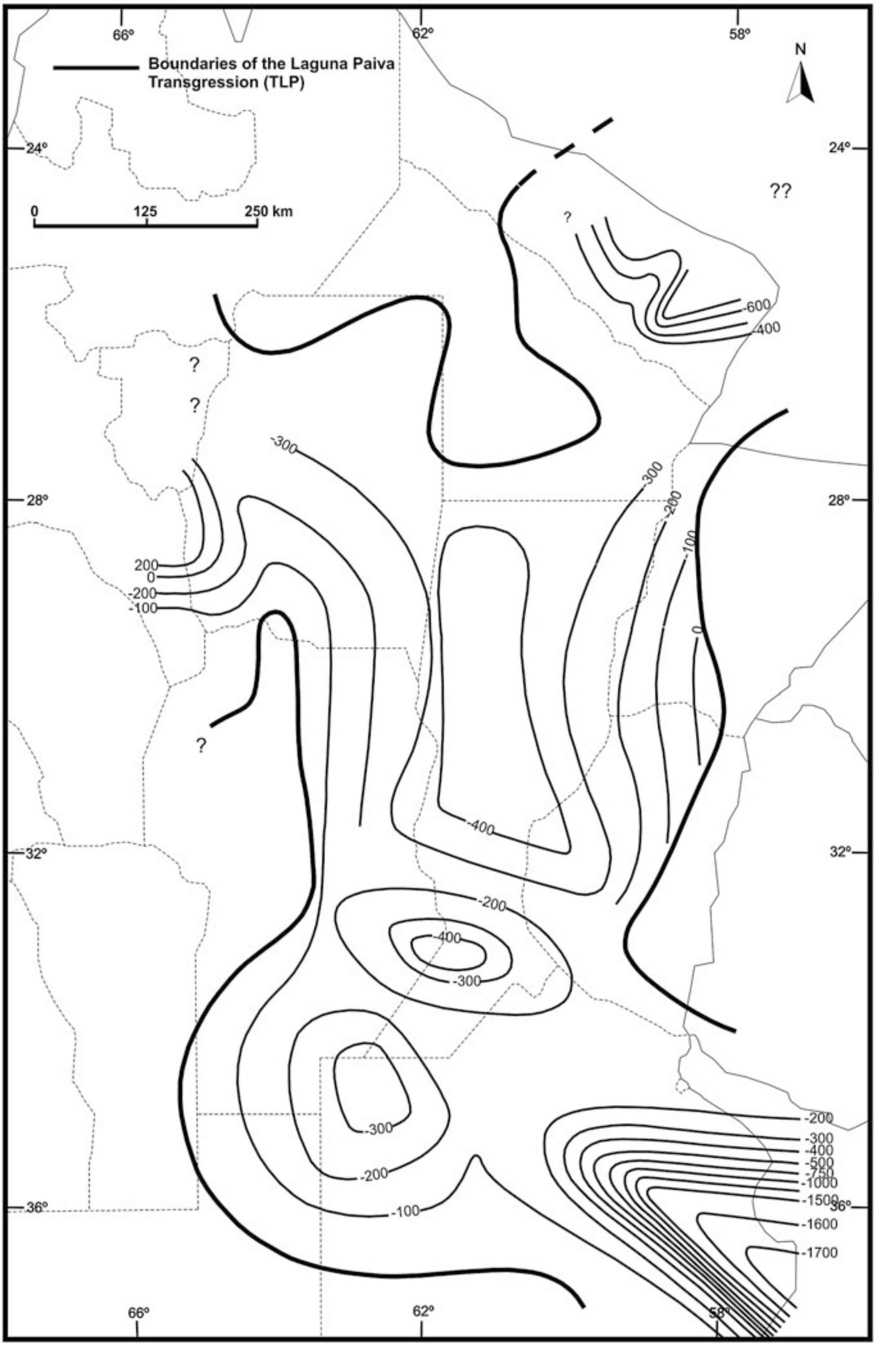

Fig. 2.2 TLP structural top in the Chacoparanense and Salado Basins

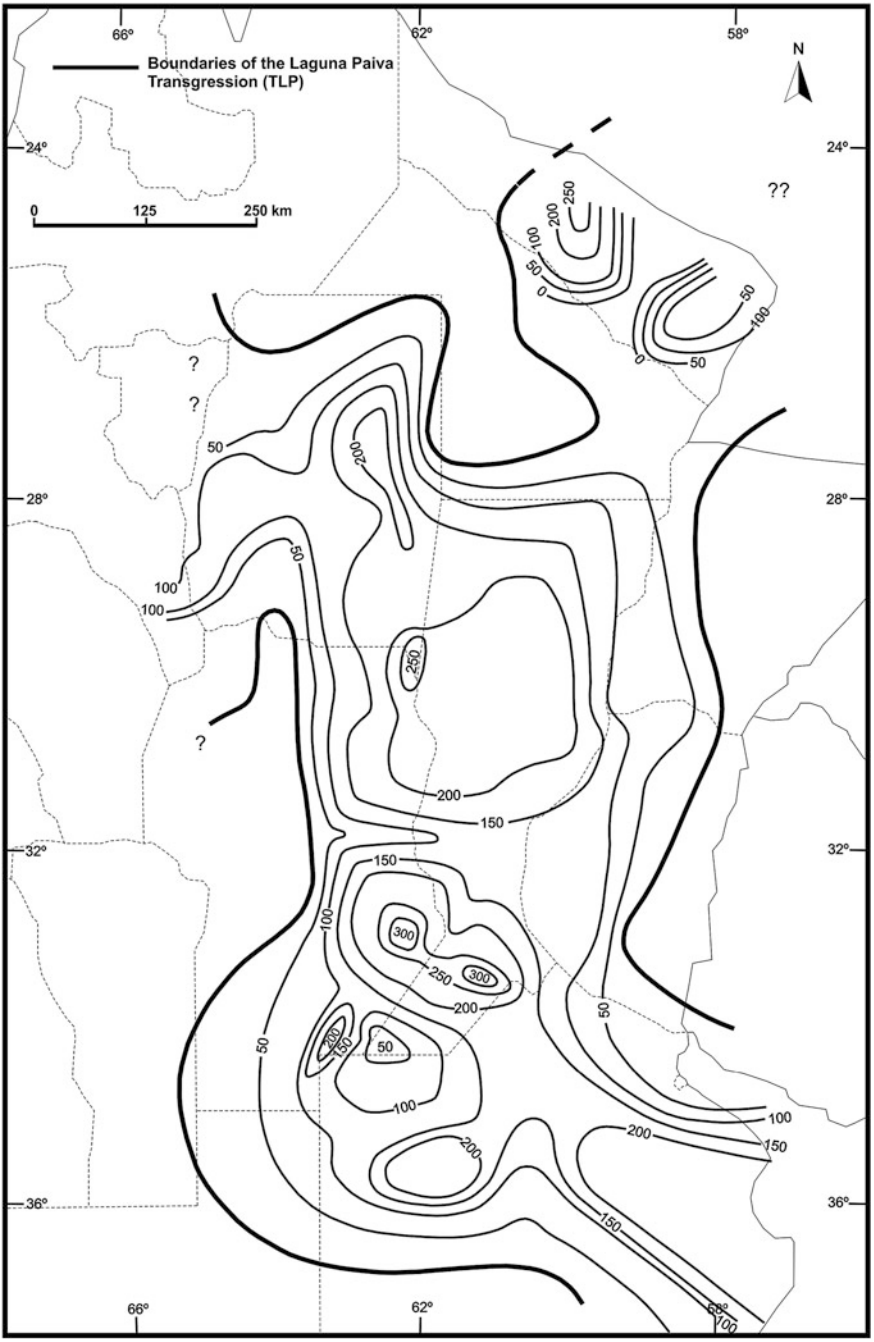

Fig. 2.3 Isopach map of the Laguna Paiva Formation in the Chacoparanense and Salado basins

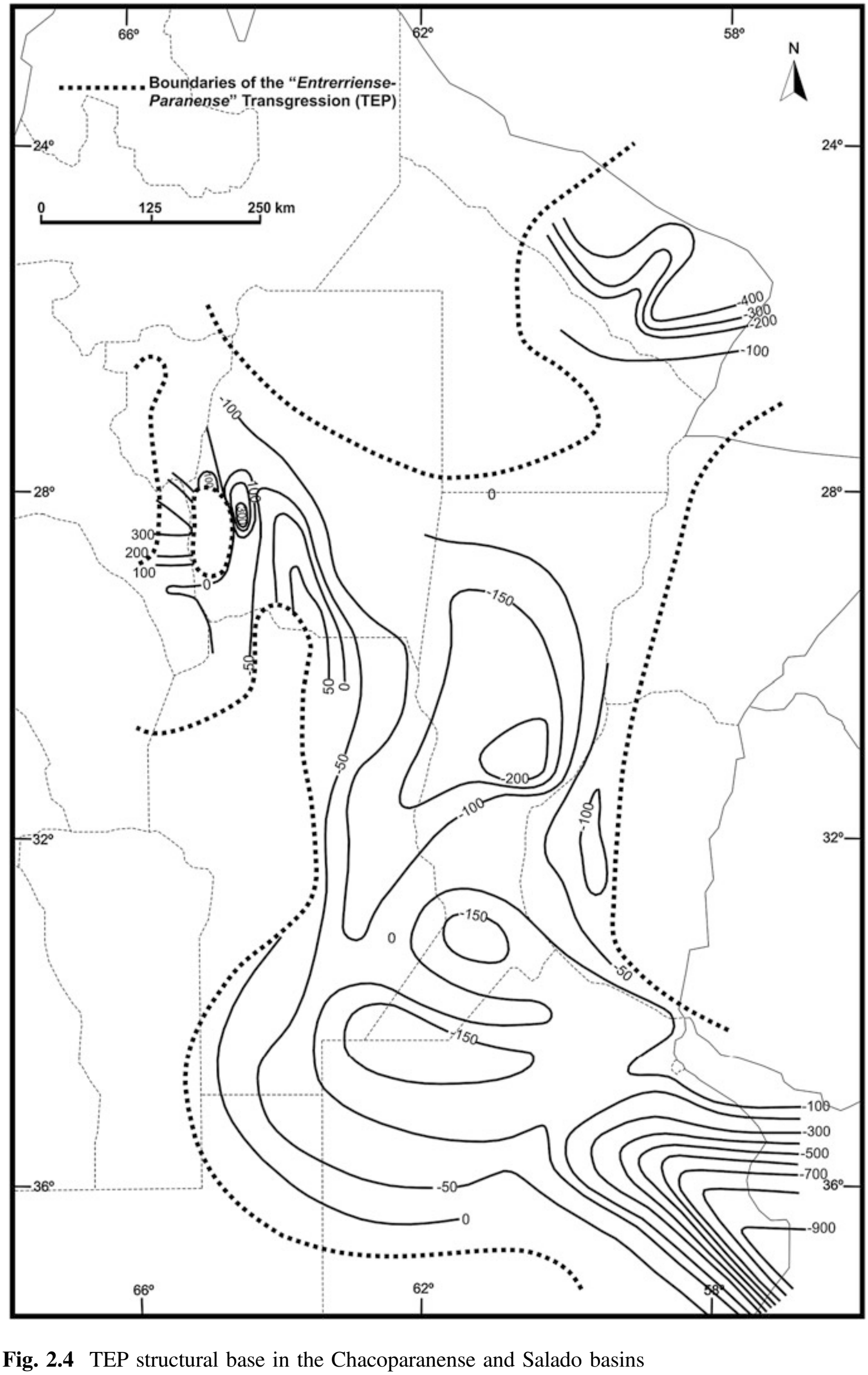

Fig. 2.4 TEP structural base in the Chacoparanense and Salado basins

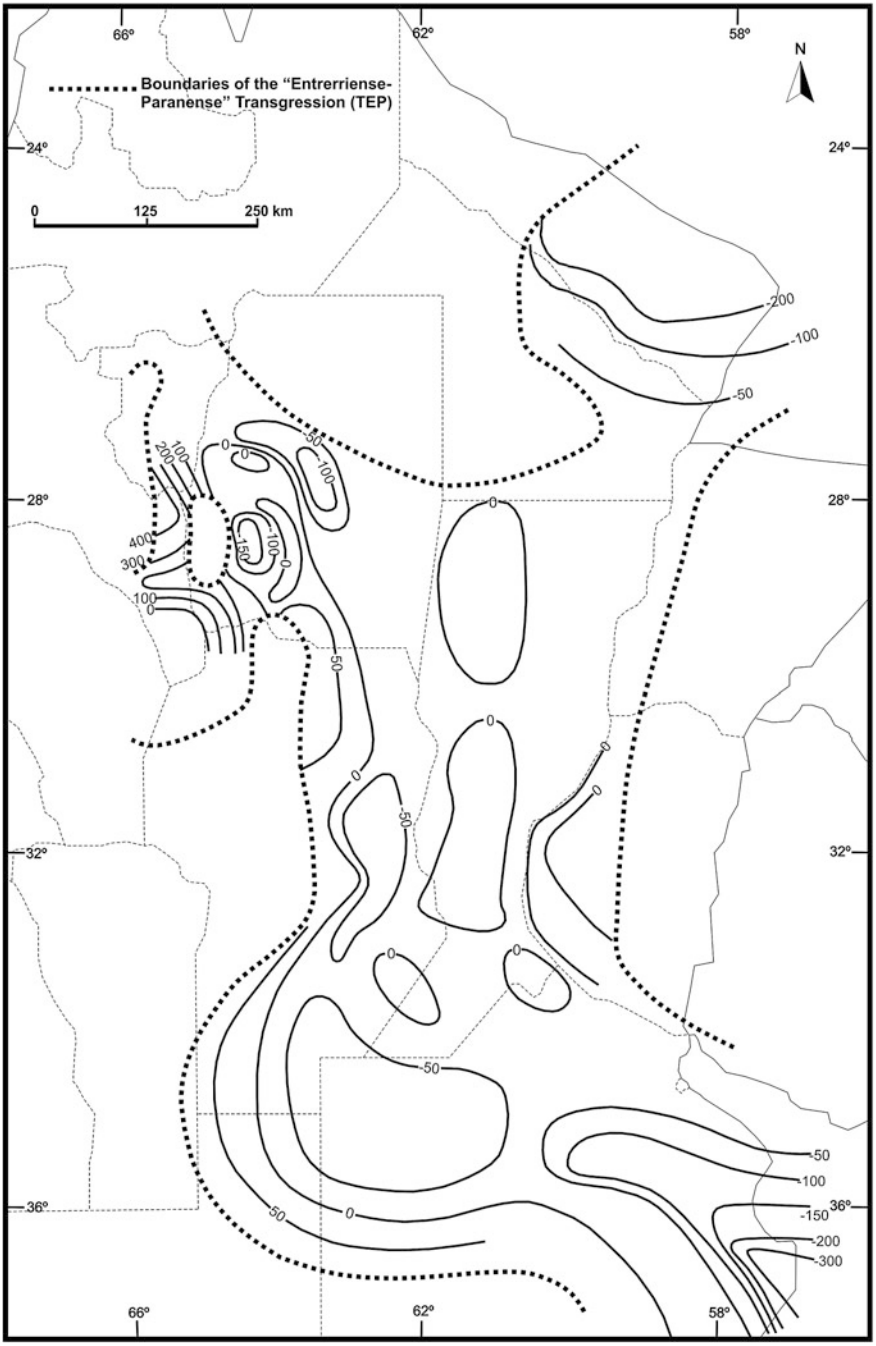

Fig. 2.5 TEP structural top in the Chacoparanense and Salado basins

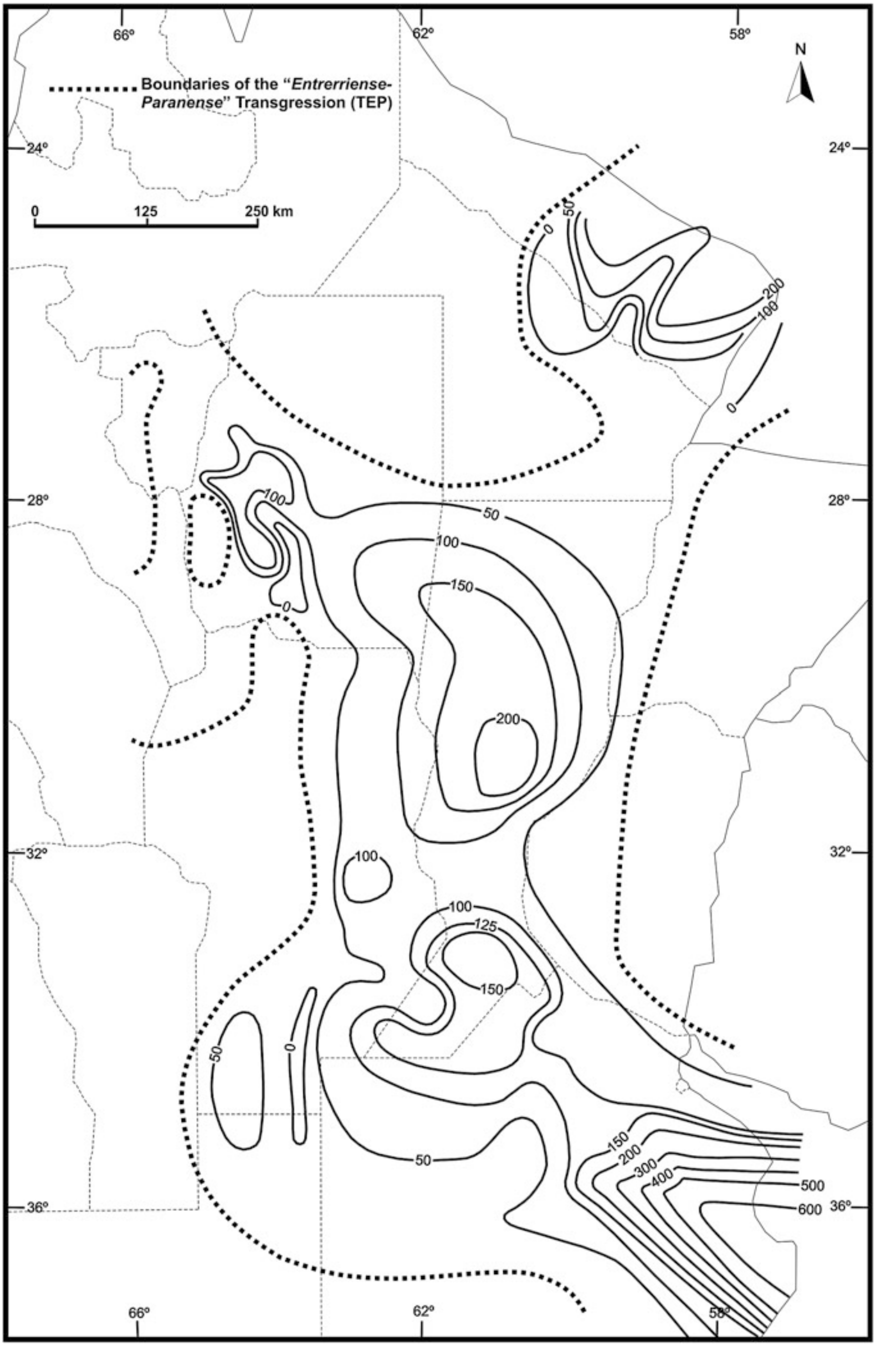

Fig. 2.6 Isopach map of the Paraná Formation in the Chacoparanense and Salado basins

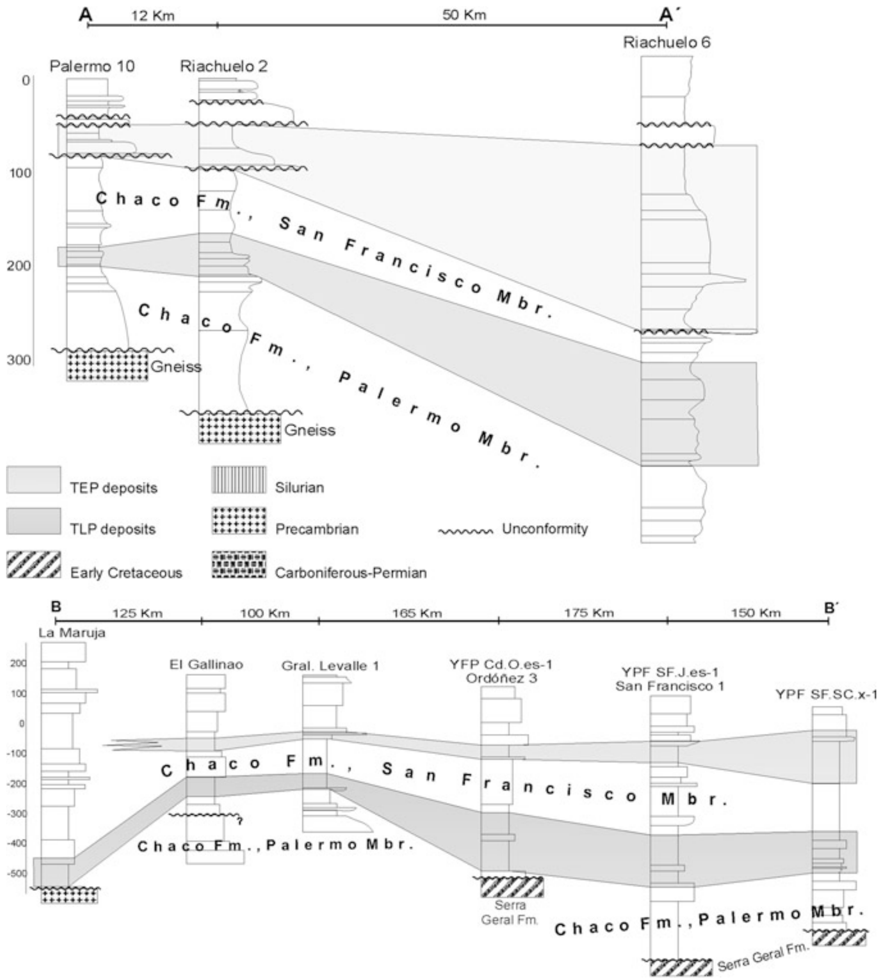

Fig. 2.7 AA′ and BB′ stratigraphic sections according to Fig. 1.2

the Chacoparanense Basin form very poor associations, usually dominated by *A. parkinsoniana*, two or three possibly new taxa of benthic foraminifera related to *Nonion* or *Haynesina*, few specimens of *Cribroelphidium*, nodosariaceans, *Quinqueloculina,* and *Peneroplis*. The preservation is moderate to poor, with frequent recrystallization and dissolution of the shells of foraminifera and ostracods. In Pozo del Tigre 1, there is strong oolitization and pyritization of the ostracods. In the boreholes around the city of Buenos Aires, the microfaunas are characterized by the abundance of large and strongly ornamented miliolids, *Cribroelphidium* spp., *Elphidium* sp. cf. *E. lens*, *B. peruviana campsi*, and large ostracods, which are all moderately preserved with frequent abrasion and recrystallization.

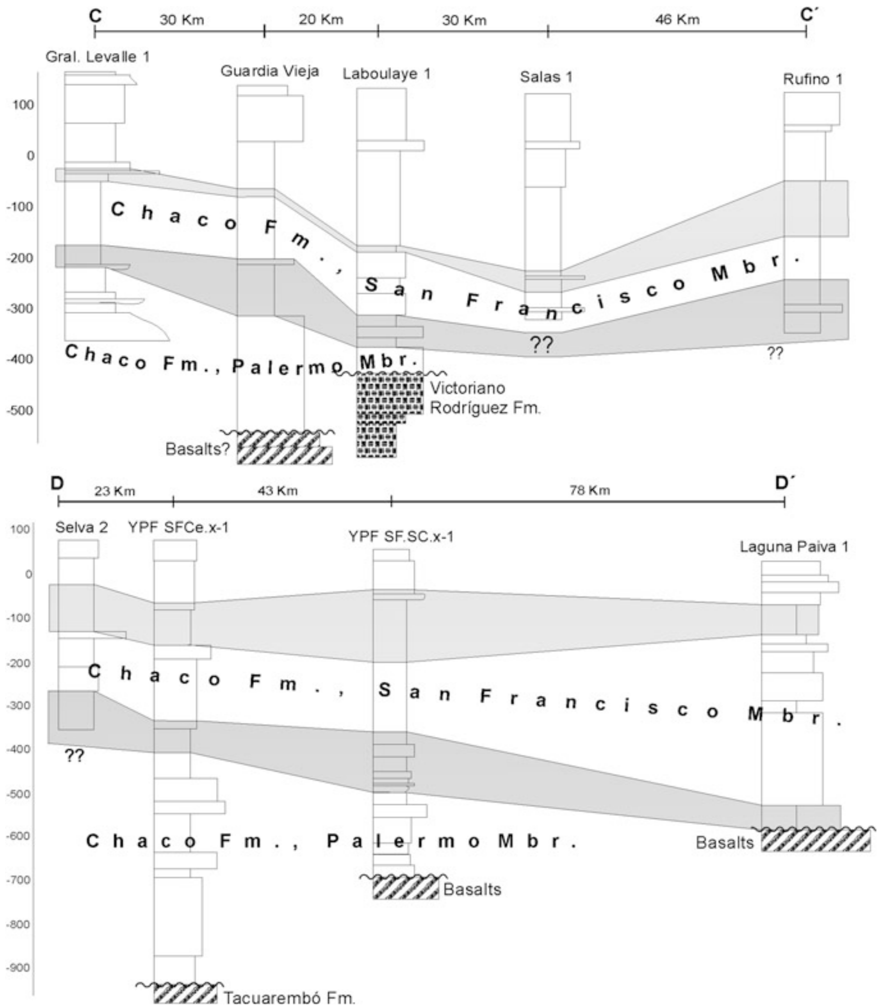

Fig. 2.8 CC′ and DD′ stratigraphic sections according to Fig. 1.2

Despite the poverty of the microfaunas, some useful elements were found to define the paleoclimatic conditions of the TLP. For instance, the Genus *Peneroplis* (San Francisco 3, Ordóñez 1) restricts the water temperature to tropical climates (Murray 1991), which is consistent with the abundance of oolites in some horizons of the boreholes in Pozo del Tigre and San Francisco localities. The remaining paleoenvironmental and paleogeographical conditions of the TLP are very similar to those previously known for the TEP, such as the dominance of *Ammonia* and *Nonion* or *Haynesina*, which have similar environmental requirements to *Protelphidium*, and the conspicuous lack of miliolids, which are appropriate indicators of very shallow water and low salinity. The abundance of pyrite in some horizons

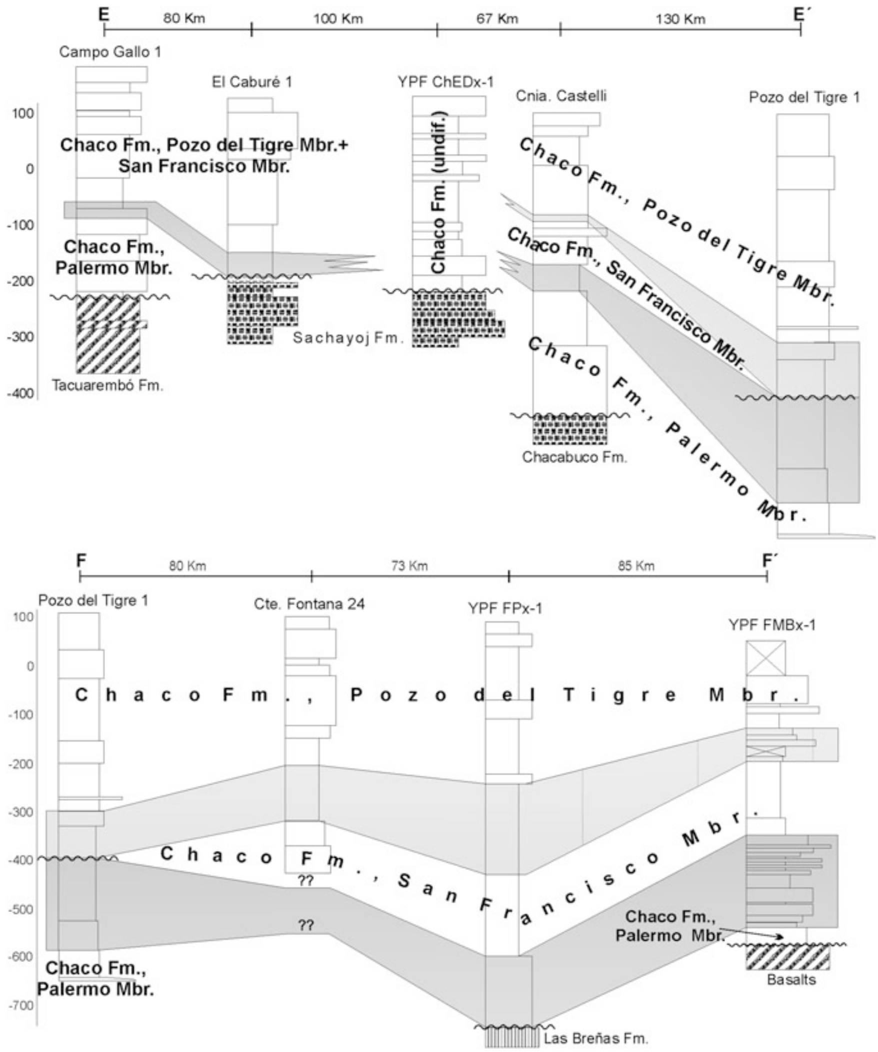

Fig. 2.9 EE′ and FF′ stratigraphic sections according to Fig. 1.2

would indicate the action of reducing bacteria that is typical in substrates with low oxygen content. The ostracods suggest shallow environments with variations of salinity, and the continental provenance is presumed by the presence of charophytes and *Candona* sp. in San Francisco 1 (Echevarría and Marengo 2006). On the northern margin of the Salado Basin, the formation of possibly warm-water hypersaline lagoons is suggested by the abundance of large and very ornate miliolids. In other sites, the salinity would have been lower, as indicated by the dominance of *Cribroelphidium discoidale* f. *pausicamerata*, which sometimes

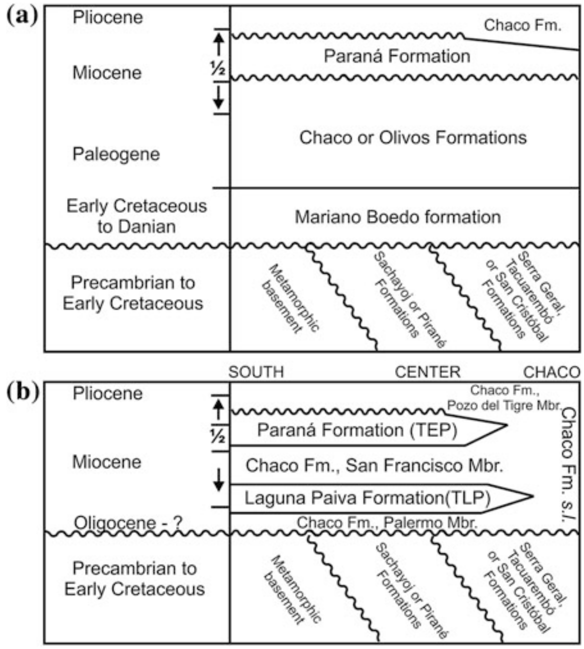

Fig. 2.10 Proposed stratigraphic outlines for the Chacoparanense Basin. **a** Modified from Padula and Mingramm (1968), Pezzi and Mozetic (1989) and Chebli et al. (1999). **b** This paper

formed monospecific associations. The abundance of young specimens of ostracods generally suggest shallow-water environments with a moderate level of energy (Echevarría and Marengo 2006).

The TLP formed a very shallow sea with successive advances and retreats of the shoreline, as implied by the interbedding of green shale with reddish mudstone and clayey sandstone rich in gypsum and gyrogonites. This feature is better developed in the northern Chacoparanense Basin, because the marine sedimentation was more continuous in the Salado Basin. Evidence to attribute these variations to eustatic, tectonic, or sedimentological causes is still not sufficient. In any case, the great sedimentary thickness recorded during the Early–Middle Miocene suggests that the sedimentation rates were very high, so some changes in the relative sea level would have been produced by the progradation of continental environments. Moreover, the number of continental interbedding within the TLP varies widely, suggesting that the advances and retreat of the sea were regulated by local differences in sediment supply.

2.1.1.3 Age

There are several reasons to assign the beginning of the TLP to the base of the Miocene or the latest Oligocene, but there is no certainty about its completion, which could have occurred in the Late Aquitanian. The finding of calcareous

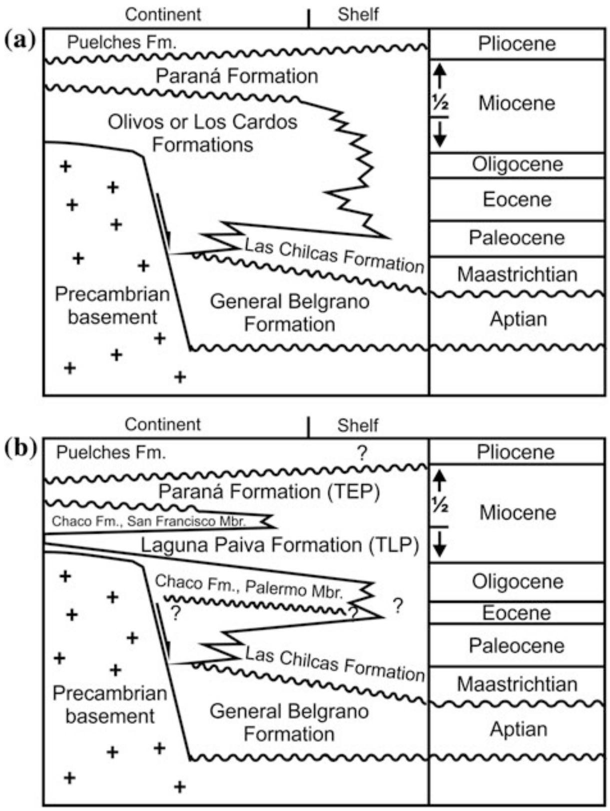

Fig. 2.11 Proposed stratigraphic outlines for the Salado Basin. **a** Modified from Yrigoyen (1999). **b** This paper

nannoplankton in the Riachuelo II borehole (194.7–197.0 mb.g.s.), near the base of the TLP, is the most accurate element of dating and the unique finding of this group of fossils in the TLP. *Triquetrorhabdulus carinatus* is an index fossil that defines the top of the Oligocene and the bottom of the Miocene, with a biochron restricted to the Zones NP25-NN2, whereas *Cyclicargolithus abisectus* appeared during the Oligocene and became extinct during the Early Miocene, with biochron in Zones NP25-NN1 (Martini 1971, Young 1998). On the basis of these two species, the base of the TLP can be assigned to the Late Oligocene–Early Miocene, Zones NP25-NN1 (Marengo and Concheyro 2001).

The *Ammonia* and *Peneroplis* genera appeared globally at the base of the Miocene (Loeblich and Tappan 1988) and were recorded near the base of the TLP in San Francisco 1, Ordóñez 3, and Pozo del Tigre 1 boreholes; consequently, the beginning of the TLP could be located with few doubts at the base of the Miocene. The rest of the foraminifera are endemic and are unknown in other deposits of the country or have a very broad biochron; therefore, they are not useful for biostratigraphical purposes. However, some of these endemic taxa could serve as index fossils for the TLP given its abundance, such as the case of *Quinqueloculina boueana* d'Orbigny 1846, *Massilina secans* (d'Orbigny 1826) f 1 and 2, *Cycloforina brongniartiana* (d'Orbigny 1839a), *Cribroelphidium paivensis* sp. nov., *Cribroelphidium discoidale pausicamerata,* and *Nonion depressulus* (Walker and Jacob 1798) in the northern margin of the Salado Basin, and *Peneroplis* sp., *Nonion* sp. 1 and *N. depressulus* in the Chacoparanense Basin.

The ostracods gave similar, although less accurate, results (Fig. 2.12). The ages were assigned by comparison with Patagonian faunas with little bounded ages. *Soudanella cleopatrae* and *Patagonacythere* sp. 1 have affinities with species whose biochron extends until the Late Aquitanian. According to Marengo et al. (2005), *Ambostracon paranensis*, *Argenticytheretta miocenica*, *Callistocythere marginalis*, *Cytheretta punctata*, *Garciaella leoniana*, *Henryhowella* aff. *Evax,* and *Quadracythere neali*, from the Salado Basin, are the only species previously known in the region. They were found in sediments of the Miocene–Holocene in the Pelotas Basin (southern Brazil), the Late Miocene–Early Pliocene and Quaternary in the Salado and Colorado Basins, the Late Miocene–Early Pliocene in the Valdés Basin, the Eocene–Miocene of the Austral Basin, and the Holocene of the Río de La Plata estuary and the Argentine continental shelf. They also noted affinities with species of the Holocene in the Pelotas Basin and the continental shelves of Brazil and Uruguay. Finally, Echevarría and Marengo (2006) studied the specimens of Pozo del Tigre 1, San Francisco 1, and San Cristobal l boreholes, finding only one species previously recognized in the country, *S. cleopatrae*, from the Oligocene of the south-central and southeastern Santa Cruz province. Two species have morphological similarities to other previously known from Holocene deposits of the Argentinian, Brazilian, and Uruguayan continental shelves.

There are indirect elements, although very consistent with the fossil record, such as the global eustatic sea level curve (Haq et al. 1987) and the rate and obliquity of the convergence between the Nazca and South America plates (Somoza 1998), as summarized in Fig. 2.13. A good correlation is observed between the ages of the microfossils and nannofossils, the tectonic events in the Pacific margin, and the global sea level changes. Likely, there is not a direct relationship between the tectonic and eustatic factors, whereas it is clear that the occurrence of a period of very strong deformation at the western margin of the continent would have been enough to cause the subsidence in the Chacoparanense Basin, allowing the income of the sea during the eustatic rise at the end of the Oligocene. In the same figure, the combination of these factors is useful for explaining the ingression of the TEP during the Serravallian, although it is less obvious because the variation of the convergence does not appear to have been so sharp. Accordingly, the onset of TLP occurred between the end of the Oligocene and the beginning of the Miocene, which otherwise is the age when many transgressive events occurred in the Pacific and Atlantic coasts of all of South America (Sect. 1.4.3 and Fig. 1.1). The eustatic

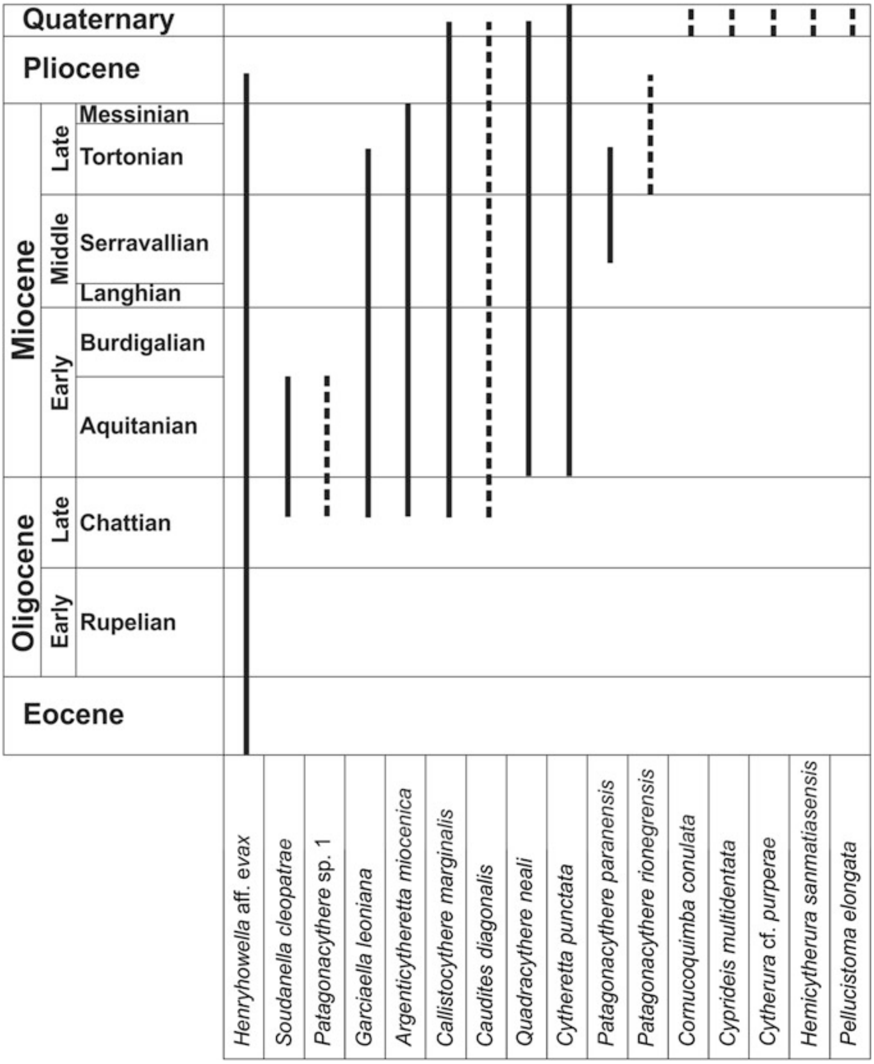

Fig. 2.12 Some TLP ostracod ages according to previous works in Argentina, Uruguay, and Brazil. *Dotted lines* indicates the ages of species with affinities to those found in this investigation

fall and the decline of the convergence and obliquity rates towards the end of the Aquitanian possibly indicate the maximum age for the regression of the sea. The thick continental sedimentary mantle, up to 200 m thick, deposited above the TLP is an additional tool to estimate the age of the top. These continental sediments would have been deposited in a period of approximately 5–6 million years, which means a sedimentation rate of approximately 3–4 cm/ky—a consistent value for loessoid and fluvial deposits.

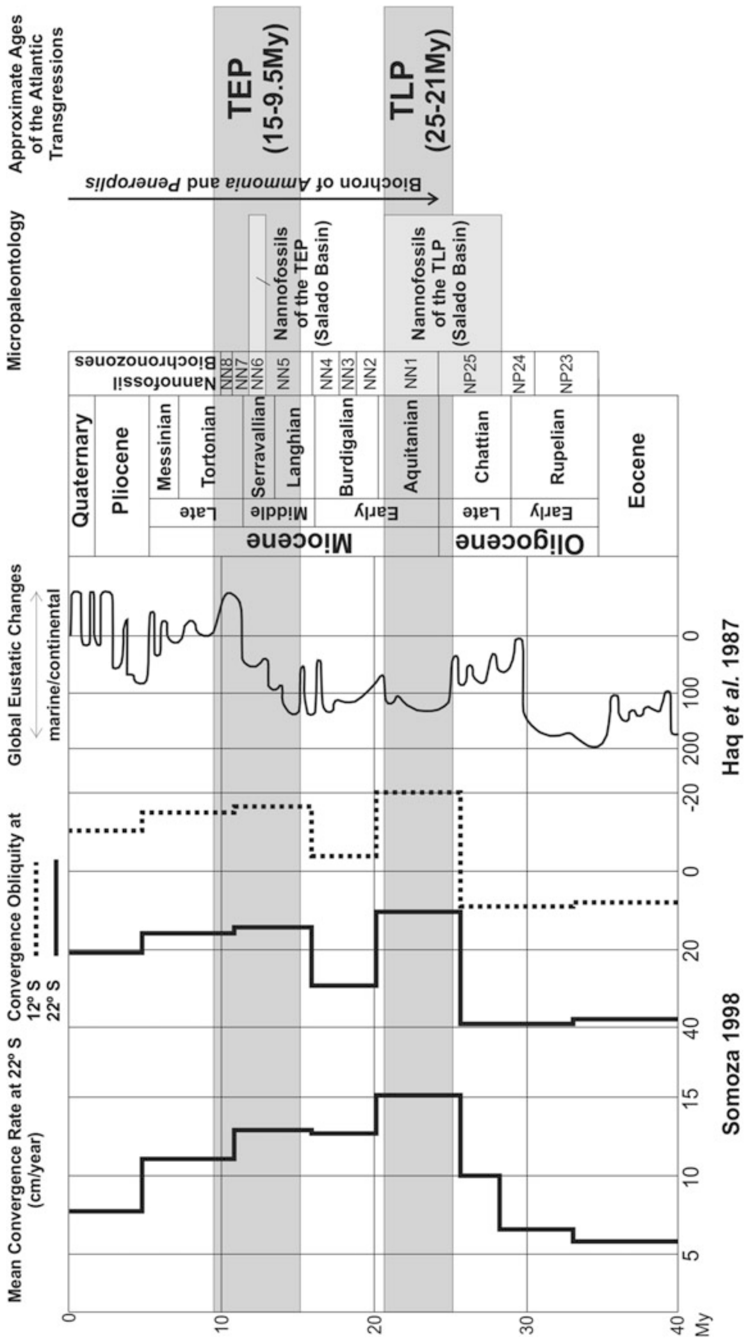

Fig. 2.13 Correlation between the microfossil ages of the TLP and TEP, the eustatic curve after Haq et al. (1987), and the convergence rate and obliquity between Nazca and South America (Somoza 1998)

2.1.1.4 Older Marine Deposits

As seen in Sect. 1.4.2, some authors have pointed out a Cretaceous–Paleocene age for the Mariano Boedo formation, and consequently for the deposits equivalent to the TLP. It should be noted that no Cenozoic marine sediments prior to the TLP were found in any borehole. Most of the continental deposits located below the TLP (Palermo Member) apparently belong to the same Neogene depositional cycle, as they have very similar mineralogical and diagenetical characteristics to the San Francisco Member (Sect. 2.1.4.2). Consequently, there are no reasons to consider that the Maastrichtian–Danian transgression had flooded beyond the center of the Salado basin. Therefore, the paleogeographical reconstructions where this older transgression is spread throughout the Chacoparanense Basin to the NOA (Uliana and Biddle 1988; Spaletti et al. 1999) need to be revised. In some areas where the Palermo Member is thicker than usual, there are continental deposits that could be Paleogene or older, such as those studied in the YPF Cd-Saira-Ex.1 borehole (province of Córdoba; Musacchio 2000; Musacchio et al. 2002), between 630 and 732 mb.g.s., where the gyrogonites *Nitellopsis supraplana* (*s.l.*), *Porochara gildemeisteri* and *Gobichara* (*Pseudoharrisichara*) sp. were found, which are characteristic of the latest Cretaceous.

2.1.2 The Entrerriense-Paranense Transgression

2.1.2.1 Distribution and Lithology

The TEP formed a shallow sea that entered through the Salado Basin, flooded the Chacoparanense Basin, and possibly reached southern Bolivia, crossing the NOA region. It is also likely that some sea branches have advanced westward, bordering the northern Pampeanas Ranges, and reached some regions currently occupied by the Andes Mountains. There are some doubts about their actual geographical distribution arising from the discovery of the TLP, to which some of the records assigned prior to the TEP in the Andean region, the NOA, and southern Bolivia probably correspond. This uncertainty may only be clarified by reviewing the microfaunas of the San José, Anta, and Yecua Formations, among other profiles.

The distribution of the TEP in the Chacoparanense Basin (Fig. 1.2) is very similar to the TLP although somewhat smaller, possibly by partial filling of the basin at the Middle Miocene. There was also a slight tectonic uplift in the Subandinas Ranges (Fig. 2.14), which prevented the flooding in northern Santiago del Estero and western Chaco and Formosa provinces. In Mesopotamia, the large region located in between the Paraná and Uruguay rivers, the transgression was restricted to a fringe near the area of the current Paraná River, probably due to a slight rise of this region. Its thickness is smaller and more constant than in the TLP (Figs. 2.3 and 2.6), in general between 50 and 100 m, with a maximum of 200 m in eastern Formosa and central Santa Fe provinces. In the center of the Salado Basin,

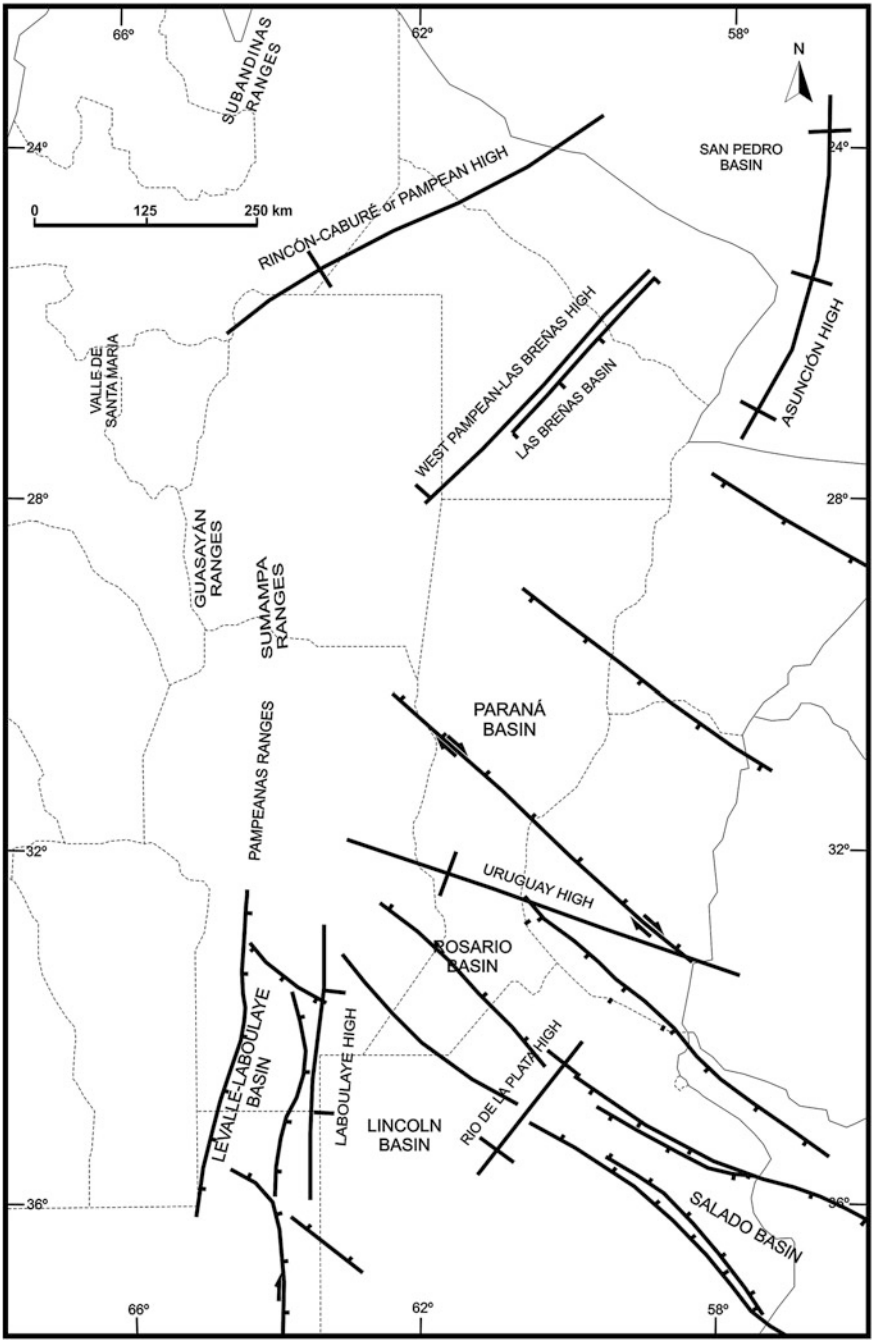

Fig. 2.14 Main structural features in the Chacoparanense and Salado basins, after Chebli et al. (1999) and Yrigoyen (1999)

the thickness is much larger because marine sedimentation was continuous along most of the Neogene and Quaternary.

The sediments are mainly light-olive mudstones, with a few rather sandy intercalations. In the three boreholes obtained in the city of Buenos Aires, the base consists of yellowish-brown conglomeratic sands with marine megafauna. The megafauna from boreholes is scarce and badly preserved. Except for the relative abundance of eroded oyster fragments, the remaining shells fragments are unidentifiable. Some specimens of the bryozoan *Cupuladria canariensis* Busk were found in the northern margin of the Salado Basin.

2.1.2.2 Microfossils and Paleoenvironments

The foraminifera in the Chacoparanense Basin were found in nine sites, but ostracods were only found in three sites; neither planktonic foraminifera nor calcareous nannoplankton were found. In the Salado Basin foraminifera, ostracods and calcareous nannoplankton were found in three boreholes. The distribution charts, the systematic list, and pertinent illustrations can be found in Appendices C, D, and E.

The Chacoparanense Basin (Figs. C.1–C.3 and C.9)

The main characteristics of the microfaunas were referred to by several authors and synthesized within a regional scheme by Herbst and Zabert (1987). The information obtained in this work significantly increases the amount of information on the microfossils of this region. The foraminifera are typical of very shallow, usually hyposaline seas, suggesting a temperature similar to the current Argentine continental shelf. The only exception is *Disconorbis bulbosa*, a benthic foraminifer now restricted to the northern Brazil shelf; therefore, the water temperature of the TEP could have been slightly higher than the current for the same latitude. The dominant foraminifera in all the sites are *P. tuberculatum* and *A. parkinsoniana*; both species are highly tolerant to lower salinities (Malumián 1978; Murray 1991). In the upper section of the Paraná Formation at Diamante, Entre Ríos province, the diversity of ostracods and foraminifera is higher and there is a considerable increase in the abundance and diversity of miliolids; thus, they represent a moment where the salinity would have been closer to normal, and the TEP would have reached the maximum depth and the peak of flooding.

The most diverse microfaunas were recognized in southwestern Entre Ríos and eastern Santa Fe provinces; to the north and northwest of the country, they became dramatically impoverished due to a decrease in depth and mixture with freshwater. The highest diversity was recorded in the Diamante area, where some new species of foraminifera for the basin were found, such as *Miliammina* sp., *Textularia candeiana*, *Pyrgoella* sp., *D. bulbosa*, *Fissurina quadricostulata*, *Guttulina problema*, *Lagena* sp., and *Neoeponides* sp. Outside the area of Diamante, the ostracods were only found in Pozo del Tigre 1, San Francisco 1, and Selva 2 boreholes. Nine podocopids genera, four genera with doubts and two indeterminate ones, and 11 species were found. These microfaunas indicate that the sediments were deposited in a shallow marine environment with changes in salinity. *Cytheridella ilosvayi* suggests oligohaline conditions in the sample Pozo del Tigre 1–89 (491.05–501.05 mb.g.s.).

Northern Margin of the Salado Basin (Figs. C.4–C.7 and C.9)

Near the top of the TEP, at the sample YPF Palermo 10 (51–65 mb.g.s.), calcareous microfossils are very scarce, being also altered by dissolution and pyritization. The pyritization is revealed by the abundance of framboidal pyrite and pyrite casts of microgastropods and foraminifera, whereas solution is suggested by the scarcity or total absence of calcareous material. From 65 mb.g.s. to the bottom, the dissolution and pyritization were less intense, and the foraminifera and ostracod microfaunas have greater diversity and abundance. In the samples located at 65–66 and 69–70 mb.g.s., two peaks of diversity were recorded with a similar abundance of microfossils, although the latter has a much higher proportion of planktonic foraminifera and the only finding of calcareous nannoplankton in this well. The microfossils in Riachuelo II borehole have the same preservation characteristics than in YPF Palermo 10, although the alteration is somewhat less intense. From 60 mb.g.s. to the bottom, associations with greater abundance and diversity of foraminifera and ostracods were recovered; between 65 and 70 mb.g.s., about the middle portion of the TEP, there is a peak of maximum diversity and abundance of planktonic and benthic foraminifera and ostracods, as well as the only record of calcareous nannoplankton. The samples were taken at very irregular intervals in the Riachuelo VI borehole, with large sections without samples. Both sectors with the greatest diversity and abundance of microfauna were found in samples 147.0–150.0 and 280.0–291.35 mb.g.s. The latter is near the base of the TEP and has the greatest diversity and abundance of benthic and planktonic foraminifera and ostracods, and the only record of calcareous nannoplankton.

In summary, the TEP would have started with very high-energy environments that eroded the previous continental sediments (San Francisco Member), depositing conglomeratic sands with or without pelecypod fragments. Towards the center of the sections, the TEP would have reached the maximum extension as indicated by the composition of microfossils and nannofossils. To the top, the microfaunas are quickly depleted, indicating a gradual decline of the marine environment. The microfaunas located above the maximum flood peak have very low diversity and are characteristic of nearshore environments. Particularly, the ostracods indicate shallow environments, such as the genus *Perissocytheridea* found at the top of the Riachuelo VI borehole, which is typical of water bodies with sharp salinity shifts (Marengo et al. 2005). The nannofossils are rare and restricted to the levels with greater diversity. They indicate somewhat different environmental characteristics from those inferred by foraminifera and ostracods. *Discoaster broweri* is a Cenozoic discoasterid characteristic of temperate-warm waters, whereas *Braarudosphaera bigelowi*, *Thoracosphaera heimii*, *Rhabdosphaera clavigera*, *Pontosphaera multipora,* and several species of *Helicosphaera* are indicative of shallow marine nearshore environments, with normal salinity to slightly hyposaline water (Perch-Nielsen 1985).

2.1.2.3 Age

The nannofossils are characteristic of the Biozone or Interval D (Young 1998), between the last occurrence of *Sphenolithus heteromorphus* and the first appearance of *Catinaster coalitus*, and are characterized by *Reticulofenestra pseudoumbilicus*, *Coccolithus pelagius*, *Calcidiscus leptoporus*, *Discoaster exilis*, *Helicosphaera carteri*, *Umbilicosphaera jafari* and *U. rotula*. Other common species in the association include *Discoaster kugleri* and *Helicosphaera orientalis*. *Calcidiscus premacyntyrei*, *H. orientalis*, *H. walbersdorfensis,* and *R. pseudoumbilicus* are also relevant, which restrict the association to the Zone NN6 (Martini 1971 and Young 1998), corresponding to the middle of the Serravallian (Middle Miocene). The benthic foraminifera do not allow for further clarification of the age than that indicated by Malumián (1970, 1972) for the informal zone of *P. tuberculatum* (Middle–Late Miocene in the Colorado and Salado Basins). The planktonic foraminifera found in the northern Salado Basin are very small, belonging to juvenile specimens or being broken.

Some specimens of *Globorotalia prescitula* Blow 1959 and *Neogloboquadrina continuosa* (Blow 1959) transitional to *Paragloborotalia mayeri* (Cushman and Ellisor 1939) could be determined, which possess broader biocrone culminating between biozones N12 and N14 (Fig. 2.15), very similar to the age indicated by the nannofossils. The ostracoda are not good age indicators; the age of nearby sites where common species with the TEP were found is detailed (Fig. 2.16): *Ambostracon paranensis*, *Aurila* sp. 3 *Valicenti*, *Callistocythere marginalis*, *Coquimba* sp. *Echevarria*, *Henryhowella* aff. *evax*, *Perissocytheridea victoriensis*, *Wichmannella deliae,* and *Wichmannella juliana* were previously recognized in the Miocene sediments of the Chacoparanense Basin, in the Miocene-Quaternary of the Pelotas Basin, in the Late Miocene–Early Pliocene basins of the Colorado and Valdés Basins, and in the Eocene–Early Miocene of the Austral Basin; *Argenticytheretta miocenica* was previously found in sediments from the Oligocene of south-central Santa Cruz province, the Miocene subsurface of the city of Buenos Aires, the Late Miocene of Entre Ríos and Santa Fe provinces, the Early Miocene of the island of Tierra del Fuego, and the Late Miocene–Early Pliocene of Puerto Pirámide, Chubut province, and *Cytheridella ilosvayi* was recognized in Holocene deposits in southern Buenos Aires province. Also, some species have morphological similarities to species from the Eocene of southern Santa Cruz, the Late Pliocene of southwestern Atlantic Ocean, the Holocene of southeastern Buenos Aires province, and the Holocene of the coast of Chubut and Santa Cruz provinces, eastern Tierra del Fuego, southern Brazil, and the western portion of the Strait of Magellan (Marengo et al. 2005).

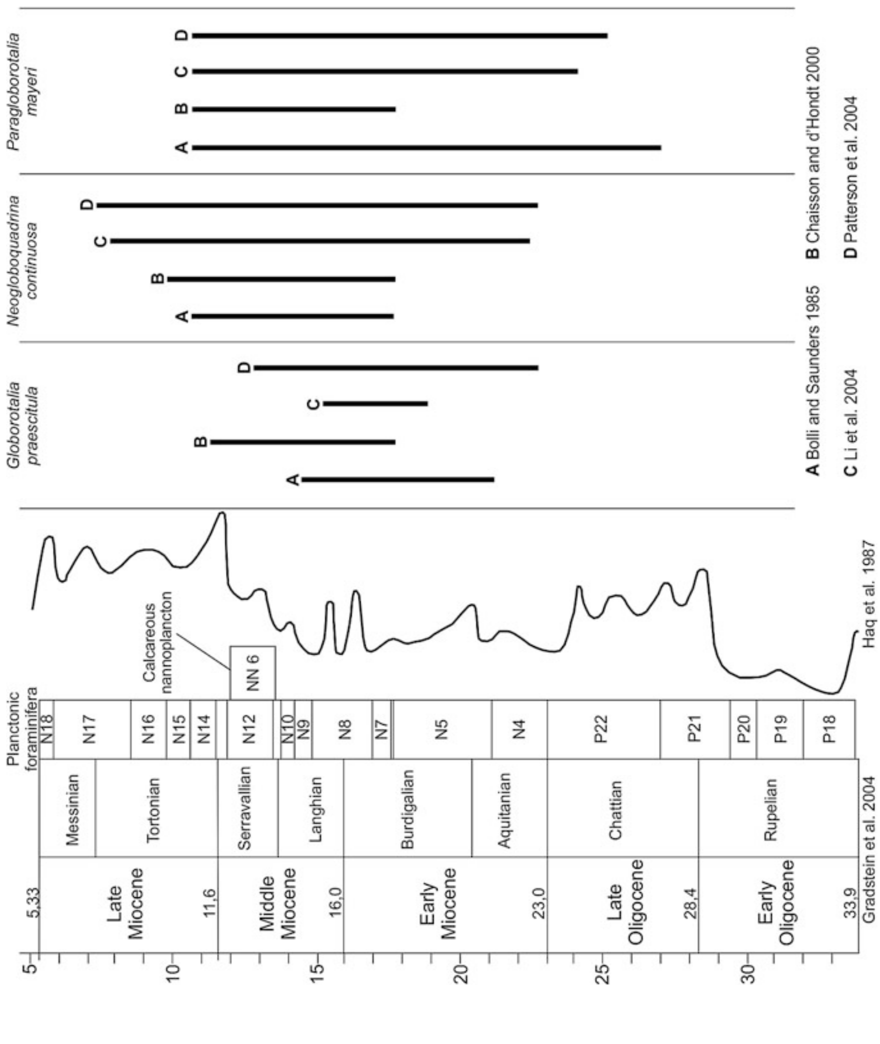

Fig. 2.15 Age of planktonic foraminifera and calcareous nannoplankton in the TEP of the Salado Basin

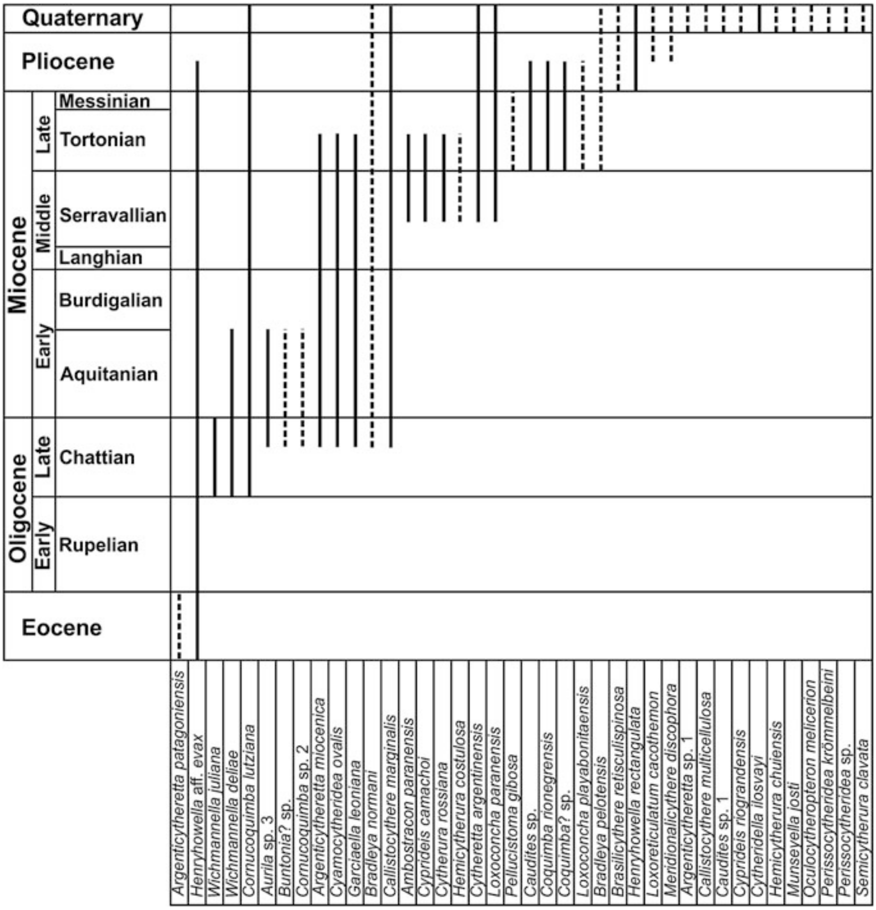

Fig. 2.16 Some TEP ostracod ages according to previous works in Argentina, Uruguay, and Brazil. *Dotted lines* indicates the ages of species with affinities to those found in this research

From the study of these fossil groups, it can be concluded that age is better determined by the nannofossils, which indicate that the middle sector of the TEP in the Riachuelo II and Palermo 10 boreholes, as well as the lower to middle sector in Riachuelo VI borehole, were deposited in Zone NN6 (Martini 1971; Young 1998), Serravallian, Middle Miocene. The recent dating of the upper section at Diamante (9.47 Ma, Pérez 2013) is helpful to estimate the end of the TEP, but there are no clues to determine the beginning of it, although the correlation with the global eustatic cycles and convergence rates in the western margin of southern South America (Fig. 2.13) suggest that it may have occurred about at the end of the Langhian. Taking all of these factors into account, it can be estimated that the TEP was developed between 15 and 9.5 Ma.

2.1.2.4 The TEP in Diamante, Entre Ríos Province

The most relevant lithology and micropaleontological content were studied in four wells in the town of Diamante, Entre Ríos Province. In Fig. A.3, an ideal section of the area is shown. The following distribution of microfossils for the Diamante region was determined:

- 47–53 mb.g.s.: moderate diversity dominated by *P. tuberculatum*, *A. parkinsoniana*, *H. boueana*, miliolids, *Paracypris* sp. *Cyprideis camachoi*, *Cyamocytheridea ovalis,* and *Patagonacythere* spp. Towards the roof, diversity decreased and there was a significant increase in the proportion of *H. boueana* and the disappearance of the miliolids and ostracods.
- 55–60 mb.g.s.: lower diversity and abundance dominated by *P. tuberculatum* and *A. parkinsoniana*, and fewer specimens of *H. boueana*, *B. campsi peruviana*, *C. discoidale*, and ostracods.
- 85 mb.g.s.: very few specimens of *P. tuberculatum* and *A. parkinsoniana*.

The deposits of the TEP start with a sharp contact on the loess-like deposits of the Chaco Formation. This contact would not have been erosional because it lacks the coarse fraction typical of a lag deposit. The first 40 m of the Paraná Formation are composed of marine olive mudstones with fewer microfossils and fragments of oysters, interbedded with thick deposits of continental sands that would indicate a long period during which the progradation of coastal sediments competed with rising sea level. Frenguelli (1920) explained the interbedded sandy layers in the Paraná Formation as a result of several transgressive–regressive cycles associated with orogenic movements. Stappenbeck (1926) interpreted that those were produced by the progradation of a deltaic system on the coastal environment; in turn, Aceñolaza and Aceñolaza (2000) considered that these sandy layers were deposited in an environment of coastal dunes. The finding of very fresh fragments of wood and thin insertions of dark shales in the Diamante boreholes would support the interpretation offered by Stappenbeck.

Then, one or two sandy levels with abundant marine microfauna and megafauna were deposited. These sandy levels have a faunal assemblage equivalent to that found in outcrops along the river coast at Diamante, which may be correlated throughout southwestern Entre Ríos province. At the top of the sequence, the peak of maximum flooding would have been reached, as deduced from the composition and diversity of the microfauna. The marine or transitional sedimentation ends with the deposition of a thick bed of occasionally laminated green shale with calcareous concretions and very well-developed gypsum crystals, and a bed of fining upward sandstone strongly cemented; this bed suggests the final regression of the sea. Finally, a new level of massive red mudstone with calcareous concretions of undoubtedly continental origin was deposited.

In summary, the Paraná Formation at Diamante seems to be the result of a single very shallow marine ingression, regulated by the progradation of coastal environments. Towards the top, the sea reached its maximum elevation and areal expansion, after which the regression took place and distinctly continental sedimentation was restored. If the Paraná Formation is considered as the greenish–yellowish marine and transitional deposits clearly distinguished from the reddish continental sediments, this unit is about 60 m thick, of which only the upper 20–25 m crop out.

2.1.2.5 The TEP in the Chacoparanense Basin and the Arm of Tethys

The TEP deposits from the northern Salado Basin to its northernmost probable records in southern Bolivia have fairly uniform lithology. They consist of massive green mudstones and shales and green to yellow sandstones, with a variable content of marine fossils and frequent levels rich in gypsum. The marine microfossils are usually found in green or yellow sandstones with megafauna, and they are rare and poorly preserved in the green mudstones. The microfaunas are typical of very shallow, usually hyposaline marine environments. Foraminifera have moderate to low diversity, with a sharp depletion of the diversity and an increase in the proportion of *A. parkinsoniana* towards the continental hinterland. The sea entered from northern Buenos Aires province and spread towards the center and northern portions of Argentina, probably reaching southern Bolivia and Paraguay (Fig. 1.1), with an inland marked impoverishment of the microfaunas and the disappearance of the species of normal salinity beyond Santa Fe province.

Based on the remarkable similarity between the Caribbean and TEP malacofaunas, Ihering (1927) postulated the migration of some genus of tropical mollusks from the Caribbean Sea to the coast of Argentina, through a seaway that would have crossed inner South America along the western part of the continent, which he named as "The Arm of Tethys" (Fig. 1.1). Many authors who studied the TEP agreed with this hypothesis (Boltovskoy 1958, 1979; Boltovskoy and Lena 1974; Closs 1962; del Río 1990; Pérez and Ramos 1996). The microfossil distribution of the TEP (Fig. 2.17) clearly indicates that the migration of the faunas may have not taken place through this hypothetical inland sea because the number of genera decreased rapidly towards the interior of the continent. In Bolivia, only one genus of foraminifera and two genera of freshwater ostracods were recognized. Moreover, the malacofaunas related to the Caribbean Sea and southwestern Entre Rios province were not found beyond the center of Santa Fe province. It is much more likely that the migrations had occurred through the eastern continental shelf of South America, as was already suggested by Malumián (1970) and Sprechmann (1978).

	Genera of Foraminifera	Genera of Ostracoda
Salado Basin	42	24
SW Entre Ríos	25	39
Santa Fe	17	24
Córdoba and Santiago del Estero	17	12
Corrientes, Chaco and Formosa	5	5
Tucumán and Catamarca	6	3
Bolivia	1	2

Fig. 2.17 Microfossil genera of the TEP according to this study and the work of previous authors

2.1.3 Main Features of the Basins

The reactivation of the Chacoparanense depocenters would have occurred since 26 Ma ago, during the Late Oligocene (Ramos 1999b); thereafter, a process of subsidence with two peaks of maximum rate began, broadly coincident with the age of the TLP and the TEP (Fig. 2.13). The sedimentary infill may widely be considered as distal deposits of the Andean foreland (Ramos 1999a), dominated by alluvial and eolian sedimentation (the Chaco Formation and Quaternary deposits), interrupted by two periods of marine sedimentation.

The geographical distribution of both transgressions was very similar but slightly larger for the TLP, indicating the coalescence of ancient depocenters active in the region during the Paleozoic–Early Cretaceous: Lincoln, Laboulaye-Levalle, Rosario, Paraná, and Las Breñas. The structural map of the floor of the TLP (Fig. 2.1) indicates that the depocenters of the Chacoparanense Basin during the Neogene were developed partly equivalent to the older basin areas. On the other hand, the structural map of the top of the TEP (Fig. 2.5) shows the almost complete silting of these depocenters and therefore a marked decrease of the subsidence, except in the northwestern part. In all sections, the TLP and TEP are separated by the continental San Francisco Member (Chaco Formation), and there are no signs of unconformities or nondepositional hiatuses. The unique exception was found in the Pozo del Tigre 1 borehole, where the deposits of both transgressions are in erosional contact. Although it is not possible to unequivocally identify discordant surfaces in borehole samples, the preservation of the microfauna at the roof of the TLP suggests a period of subaerial exposure; foraminifera are partially dissolved, with a different type of solution compared to the rest of the samples, and are covered by a thin patina of iron oxide. Consequently, it would have been assumed that there was a slight tectonic rise between the end of the TLP and the beginning of the TEP, possibly correlated with the Quecha I Tectonic Phase (Salfity and Marquillas 1999), which separates the Metán and Jujuy Subgroups in the NOA.

2.1.4 Proposed Litostratigraphic Units

The existing stratigraphic divisions are incomplete and mostly do not meet the standards of the *Comité Argentino de Estratigrafía* (1992). Due to the huge distribution of the deposits, their relative simplicity and lithological homogeneity, and the presence of marine deposits with known ages, it is possible to make a useful lithostratigraphic division for the entire region, defined at a time by their lithological characteristics and relationships between the different units, while also incorporating information about its genesis and age. Of all the units in use, only the Paraná Formation (Bravard 1858) meets the requirements of the Argentine Stratigraphic Code. All other units are not precisely defined or were not defined ever as the Chaco or Olivos formations. The Fray Bentos Formation is correctly defined in

Uruguay but belongs to a different basin. According to the present knowledge, it is not possible to correlate it within the Chacoparanense Basin because its type profile has very little vertical development, and the relationship with the Paraná Formation in the Argentine outcrops is not exactly known. A new lithostratigraphic division for the entire region is proposed. This division is valid for the sediments deposited after the outflowing of the basalts of the Serra Geral Formation or older units, until completion of the TEP or until the deposition of Quaternary units in the northern Chaco Plain. This division tries to keep the existing terms as much as possible, avoiding the generation of too much instability in the nomenclature, although some units should be disposed because they are synonyms. Consequently, the Litoral Group has been created, covering all considered deposits. The Chaco Formation has been formalized and divided into three members. Finally, the Laguna Paiva Formation has been formalized too, and one Hypostratotype is proposed for the Paraná Formation.

2.1.4.1 The Litoral Group

Definition

The Litoral Group comprises continental and marine sediments distributed in the Chacoparanense Basin and northern margin of the Salado Basin, including the Chaco, Laguna Paiva and Paraná Formations. It consists mainly of olive-green, reddish-brown or brown shales and sandy claystones, with some levels of yellowish or reddish sand or sandstone; some sectors are very rich in calcareous concretions and gypsum.

The Holostratotype is located in the sections 50.0–287.0 mb.g.s. of the YPF Palermo 10 borehole, located in the Palermo neighborhood of the city of Buenos Aires (Fig. A.10). As Parastratotypes, the profiles of the boreholes Laguna Paiva 1 at 122.5–610.8 mb.g.s., San Francisco 1 at 140.0–680.0 mb.g.s., and Pozo del Tigre 1 at 3.65–760.75 mb.g.s. are proposed.

Geographic Distribution

The Litoral Group occupies at least 700,000 km^2 in Argentina and an undetermined, large area in portions of western Paraguay and eastern Bolivia. Its complete distribution has not been established, but it is broader than the TLP (Fig. 2.1), mainly in the center and western parts of the Chaco province, where there is no record of marine sedimentation. Towards the west, it is limited by the Pampeanas Ranges and then underground through southern Córdoba and northern La Pampa provinces. To the north of the Guasayán and Sumampa Ranges (Fig. 2.14), it continues westward, mingling with the Neogene synorogenic deposits of the central segment of the Andes; to the northwest, it occupies almost the entire Santiago del Estero province and extends to the Catamarca, Tucumán, and Salta provinces, where some outcrops of the marine and continental units are likely to exist, and it would be partially equivalent to the Metán Subgroup. Towards the east, it is approximately limited to the western half of the Entre Rios and Corrientes provinces, whereas in Buenos Aires province it is restricted north of the Salado River; it has not been studied yet further south.

The thickness is highly variable, with minor development in areas close to the Pampeanas Ranges. In the vicinity of the city of Buenos Aires, it ranges between 250 and 300 m, becoming much stronger towards the center of the Salado Basin. In the Chacoparanense Basin, it is thicker than 800 m at the YPF Ceres x-1 borehole, and it is about 700 m thick in the Pozo del Tigre 1, YPF San Cristóbal 1 and YPF Josefina es-1 boreholes. In many sites, the complete Litoral Group was not completely drilled; thus, its thickness could be even larger.

2.1.4.2 The Chaco Formation

The Chaco Formation was defined by Russo et al. (1979) as "the reddish and purple sandstones and mudstones, between the Mariano Boedo and Paraná formations, and when the latter is absent between the Mariano Boedo and Pampa formations." These authors did not designate either a type location or a type section. According to Fernández Garrasino and Vrba (2000), this unit is not equivalent to the Chaco Group of the Cordillera Oriental (Fossa Mancini 1938), or the *Estratos del Chaco* of the Subandinas Ranges of Salta province. The original definition (Russo et al. 1979) is quite brief and it does not sufficiently reflect the lithological variability; additionally, it is limited by its relationship with the Mariano Boedo formation, which is invalidated in this work. Consequently, to avoid instability in the nomenclature the name of the Chaco Formation remains, its definition is extended, and one Lectostratotype is designated.

Definition

The Chaco Formation comprises essentially Neogene sediments of continental origin, distributed in the subsurface of the Chacoparanense and northern margin of the Salado basins. It is composed mainly of reddish-brown to brown shales, friable sandstones and sandy mudstones with little carbonate cement, some levels of yellowish or reddish sand and conglomeratic sand, and a few greenish mudstone intercalations; some parts of it are very rich in gypsum and calcareous concretions. It was deposited unconformably on basalts of the Serra Geral Formation or older units depending on their location, and it is limited at its top by the Paraná Formation or Quaternary continental sediments. The Lectostratotype is chosen in the section between 80 and 670 mb.g.s. of the YPF Las Breñas 2 (YPF Ch. LB x−2) borehole because this section is the best described and has no marine intercalations. A summary of its original description is outlined in Appendix A.

Overview

The Chaco Formation has the same geographical distribution of the Litoral Group and constitutes most of its thickness. The interbedding of the marine levels of the Laguna Paiva (TLP) and Paraná (TEP) formations allows the separation of this unit into three members, except in the central and western part of the Chaco province and western Formosa provinces, where the continental sedimentation was continuous. Although it has a marked lithological homogeneity, small macroscopic and mineralogical differences between the three members were observed.

Correlations

This unit is considered equivalent to the Olivos formation (Groeber 1961). The latter was mentioned by several authors mainly in northern Buenos Aires Province, but it was never defined by P. Groeber. In fact, he only mentioned the "layers of Olivos" twice, without further explanation. The Olivos formation is equivalent to the San Francisco and Palermo Members. The Fray Bentos Formation is correctly set but belongs to another basin, and it is very difficult to establish a precise correlation with the Chaco Formation. The Fray Bentos Formation is a very thin outcropping unit, and the relationship with the marine units of the Chacoparanense Basin is still unclear. Furthermore, the Chaco Formation is equivalent to some sectors previously described in the Mariano Boedo formation, particularly some undoubtedly continental deposits usually located at the lower section.

The Palermo Member

The Palermo Member is the oldest member of the Chaco Formation and underlies the Laguna Paiva Formation in apparent conformity. Its base has been reached in few holes, in which it was observed that it was deposited unconformably on the basalts of the Serra Geral Formation or older units. Its composition, diagenesis, preservation, and the gradual contact with the marine deposits of the TLP suggest that it belongs to the same sedimentary cycle that deposited the Litoral Group; therefore, the age is estimated between the Late Oligocene and Early Miocene. However, as discussed in Sect. 2.1.1, an association of Maastrichtian gyrogonites was found at the bottom of this member in Saira locality, and the same would be expected in other areas of thicker development. In Fig. 2.13, it is possible to estimate that the period of deformation which started in the Late Chattian has been responsible for the reactivation of subsidence in the Chacoparanense Basin, generating the space and availability of large amounts of sediments deposited in the Litoral Group.

The Palermo Member is composed of brown, reddish brown, to whitish clayey silty sandstones, siltstones, and conglomeratic sandstones, with abundant calcareous concretions and sometimes very well developed gypsum crystals. The Holostratotype is designated in the sections 198.0–287.0 mb.g.s. of the YPF Palermo 10 borehole, from the Palermo neighborhood of the city of Buenos Aires. Although is quite similar to the other members of the Chaco Formation, it is the only one with gravel size clasts, and the gypsum crystals are more abundant. In some sites, deposits of green mudstones with neogene gyrogonites were found, probably of marshy origin (Musacchio, personal communication). Near the base of the Pozo del Tigre 1 borehole, there are abundant basalt fragments, which could indicate the proximity of outcrops of the Serra Geral Formation during the deposition of the Palermo Member.

The mineralogical study of 61 samples from 5 boreholes (Figs. 2.18 and B.1) was performed. In the lower half of the Palermo Member in the type section, the volcanic shards are very abundant; these concentrations were not found in other holes, but certainly tephra falls must have been an important phenomenon of wide distribution. In Riachuelo VI and Frías 1 boreholes, there is a higher percentage of minerals from the metamorphic-plutonic basement, corresponding to the Río de la Plata Craton and the Pampeanas Ranges, respectively. In the San Cristóbal 1 borehole, the mineralogy is dominated by volcaniclastic material and the basement provenance is minimal, according to their distance to the cratonic outcrops.

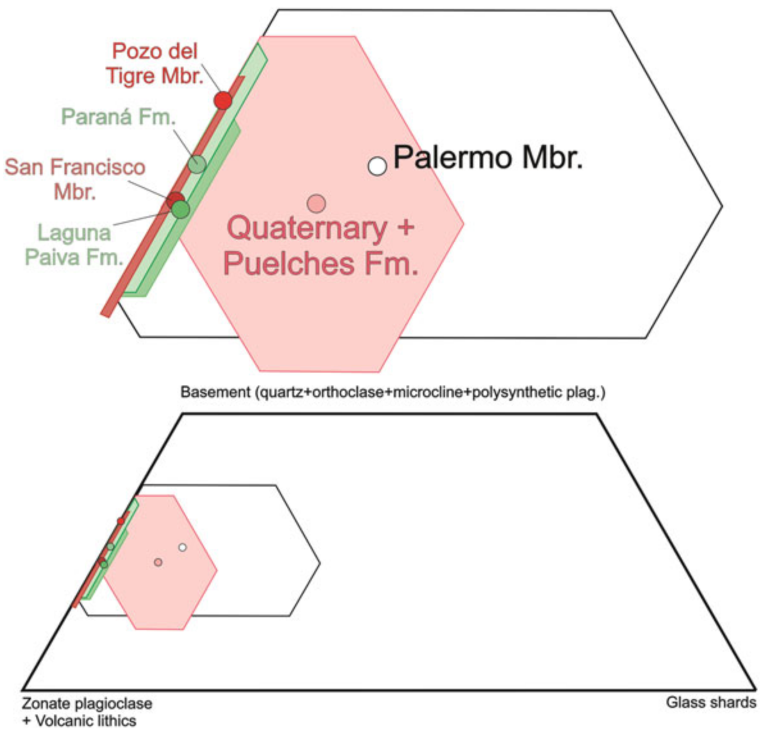

Fig. 2.18 Compositional triangle of light minerals of the Litoral Group

Apparently, the volcaniclastic contribution was characteristic of the central and southern Chacoparanense Basin during the Neogene, as can be seen in the composition of all the units in San Cristóbal 1 and Ordóñez 3 boreholes. Finally, the sand percentage is the largest of all units—a feature that may be useful for differentiation from other members—and could indicate a greater availability of nearby rocky outcrops and higher energy conditions as a result of fast subsidence. The rest of the units of the Litoral Group have similar values, as shown in Fig. 2.18, which may reflect greater mineralogical maturity or more homogeneous provenance than the Palermo Member.

The San Francisco Member

The San Francisco member is interposed between the Laguna Paiva and Paraná formations; consequently, it was deposited between the Late Aquitanian and Late Langhian. It is apparently conformant with the TLP and TEP marine deposits, except north of the Salado Basin, where the base of the Paraná Formation was erosive. In some sites, there is common interbedding of greenish clayey beds without microfossils; therefore, it is difficult to assign a marine or continental origin to all the sections. This member was found in all the places where both marine transgressions are present, except in the Pozo del Tigre 1 borehole, where the Paraná Formation was deposited unconformably over the Laguna Paiva Formation. This unconformity may be possibly correlated with the Quechua I Tectonic Phase, which produced an unconformity of similar age in the Subandinas Ranges (Salfity and Marquillas 1999). The Holostratotype corresponds to sections 260.0–440.0 mb. g.s. of the San Francisco 1 borehole.

The lithology is similar to that of the Palermo Member, although it is more homogeneous and has a much higher content of fine sediments, prevailing reddish brown clays and sandy mudstones, and a high proportion of gypsum and calcareous concretions. The sandy levels are sporadic and underdeveloped. Figure B.1 shows the mineralogical analysis of 13 samples with a similar average composition as the Palermo Member, although the contribution of basement minerals is slightly lower. The sand content is about one-third of the Palermo Member, indicating lower energy environments or scarce availability of sand.

The Pozo Del Tigre Member

This unit was found in some sites of the Chaco and Formosa provinces, and it was only described in the Pozo del Tigre 1 borehole. The Holostratotype is defined in the latter between 3.65 and 409.45 mb.g.s. The contact with the Paraná Formation is apparently transitional; the upper limit is very difficult to establish and is tentatively placed below the layer with abundant organic matter of the Holocene. The age is broadly estimated as Late Miocene-Quaternary.

It consists of alternating reddish brown mudstones and clayey sand, with abundant crystals of gypsum and calcareous concretions. The sharp increase in the percentage of monocrystalline quartz (Fig. B.1) with respect to the other members of this unit indicate a greater fluvial rework, as suggested also by the marked increase in the rate of sand. These sediments were poorly studied, but presumably at any sector of this member, they have started the settling of the huge alluvial fans that characterize the Chaco Plain during the Quaternary.

2.1.4.3 The Laguna Paiva Formation

The Laguna Paiva Formation is widely developed in the subsurface of the Chaco-Pampa Plain. It occupies an even larger area than the Paraná Formation and is an excellent guide level. The principle of priority is respected; therefore, it is herein formalized using the name given by Stappenbeck (1926) in the Laguna Paiva borehole. It represents the record of the first great Cenozoic transgression in central and northern Argentina.

Definition

Massive mudstones are usually olive-green, but with some sectors of dark gray to brown colors, and some reddish-brown interbedded layers and subordinate sandstones or loose sands. It has abundant gypsum and few calcareous microfossils and mollusk fragments. It was deposited unconformably over the Serra Geral Formation or older units, or it is transitional with the Palermo Member. The top is transitional with the San Francisco Member, except in the Pozo del Tigre 1 borehole, where the contact with the base of the Paraná Formation is erosive. Stappenbeck (1926) did not formally define the stratotype of the "*capas de Paiva*" but provided data of its distribution in several boreholes. Consequently, his criterion is respected, and thus the Lectostratotype is located between 324.10 and 601.56 mb.g.s. of the Laguna Paiva drilling. Stappenbeck confused the true location of the Paraná Formation in this borehole, assigning it to the green clays that appear at 324.10 mb.g.s., while it actually corresponds to the green clays located at 122.50 mb.g.s. The samples of the Laguna Paiva borehole are lost, but there is a good description of the original ones, and samples of other sites were also studied in detail. The Hypostratotypes were designated in the sections 175.7–200.0 mb.g.s. of the Riachuelo II and 506.05–697.30 mb.g.s. of the Pozo del Tigre 1 boreholes.

Overview

The Laguna Paiva Formation records the sedimentation of a very shallow sea over an extended period of time, with successive stages of flooding over the continental environment. The marine deposits of the TLP typically have a thickness of 100–

250 m and must have been deposited with significantly high sedimentation and subsidence rates. The stratigraphic sections (Figs. 2.7, 2.8 and 2.9) and the structural maps (Figs. 2.1, 2.2, 2.4, and 2.5) give an idea of the subsidence over some sectors of the Chacoparanense Basin between the beginning of the deposition of the TLP and the completion of the TEP, when the basin clogs. Some sectors had more subsidence than others and were maintained, although at a much lower rate after the completion of the TEP, as the depocenters of Lincoln, Rosario, Paraná, and the Salado Basin. The estimated thickness in the center of the Salado Basin is uncertain, and it possibly may be exaggerated due to the lack of adequate biostratigraphic control. The shallow nature of the TLP is exposed by frequent interbedding of continental sediments; by the association of foraminifera and ostracods; and by the abundance of gypsum, gyrogonites, and oolites in some drillings. Except for the Salado Basin, where some specimens of calcareous nannoplankton were found, the microfaunas are generally typical of very shallow environments and are tolerant to low salinity.

The mineralogy of 70 samples from six boreholes (Figs. 2.18 and B.2) is very similar to those of the Palermo and San Francisco Members and the Paraná Formation. This indicates a regular supply during the deposition of the Litoral Group, with a marked predominance of mesosilicic volcanic minerals, except in the Frías 1 borehole located near Pampeanas Ranges, wherein there is a slight increase in the provenance from the igneous-metamorphic basement. These features suggest very little reworking of the original materials.

Correlations

This unit is equivalent to the marine layers of the Mariano Boedo formation and probably to some subsurface levels of the Anta Formation, after the age assigned to the latter by Salfity and Marquillas (1999). It also corresponds to the top of the Las Chilcas Formation, but it is still impossible to determine the boundary, with older deposits at the center of the Salado Basin. Further south, it correlates with the Patagonian, especially with the *Leonense*—for example, the lower section of the Barranca Final Formation in the Colorado Basin, the Catalina and Gaiman Formations in northeastern Chubut, the Chenque Formation in the Golfo de San Jorge Basin, and the Monte León Formation in the Santa Cruz coast.

2.1.4.4 The Paraná Formation

This unit was originally defined by Bravard (1858), who referred to it as "marine terrains of Paraná or marine Paraná formation." He described two profiles near the city of Paraná and settled there its type area. Aceñolaza (2000) provided a complete summary of the distribution in the type area, the fossiliferous content, the lithology, and the synonymy. The integrated section of the Diamante area (Fig. A.3) is designated as Hypostratotype, complementing the knowledge of the Paraná Formation in an area with particular characteristics (Sect. 2.1.2.4).

Overview

The Paraná Formation has fairly uniform characteristics in all the areas of distribution. It is mainly composed of massive olive-green mudstones and clayey sandstone, with high content of mollusks and calcareous microfossils. In the Salado Basin, the base is erosive over the San Francisco Member, composed of coarse fossiliferous sand with abundant gravel size bioclasts, whereas the middle and upper sections are argillaceous. In southwestern Entre Ríos province, the Paraná Formation is much more complex because there are frequent sandy intercalations interpreted as the progradation of a deltaic system (Sect. 2.1.2.4).

It has a distribution similar to the Laguna Paiva Formation, although slightly reduced in area and thickness (Fig. 1.2), as it was deposited when the basin was partially in-filled. The retreat of the TEP marks the ending of the great Atlantic transgressions in southern South America; thereafter, only 50–150 m of continental sediments were deposited, with the exception of the center of the Salado Basin and the northern Chaco Plain, forming the current topography of the Chaco-Pampa Plain. The thickness is quite regular, between 50 and 100 m, with a maximum of about 200 m in northern Formosa and the center of the Paraná sub-basin; in the center of the Salado Basin, it is much thicker due to the persistence of the marine environment during most of the Neogene. Forty-nine samples of the light sand fraction were herein analyzed (Fig. B.2), which has very similar mineralogical characteristics to the Laguna Paiva Formation, with only a small increase of glauconite pellets and greater percentage of the sand fraction.

Correlations

Full synonymy is extensive for this unit; the different names received in the Chacoparanense Basin are available in Aceñolaza (2000). In other regions, it can be correlated with the upper section of the Barranca Final and Macachín Formations in the Colorado and Macachín basins, the Puerto Madryn Formation in northeastern Chubut, and the *Entrerriense* levels quoted in the Golfo de San Jorge. Historically, it has been correlated with the San José and Anta Formations of the NOA, although due to the dating of the Laguna Paiva Formation, more detailed studies are needed to determine if they correspond to the TLP or the TEP, as the described microfaunas are not diagnostic.

2.1.5 Regional Context of the TLP and TEP

The dating and knowledge of TLP distribution suggest profound changes in our understanding of the Chacoparanense Basin. It was thought that these deposits originated by a transgression of the Late Cretaceous or Early Paleogene. Consequently, it was considered that the continental deposits located under the TEP had an indefinite age, such as Paleocene–Middle Miocene. However, during most of this time, it seems that the Chacoparanense Basin was an upland composed of ancient rocks from the Precambrian Basement to the Early Cretaceous basalts (Figs. 2.7, 2.8 and 2.9), possibly a similar landscape to that of the present eastern Paraguay. The beginning of the subsidence during the Late Oligocene (Ramos 1999b) coincides with a sharp increase of the convergence in the active margin of the continent, which led to the beginning of the structuring of the Andes Ranges. However, the tectonic mechanisms that produced the subsidence in the Chacoparanense Basin, located 800 km from the active margin, are still unclear. Lima (2000) proposed the buckling of the lithosphere by lateral compression to explain the subsidence of the Pantanal Basin, a northern analogue of the Chacoparanense Basin. Dávila and Lithgow-Bertelloni (2013) considered that the Neogene actual subsidence of the Chacoparanense Basin was greater than that predicted by the flexural model, and the difference can be attributed to dynamic subsidence; the latter would be produced by mantle drag forces in the basement of the Pampas.

The ages of both transgressions reasonably correlate with two peaks of deformation in the Andes: the Pehuenche and Quechua I phases. These tectonic phases broadly correspond with an increase of convergence between the Nazca and South America Plates (Somoza 1998). As a result of orogenic activity, huge amounts of synorogenic deposits were produced (Fig. 2.19); the eastern expression of these deposits is recorded in the marine and continental deposits of the Litoral Group. Moreover, the volcanic activity increased significantly in the Andes around the Late Oligocene (from north to south: Pirurayo Volcanic Complex, Moreta Formation, Cerro Rajado Formation, Las Trancas Formation, Doña Ana Group, Hornillas Andesitic Breccia, Contreras Formation, Los Cerrillos Formation, and Molle Formation, among others), as recorded in the tuffaceous deposits at the base of the Palermo Member. The volcanism continued to be very active during the deposition of the entire Litoral Group (Fig. 2.18).

Both margins of the basin were subjected during the Neogene-Quaternary to west-east compressive lateral stresses; this situation is very clear along the western margin. It is generally considered that the eastern Pampeanas Ranges began to be structured during the Miocene (Ramos 1999b). However, the high proportion of basement debris in the Palermo Member in the Frías 1 borehole (Fig. B.1) indicates exposition of crystalline rocks by the Late Oligocene. The finding of possible Eocene continental deposits also suggests an early rise of the Sierra Chica de Córdoba (Astini et al. 2014). The distribution of the TLP and TEP suggests that the eastern margin of the basin was structurally controlled. The evolution of the filling of the Litoral Group (Figs. 2.1, 2.2, 2.4, 2.5, 2.13, and 2.14) indicates a west migration of the coastline during the Miocene. This migration could be attributed to the rise of the megablock of the Mesopotamia (Corrientes and Entre Rios provinces), limited by a north-south fault located approximately in the current course of the Paraná River, still active during the Quaternary (Marengo 2008). An analogous situation can be founded further north, where the eastern margin of the Pantanal Basin is being uplifted (Lima 2000).

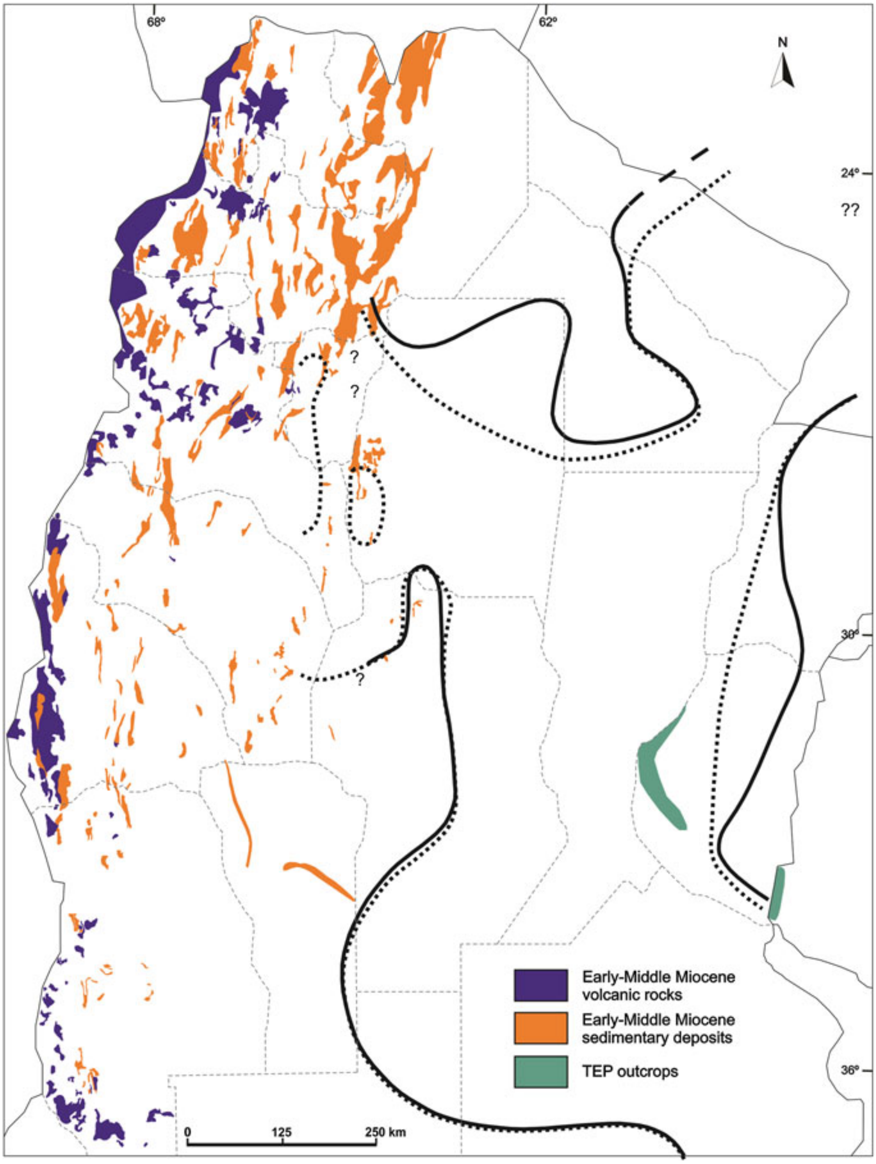

Fig. 2.19 Early–Middle Miocene outcrops in central-northern Argentina

2.2 Península de Valdés

2.2.1 Main Features of the Sections

Three sections in the area of the Península de Valdés were analyzed. They correspond to those studied by Scasso and del Río (1987), del Río et al. (2001), and Scasso et al. (2001), in Puerto Pirámide, Playa El Doradillo, and Eje Tentativo sites (Figs. 1.1 and A.13–A.15). These authors described in detail the profiles and the megafauna found in them, and they interpreted the lithofacies according to the relative height of sea level. Toward the west of Península de Valdés emerges the contact between the TEP or *Entrerriense* (Puerto Madryn Formation) and the underlying TLP or *Patagoniense* (Gaiman Formation). To the east of it, this contact is located under sea level and at the Lobería (i.e., a sea lion colony) of Puerto Pirámide, only the *Entrerriense* crops out. del Río et al. (2001) proposed a correlation of several of these profiles; they determined the most relevant paleobathymetric characteristics of each of the lithofacies from the study of the malacofauna assemblages and the physical continuity of some strata. These interpretations were corroborated in general by the micropaleontological analysis presented here, but due to the lack of appropriate microfaunas in many levels (by dissolution or incorrect exposure), a poorer definition was obtained.

In the Playa El Doradillo and Eje Tentativo sites (Figs. A.13 and A.15), the TEP is erosionally deposited over the *Patagoniense* beds. The lowest part of the TEP corresponds to the Transgressive Phase of del Río et al. (2001), at the end of which the maximum abundance of foraminifera and ostracods was recorded; this sector culminates in the Maximum Flooding Surface. The section continues in the Maximum Highstand Phase, with some secondary peaks in diversity and abundance of microfauna. Finally, the Regressive Phase of the section is recorded, including the upper portion of the *Entrerriense* and the *Rionegrense* units. The Maximum Highstand and Regressive Phases could not be identified unequivocally by the micropaleontological study, due to scarcity or poor preservation of the microfossils. In Playa El Doradillo, the Puerto Madryn Formation is much thinner than in the other two profiles, probably because it corresponds to environments closer to the coast subjected to reworking by waves. The contact between the *Entrerriense* and the *Patagoniense* beds is sharp. The abundance of boulders, intraclasts of the *Patagoniense*, and worn fragments of fossils at the base of the Puerto Madryn Formation clearly indicate the erosive surface. The contact between the *Entrerriense* and the *Rionegrense* is transitional. On the section at Puerto Pirámide (Fig. A.14), only the Puerto Madryn Formation outcrops, both its lower section and the top of the *Patagoniense* beds, are under sea level. The contact between the *Entrerriense* and the *Rionegrense* is transitional, lacking micropaleontological, sedimentological or any major mineralogical differences. According to Scasso and del Rio (1987), both informal units were deposited over the same sedimentary cycle in a regressive context.

The correlation of the microfossil and glauconite pellets abundance was attempted to identify significant eustatic variations. In Puerto Pirámide, there are three sectors with acceptable coincidence of both components (samples PP-1 to 4, PP-9 to 12, and PP-16 to 25), but they could be more due to covered sectors without samples. In the Eje Tentativo locality, the correlation is much better, with a peak of glauconite at the beginning of the transgression (ET-3), but with scarce microfossils probably due to strong dissolution; then, there is a sector with abundant microfossils and glauconite at the end of the Transgressive Phase and during the Maximum Highstand Phase (ET-15 to 20), and a third sector during the Maximum Highstand Phase and the onset of the Regressive Phase (ET-28 to 31). In the Playa El Doradillo site, the correlation was not good, probably because the high energy of the environment has inhibited the generation of glauconite pellets or has led to strong reworking.

2.2.2 Microfossils

In Eje Tentativo, the microfossils are generally well preserved but are frequently recrystallized; in some sections, they were subjected to a severe partial solution (samples ET-6 to ET-12), where the megafauna is scarce and only rusty molds were found. In the Puerto Pirámide and Playa El Doradillo localities, the preservation is even worse, so there is a higher degree of crystallization and partial dissolution. The distribution charts are shown in Figs. C.10–C.14.

2.2.2.1 Foraminifera

The foraminifera of the three profiles are characteristic of the *P. tuberculatum* informal zone (Malumián 1970), characterized by hyaline benthic foraminifera from shallow water, few miliolids and agglutinated, and very few planktonic species. Some taxa were found hitherto unrecorded in the TEP, such as *Uvigerina bifurcata*, *Pyrgo elongata*, *Marginulinopsis* sp., and *Asterigerinata* sp. In the locality of Puerto San José, two samples were taken within infaunal mollusks in life position, with the aim of knowing the occurrence of unmixed associations. Low-diversity microfaunas typical of the TEP were found, but with excellent preservation and a higher proportion of miliolids. According to del Río et al. (2001) the profile of Puerto San José locality is part of the Regressive Phase of the TEP.

The composition of the foraminiferal microfauna in the three profiles is generally not useful to paleobathymetric purposes, possibly due to the mixing of the assemblages by reworking of the sediment. However, the abundance of *Buliminella elegantissima*, from the base of the Puerto Madryn Formation in Playa El Doradillo (samples ED-3 and 4), is a good indicator of the transgressive conditions during the beginning of the TEP. *B. elegantissima* is an infaunal foraminifer found in very few TEP locations as an accessory component; in present and fossil examples, it usually has an opportunistic behavior with excellent development in environments subject to strong stress, sucg as as those generated during a fast marine transgression (Malumián and Caramés 1995). The taphonomic and sedimentological features of this part of the section are consistent with this interpretation (Scasso and del Río 1987, del Río et al. 2001).

In the tempestite levels of the samples ET-25 and ET-27 (del Río et al. 2001), four specimens of *Pachymagas pyramidesia* were collected. This is a terebratulid brachyopod generally found with closed valves, even in places where other marine megafossils have been transported by high-energy currents. These samples are named ET-S/N, ET-BC, ET-BM, and ET-BG; with the exception of the second one, they have provided microfaunas with higher diversity and abundance of foraminifera and ostracods. The ET-S/N sample has an association dominated by about 90 % of *Cibicides aknerianus*, a benthic foraminifer that lives attached to vegetation, typical of seagrass environments (Brasier 1975, Murray 1991). ET-BG has abundant microfauna with the greatest diversity of foraminifera and ostracoda found to date in the TEP in any location of Argentina, including several specimens of very recrystallized planktonic foraminifera. The ET-BM sample has a much less diverse and abundant assemblage than ET-S/N and ET-BG. It is striking that in the matrix of the tempestites, the microfossils are very scarce; the microfaunas inside the brachyopods, on the other hand, are very abundant, different from each other, and typical of very different environments. To date, a satisfactory explanation has not yet been found because the number of samples is small. A preliminary hypothesis suggests that the dead brachyopod specimens came originally from different areas of the platform, keeping inside the sediments (and consequently the microfossil assemblages) characteristics of each position in depth. Later, during stormy events, the concentration of the brachiopod shells may have taken place. These kinds of brachyopods have valves that can stick together during transport, and the globose form could favor their transport through the substrate during stormy events; also, the foramen located in the pedicle valve is wide enough to allow the entry of the sediment inside the shell.

2.2.2.2 Ostracoda

The ostracods were only classified in samples with more abundant and better preserved specimens. The systematic determinations and main stratigraphic and environmental conclusions follow those of Echevarría (2004) and Echevarría and Marengo (2005), and they were not included in Marengo (2006). The ostracods of the Puerto Madryn Formation have been poorly studied to date, despite being very abundant and highly diverse microfaunas. Rossi de García (1970) described some species of the site of Puerto Pirámides, whereas Bertels (1976) studied specimens of *Henhyhowella* aff. *evax* from the same site. The results from 29 fertile samples from the sections Eje Tentativo, Playa El Doradillo, Puerto San José, and Puerto Pirámides are shown in Figs. C.13–C.14. A total of 906 fairly to poorly preserved specimens were studied, which were classified into the orders Podocopida (46 genera, 100 species) and Platycopida (2 genera, 4 species).

In all sections, the sedimentation rate was moderate to high (but occasionally slightly low) due to the predominance of shells over valves. The scarcity of juvenile specimens suggests higher energy conditions. A shallow environment with variations of salinity is pointed out in *Perissocytheridea*, among other taxa. In Eje Tentativo, Playa El Doradillo, and Puerto Pirámides sites, the environmental features were similar, but *Callistocythere*, *Caudites* and *Munseyella* also suggest warmer waters. Among the species that could be accurately determined, 18 of them are known, in order of importance, from the Middle–Late Miocene of Entre Ríos and Santa Fe provinces and southern Brazil, the Holocene of Argentine and Brazil continental shelf, and the Late Oligocene–Early Miocene of Buenos Aires province and south-western Santa Cruz. They are also known from the Oligocene of south-central and eastern Santa Cruz province, the Late Miocene–Early Pliocene of eastern Río Negro and Chubut provinces, the Eocene and Miocene of eastern Tierra del Fuego, the Late Eocene–Early Oligocene of eastern Santa Cruz province, and the Holocene of southeastern Buenos Aires province.

2.2.3 Mineralogy and Paleoclimate

The detrital modes of the three sections reveal that most of the material came from areas associated with a transitional arc environment (Fig. 2.20). The abundance and good preservation of the volcanic lithic fragments, zoned plagioclase, and volcanic

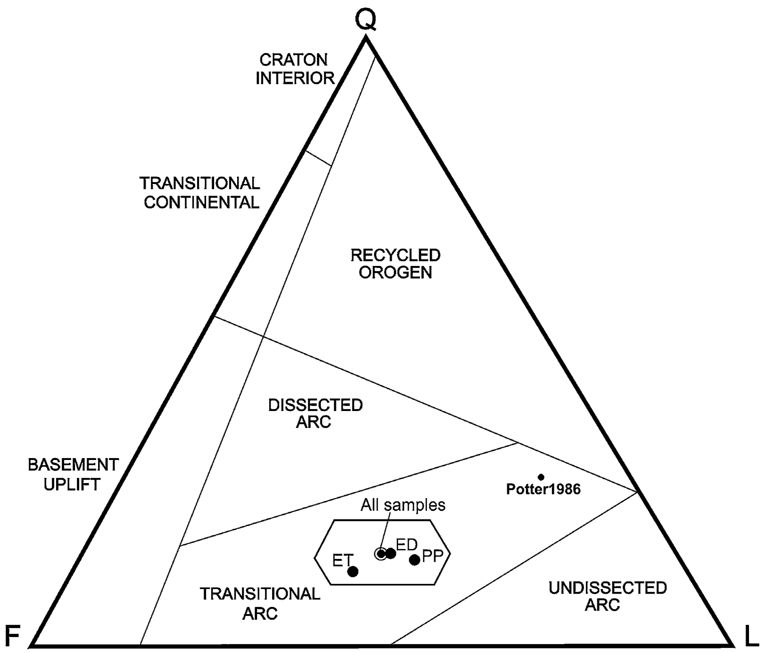

Fig. 2.20 ET, PP, and ED modal QFL analysis. Provenance tectonic features are according to Dickinson et al. (1983). The mean of each outcrop as well as the mean and the standard deviation of all the samples are shown. The mean value published by Potter (1986) is also shown

glass shards, mixed with poorly preserved minerals, would indicate that the clastic material was supplied by contemporary volcanic activity mixed with recycled or long transported volcaniclastics. The contribution of the basement rocks is quite low, with an apparent dominance of metamorphic over plutonic supply, as revealed by the composition of the heavy minerals. The abundance and excellent preservation of the hornblende and pyroxenes, particularly the hypersthene, are quite remarkable. The high roundness of the monocrystalline quartz contrasts sharply with the rest of the major components, suggesting that it was reworked; the marked variation in the abundance would indicate variation in the rate of sediment supply to the basin. In the QFL compositional triangle (Fig. 2.20), most of the samples, the mean of the profiles, and the standard deviation of all the samples are restricted to the field of transitional arc, whereas few samples plotted in the fields of undissected arc and dissected arc. Potter (1986) and Etchichury and Tófalo (1996) obtained similar compositions in their studies of Holocene sands in the Patagonian coast. They attributed this anomalous composition to the arid climate and the relative short distance to the Andean orogenic front. Teruggi and Andreis (1971) studied the stability of the minerals in recent sands of the Patagonian coast, attributing the higher concentration of amphibole and pyroxene to the lower chemical weathering as a result of the very arid climate. The similarity between the composition of the *Entrerriense* beds and current light and heavy minerals suggests that the dominant climatic conditions in the continent during the deposition of the TEP in northeastern Chubut were very similar to those in the Holocene.

Regarding the climatic characteristics inferred from mineral stability, it is interesting to briefly summarize the paleoclimatic background of the *Entrerriense* beds and related continental units. It is widely accepted that during the deposition of the *Entrerriense* units the climate was much warmer and wetter than today. In Mesopotamia (northeastern Argentina), this was amply corroborated by vertebrate faunas typical of the hot and humid climate (Gasparini 1968; Pascual and Odreman Rivas 1971; Gasparini and Báez 1975; Cione 1978) and by mollusks (del Río 1990). In Patagonia, although marine faunas of warm waters have been found (Cione 1978; del Río 1990), the finding of tropical to subtropical continental vertebrates is restricted almost exclusively to the lower section of the *Santacrucense* beds (Lower–Middle Miocene; Pascual and Odreman Rivas 1971; Tauber 1997). At the top of the *Santacrucense* and in the *Friasense* (Middle Miocene) beds, the vertebrates and palynomorphs (Volkheimer 1970; Pascual and Odreman Rivas 1971; Quattrocchio et al. 1988) indicate much drier conditions and markedly seasonal climate, and the sharp withdrawal of subtropical vertebrates. Palazzesi and Barreda (2005) and Palazzesi (2008) found pollen associations indicative of xerophytic and halophytic shrubs and herbs in the Puerto Madryn Formation. This is in contrast to the pollen found in the Gaiman Formation (Lower Miocene), which indicated the existence of nearshore forests. Consequently, the good correspondence between the mineralogical and paleontological information suggests that during the TEP, the climate in northern Patagonia was similar but probably slightly warmer than the present one.

A good correlation is observed in Figs. 2.21, 2.22 and 2.23 between the distribution of some minerals, such as the inverse ratio between green–brown

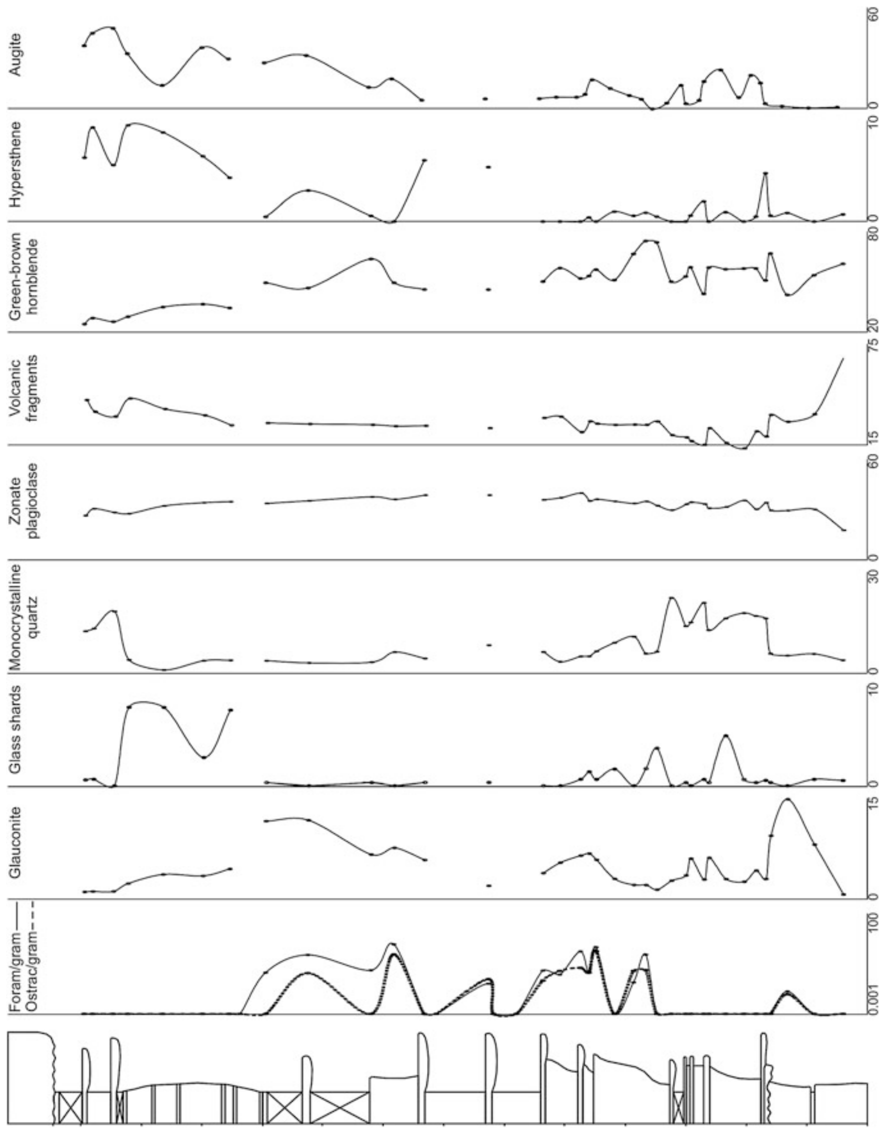

Fig. 2.21 Some minerals (in %) in the Eje Tentativo locality

hornblende and hypersthene or augite (the latter to a lesser degree); the inverse ratio between volcanic lithic fragments and zonal plagioclase; or the less obvious direct ratio between the zoned plagioclase and green brown hornblende. These variations have been interpreted as compositional changes of the contemporary volcanism (Marengo 1999). Comparison of the relative percentages of the components suggests that background volcaniclastic sedimentation was provided by older deposits or

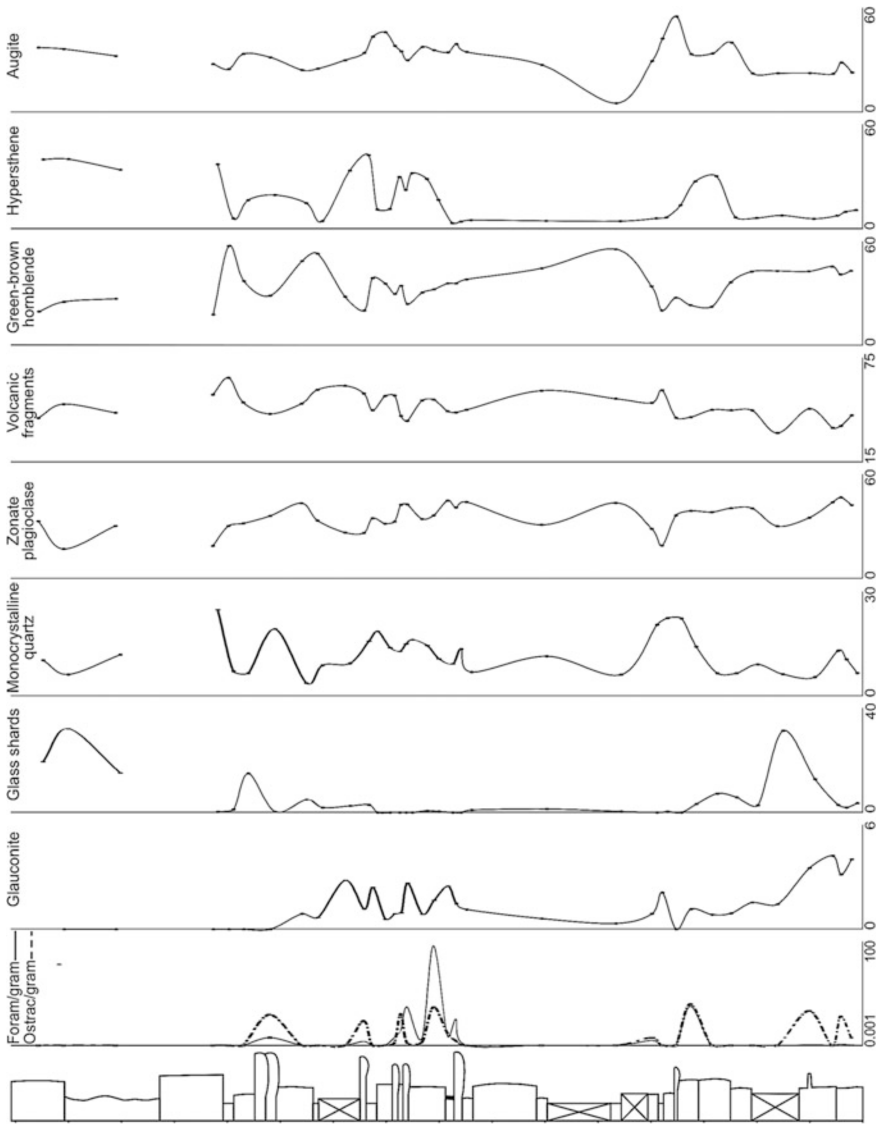

Fig. 2.22 Some minerals (in %) in the Puerto Pirámide locality

weathered volcanites located in the source areas, rich in zonal plagioclase, volcanic lithic fragments, green–brown hornblende, and augite. Contemporary volcanicastic rocks with compositions ranging between typical andesites to hypersthene-andesites or even basalts could have been added to the background composition. A pattern for the variation of glass shards was not found at the scale of sampling. The abundance of volcanic glass could be regulated by the high energy of the environment, because

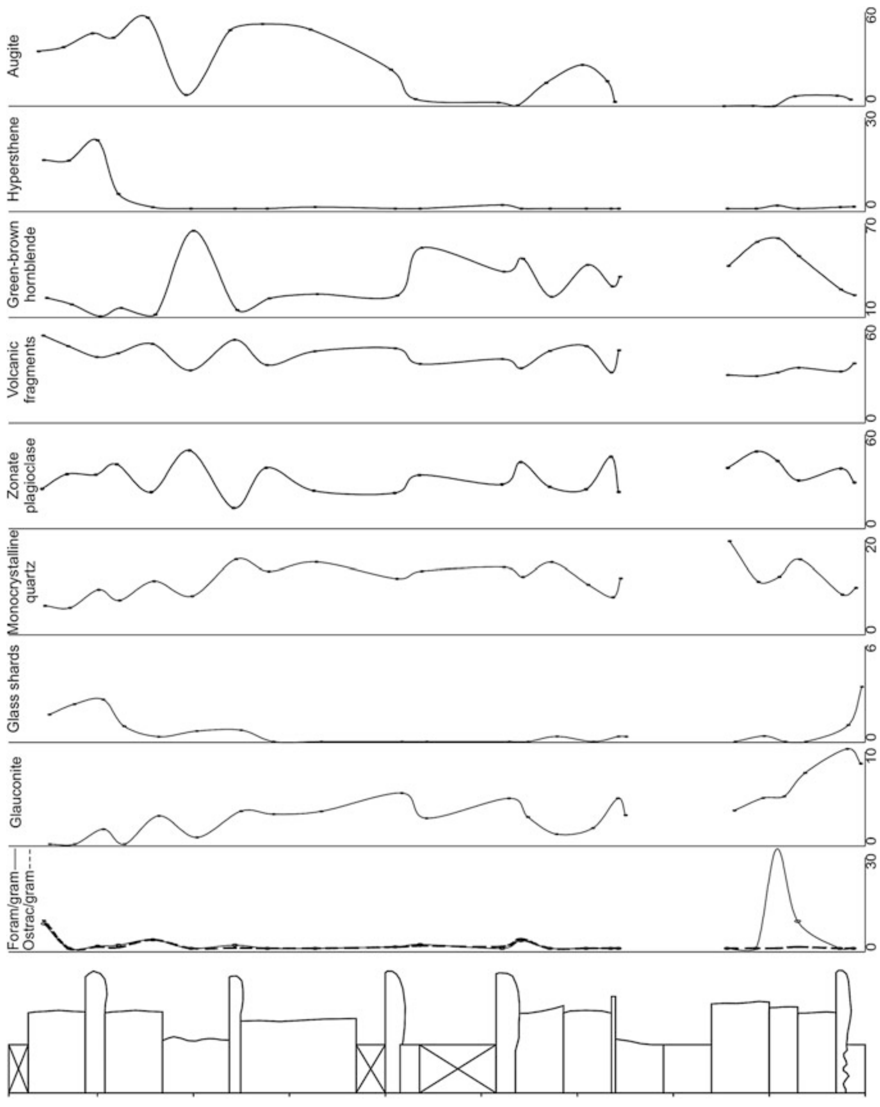

Fig. 2.23 Some minerals (in %) in the Playa El Doradillo locality

the lower density of the fragments allows the suspension and subsequent deposition in lower-energy places. In this sense, the increase of the percentage from Playa El Doradillo to Puerto Pirámide localities is noteworthy, and a decrease in the average marine energy between these locations can be assumed due to the paleogeographical location. Diagenetic causes to these variations were discarded because of the excellent preservation of the glass shards in nearly all samples.

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