Chapter 1
Introduction

1.1 Nature of the Work

This book is an update of the author's doctoral dissertation, which was submitted in 2006 and defended at the University of Buenos Aires in June 2007. Funding for the work was possible thanks to grants provided by CONICET between July 1996 and June 2000. Borelog samples are property of the Argentine Geological Survey (SEGEMAR).

This work reflects more than 10 years of research on a vast and insufficiently known theme: the Neogene of the Chacoparanense and Salado Basins and the Península de Valdés. These regions, taken in the broadest sense, cover more than 1 million km^2. This research began as an attempt to deepen the micropaleontological and sedimentological knowledge of the *Entrerriense* and *Paranense* marine deposits. The finding of unknown older Neogene marine microfossils radically altered the scope of the study. Therefore, very different results were achieved: On the one hand, there were detailed mineralogical and micropaleontological analyses of areas with good sampling, such as the basement of Buenos Aires City and the Diamante area, as well as the outcrops in the Península de Valdés. On the other hand, several sites with widely spaced sampling allowed an investigation of the characteristics of the sedimentary fill and microfaunas during the major transgressions in the Chacoparanense Basin. Finally, the analysis of approximately 200 sites allowed investigations of the boundaries, sediment thickness, facial and environmental variations of the deposits, and the relationship with related deposits in Argentina and South America.

1.2 Area and Material of Study

The Chacoparanense Basin was considered in a broad sense, including the area of the present basin, the northern half of the Buenos Aires province, and the western part of Corrientes and Entre Ríos provinces. Several profiles, cropping out in the

H. Marengo, *Neogene Micropaleontology and Stratigraphy of Argentina*,
SpringerBriefs in Earth System Sciences, DOI 10.1007/978-3-319-12814-6_1

southwest of Entre Ríos province and the southern coast of Península de Valdés, as well as various boreholes of Buenos Aires, Entre Ríos, Santa Fe, Córdoba, Santiago del Estero, and the Formosa provinces of Argentina were analyzed (Figs. 1.1 and 1.2). The *Entrerriense-Paranaense Transgression* (TEP) includes all of the marine sediments deposited by the transgressions of the Middle–Late Miocene, with megafossils related to those of the southwest Entre Ríos and the Península de Valdés. The *Laguna Paiva Transgression* (TLP) includes the marine subsurface sediments of the Chacoparanense Basin, previously known as the layers or strata of Paiva or the Mariano Boedo formation. The deposits of the TEP are present in large areas of Argentina and in small sectors of Uruguay, Paraguay, and Bolivia (Fig. 1.1). Existing information was available about the outcrops in the southwest of Entre Ríos and the northeast coast of Chubut, as well as several drillings in the Buenos Aires province, especially in the Colorado and Salado Basins. The outcrops in eastern Río Negro province and the subsoil of the Chacoparanense Basin have been poorly studied. Furthermore, both in outcrop and subsurface, have been assigned to the TEP deposits in the region of Cuyo, the northwest of Argentina (NOA), and the Golfo de San Jorge Basin.

The drilling materials correspond to cores, cuttings, and grab samples that belong to the SEGEMAR repository. The Península de Valdés samples were obtained in three sections during 1997 and 1998. Approximately 750 samples from 23 boreholes and outcrops were processed for micropaleontological studies. Approximately 170 samples were fertile. In total, more than 21,000 specimens of foraminifera and approximately 2,600 specimens of ostracods were found and classified. Fifteen samples from the Salado Basin were processed for calcareous nannofossil analysis. The samples of several boreholes did not yield positive results and therefore were not included in this work, but it is important to mention them for future research. In the boreholes Macachín 1 and Uriburu 1, the microfossils were rare and extreme recrystallized. Therefore, it is likely that the Macachín Basin has no promising prospects for further study. The samples from deep boreholes in General Madariaga, San Clemente del Tuyú, and General Belgrano from the center of the Salado Basin had abundant and well-preserved microfaunas, but they are apparently unrelated to the Miocene and belong to younger deposits. Finally, in several drillings from the Chacoparanense Basin, no microfossils were found: these included the TEP of Crespo and Santa Fe 4, as well as the TEP and TLP of Rufino 1, Gualeguay IV, and San Cristóbal 3.

1.3 Methodology

The megafauna were classified by comparison with specific literature and with the valuable aid of C.J. del Río. The usual techniques for the preparation of micropaleontological samples were followed: disaggregation was performed with hydrogen peroxide for 48 h up to 60 °C; the material was sieved in mesh ASTM 230 (62.5 μm); then all microfossils were separated using a binocular microscope.

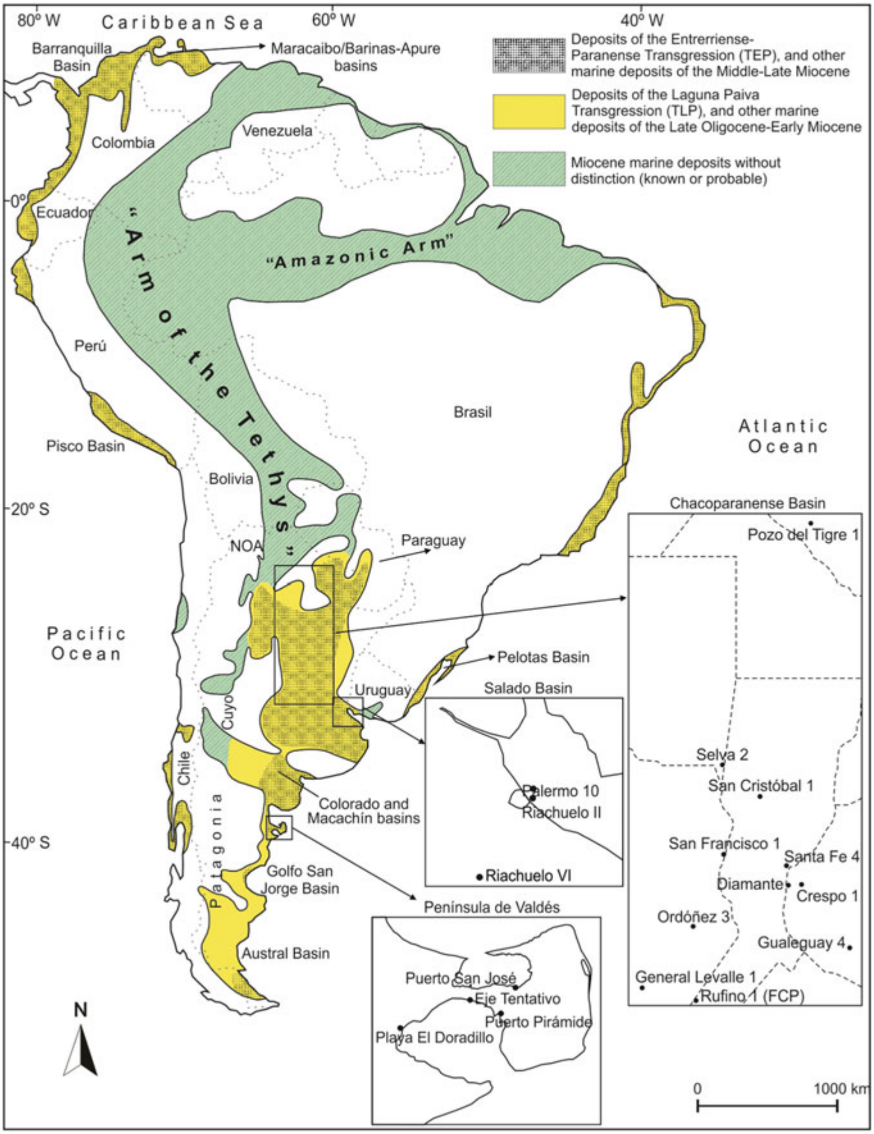

Fig. 1.1 South America's paleogeography during the Late Oligocene–Middle Miocene, according to Ramos (1982) and Bossi and Gavriloff (1998), including the geographic location of the studied sections and the main Miocene basins

Classification was made by comparison with the specific literature and the micro-paleontological collections of SEGEMAR. The genera of foraminifera were updated according to Loeblich and Tappan (1988) and Luczkowska (1974). The final classification of ostracods was conducted entirely by A. Echevarría. The samples

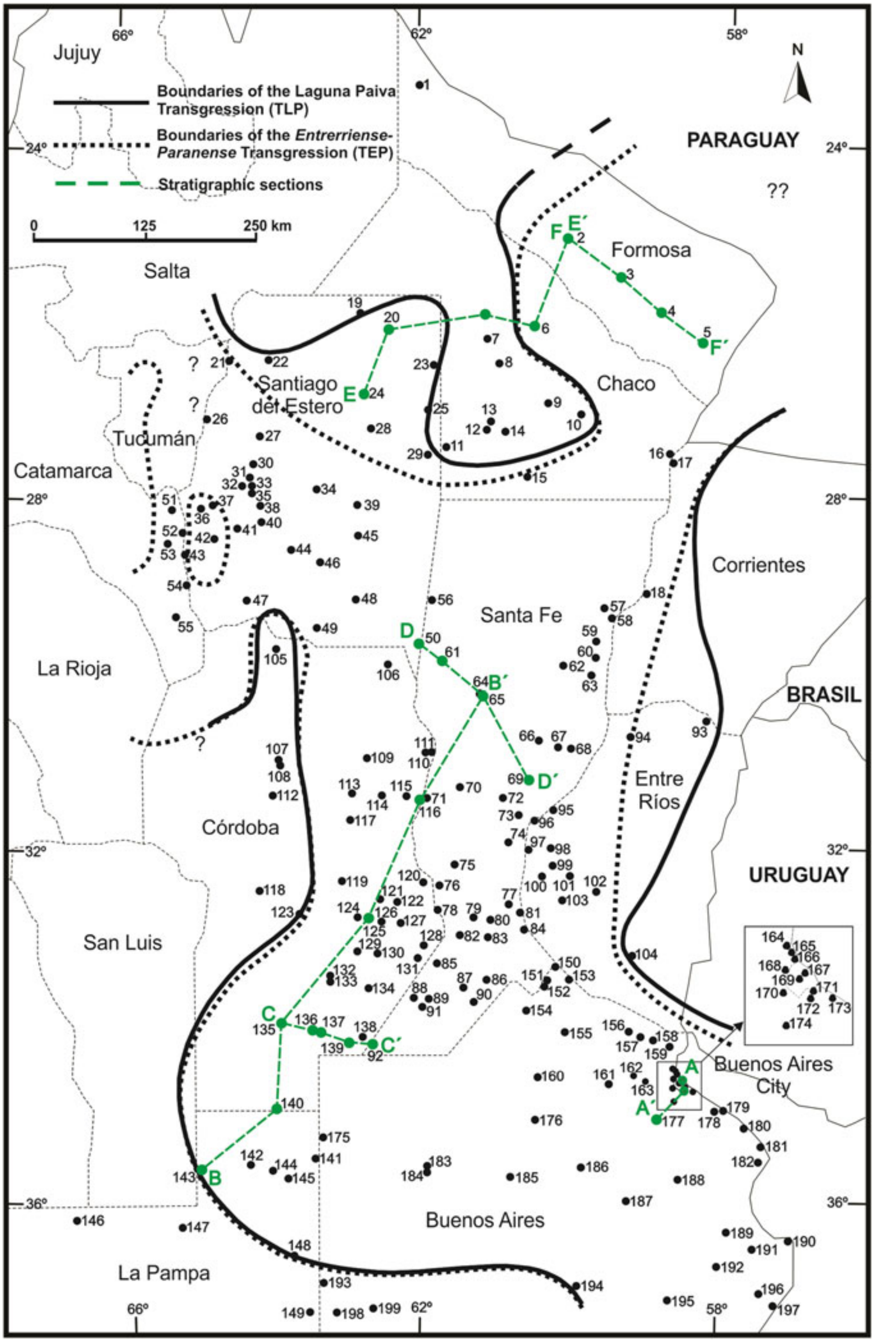

Fig. 1.2 Locations used to draw the structure and isopach maps

for nannofossil analysis were prepared using the smear slide technique (Edwards 1963) and were observed under a microscope with parallel and polarized light. The study was semiquantitative, counting the nannofossils in at least two successive traversals of the preparation. The taxonomic determination was performed by A. Concheyro. The material was photographed using scanning electron microscopes (SEM) from CITEFA, INTEMIN, and BGR (Hannover, Germany).

The mineralogy of sandy samples was performed on preparations of loose grains. All of the samples from the Península de Valdés were separated into light and heavy fractions using bromoform. At least 300 grains in each fraction were counted per sample, in the range of 250–62.5 µm. The mineralogy of the Litoral Group was plotted in a compositional triangle (basement minerals–volcanic minerals–glass shards), such as that applied by Marengo (2003) for the Quaternary of Santa Fe province; this approach better represents the characteristics of the Chacoparanense Neogene sediments than the traditional QFL (Dickinson et al. 1983).

The subsurface sections were described from top to bottom. The outcrops were described from bottom to top; the thickness corresponds to beds or bedsets, and the sample position refers to the distance from the bottom of the beds or bedsets. The samples or intervals with microfauna are shown in bold characters. The directions on the lithostratigraphic nomenclature by the Comité Argentino de Estratigrafía (1992) were respected. In the case of informal or not-current units, "formation" has been used instead of "Formation." The structural maps of the TEP and TLP refer to the mean sea level. The information was gathered from numerous sources, such as bibliographic records, borehole records of the SEGEMAR and Yacimientos Petrolíferos Fiscales (YPF, the Argentine national oil company), and our own data. The top and bottom values of the TEP are reliable because the information is abundant and the identification of those surfaces is simple. The top and bottom values of the TLP are less reliable due to the smaller amount of data and the difficulty of establishing the true boundaries in some boreholes, as the contacts are typically transitional. In the Chacoparanense and Salado Basins information was evaluated from 199 locations (Fig. 1.2).

1.4 Background

1.4.1 The Entrerriense-Paranense Transgression

Since 1827, when Alcide d'Orbigny made geological observations on the Cenozoic near the city of Paraná, much work on the Miocene marine transgressions has been published in Argentina. These studies expanded our knowledge of these deposits. However, because of the logical difference of criteria used during almost two centuries of research and the extensive areal distribution of the deposits, many contradictions and inaccuracies were generated concerning the stratigraphy of these units.

1.4.1.1 Overview

Alcide d'Orbigny toured the Paraná region between 1827 and 1828 conducting stratigraphic observations, a milestone that marks the beginning of geological research in Argentina (Aceñolaza 1976). These observations were published in his work of 1842, in which grouped the outcropping Cenozoic marine sediments from the Strait of Magellan to Entre Ríos under the name of *terrain tertiaire Patagonien* (Patagonian tertiary land). d'Orbigny assigned them a similar age as the Eocene deposits of the Paris Basin. Darwin (1846) grouped the same levels under the name "Patagonian tertiary formation," correlating the outcrops along the coast of Patagonia and Entre Ríos, based on megafaunal remains. Darwin tentatively correlated the Patagonian Formation with the Eocene of Europe. Ameghino (1889) noted that the terrains of Patagonia were older than those of Entre Ríos. Accordingly, he differentiated the *Formación Patagónica* and the *Formación Entrerriana*. In 1907, Ihering published a catalog of mollusks, establishing the criteria in the recognition of the megafauna; he analyzed the marine index fossils of the Cretaceous-Cenozoic of Argentina. Ihering (1927) explained the affinities between the *Entrerriense* and the Caribbean faunas through an intracontinental marine connection (the so-called Arm of Tethys). This connection would have connected the Río de la Plata region with the Caribbean Sea, which would have developed along the eastern portion of the Andes (Fig. 1.1).

1.4.1.2 Southwestern Entre Ríos Province

d'Orbigny (1842) described the outcrops on the left bank of the Paraná River near La Bajada (nowadays, the city of Paraná). He mentioned the levels *Grés tertiaire marin* D, *Grés Ostréen* H, and *Calcaire arenifére* I, which he considered to be products of a single transgression. de Moussy (1857) studied the same sections and assigned them to the Jurassic-Tertiary. Bravard (1858) identified about 32 m of outcropping marine sediments, which he called *formación marina del Paraná* (Paraná marine formation), establishing the priority for further lithostratigraphical nomenclature. Doering (1882) found a continental sedimentary intercalation between deposits of two different positions of sea level. Frenguelli (1920) defined three units of marine origin, the *Paranense cuspidal*, *Entrerriense*, and *Rionegrense marino*, interbedded with two continental units: the *Mesopotamiense* and *Rionegrense continental*. He assigned the *Paranense cuspidal* to the Late Miocene, and the *Entrerriense* and *Rionegrense marino* to the Pliocene. In 1947, Frenguelli considered that the *Paranense* was developed prior to the Second Stage of the Tertiary Andean Orogeny, and that it "was a great inland sea that completely occupied the vast area of the current Pampas, and whose perimeter was marked by the reliefs that nowadays circumscribe the vast region of the Pampa Plain," whereas the *Entrerriense* and *Rionegrense* seas occupied a "narrow marine bosom" from the Río de la Plata estuary and the Paraná valley, until shortly north of the city of Victoria.

Aceñolaza (1976) considered that the three marine levels that Frenguelli had described are concordant and actually belong to a single Miocene sedimentary sequence. He explained the continental interbedding by the confusing field relationships between the Paraná and the overlying Ituzaingó (continental, Pliocene) and Hernandarias (continental, Pleistocene) Formations. Aceñolaza and Aceñolaza (1996) presented a paleo-phytogeographical map in which the emerged areas were divided into the *Brasiliano* and *Pampásico-Ándico* territories. The paleofloras found in the southwestern Entre Ríos province would belong to the *Brasiliano* territory, with tropical to subtropical-temperate climate. The main micropaleontological studies were done by Rossi de García (1966, 1969a), Zabert and Herbst (1977), and Zabert and Barbano (1984). They described the main characteristics of the foraminifera and ostracoda present in these units and broadly proposed a Miocene age for the Paraná Formation. In 2000, a book with reviews on the TEP was published, including stratigraphical and paleogeographical aspects (Aceñolaza 2000), marine and freshwater vertebrates (Cione et al. 2000), malacofauna (del Río 2000), calcareous microfossils (Marengo 2000), and phytoliths (Zucol and Brea 2000). Finally, the first $^{87}Sr/^{86}Sr$ age of 9.47 Ma from the upper section of the Paraná Formation cropping out in Diamante (Pérez 2013) and a new revision of the megafauna (Pérez et al. 2013) were published.

1.4.1.3 The Chacoparanense and Salado Basins

Stappenbeck (1926) provided a detailed commentary on drill descriptions, explaining the changes in the level of the *Paranense* sea through successive periods of flooding and subsidence in a deltaic environment, as opposed to the ideas of Frenguelli (1920). Zabert (1978), Bertels and Zabert (1980), Zabert and Barbano (1984), and Herbst and Zabert (1987) studied the microfauna from some drill cores. They recognized foraminifera typical of the *Entrerriense*, with low to very low diversity. Marengo (2000) summarized the previous micropaleontological knowledge and updated the nomenclature. He described the findings of foraminifera and ostracoda on new boreholes and identified several new species for the region, considering that the temperature of the sea was very similar or slightly higher than the current Atlantic coast at the same latitude.

Wahnish (1939, 1942) described the megafauna of the boreholes Riachuelo V and Monte Veloz, very similar to that of southwestern Entre Ríos province and Península de Valdés. González Bonorino and Cetrángolo (1960) provided mineralogical and sedimentological data on the "green clays" in the subsurface of the city of Buenos Aires. Malumián (1970, 1972) studied the foraminifera in two boreholes, placing the *Entrerriense-Paranense* of the Salado Basin in the Late Miocene. Marengo and Concheyro (2001) identified new species of foraminifera in three boreholes located in the Buenos Aires urban area. On the basis of changes in the diversity and taxonomic composition, they identified atleast two eustatic rises in the lower half of the TEP deposits. Their finding of calcareous nannofossils with good stratigraphic resolution allowed them to assign the lower half of the TEP to the Biocronozone NN6 (Serravallian).

FORMOSA PROVINCE
1 Palmar Largo
2 **Pozo del Tigre**
3 *Comandante Fontana*
4 *Pirané*/5 *Mariano Boedo*

CHACO PROVINCE
6 Castelli/7 El Desierto
8 Las Breñas 2
9 Presidencia Roque Saenz Peña
10 *Machagay*/11 Gancedo
12 Charata/13 Las Breñas 1
14 Las Breñas Oriental
15 Villa Angela
16 Resistencia

CORRIENTES PROVINCE
17 *Corrientes*/18 *Santa Lucía*

SANTIAGO DEL
ESTERO PROVINCE
19 Monte Quemado
20 El Caburé/21 Rapelli
22 Los Horcones
23 Coronel Rico
24 Campo Gallo
25 Arbol Blanco
26 Tacanas/27 Huyamampa
28 Alhuampa/29 Roversi
30 *El Silencio*
31 *Santiago del Estero*
32 Mercedes/33 Rodeo
34 Suncho Corral
35 Santa María/36 Tres Flores
37 Santa Catalina
38 Simbol/39 Km. 511
40 Villa San Martín
41 Laprida/42 Choya
43 *Frías*/44 *Medellín*
45 Añatuya/46 *Salavina*
47 *El Bordito*/48 Las Abras
49 Sol de Julio/50 ***Selva***

CATAMARCA PROVINCE
51 *Bañado de Ovanta*
52 Tapso/53 *Dos Pocitos*
54 San Antonio/55 Esquiú

SANTA FE PROVINCE
56 Tostado/57 Avellaneda
58 San Jerónimo
59 *Romang*/60 *Colonia El Ceibo*
61 Ceres/62 Calchaquí
63 *Alejandra*
64 San Cristóbal 2
65 **San Cristóbal 1** and **3**
66 *San Justo*
67 *Paraje La Noria*
68 Saladero Cabal
69 Laguna Paiva
70 Rafaela/71 *Josefina*
72 Esperanza
73 **Santa Fe**
74 Coronda/75 El Trébol
76 Bouquet
77 Salto Grande
78 Tortugas
79 Cañada de Gómez
80 Carcarañá
81 San Lorenzo
82 San Ricardo
83 Casilda/84 Rosario
85 Berabevú/86 Alcorta
87 Melincué
88 Maggiolo/89 Venado Tuerto
90 Hughes/91 San Eduardo
92 **Rufino**

ENTRE RÍOS PROVINCE
93 El Yacaré/94 Estacas
95 *Villa Urquiza*/96 *Paraná*
97 ***Diamante***/98 **Crespo**
99 Villa General Ramírez
100 Molino Doll
101 Hernández
102 Nogoyá/103 *Victoria*
104 **Gualeguay**

CÓRDOBA PROVINCE
105 San Francisco del Chañar
106 Los Porongos
107 Jesús María/108 Colonia Caroya
109 *Marull*
110 Cotagaita/111 Seeber
112 Córdoba
113 Santiago Temple
114 *La Francia*/115 *Devoto*
116 **San Francisco**
117 Sacanta/118 Las Peñas
119 Villa María
120 Saira/121 Bell Ville
122 San Marcos
123 General Deheza
124 Idiazábal
125 **Ordóñez**
126 Justiniano Posse
127 Monte Buey
128 *Camilo Aldao*
129 Las Pascanas
130 Escalante
131 Corral de Bustos
132 Barreto/133 La Carlota
134 Canals/135 **General Levalle**
136 Guardia Vieja
137 Laboulaye
138 Laguna del Monte
139 Salas/140 Gallinao

LA PAMPA PROVINCE
141 Santa Aurelia
142 Arata
143 La Maruja
144 Trenel/145 Metileo
146 Santa Isabel
147 Telén/148 Uriburu
149 **Macachín**

BUENOS AIRES PROVINCE
and The CITY of BUENOS
AIRES
150 San Nicolás
151 Erézcano/152 Conesa
153 Ramallo/154 Pergamino
155 Arrecifes
156 Lima/157 Zárate
158 Campana
159 Paraná Miní
160 Chacabuco
161 Mercedes/162 Luján
163 General Rodríguez
164 San Fernando
165 San Isidro/166 Olivos
167 **Palermo**/168 San Martín
169 Flores/170 San Justo
171 Avellaneda
172 **Lanús** (Riachuelo II)
173 Quilmes/174 Ezeiza
175 Villa Sauze/176 Bragado
177 **Cañuelas** (Riachuelo VI)
178 La Plata/179 Río Santiago
180 Magdalena
181 Punta Indio
182 *Monte Veloz*
183 Larramendy/184 Pehuajó
185 Huetel/186 Saladillo
187 *Las Flores*
188 ***General Belgrano***
189 Dolores
190 **San Clemente del Tuyú**
191 Las Chilcas
192 General Guido
193 Maza/194 Azul
195 Ayacucho
196 General Madariaga
197 Sun-Fx-2
198 Rivera/199 Lago Epecuén

Localities corresponding to Fig. 1.2. Those sections studied with detail in this work are printed in bold type; localities with previous TEP microfossil knowledge are in italic type.

1.4.1.4 The Colorado Basin

Malumián (1970, 1972) studied the foraminifera, ostracoda, and calcareous nannoplankton, and described associations of Maastrichtian-Danian, Oligocene, Miocene, and Quaternary ages. He considered that the *Entrerriense* was deposited during the Middle Miocene, a bit older than in the Salado Basin. Becker and Bertels (1978) identified six micropaleontological associations in an offshore drilling east-southeast of the city of Bahía Blanca, where the Colorado Basin reaches its maximum depth. The assemblages were dated as Late Eocene–Early Oligocene, Oligocene, Early Miocene, Middle–Late Miocene, Late Miocene–Early Pliocene, and Pliocene. Boltovskoy (1980) described the foraminifera of the borehole Gil 1 and found Late Oligocene, Early Miocene, Miocene, and Quaternary microfaunas. He correlated the Miocene faunas with the *Entrerriense*, and pointed to a climatic deterioration from the Late Oligocene, with a gradual decrease in temperature and the foraminiferal associations related to the Brazilian marine current. Guerstein and Quattrocchio (1988), Quattrocchio et al. (1988), and Guerstein (1990) studied the paleoclimatic, paleoenvironmental, and eustatic variations through palynological analysis in boreholes from the Bahía Blanca area and offshore.

Echevarría (1988) found similarities between the ostracods of the *Rionegrense* of Playa Bonita with associations of the *Entrerriense* of southwestern Entre Ríos province and Península de Valdés. Malumián et al. (1998) found species of the *Protelphidium tuberculatum* informal zone (Middle–Late Miocene) in the type section of the Barranca Final Formation. Guler et al. (2002) studied the dinoflagellate cysts of the same site and estimated that their lower section was deposited during the Middle–Late Miocene, whereas the upper section would correspond to the Late Miocene. The dinoflagellate associations are characteristic of estuarine environments, with short periods of increased flood and warm-temperate to warm waters.

1.4.1.5 Northeastern Chubut Province

Darwin (1846) was the first one to study the outcrops in this region, which were included in his "Patagonian tertiary formation." Rovereto (1921) found the *Aonikense*, an equivalent of the *Superpatagoniano*, between the *Patagoniano* and the *Entrerriense*. Frenguelli (1927) assigned a Miocene-Pliocene age to the *Entrerriense-Rionegrense* and considered that the first unit was developed in an open marine environment, whereas the latter recorded a gradual continentalization. Moreover, he described the *Rionegrense continental*, between the *Entrerriense* and the *Rionegrense marino*. Feruglio (1949) considered that the contact between the *Entrerriense* and the *Rionegrense* is transitional, and that the *Aonikense* is actually the bottom of the *Entrerriense*.

Haller (1978) named the *Patagoniano* as CF and the *A*-*E*-*R* as Puerto Madryn Formation. Scasso and del Río (1987) maintained this lithostratigraphical division and granted fundamental importance to the action of storms and tidal regimes in the accumulation of the *Entrerriense-Rionegrense* sequence. They considered that the contact between the *Patagoniano* and the *Entrerriense* was a probable surface of no deposition. Sato (1981) mentioned some foraminifera and ostracoda that were characterized by low diversity and poor preservation. del Río (1988, 1990, 1991) reviewed the systematics of the mollusks and proposed tropical to subtropical conditions for the Miocene sea, due to the high affinity with malacofauna of the Caribbean, Panamanian, Carolinian, and the Gulf of Mexico bio-provinces. Scasso et al. (2001) obtained $^{87}Sr/^{86}Sr$ ages between 9 and 11 Ma (Tortonian) for the upper section of the *Entrerriense*.

In 2005, several abstracts were presented at a special meeting on the geology of the Península de Valdés. Among them, several should be mentioned here: Scasso (2005) described sedimentary environment and depositional sequences of the Puerto Madryn Formation, and Palazzesi and Barreda (2005) presented advances on the first study in palynomorphs of the Puerto Madryn Fm. In addition, Casadío et al. (2005a, b), Cione (2005), Cozzuol (2005), del Río (2005), Echevarría and Marengo (2005), Gosztonyi and Riva Rossi (2005), and Tambussi and Acosta Hospitaleche (2005) presented updates or descriptions of various groups of marine fossils. Finally, Dozo et al. (2010) described the first finding of continental vertebrates (fishes, birds, and mammals) in the Puerto Madryn Formation, from the upper part (*Rionegrense* beds) of the Regressive Phase.

1.4.1.6 The Golfo San Jorge Basin

The Cenozoic stratigraphy of this basin is highly controversial. It is generally considered that all levels cropping out from the Atlantic coast to the Pampa del Castillo belong to the *Superpatagoniense-Patagoniense* cycle. There are few scientific quotes about the probable finding of the *Entrerriense*: Frenguelli (1929) mentioned a few meters with *Entrerriense* and *Rionegrense* faunulas in some sections around Comodoro Rivadavia. In turn, Tapia (1929) found near of Pampa del Castillo deposits of both levels characterized by *Ostrea alvarezi* and *O. madryna,* respectively. Legarreta and Uliana (1994) recognized unconformities between the *Juliense*, *Leonense*, *Superpatagoniense*, and *Entrerriense* and its continental counterparts. In contrast, Bellosi and Barreda (1993) refused to accept the existence of *Entrerriense* deposits in the region; in their opinion, subsidence did not take place during the Middle Miocene.

1.4.1.7 Northwestern Argentina and Cuyo Regions

Bertels and Zabert (1980) and Zabert (1984) described a few species of ostracods and benthic foraminifera related to the TEP, from the Valle de Santa María (Tucumán and Catamarca provinces). This microfauna suggests conditions of a very shallow marine environment with salinity over the usual. Bossi and Gavriloff (1998) and Gavriloff et al. (1998) synthesized the knowledge on the stratigraphy and paleontology of the Late Miocene deposits of the Valle de Santa María and nearby regions. They described more diverse associations of foraminifera and ostracods.

Russo and Serraiotto (1984) founded foraminifera and other marine fossils in the Anta Formation; however, they could not recognize the faunal composition and tentatively correlated it with the Paraná Formation. Cione et al. (1995) described a freshwater fish fauna from the base of the Anta Formation and assumed it was deposited during the end of the *Paranense*, during the Tortonian (10–11 Ma). Ramos and Alonso (1995) discussed a letter sent by F. Ameghino to H. von Ihering in 1909, in which they mentioned the discovery of Patagonian marine mollusks on the banks of the Río Grande de Jujuy. On the basis of this letter, Ramos and Alonso estimated the likelihood that the *Paranense* sea had flooded eastern Jujuy province. Alonso (2000) considered that the Quechua tectonic front during the Miocene was an effective barrier which isolated the Puna region during the marine ingression, and attributed the formation of the marine engulfments in the region to major tectonic subsidence as a result of the Quechua Phase. Pérez and Ramos (1996) reported microforaminifera from the Chinches Formation (Cordillera Frontal of San Juan province) at 3,100 m a.s.l. They correlated these deposits with the *Paranense* and assigned an age of 15 Ma (Middle Miocene) by the fission track dating of tuffs. They also correlated these deposits with various similar sites of the Andes in Mendoza, southern San Juan, and northern Neuquén provinces. No unambiguously marine facies or isotopic signatures were recently recognized in the Saguión (Salinas Grande, Córdoba), Anta, Del Buey and Del Abra (Famatina Ranges, La Rioja), and Chinches Formations (Ruskin et al. 2011).

1.4.2 The Laguna Paiva Transgression

The information herein presented is restricted to the marine ingression occurred during the Early Miocene in the Chacoparanense and Salado basins. This same transgression is known in Patagonia as the *Patagoniense*, among other informal names, and has been widely studied in the Colorado Basin and along the Patagonian coast. Several authors performed very complete reviews, among which Bellosi and Barreda (1993) and Legarreta and Uliana (1994) should be mentioned. The first mention of sea levels older than the TEP in the Chacoparanense and Salado basins was made by Stappenbeck (1926), who described one or more marine levels in boreholes from Santa Fe (Laguna Paiva), Córdoba (Seeber, Ordonez, Guardia Vieja, Justiniano Posse, and Cotagaita), Buenos Aires (Villa Sauze and Pehuajó), and La Pampa (Meridiano Quinto) provinces (Fig. 1.2). These deposits are located below the TEP by approximately 100–300 m from the "brown clay" (Olivos and Chaco formations). Stappenbeck defined the *capas de Paiva* as one or a series of green clay layers interbedded with brown clay and gypsum, and tentatively correlated with the *formación patagónica miocena*. He located the type section between 547.50 and 601.65 mb.g.s.in the Laguna Paiva borehole.

In the 1960s, research on the Chacoparanense Basin stratigraphy resumed as a result of the reactivation of the prospective activity by YPF. Padula and Mingramm (1963) mentioned, without a formal definition, the Mariano Boedo formation in the subsurface of the Formosa province, between 508 and 600 mb.g.s. of the YPF Mariano Boedo 1 borehole. This unit consists of a basal conglomerate with boulders of basalt, whitish pink calcarenites with interbedded shales in the lower and middle sections, and pink and red shales and marls in the upper part. Subsequently, Padula and Mingramm (1968) mentioned the Mariano Boedo formation in several boreholes in Santiago del Estero, Córdoba, Santa Fe, and Entre Ríos provinces, although with marked lithological variations with respect to the type section. They assigned this unit to the Late Cretaceous-Paleocene, based on regional stratigraphic relationships, and considered it to be discordant over the Early Cretaceous deposits (San Cristóbal Formation, Alhuampa Gr., Tacuarembó Formation or the basalts of Serra Geral). Finally, they correlated this unit with the Asencio and Mercedes Formations (Uruguay) and the Bauru Formation (Brazil). As a consequence, many authors published comments on the Mariano Boedo formation, although usually without new information. Yrigoyen (1969) considered that the Danian Sea was continuous with the Maastrichtian transgression, and "let shallow-water deposits, in partly of paralic and semiparalic environments, distributed from Tierra del Fuego up to engage with homologue deposits that enter again in Argentina from Peru through southern Bolivia."

Yrigoyen (1975) correlated the Mariano Boedo formation with the Las Chilcas Formation and *capas de Laguna Paiva*. Bracaccini (1972) correlated the *capas de Laguna Paiva* to "the Senonian of General Belgrano," the Mariano Boedo formation, and with some levels found in a borehole in Conesa (San Nicolás, Buenos Aires province) and considered that "it was in fact the lower part of the Tertiary." Zambrano (1974) considered that the deposits of the Salado, Rosario, Laboulaye, and Paraná basins began to coalesce to each other during the Late Cretaceous. When the subsidence was increased, sometime about the Maastrichtian-Paleocene boundary, it forced the development of very extensive continental and marine deposits (Mariano Boedo, Las Chilcas, and Paraná Formations), which overlapped extensively the earlier deposits. Russo et al. (1979) linked the Mariano Boedo formation with the *estratos de Laguna Paiva*, the top of the Salta Group, the Maastrichtian-Paleocene of the Salado Basin, the Abramo Formation of the Macachín Basin, the Roca Formation of eastern La Pampa province, the Caiuá and Baurú Formations of the Santa Catarina Basin (southeastern Brazil), and the Mercedes, Guichón, and Asencio Formations of Uruguay. They considered that the Mariano Boedo formation "is of Upper Cretaceous-Paleocene age, not because of the finding of defining paleontological evidence, but by the relationship it has with the Tacuarembó Formation The red sandstones, with quartz grains stained by iron oxide, indicate continental deposits in oxidizing environments. The sandy limestones and calcareous sandstones suggest nearshore marine deposits."

Uliana and Biddle (1988) reconstructed the paleogeography of southern South America during the Late Cretaceous (ca. 70 Ma). They postulated a marine ingression that linked the Salado Basin with northwestern Argentina (NOA) and southern Bolivia, through a thin marine branch that would have crossed the Chacoparanense Basin from south to north. Chebli et al. (1989) correlated the Mariano Boedo formation with some outcrops of eastern Entre Ríos and Corrientes provinces, and some places of Uruguay with Senonian vertebrate faunas. Moreover, Pezzi and Mozetic (1989) considered that the Mariano Boedo formation was deposited in paraconformity with the Early Cretaceous, and with much greater areal development. They proposed a continental origin and a marked lithological and tecto-sedimentary link to the Early Cretaceous, so it would be older than the Maastrichtian. Finally, Spaletti et al. (1999) proposed that the deposition of the Mariano Boedo formation would have started in the Campanian-Maastrichtian (ca. 75 Ma) and would be characterized by fluvial-lacustrine facies. The Late Cretaceous marine transgression would have been limited far to the South (the Salado and Punta del Este basins), and would have taken place during the Campanian-Maastrichtian, represented by the Las Chilcas Formation. Closer to Stappenbeck's opinions, Bracaccini (1980) proposed to give formational rank to the *capas de Paiva* (but unfortunately he did not), and hereinafter he eliminated the use of Mariano Boedo formation in the Chaco-pampean Plain. He considered that the Paiva formation was deposited mainly in marine environments and mentioned the first fossils (foraminifera) undoubtedly associated with marine sedimentation, but he did not specify the age or the taxonomic composition of the fauna.

1.4.3 Miocene Transgressions in South America

Sprechmann (1978) described marine fossils of the TEP in the Chuy 364 borehole, in the southern portion of the Pelotas Basin, northeastern Uruguay. He found very diverse foraminifera, ostracods, mollusks, bryozoans, and fishes, broadly assigned to the Miocene. These faunas have significant affinities with the TEP, except for the record of a high percentage of *Amphistegina gibbosa*, foraminifera of warmer waters currently unknown in the TEP of Argentina. Based on the finding of *A. gibbosa*, Sprechmann concluded that during the Miocene, the marine current of northern Brazil reached the shores of northeastern Uruguay.

Sempere et al. (1990) correlated the Petaca and Yecua Formations (southern Bolivia) with the *bancos de Salla*, dated as Late Oligocene-Early Miocene by magnetostratigraphy and radiometry. In turn, Marshall et al. (1993) found *Ammonia beccarii*, *Cyprideis* sp., *Bythociprys* sp., *Balanus* sp., mollusks, and decapods in the Yecua Formation. This association is typical from a very restricted marine to lacustrine environment; it was correlated with the *Paranense* and the Chasicoense mammal age (11–9 Ma) based on field relationships with continental deposits bearing vertebrate faunas. The Yecua Formation has a thickness of up to 300 m; it mainly consists of green to black marl and subordinate calcareous sandstones. Welsink et al. (1995), Sempere (1995), and Dunn et al. (1995) located the Yecua Formation in 20–21 Ma, and Baby et al. (1995) considered it was deposited between 11 and 7.5 Ma, although in neither case was new direct evidence on these ages provided. Wiens (1995) found thin levels of Middle Miocene marine sediments, interbedded within the Chaco Formation in the subsurface of center and western Paraguay. Räsänen et al. (1995) described sedimentary deposits with tidal structures in the Solimoes Formation, Amazonian foreland basin; they related these Late Miocene sediments with the "The Arm of the Tethys," and they considered the *Paranaense* or Pebasian as an inland sea surrounded by tidal flats that enabled the start of the initial phases of the Great American Biotic Interchange. Furthermore, Webb (1995) explained the huge diversity of native species in freshwater and terrestrial biota of the Amazon basin, from the evolution of marine species and the generation of continental environments separated by geographical barriers, after the flooding of the region by the sea during the Middle or Late Miocene.

In recent years, several groups have been working on the Miocene paleogeography of South America, mainly in relation to the *Paranense* and Pebasian transgressions. Although there is still far from agreement about the age of the marine deposits in the Chacoparanense and Amazon regions, it is possible that if there was ever a marine connection between both, it would be represented by the deposits of the Yecua Formation of central Bolivia. A significant faunal difference has been observed between the *Paranense* and Pebasian deposits. The available dating, yet unreliable, indicates that marine deposits within the Pebasian sequence are somewhat younger than the *Paranense*. The latest developments on the sedimentological and paleontological knowledge on the Yecua Formation and related units in central and southern Bolivia can be found in Hernández et al. (2005), Hulka et al. (2006), and Roddaz et al. (2006), among others, whereas Lovejoy et al. (2006), Muñoz-Torres et al. (2006), Rebata et al. (2006), Wesselingh and Macsotay (2006), and Westaway (2006) provided updated results on the study of ostracods, fishes, and sedimentary facies in the Amazon region.

DeVries (1998) described a depositional sequence of 15–11 Ma in the Pisco Formation of southcentral Peru, characterized by *Turritella infracarinata*. DeVries considered that the Cenozoic transgressions of the Peruvian coast were the result of global eustatic changes with local tectonic influences. According to N. Malumián (personal communication 2005), the Pisco Formation has the same age as the TEP, whereas the Cumana Formation is equivalent to the TLP, due to the finding of *Transversigerina transversa*. In the region of Barranquilla, in the Caribbean coast of Colombia, the Tubara strata have a rich fauna of mollusks and microfossils of open warm water and medium depth, similar to other Miocene faunas of the Caribbean Sea or the North Pacific Ocean. The foraminifera of the Tubara marine strata were divided into Zone I (Middle Miocene) and Zone II (Late Miocene; Redmond 1953). Macellari (1995) described several marine formations of the Late Oligocene–Early Miocene in the southwestern Caribbean basins of Colombia and

Venezuela. These marine units correspond to the C1 (Late Oligocene) and C2 (Early Miocene) subcycles, and they lie unconformably on Jurassic-Late Eocene rocks. In some basins, there is an unconformity between the sediments of the Late Oligocene and the Early Miocene. The C2 subcycle was characterized by the intercalation of continental and marine facies, whereas the C1 is predominantly of marine nature. The overlying B cycle was deposited on an unconformity usually restricted to the end of the Early Miocene, but in some places it reaches the median portion of the Middle Miocene. This cycle culminates at the end of the Miocene, and it is characterized by interbedded marine and continental sediments.

In the Lake Maracaibo and the Barinas-Apure basins in western Venezuela, two super sequences dominated by marine sedimentation were described: the Super Sequences E (Late Eocene–Early Miocene) and F (Middle Miocene-Pleistocene)—both of them deposited in a context of collision during the rising of the Mérida Ranges (Parnaud et al. 1995). The T5 sequence (Late Oligocene–Early Miocene) reached a large extension in the region, widely overlapping the deposits of the Late Eocene–Early Oligocene, due to a major marine transgression. During the deposition of the Super Sequence E, the marine environment retreated northward but remained more or less continuous in the region of Lake Maracaibo, where a new transgressive pulse took place during the Middle Miocene.

1.4.4 State of the Art

1.4.4.1 Paleoenvironments

There is little information about the sedimentary environments of the TEP. These studies were done on outcropping sections, and it is usually agreed that they were generated in very shallow marine environments, from estuaries and tidal flats with storm influence in Patagonia (Scasso and del Río 1987; del Río et al. 2001) or very marginal environments with marked continentalization in Mesopotamia, the Santa María Valley, and the Andes of San Juan and Mendoza (Aceñolaza 1976; Bossi and Gavriloff 1998; Pérez and Ramos 1996; Ruskin et al. 2011). Where the TEP is exclusively at the subsurface, the paleoenvironmental information is restricted to few groups of fossils. In the Salado and Colorado Basins (Malumián 1970; Boltovskoy 1980), the sections with greater diversity of microfossils suggest the development of inner shelf environments during the periods of maximum flooding, within an overall context of shallow to very shallow environments dominated by the informal zone of *P. tuberculatum*. In the Chacoparanense Basin, the microfaunal associations are typical of shallow to very shallow brackish environments (Herbst and Zabert 1987; Marengo 2000).

The information on deposits related to the TLP has been reduced to a discussion of whether they were mainly marine (Stappenbeck 1926; Yrigoyen 1969, 1975; Bracaccini 1980), mainly continental (Spalletti et al. 1999; Pezzi and Mozetic 1989), or mixed (Zambrano 1974; Russo et al. 1979).

1.4.4.2 Paleoclimates

For the TEP, the interpretations depend on which group of fossils are being considered; in some cases, the results were very different. The taxonomic composition of the faunas of mollusks and foraminifera are fairly uniform from southwestern Entre Ríos province to the center of coastal Chubut province. However, although the mollusks indicate mostly warm waters (del Río 1988, 1990, 1991; Martínez and del Río 2002), the foraminiferal associations suggest very similar temperatures to the current platform for Argentina (Malumián 1972; Zabert and Herbst 1977; Becker and Bertels 1978; Boltovskoy 1980; Marengo 2000), and only tropical to subtropical taxa were identified in high proportions in northeastern Uruguay (Sprechmann 1978). The distribution of *Cupuladria canariensis* (Busk) in the TEP is remarkable because it is a bryozoan currently restricted to warm waters. *C. canariensis* is common in the Salado Basin but has not been found in southern regions (Malumián 1999), although Casadío et al. (2005b) reported the warm-water bryozoans *Cupuladria* cf. *biporosa* Canu and Bassler and *Discoporella* n. sp. aff. *depressa* (Conrad) in outcrops near Puerto Pirámide. Studies on the palynomorphs of the TEP were made in the subsurface of the Colorado Basin and indicated a marked seasonality and much drier climates than in the Early Miocene (Quattrocchio et al. 1988). The continental vertebrates in Mesopotamia were typical of tropical to subtropical conditions (Gasparini 1968; Pascual and Odreman Rivas 1971; Gasparini and Báez 1975; Cione 1978), whereas in Patagonia these faunas dominated during the Early Miocene (Pascual and Odreman Rivas 1971; Tauber 1997). In the Middle Miocene a marked shrinkage was observed, with an increase in the proportion of more temperate faunas (Pascual and Odreman Rivas 1971).

No prior information on the paleoclimate of the TLP is available; however, many studies conducted in deposits of the same age in the Patagonia and the Colorado Basin indicated generally warm-temperate waters in the coastal marine environment and humid warm-temperate climates in the continent (Quattrocchio et al. 1988; Tauber 1997; Barreda and Palamarczuk 2000). However, the influence of Antarctic waters would have produced a pronounced decrease of the temperature in the outer shelf (Malumián 1999).

1.4.4.3 Calcareous Microfossils

The micropaleontological characteristics of the TEP are fairly homogeneous in almost all basins. Generally, the foraminifera belong to the informal zone of *P. tuberculatum* (Malumián 1970), which is characterized by hyaline shallow water benthic foraminifera, with few miliolids and agglutinated taxa. The informal zone of *P. tuberculatum* was founded in the Camacho Formation (western Uruguay), the Paraná Formation (Chacoparanense Basin), the Puerto Madryn Formation (northern coast of Chubut), the Barranca Final and Gran Bajo del Gualicho Formations (northeastern Río Negro province), and the TEP of the Colorado and Salado Basins. In some sites, some variations were recognized with respect to the typical composition of the informal zone of *P. tuberculatum*. In some levels of the Salado and Colorado Basins, the microfaunas have greater diversity and comprise some planktonic species; therefore, they are characteristic of deeper water, possibly related to periods of maximum flooding. In the Chuy 364 borehole (Pelotas Basin), the abundance of *Amphistegina gibbosa*, a warm-water benthic foraminifera, is remarkable; it was previously unrecognized in another region of the TEP. In southern Bolivia, the NOA, and many levels of the Chacoparanense Basin, there is a marked impoverishment of the microfaunas due to the progressive continentalization and the consequent increase of brackish environments, with a sharp dominance of *Ammonia parkinsoniana*.

The sea was usually very shallow, except during maximum flood in areas closest to the Atlantic coast; consequently, the planktonic foraminifera are very rare. The planktonic foraminifera are only suitable as markers in the Colorado Basin (Malumián 1970, 1972), which indicated a Middle Miocene age. Other estimations on the age of the TEP based on foraminifera are not very reliable. The ostracods have yet not been thoroughly studied, except perhaps in southwestern Entre Ríos province (Rossi de García 1966, 1969a; Zabert and Herbst 1977), and to a lesser extent in the Colorado and Salado Basins (Malumián 1970) and the Chacoparanense Basin (Zabert 1978; Bertels and Zabert 1980; Zabert and Barbano 1984). Even though all available data have not been compared, these ostracod faunas would be very homogeneous and indicate the same environmental conditions as the foraminifera. To date, calcareous nannofossils were not recognized at any level associated with the TEP, except for those described by Marengo and Concheyro (2001). With regard to the TLP, there is no prior information on microfossils and megafossils.

1.4.4.4 Lithology

The characteristic lithology of the TEP is olive-green massive mudstones, with or without megafauna. Light-gray and light-yellow to pale-olive sandstones and clayey sandstones with or without megafauna are also common, mainly in northeastern Chubut and southwestern Entre Ríos provinces. In some localities, fossiliferous limestones and conglomerates were found. The TLP is characterized by alternating beds of olive-green shales, with very few fragments of oysters, and very friable light to dark reddish-brown mudstones and pelitic sandstones, with abundant crystals and aggregates of gypsum and few calcareous concretions. In some places, calcarenites and oolitic sandstones were found.

1.4.4.5 Stratigraphy and Age

The deposits related to the TEP received various names, depending on the region: *Entrerriense* or Puerto Madryn Formation in northeastern Chubut; the Gran Bajo del Gualicho Formation in northeastern Río Negro province; *Entrerriense* or Barranca Final Formation in the Colorado Basin; Macachín Formation (Salso 1966) in the

Macachín Basin; Saguión Formation (Bertolino et al. 2002) in northern Pampeanas Ranges; *Entrerriense*, *Paranense,* or Paraná Formation in the Salado Basin, southwestern Entre Ríos province, the Chacoparanense Basin, some outcrops of the NOA, Andes of Mendoza and San Juan provinces, and southern Bolivia; and *Entrerriense* or Camacho Formation in western Uruguay. The age ranges primarily from the Miocene in general to the Early Pleistocene, with greater agreement in the Middle–Late Miocene. The deposits of the TEP rely apparently conformably over the continental deposits of the Chaco, Fray Bentos and Olivos Formations in the Chacoparanense and Salado basins, over the Elvira (Oligocene–Early Miocene, marine) and Ombucta (continental) Formations in the Colorado Basin, and discordantly over the Catalina or Gaiman Formations or the *Patagoniense* in northeastern Chubut. They are covered by continental sediments of the Puelches Formation and equivalent units in the Chaco-pampean Plains, and by the *Rionegrense continental* in the Patagonian coast.

The deposits of the TLP are known by the names of *estratos de Paiva*, *capas de Paiva*, formación Paiva, Mariano Boedo formation, or have been included within the Chaco Formation. The relationship of the TLP with Las Chilcas Formation (Salado Basin) is unknown, as well also with some sections outcropping in the NOA included in the Anta Formation. The age of the TLP has been determined on the basis of regional stratigraphic relationships, in any case by paleontological studies, and has been assigned by various authors to the Miocene, Oligocene, Maastrichtian-Paleocene, Late Cretaceous, and even the Early Cretaceous. The basal contacts of the TLP are not well known, although it is supposed that they are usually unconformably lying over rocks of the Early Cretaceous (San Cristóbal and Tacuarembó Formations and Serra Geral basalts). The top is concordant with the Fray Bentos, Chaco, and Olivos Formations. Finally, the continental deposits associated with both the TEP and TLP have received little attention and in general were mainly dated through dubious correlations. Due to their wide geographical and stratigraphical distribution, they received several names and were generally poorly described. As a result, only the Fray Bentos Formation has been acceptably defined in Uruguay, although it is not part of the Chacoparanense Basin *s.s.* The rest of the units remain informal, as the Chaco and Olivos formations, the continental deposits of the Mariano Boedo formation, or those sedimentary levels known simply as *arcillas pardas*, *formación Terciaria arcilla parda*, or *Mioceno rojo*.

1.4.4.6 The Arm of Tethys

In 1927, Hermann von Ihering postulated the hypothesis on the migration of marine mollusks from the Caribbean to the Río de la Plata region, through an intracontinental seaway called “The Arm of Tethys,” which would have developed in the Andean foreland basins in times of the TEP. Since then, many authors have adhered to this idea and correlated outcrops of possible marine sediments with the TEP in the continental interior of South America. It should be noted that most of these “correlations” were based on the apparently marine character of possibly Neogene sediments or on the discovery of few fossils with doubtful stratigraphical value.

The latter is the case for *Ammonia parkinsoniana*, a benthic foraminifer that is tolerant to broad environmental changes and is very common worldwide throughout the Neogene. Thus, each finding of this species was useful to assign the bearing sediments to the TEP, reinforcing the hypothesis of "The Arm of Tethys." On the other hand, in the continental interior, the abundant and diverse fauna of mollusks mentioned by von Ihering was never found, beyond southern Entre Ríos and Santa Fe provinces. The associations found in the NOA and Bolivia are restricted to generally extremely poor faunas, indicating very shallow and very hyposaline waters. The quotes that related the outcrops of the NOA, Cuyo, Bolivia, and the southern Amazon Basin with the TEP were summarized in Sects. 1.4.1.7 and 1.4.3. A few articles presented alternative correlations, among which Sempere et al. (1990), Sempere (1995), and Dunn et al. (1995) should be mentioned; they assigned the Yecua Formation to the Late Oligocene–Early Miocene, based on correlations with nearby profiles dated by radiometric methods.