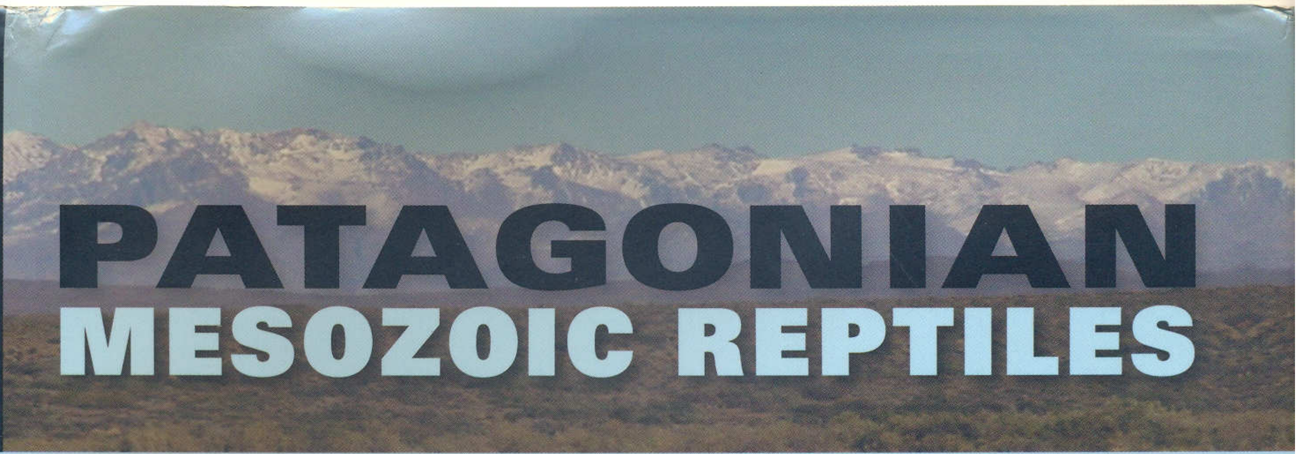
Gasparini
Salgado
and
Coria

PATAGONIAN MESOZOIC REPTILES



Edited by

Zulma Gasparini, Leonardo Salgado, and Rodolfo A. Coria

INDIANA

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2. Mesozoic Paleogeography and Paleoenvironmental Evolution of Patagonia (Southern South America)

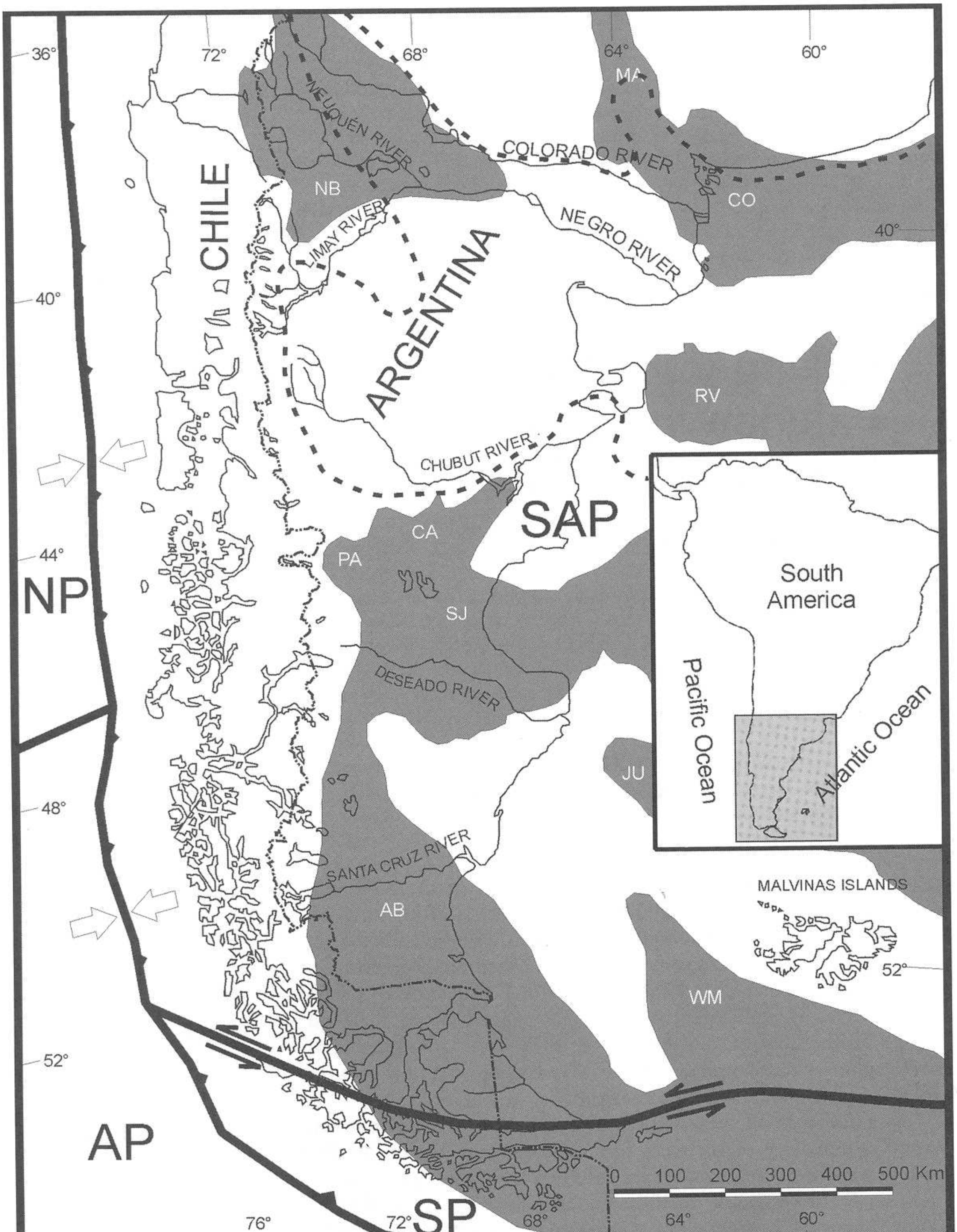
Luis A. Spalletti and
Juan R. Franzese

Introduction

Patagonia and the southern Pampas (south of the 33°S latitude) extend for more than 2500 km and average 1000 km in width (Fig. 2.1). During Mesozoic times, this region was the scene of paleogeographic changes triggered by different tectonic processes: intracontinental strike-slip deformation along transcrustal megashears, a largely convergent proto-Pacific margin along the west side of South America, and the impact of a series of hot spots or mantle plumes that impinged on or between the cratonic regions and resulted in the Gondwana breakup.

As a result of all these structural and major tectonic controls, several sedimentary basins were formed during the Mesozoic. The main groups of sedimentary basins resulting from these processes in southern South America are isolated Triassic rifts and pull-apart basins, Jurassic-Cretaceous extensional and back-arc basins, Cretaceous rifts (mainly located along the eastern or Atlantic margin of Argentina), and foreland basins developed along the Andes foothills.

The aim of this chapter is to present the paleogeographic evo-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SP
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lution of Patagonia and the main depositional systems of its sedimentary basins through a series of maps plotted on a palinspastic plate reconstruction. These maps start in the Middle Triassic and continue in 15-Ma steps through the Mesozoic.

Methods

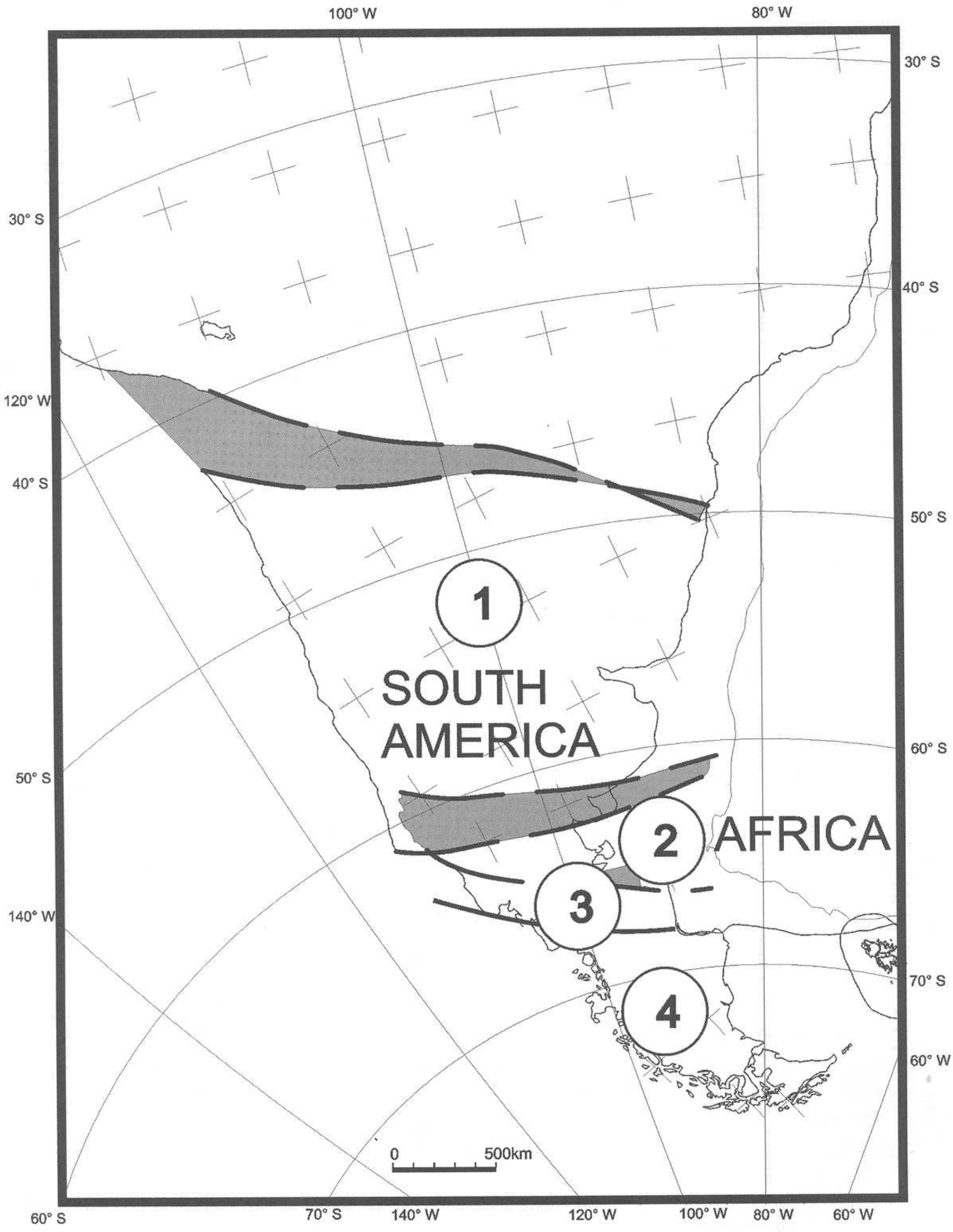
Different partial paleogeographic reconstructions of southern South America have been presented in previous works by Harrington (1962), Camacho (1967), Riccardi (1987), Uliana and Biddle (1987, 1988), Macellari (1988), Light et al. (1993), Urien et al. (1995), Urien and Zambrano (1996), and Jacques (2003a,b). Despite this, in order to accomplish a better understanding of basin evolution and to achieve the closest fit of the original continental plates, new palinspastic plate reconstruction will be required. In the present case, the base maps were developed by Lawver et al. (1999) and Dalziel et al. (2000).

To achieve a tight-fit reconstruction, South America was split into different tectonic plates along northwest-southeast lineaments and was subdivided into four rigid continental plates (Fig. 2.2), as follows: (1) a north-central Paraná plate, bounded to the south by the Colorado-Huincul fault system (Chernicoff and Zappettini 2003; Ramos et al. 2004); (2) a northern Patagonia plate, bounded to the south by the Gastre fault system (Rapela and Pankhurst 1992); (3) a central Patagonia plate, bounded to the south by the Deseado fault system (Ramos 1996, 2002; Chernicoff and Zappettini 2003); and (4) a southern Patagonia plate (Dalziel et al. 2000). The existence of these major lineations along northwest–southeast fault systems in South America is evident in geological maps of a continental scale (Rapela and Pankhurst 1992; Scotese et al. 1994, 1999; Lawver et al. 1999; Jacques 2003b). Geological fieldwork suggests continental strike-slip faulting during the Late Triassic and Early Jurassic to reconstruct southern South America into its present-day shape. In our pre-195-Ma palinspastic reconstructions, the southern plates were displaced east relative to the northern plates. Before 180 Ma, dextral movement along the Gastre fault and the Deseado fault systems (Rapela et al. 2005) brought the three segments of South America together in their present-day orientation.

These lineaments were later important controls in the orientation of the Atlantic marginal basins of Argentina. Furthermore, reconstruction of the Cretaceous north to south component of extension along these faults solved the problem of the excessive length of the Atlantic margin of South America compared with the West African margin.

The block of crust north of the Río Colorado–Huincul structure (Fig. 2.2) has been rotated to the north along its western edge in order to close the zone of underlap and to distribute extension across a wider area. The southern block (south of the San Jorge Gulf) has been displaced to the west along its southern edge to take

Figure 2.1. (opposite page) Present-day plate tectonic setting of southern South America and sketch map showing the main geographical features of Patagonia. AB = Austral Basin; AP = Antarctic Plate; CA = Cañadón Asfalto Basin; CO = Colorado Basin; JU = San Julián Basin; MA = Macachín Basin; NB = Neuquén Basin; NP = Nazca Plate; PA = Pampa de Agnia Basin; RV = Rawson-Valdés Basin; SAP = South American Plate; SJ = San Jorge Basin; SP = Scotia Plate; WM = Western Malvinas Basin. Dashed lines indicate the extension of the North Patagonian Platform.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out Late Cretaceous and Tertiary strike-slip movement. Scotia was restored along the transforms by several rectilinear displacements along strike slips and by slight desrotation of neighbor terranes (northern Antarctic Peninsula, and southernmost Patagonia, Tierra del Fuego, Estados, and South Georgia Islands). Every displacement of terranes for these new base maps was made in order to avoid significant changes in paleolatitudinal positioning.

Afterward, the facies and paleoenvironmental information was incorporated on the plate-tectonic reconstruction. We made final adjustments between geophysical reconstructions and geological information, regional correlations, and paleoenvironmental sections. Yet the resulting paleogeographic maps presented here do not contain all of the original data points, but our paleoenvironmental interpretation of them.

The reconstructions of the Patagonian paleogeography consist of 12 maps in 15-Ma steps through the Mesozoic. The following time slices are represented in the reconstructions: (1) Anisian-Ladinian (Middle Triassic, 240 Ma), (2) Carnian–early Norian (Late Triassic, 225 Ma), (3) late Norian–Rhaetian (Late Triassic, 210 Ma), (4) Sinemurian-Pliesbachian (Early Jurassic, 195 Ma), (5) Toarcian-Aalenian (Early–Middle Jurassic, 180 Ma), (6) Bathonian-Callovian (Middle Jurassic, 165 Ma), (7) Kimmerigian-Tithonian (Late Jurassic, 150 Ma), (8) Valanginian-Hauterivian (Early Cretaceous, 135 Ma), (9) Aptian (Early Cretaceous, 120 Ma), (10) Albian (Early Cretaceous, 105 Ma), (11) Cenomanian-Turonian (Late Cretaceous, 90 Ma), and (12) Campanian-Maastrichtian (Late Cretaceous, 75 Ma).

Chronological Review

Anisian-Ladinian (240 Ma) (Fig. 2.3A). Rifting occurred in west-central Argentina and resulted in extensional bimodal volcanism (late stage of the Choiyoi Group) dated around 239–240 Ma, and opening of a series of narrow rifts, such as the San Rafael depocenter, where fluvial-dominated deposits are associated with acidic pyroclastic flow deposits (Puesto Viejo Formation).

As shown in Fig. 2.3A, large areas of Patagonia remained as interbasinal highlands. In northern Patagonia, the intrusion of Gondwanan batholiths (Calvo Granite, Dos Lomas Complex of La Esperanza bimodal magmatism, dated 240 Ma) reveals a new pulse of magmatic activity with alkalic affinities. A subduction system along southern Chile was operating, with accretion and deformation of the Tarlton Limestone and the Denaro complex.

Carnian–early Norian (225 Ma) (Fig. 2.3B). Coeval strike-slip movements at the Gondwana paleo-Pacific margin led to the opening of several rifts (El Quereo–Los Molles and Curepto–Quitacoya Basins) in central Chile, characterized by fluvial and shallow marine facies.

The Los Menucos depocenter in north-central Patagonia was

Figure 2.2. (opposite page) South American tectonic plates. The region was subdivided into four rigid continental plates: (1) north-central Paraná plate, bounded to the south by the Colorado-Huincul fault system; (2) northern Patagonia plate, bounded to the south by the Gastre fault system; (3) central Patagonia plate, bounded to the south by the Deseado fault system; and (4) southern Patagonia plate.

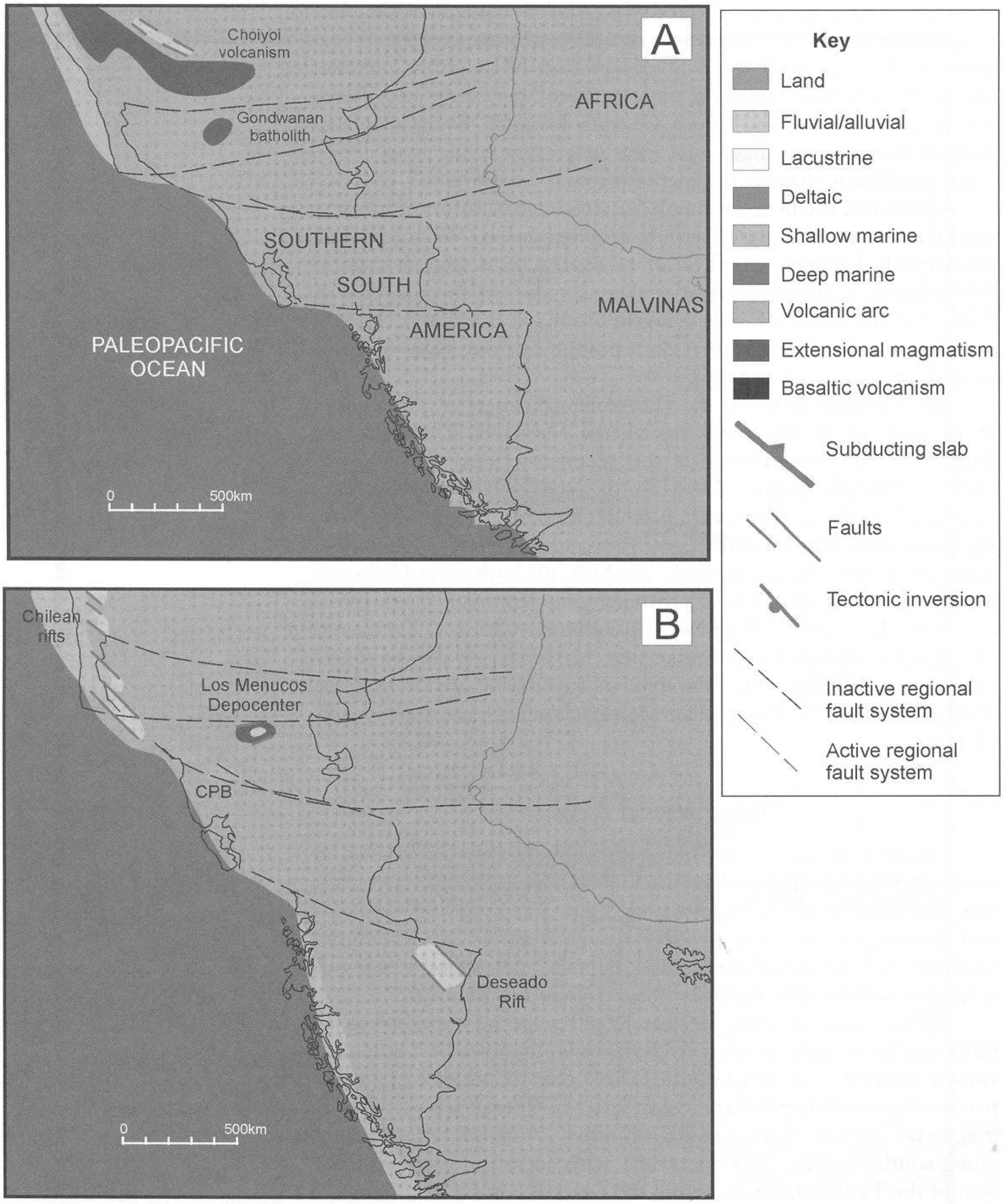

Figure 2.3. (A) Reconstruction of Patagonia at 240 Ma (Anisian-Ladinian, Middle Triassic). (B) Reconstruction of Patagonia at 225 Ma (Carnian–early Norian, Late Triassic). CPB = Central Patagonia batholith. (See Plate 9 in the color section.)

dominated by acidic pyroclastic flow deposits and stream-reworked pyroclastic rocks. The age of these rocks was defined by fossil plants and by radiometric data (223 Ma).

In southern Patagonia, the Deseado Rift is a narrow depocenter with a record of fluvial deposits showing paleocurrent directions to the south and southwest (El Tranquilo Group). An early Late Triassic age for the Deseado Rift is defined by a well-documented paleoflora.

It is likely that the Patagonian western margin was active by these times, although the extent of active volcanism is uncertain because of later overprinting. Subduction operated at least in two areas along the western margin of Gondwana: west-central Patagonia and southern Chile. In west-central Patagonia, the first evidence of calk-alkaline magmatism occurred at about 220 Ma (Central Patagonia batholith; dated 220–207 Ma). The present-day orientation of this batholith is oblique to the continental margin and suggests a very different configuration of the subduction system. Along the continental margin of southern Chile, a subduction-related deep marine succession started (Duque de York Flysch).

Late Norian–Rhaetian (210 Ma) (Fig. 2.4A). In the Late Triassic, the region adjacent to the proto-Pacific margin of Gondwana between 30° and 40°S was subjected to continental extension. As a result, several half-grabens were opened in western Argentina and Chile (e.g., Llantenes-Atuel, Paso Flores–Lapa, Panguipulli, Gomero). The sediments are coarse-grained fluvial deposits (alluvial fan, gravelly braided systems) and local lacustrine deposits. Coeval pyroclastic flow deposits are commonly intercalated. Most of these sediments bear abundant Upper Triassic fossil plants.

For the Late Triassic times, several areas of plutonic rock emplacement were defined in Patagonia: to the north granites of Chasicó-Mencué (210 Ma), slightly south the Gastre-Lipetrén intrusives, and far south the Triassic (202 Ma) La Leona Granite. The Gastre-Lipetrén granites are part of the Central Patagonia batholith. They are characterized by calc-alkaline compositions and have been related to oblique subduction of the proto-Pacific plate beyond western Gondwana.

Convergent tectonic activity along the western Gondwana margin is evidenced by the geochemical signature of the Central Patagonia batholith as well as by the Madre de Dios–Chonos–Chiloé subduction complex. Turbiditic trench deposition is preserved in the Duque de York Flysch, dated 234–195 Ma.

Sinemurian-Pliensbachian (195 Ma) (Fig. 2.4B). Continental extension continued along the northern proto-Pacific margin of Patagonia. The most important expression of this was the development of a system of half-grabens infilled by volcaniclastic and pyroclastic deposits associated with lava flows and plutonic intrusions. Coeval magmatism has a bimodal signature consistent with the interpretation of an extensional tectonic regime. The depocenters located to the west (e.g., Curepto and Lonquimay in Chile,

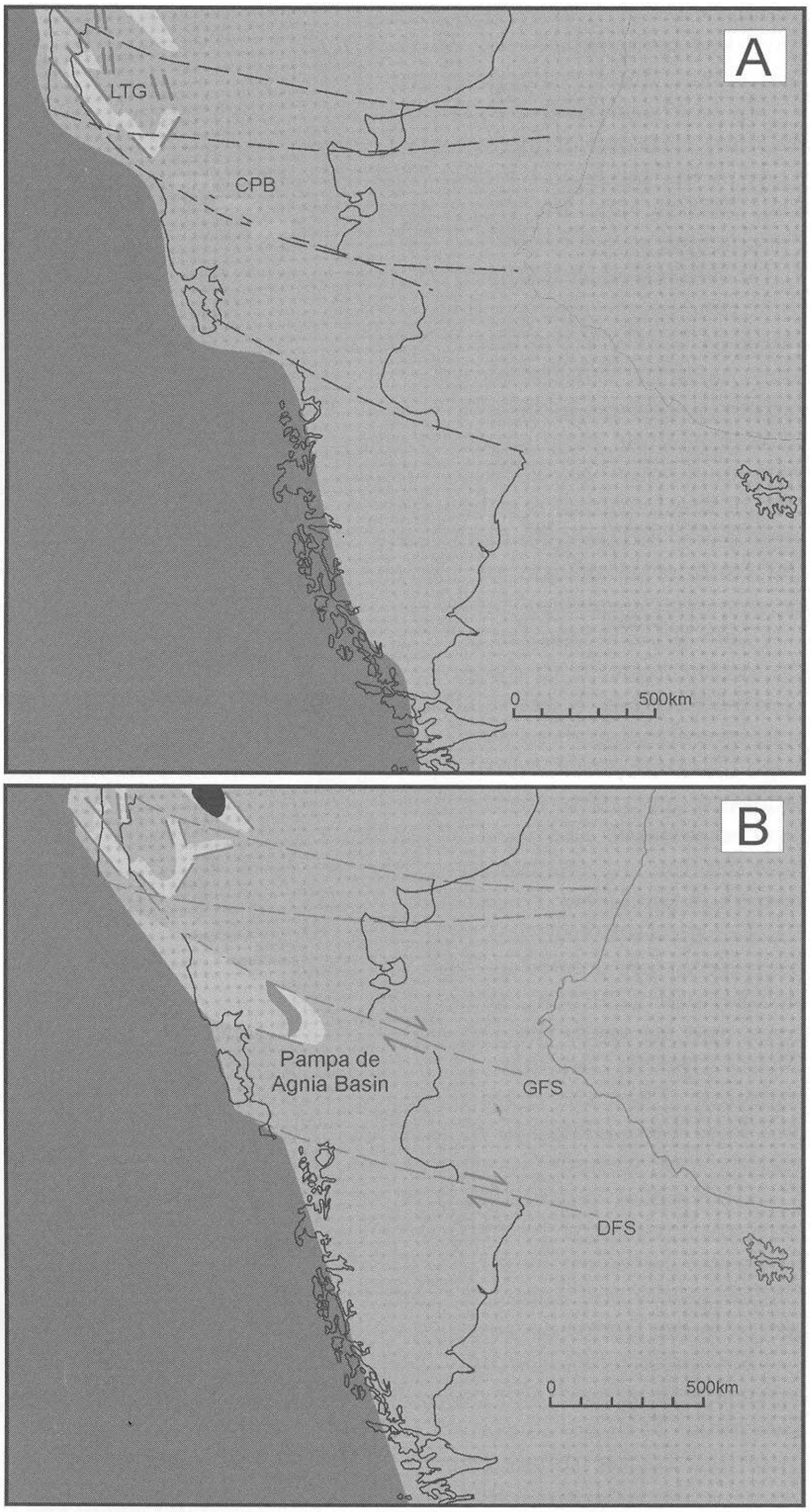

Figure 2.4. (A) Reconstruction of Patagonia at 210 Ma (late Norian–Rhaetian, Late Triassic). (B) Reconstruction of Patagonia at 195 Ma (Sinemurian-Pliesbachian, Early Jurassic). CPB = Central Patagonia batholith; DFS = Deseado fault system; GFS = Gastre fault system; LTG = Late Triassic grabens. (See Plate 10 in the color section.)

Atuel and Malargüe in Argentina) are characterized by marine deposits and/or alternance between continental and marine deposits (El Freno, Puesto Araya Formations, and correlative units), whereas those located toward the Gondwana interior (e.g., Neuquén Embayment, Chachil, Piedra del Águila in Argentina) are entirely dominated by continental (alluvial-fluvial-lacustrine) sedimentation (Lapa, Sañicó Formations). Toward the end of this time slice, the first widespread transgression occurred in the Neuquén Basin (Piedra Pintada, Los Molles Formations).

Patagonia received shallow marine sedimentation from the proto-Pacific Ocean in the Pampa de Agnia Basin, a depocenter oriented northwest-southeast, which coincides with the trace of the Gastre fault system. In the Pampa de Agnia Basin, a mixed clastic-carbonate association (Lepá and Osta Arena Formations) bearing a rich invertebrate fauna is interpreted as a tidal-dominated shallow marine system. Deltaic facies prograded from the north (Piltriquitrón Formation), and toward the southeast a belt of proximal fluvial deposits appears (El Córdoba, Puntudo Alto, and Puesto Lizarralde Formations). Paleocurrent trends from marine sediments suggest a positive area to the west of the Pampa de Agnia Basin.

Along this lapse, Patagonia was affected by a regional strike-slip tectonic regime. Movement along the Gastre fault system started. Magmatism with arc affinities (El Maitén Belt; approximately 190–200 Ma) is defined along a belt located to the south. Further south of the Gastre fault system, large areas of Patagonia remained as interbasinal highlands. The Deseado Rift was closed; even so, a narrow north-south rift, a precursor to the Austral Basin in southernmost Patagonia, is inferred from seismic sections. Deep marine deposition of the youngest Duque de York turbidites and the accretionary prism of Madre de Dios–Chonos–Chiloé suggest a protracted active convergent margin along southwestern Chile. Basic dykes dated about 192 Ma appear at south of the Gran Malvina (West Falkland) Island, as a first manifestation of the Karoo volcanism in South America.

Toarcian-Aalenian (180 Ma) (Fig. 2.5A). The early isolated depocenters located to the northwest of the studied region were integrated in the Neuquén Basin, the largest hydrocarbon producer of western Argentina. During this time slice, a period of generalized subsidence occurred in this basin, and the first proto-Pacific transgression covered large areas of northwestern Patagonia. Turbidites and coeval shallow marine deposits (Los Molles Formation) testified the full extent of the Cuyano transgression. To the south, the deltaic succession of the Piedra Pintada Formation passed to shallow marine siliciclastic deposits and fluvial sandstones and conglomerates. The southern and eastern margins of the Neuquén Basin (Neuquén Embayment) were filled with proximal fluvial deposits (Punta Rosada Formation).

In northern and northeastern Patagonia, a widespread and dominantly acidic volcanism (Marifil Formation) was developed under an extensional tectonic regime. In central Patagonia, this vol-

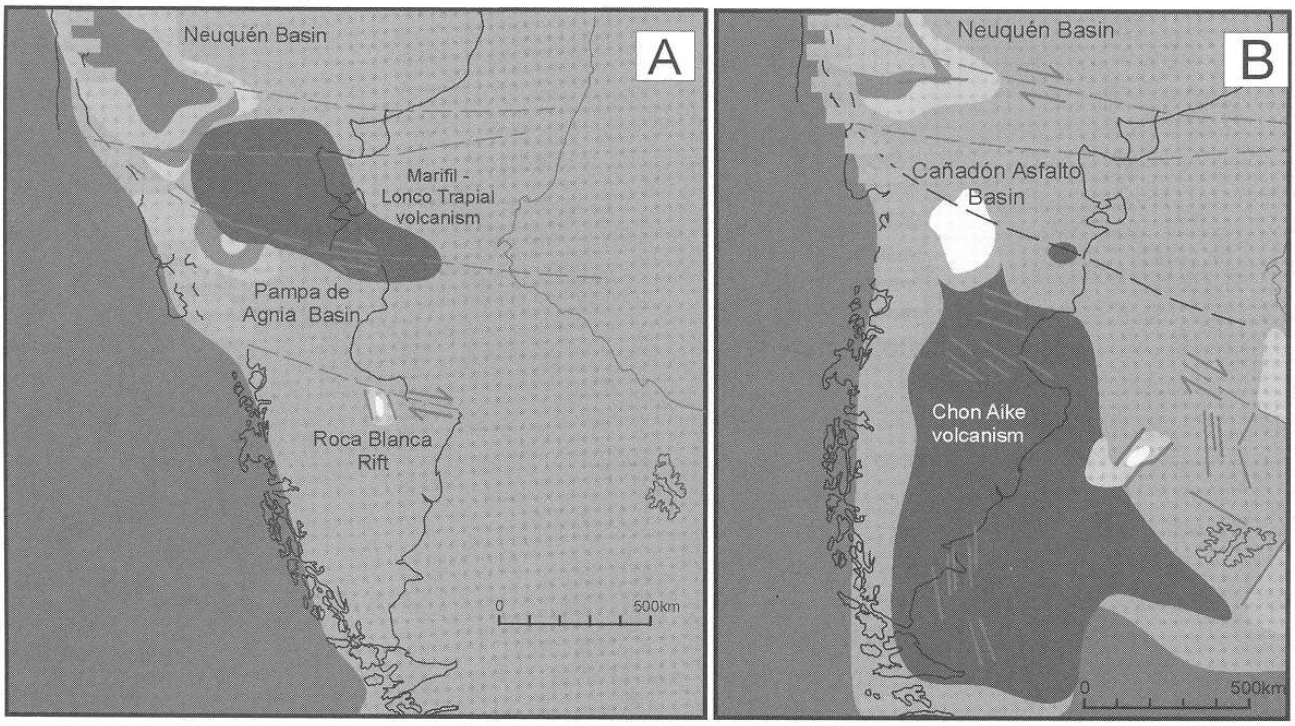

Figure 2.5. (A) Reconstruction of Patagonia at 180 Ma (Toarcian-Aalenian, Early-Middle Jurassic). (B) Reconstruction of Patagonia at 165 Ma (Bathonian-Callovian, Middle Jurassic). (See Plate 11 in the color section.)

canism, known as the Lonco Trapial Group, extends until the eastern margin of the Pampa de Agnia Basin. The Marifil-Lonco Trapial volcanism represents the northernmost and oldest episode of the Chon Aike Magmatic Province and has been dated to about 180 Ma by several Rb/Sr isochrons.

In the Pampa de Agnia depocenter, a transgressive episode (Lepá and Osta Arena Formations) extended to the southeast, and while a prograding deltaic system is located along its northeast side. Pyroclastic and volcaniclastic contributions became frequent in the Pampa de Agnia Basin during the Toarcian-Aalenian interval. The first evidence of the Andean Magmatic Arc appears to the west of the Pampa de Agnia Basin along the Argentina-Chile border between 42° and 44° south latitude (SL), and is represented by the volcanic rocks of the Lago La Plata Formation. Central and southern Patagonia still remained as a huge positive land. Nevertheless, in the Deseado Massif (to the west of the previous Permian and Triassic rifts) a north-south-oriented narrow rift, filled with fluvial and lacustrine siliciclastic facies, was developed (Roca Blanca Formation).

Bathonian-Callovian (165 Ma) (Fig. 2.5B). The Neuquén Basin passed through a critical tectonic phase and paleogeographic reorganization. The Huincul High was formed during this stage, the result of either east–west strike-slip movements or reverse inversion of original normal faults. Major regression and expansion of fluvial and deltaic facies occurred. The southern sector of the basin was dominated by fluvial (Challacó Formation, Punta Rosada Formation) and deltaic to shallow marine deposits, characterized by subtidal and intertidal sand bars, mouth bars, estuarine channels, and interdistributary bay systems (Lajas Formation and top of the Piedra Pintada Formation). Toward the basin center, protracted deep marine deposition of the Los Molles Formation prevailed.

The Pampa de Agnia marine basin evolved to an entirely continental depocenter known as the Cañadón Asfalto Basin because of the growth of the Andean Magmatic Arc. Although this basin is considered mostly extensional, late strike-slip movements along the Gastre fault system were recorded along its northern margin. It was dominated by lacustrine deposits and surrounded (especially toward the south) by fluvial sandstones and conglomerates. The Cañadón Asfalto Formation is mainly volcaniclastic, and in many places, it is closely associated with thick intermediate and basic lavas known as the Taquetrén Formation. The Leleque Granite, dated 165 Ma, seems to be the crustal counterpart of this magmatic episode.

By the end of this time slice, strike-slip movement along the Gastre fault system was completed, and granites postdating its displacement are dated about 165 Ma. The acidic volcanism recorded early in the North Patagonian area ceased. However, to the south of the Gastre fault system Patagonia was almost entirely covered by the rhyolithic lavas and pyroclastic flow deposits of the Tobífera, Bahía Laura, or Chon Aike volcanism. Several radiometric ages are about 165 Ma for this volcanic suite. This volcanism shows bimodal compositions (minor basic lavas) and constitutes the substrate of the Upper Jurassic and Cretaceous successions of southern Patagonia and the Western Malvinas Basin. At the Deseado Massif, since the Middle Jurassic, the Bahía Laura volcanics remained part of a positive land.

The acme of the Chon Aike volcanism coincides with the end of Malvinas-Falkland rotation and migration, as well as with the extensional tectonism that opened the Weddell Sea. It is also the case for the San Julián, Malvinas-Falkland Plateau, and Northern Malvinas–Falkland Basins. Southern Patagonia was also subjected to extension, and a series of gravitational faults defined a topography of alternating horsts and grabens. These fault systems trend west–east in the area to the west of the San Jorge Gulf, and north-northwest–south-southeast to the south of the Deseado Massif.

Kimmeridgian-Tithonian (150 Ma) (Fig. 2.6A). At the beginning of this time slice, a second episode of paleogeographic reorganization occurred in the Neuquén Basin. This episode is related to the growth of the magmatic arc to the west and protracted tectonic inversion of previous extensional structures. Later, a generalized transgression occurred in most of the basin with deposition of anoxic shales (Vaca Muerta Formation, main source rock for the Neuquén oil fields) and marginal carbonate-siliciclastic ramp facies to the south (Carrín Curá Formation, Picún Leufú Formation).

The volcanic arc is completely developed along the western margin of Patagonia. The bimodal volcanism in southeastern Patagonia has ceased; despite this, it is still present in the Andean

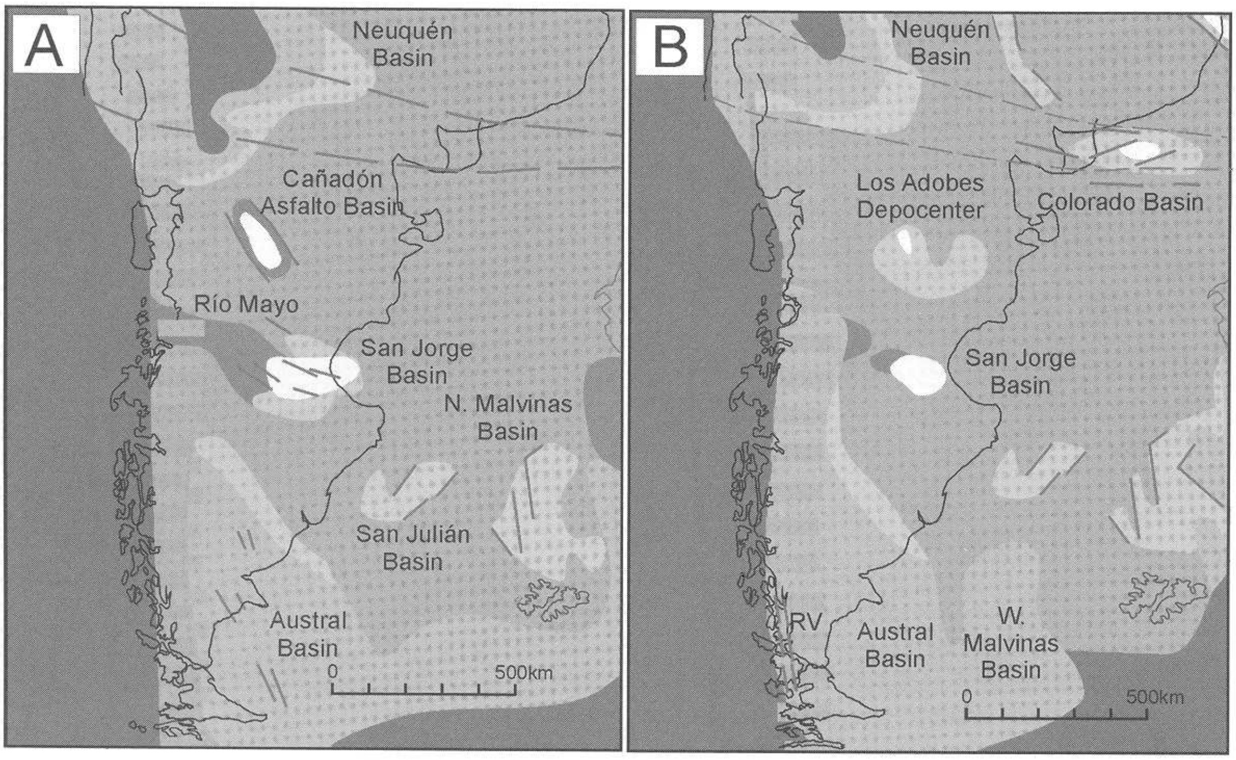

Figure 2.6. (A) Reconstruction of Patagonia at 150 Ma (Kimmerigian-Tithonian, Late Jurassic). (B) Reconstruction of Patagonia at 135 Ma (Valanginian-Hauterivian, Early Cretaceous). (See Plate 12 in the color section.)

area (Ibáñez Group, El Quemado Complex), where it seems to be related to back-arc and intra-arc extension. A submarine rhyolite suite was formed along the active margin of Patagonia between 50° and 55°SL ("Young Tobífera"), and to the east of this volcanic area, the Sarmiento-Tortuga ophiolitic complex (147 Ma) suggests the beginning of back-arc ocean-floor generation. Coevally, several depocenters are opened along western Patagonia, such as the Río Mayo Basin. All these depocenters were associated with explosive volcanism and lava flows, representing the final expression of the Chon Aike volcanism (Pankhurst et al. 2000).

Three important areas of sediment accumulation are defined in Patagonia. From north to south, they are the Cañadón Asfalto Basin, the San Jorge Basin, and the Austral Basin. The San Jorge and the Austral Basins are separated by a permanent positive land located by 48°SL known as the Deseado Massif, which extends southeast as the Dungeness or Río Chico Arch.

The Cañadón Asfalto Basin reduced its size but still generated lacustrine and deltaic deposits prograding from its western and eastern margins. Both the San Jorge and the Río Mayo Basins define a large east-west depocenter at 46°SL. The Río Mayo depression represents the western connection with the paleo-Pacific Ocean. Shallow marine carbonates (Cotidiano Formation) located by the Andean Volcanic Arc can be interpreted as intra-arc and proximal back-arc accumulations. To the east, only periodic marine episodes are recorded in the mixed siliciclastic-carbonate Tres

Lagunas Formation (composed of localized gravitational-flow deposits and patch reefs associated with isolated submarine highs). In Central Patagonia, the early infill of the extensional San Jorge Gulf Basin is represented by lacustrine deposits surrounded by proximal fluvial deposits along both its northern and southern margins (Bajo Grande and Anticlinal Aguada Bandera Formations).

A further analysis of the paleogeographic maps shows an alignment of the San Jorge Basin with the newly opened continental San Julián and Northern Malvinas–Falkland Basins. This lineation would suggest that their initial development could be controlled by strike-slip transtension linked to the Agulhas transform fault. Besides, in the Malvinas-Falkland Plateau, a marine incursion is recorded.

The Austral Basin is the largest depocenter of Patagonia. It was connected to the Pacific Ocean along its southwestern and western margins, where deep marine deposits are associated with basic lavas of the Sarmiento Complex and with the "Young Tobífera" submarine rhyolites. In southern Argentina, Tierra del Fuego Island, and the western Malvinas sector, the basin is an extended shallow marine platform characterized by tidal and deltaic deposits (Lower Springhill Formation). These sediments grade toward the northern and northeastern margins of the basin to a narrow belt of continental deposits. To the south, the Austral or Magallanes Basin is integrated to the Weddell Sea, which is floored with oceanic crust by this time. In fact, the Austral Basin represents the shallow platform of the Weddell Sea.

Valanginian-Hauterivian (135 Ma) (Fig. 2.6B). The opening of the South Atlantic Ocean produced significant paleogeographic changes along the eastern side of Patagonia. As a result of this extension, two huge taphrogenic basins (Salado and Colorado) were developed. The synrift stage in both basins is characterized by fluvial and lacustrine deposits of the Fortín and Río Salado Formations, respectively. The extensional process also affected the continental interior, where narrow and deep rift furrows composed of a thick record of continental red beds were formed (Central Argentinean Rift). This depression is composed of a chain of depocenters known as the Macachín, Levalle, Laboulaye, and Mercedes Basins, connected to the east with the Colorado and Salado Basins.

Continental and marine deposits were accumulated in the Neuquén Basin. To the north, mixed (siliciclastic and carbonate) marine ramp deposits (Agrio Formation) are widely distributed, whereas to the south, these marine deposits are followed by fluvial sandstones associated with lacustrine shales and evaporites (La Amarga Formation).

In Central Patagonia, a continental depocenter dominated by fluvial sandstones and conglomerates (Los Adobes Formation) occupied the area of the Cañadón Asfalto depression, which was enlarged to the east. To the south, the Río Mayo Embayment was drastically reduced. Its sedimentary infill is composed of siliciclastic deltaic facies (Katerfeld Formation) and shallow marine glauconitic sandstones (Apeleg Formation). These deposits suggest an effective connection of the Río Mayo Embayment with the proto-Pacific Ocean to the west, and with the northwest side of the Austral Basin to the south.

The San Jorge Basin was isolated from the proto-Pacific and was reduced to its smallest size. The restricted trough is filled with lacustrine mudstones and deltaic siliciclastic deposits prograding from the west (Cerro Guadal Formation). The Deseado Massif effectively separated the San Jorge Basin form the Austral Basin. The Río Chico Arch became narrower toward its southeastern end. Thus, the Western Malvinas Basin and the Austral Basin seem to be connected only to the south.

Coastal and shallow marine siliciclastic sediments (Upper Springhill Formation) accumulated on the wide platform of the Austral Basin. Fluvial deposits along its northeast margin surrounded it. To the south, in the Austral Basin and the Western Malvinas Basin, outer platform and slope deposits are represented by anoxic fine-grained siliciclastic facies of the lower Río Mayer, or "Favrela bearing beds." These widespread deposits bear testimony to the ample connection between the distal sectors of the Austral–Western Malvinas Basins and the Weddell Sea. To the west, the Andean margin of the Austral Basin is characterized by deep marine turbidites and hemipelagites of the Zapata-Yahgán Formations. They are part of the marginal Rocas Verdes Basin, are floored by oceanic crust, and formed as a result of intense back-arc extension. Connection between the Rocas Verdes Basin and the proto-Pacific ocean occurred across narrow paths within the volcanic chain.

Aptian (120 Ma) (Fig. 2.7A). A progressive transgression occurred in the Atlantic margin of southern South America, while the change from mechanical to thermal subsidence originated the rift/sag unconformity in the taphrogenic basins (e.g., Salado and Colorado). Fluvial deposits that laterally grade to offshore mudstones depict this change in tectonic regime. Coevally, the Macachín and Laboulaye rifts are characterized by fluvial-lacustrine facies associations.

To the west, the Neuquén Basin became a continental-restricted-marine depocenter composed of marginal fluvial red beds and a widespread muddy-evaporitic sabkha (Huitrín Formation, Rayoso Group, Lohan Cura Formation). Since the Aptian, the connection between the Pacific Ocean and the basin was definitively cut.

Between 40° and 47°SL, Patagonia was a continental land separated from the Pacific Ocean by the volcanic chain of the Andean Magmatic Arc. The San Jorge Basin was converted into a large and widespread continental trough, which incorporated the northern (Los Adobes) depocenter and a southern north-south-oriented depression located on the Permian and Triassic Deseado rifts. The marginal areas of the San Jorge Basin are represented by fluvial deposits (Matasiete Formation, upper Los Adobes Formation, and Cerro Barcino Member); deltaic systems prograded from the north-

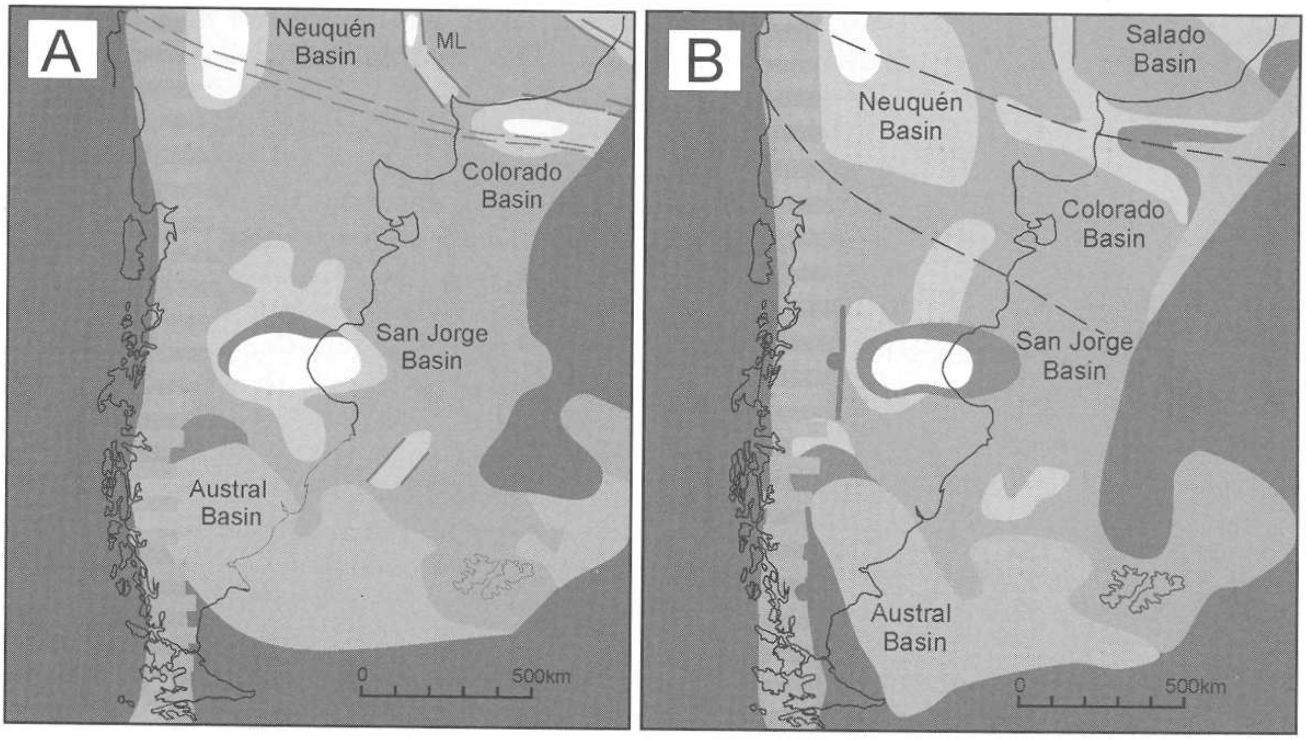

Figure 2.7. (A) Reconstruction of Patagonia at 120 Ma (Aptian, Early Cretaceous). (B) Reconstruction of Patagonia at 105 Ma (Albian, Early Cretaceous). ML = Macachín-Laboulaye rifts. (See Plate 13 in the color secion.)

ern and western margins onto a giant lacustrine system (Pozo D-129 Formation, source rock of the San Jorge oil fields).

Anoxic mudstones were deposited in wide areas of the Weddell Sea and the southern South Atlantic. In the Austral Basin, deep marine facies (interbedded shales and chert) are also widespread and grade into distal platform mudstones and shales to the north ("Lower Inoceramus": lower Palermo Aike and Lago San Martín Formations). Restricted marine conditions are represented by the Río Belgrano and Río Mayer black shales, among which storm sands intercalate. Toward its northwest corner, the Austral Basin is characterized by fluvial deposits (Río Tarde Formation). Along the foot of the Andean Magmatic Arc, black shales and turbidites of the Zapata Formation were accumulated as marginal back-arc and intra-arc deposits. In this region, the magmatic arc was almost submerged, and a tongue of deep-sea deposits "entered" from the proto-Pacific Ocean into the Weddell Sea.

Albian (105 Ma) (Fig. 2.7B). A sag stage, punctuated by widespread transgressive shales, started in the Salado (General Belgrano Formation) and Colorado (Colorado Formation) Basins; the main record of the intracontinental rifts was a thick succession of red beds formed in ephemeral fluvial systems (El Gigante Group and coeval units).

A new tectonic regime started along the convergent margin of southern South America. To the west of the Neuquén Basin, the shallowing of the subducting slab increased compression across the arc and favored the development of epidermic fold and thrust belts in the retroarc, accompanied by accumulation of fluvial red beds (lower Neuquén Group). The Neuquén Basin enlarged its area of fluvial-dominated sedimentation to the south and east.

Southern South America was separated from the Pacific by the topographic volcanic barrier of the Andean Magmatic Arc, and the first extensional plateau basalts were erupted in central Patagonia. In the San Jorge Basin, the southern fluvial domain was reduced, and the whole Deseado Massif became almost a positive land. Tectonic inversion started along the western margin of the basin, and toward the northwest, the Pampa de Agnia–Cañadón Asfalto–Los Adobes depocenter was definitively closed. Yet to the north and northeast, an expansion of the fluvial systems is clearly defined (Chubut Group red beds). At the center of the San Jorge Basin, lacustrine facies dominate (Mina El Carmen Formation), and they are surrounded almost entirely by prograding deltaic and fluvial siliciclastic facies (e.g., Castillo Formation).

The Austral Basin seems to be connected to the ocean through its southern and/or southeastern sides. At the northwest corner, a very active clastic depositional system is composed of fluvial deposits (lower Arroyo Potrancas and lower Puesto El Moro Formations), deltaic sediments (Kachaike Formation), and prodelta shales (upper Río Mayer Formation). Far south, the Palique, upper Palermo Aike, and the classic "Margas Verdes" Formations represent outer shelf shales. As a result of the magmatic arc elevation and the beginning of a compressional tectonic regime (early foreland stage), the marginal Rocas Verdes Basin was closed and the proximal back-arc was characterized by shallow marine sedimentation. Deep marine deposits are restricted to eastern Chile and southernmost Argentina, where an axial north-south-oriented turbidite system was developed (Punta Barrosa Formation).

A very effective connection existed between the Weddell Sea and the South Atlantic Ocean, but integration was less effective between the Pacific and Weddell Oceans. Incipient transforms of the proto-Scotia structure can be traced between southern South America and the Antarctic Peninsula.

Cenomanian-Turonian (90 Ma) (Fig. 2.8A). Fluvial and deltaic progradation upon shallow marine deposits occurred in the Atlantic taphrogenic basins. These deposits are known as the Upper General Belgrano Formation in the Salado Basin, and the Fortín and lower Colorado Formations in the Colorado Basin. The intracontinental rifts of Valdés and Rawson seem to be active during these times, with a continental early rift clastic infill.

Large volumes of granitic rocks (Patagonian Batholith) were intruded within the Andean Magmatic Arc. North and central Patagonia became regions of continental deposition. Thus, the Neuquén and the San Jorge Basins were integrated in a unique depocenter dominated by fluvial red beds, with subordinated shallow lacustrine and playa deposits. These deposits are represented by the red beds of the Neuquén Group in the Neuquén Basin, by the Chubut Group in northern Patagonia, the Bajo Barreal Formation

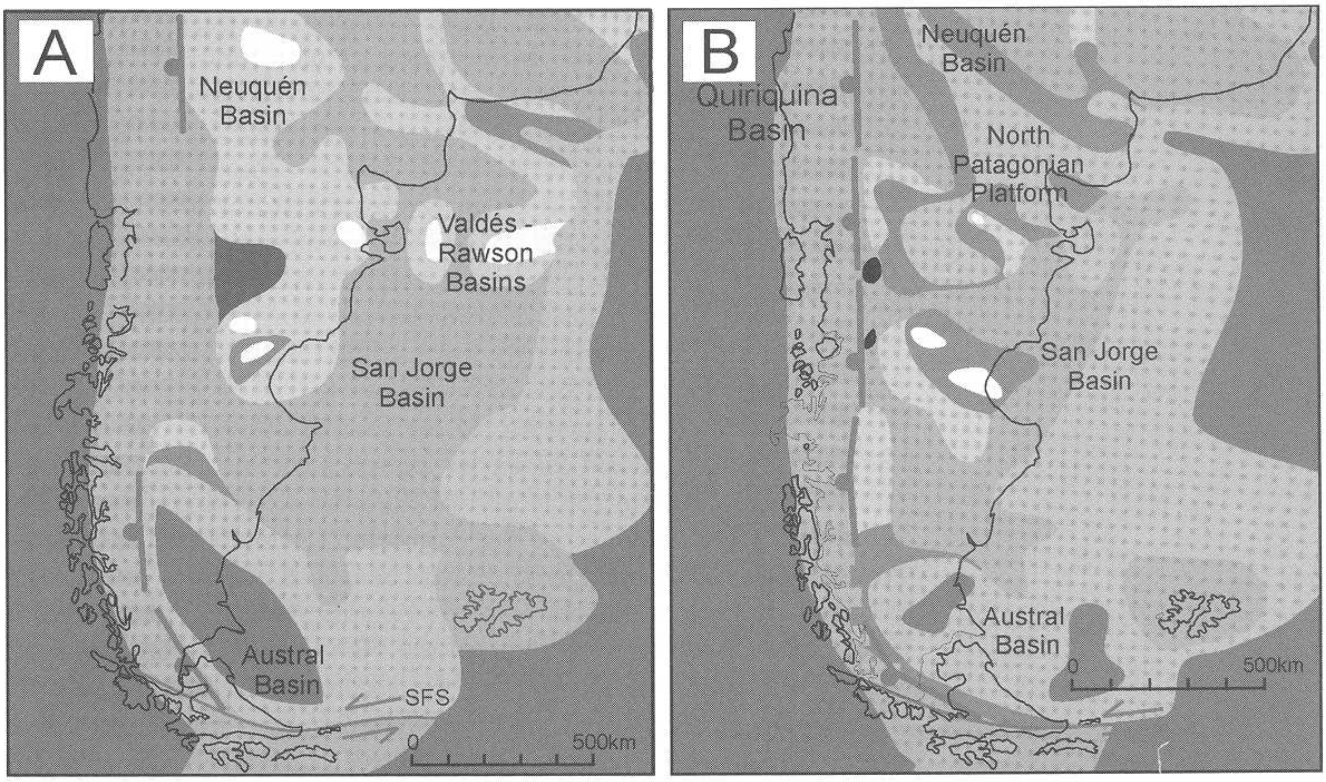

Figure 2.8. (A) Reconstruction of Patagonia at 90 Ma (Cenomanian-Turonian, Late Cretaceous). SFS = Shackleton Fault System. (B) Reconstruction of Patagonia at 75 Ma (Campanian-Maastrichtian, Late Cretaceous). (See Plate 14 in the color section.)

in the western margin of the San Jorge Basin, and the reservoir sandstones of the Comodoro Rivadavia and Cañadón Seco Formations in the subsurface of the San Jorge Basin.

The Austral Basin shows a similar facies pattern when compared with the previous map. However, because of compressional tectonics, an eastward migration of the foredeep occurred. The northwest prograding zone is characterized by fluvial facies (upper Arroyo Potrancas and upper Puesto El Moro Formations), a deltaic siliciclastics system (Piedra Clavada and Shehuen Formations), and shallow marine mudstones and fine sandstones (Lago Viedma and El Álamo Formations in Argentina, and Tres Pasos Formation in Chile). Toward the center of the basin, the Middle Inoceramus, Palermo Aike, and Cabeza de León Formations are composed of mudstones and shales deposited in deeper sectors of the platform and talus slope. North-to-south-oriented axial turbidite systems remained along the western flank of the Austral Basin (lower Cerro Toro and Lago Sofía Formations).

Intense strike-slip displacements along the Shackleton fault system in southernmost South America progressively curved Tierra del Fuego `(and neighbor islands) toward the east. This movement caused the development of an east-west-oriented ridge, with partial isolation of the Magallanes–Austral Basin from the Weddell Sea. Instead, to the east, the Austral Basin widely faced the Atlantic Ocean through the western Malvinas–Falkland Basin.

Campanian-Maastrichtian (75 Ma) (Fig. 2.8B). The Atlantic Ocean was in a drift stage, and generalized marine transgression (late sag) occurred in most of the taphrogenic basins facing the ocean. This marine incursion attained its maximum at the uppermost Maastrichtian, probably as a result of the climax of thermal subsidence combined with a global sea-level rise. Siliciclastic shallow marine facies are recorded in the Salado Basin (Chilcas Formation) and in the Colorado Basin (Pedro Luro Formation). To the east of northern Patagonia, two intracontinental rifts (the Valdés and Rawson Basins) received also shallow marine sediments related to the Pedro Luro transgression. To the northwest, the narrow Laboulaye and Macachín rifts were infilled with fluvial and lacustrine deposits (Mariano Boedo Formation).

As a result of an increase in the rate of convergence between the South American and the Pacific plates, a foreland tectonic phase started along most of the length of the retroarc. Large amounts of sediments were delivered to the Argentine Basins from the uplifted Andean chain. A generalized relative sea level rise resulted in connections of Andean Basins with the Atlantic Ocean. Therefore, the Late Cretaceous foreland stage in the Neuquén Basin is associated with shallow marine deposits of the Malargüe Group. The North Patagonian Platform was also dominated by this important transgressive (Atlantic) episode. Transgressive-regressive cycle deposits ranging from siliciclastic fluvial and lacustrine systems to mixed siliciclastic and carbonate shallow marine systems are recorded in north and central Patagonia (e.g., Puntudo Chico, Cerro Bororó, Paso del Sapo, Lefipán, Los Alamitos, Coli Toro, Arroyo Salado Formations). Toward the northeast, the North Patagonian platform was connected to the Colorado Basin.

In central Patagonia, the first plateau basalts, dated approximately 77–81 Ma, are interpreted as extensional back-arc lava flows. The San Jorge Basin is dominated by fluvial sedimentation (Upper Bajo Barreal, Laguna Palacios Formations), although ephemeral lacustrine, deltaic, and fluvial deposits developed toward the center of the depression (upper Yacimiento El Trébol and upper Meseta Espinosa Formations). The Bajo Grande shallow depression located toward the southeast just by the Deseado Massif border received coarse fluvial deposits of the Laguna Palacios Formation.

A general regressive phase is recorded in the Austral Basin, with a huge embayment toward its northwest corner. Fluvial sedimentation is represented by the Cerro Fortaleza, La Anita (La Irene Member), and Chorrillo Formations. To the south, these deposits are replaced by deltaic-estuarine clastics of the Calafate and La Anita Formations. Tidal-dominated coastal-nearshore deposits are documented in marginal areas of the basin (La Anita and upper Cerro Cazador Formations). Distal platform shales and mudstones (known as the "Arcillas Fragmentosas" or upper Cerro Cazador Formation) are widespread in most of the Austral and Western Malvinas Basins. Far south, the sinistral displacement along the Shackleton transform fault zone was active and stretched to southernmost Patagonia and the Antarctic Peninsula.

Final Remarks

The mutual influence between subduction along the western margin of Gondwana and intracontinental extension and opening of the southern Atlantic Ocean governed the evolution of the Mesozoic basins of Patagonia. They may be grouped in strike-slip depocenters, intracontinental rifts, taphrogenic basins, arc-related basins, and large and long-lived polihistory basins.

Intracontinental rifts, preferentially infilled with continental deposits, were formed during the Mesozoic as a response to different extensional processes. During the Triassic, several narrow and isolated depocenters (e.g., the El Tranquilo rift) were opened along a system of northwest-southeast fault inherited from the grain of the basement. During the Jurassic, as a result of the impact of the Karoo Plume and the opening of the Weddell Sea, central Patagonia was subjected to an extensional process and strike-slip movements along major transcurrent zones (Gastre and Deseado fault systems). The continental and volcaniclastic San Jorge and Cañadón Asfalto Basins resulted from this tectonic episode. During the Early Cretaceous, and as a consequence of the opening of the Atlantic Ocean, several elongated rifts were created. Some of them remained as isolated troughs (Valdés, Rawson); others were integrated, forming a long furrow that received continental deposition in north-central Patagonia (Macachín-Levalle and associated rifts).

Strike-slip tectonics affected Patagonia during different stages of the Mesozoic. Despite this, only a few depocenters were entirely related to this tectonic regime. Narrow "en echelon" depocenters located nearby the western margin of northern Patagonia formed during the Lower Triassic as a consequence of a transcurrent regime that precluded the development of the Andean Magmatic Arc. These basins are characterized by shallow marine and fluvial deposits. Some of them were short-lived depocenters, whereas others were lately assimilated to the wider and long-lived Neuquén Basin.

As the opening of the southern Atlantic Ocean proceeded, failed rift arms evolved as taphrogenic basins all along the Cretaceous. The main depocenters are the Salado and Colorado Basins located in the northeastern side of the studied region. These basins started as fault-controlled continental rifts and evolved to a mixed marine and continental sedimentation during the later sag stage.

Coevally with the growth of the Andean Magmatic Arc, a series of intra-arc and back-arc extensional basins related to subduction along western Patagonia were formed. Whereas the Río Mayo Basin was developed upon a continental basement, the Rocas Verdes Basin, located in southernmost Patagonia, was floored by oceanic crust. The intra-back-arc Pampa de Agnia Basin was formed in a more complex scenario that included arc-related extension and strike-slip tectonics along the Gastre fault system.

Two large depocenters characterized by a more complex evolution are recognized in Patagonia: the Neuquén Basin to the north and the Austral Basin to the south. Both basins started at different times during the Jurassic as a series of extensional troughs filled with volcaniclastic continental deposits. During the growth of the Andean Magmatic Arc, these basins passed through a back-arc stage, characterized by starvation and widespread marine sedimentation. Acceleration of plate convergence during the Late Cretaceous produced partial inversion and the development of a retroarc flexural stage, with a progressive change from marine- to continental-dominated sedimentation. All along the Cretaceous, the northeast margin of the Austral Basin remained as a stable marine platform facing the Weddell Sea and the newly opened Atlantic Ocean.

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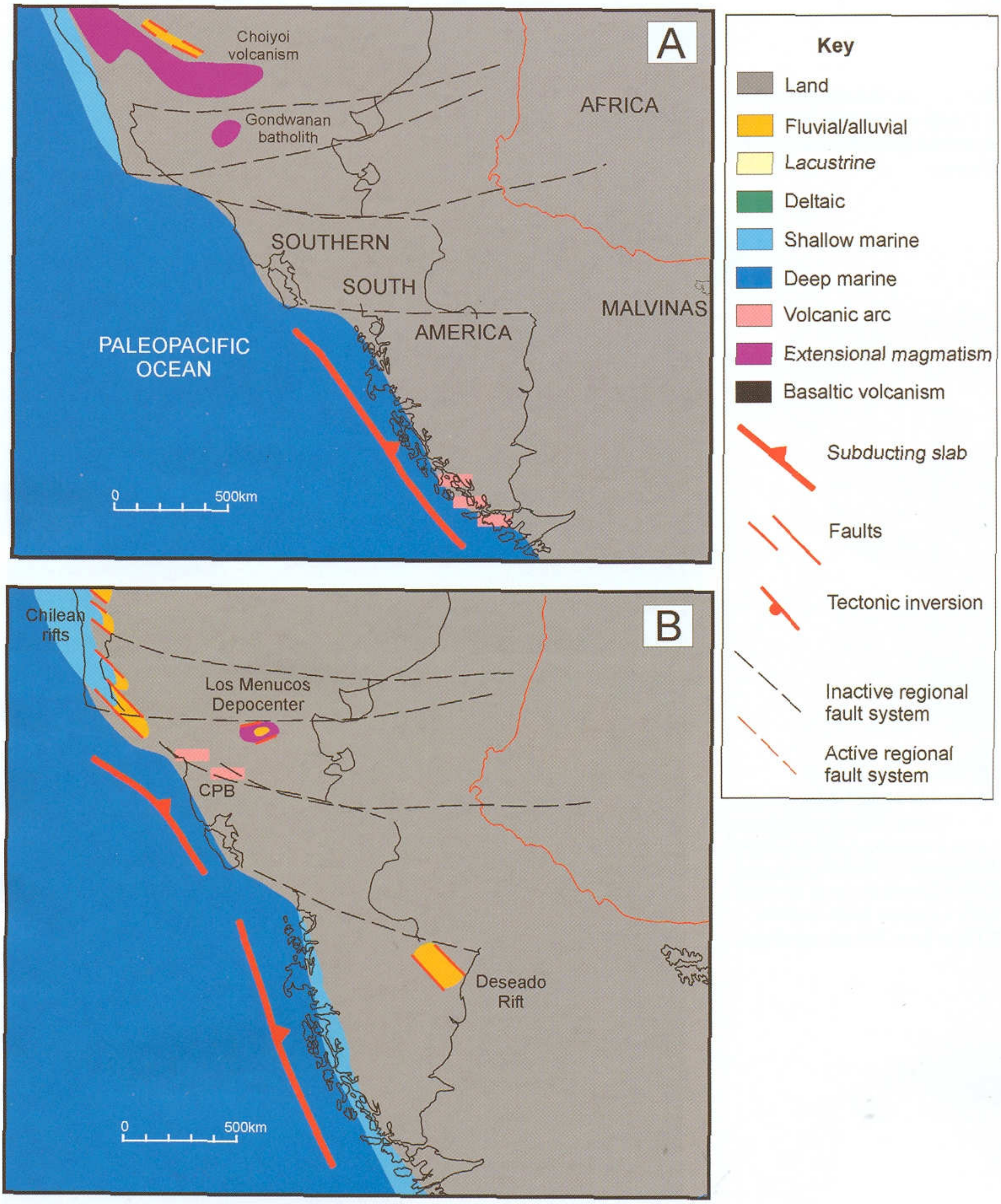
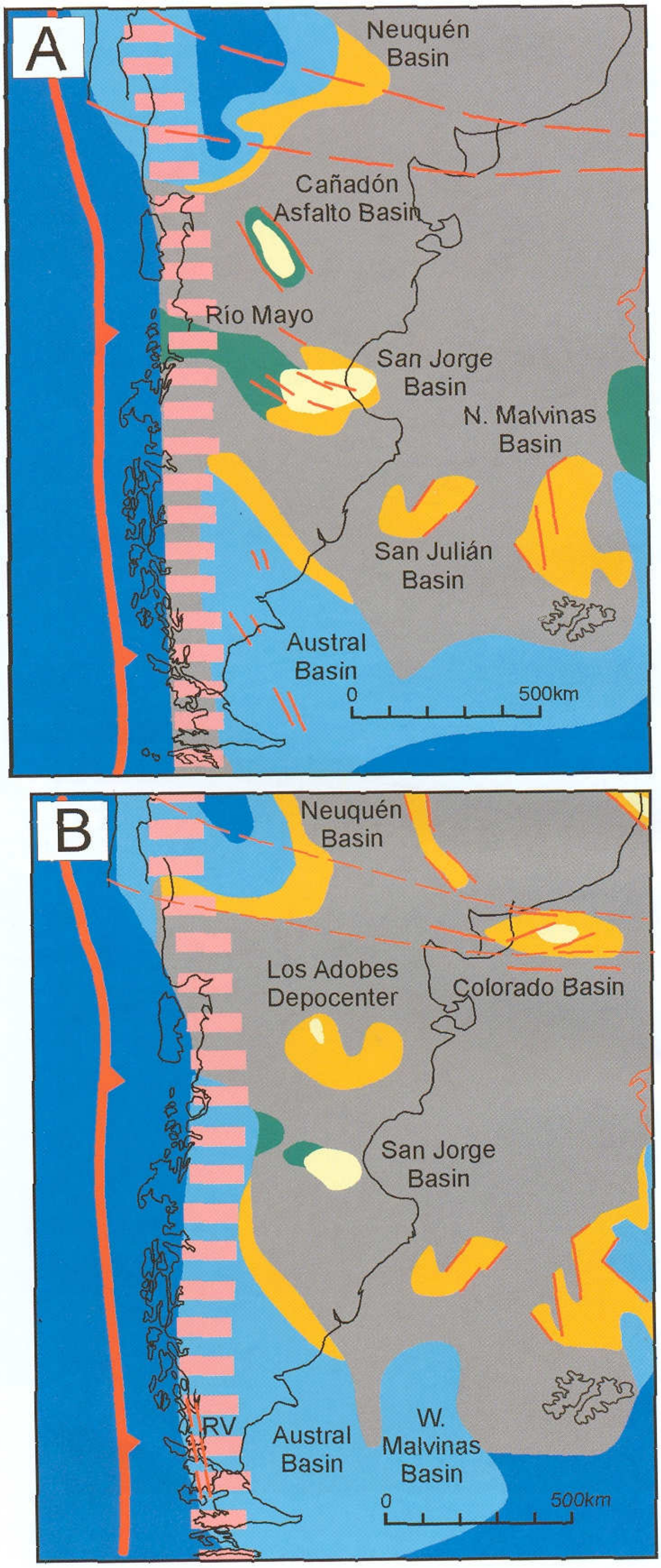


Plate 9. (A) Reconstruction of Patagonia at 240 Ma (Anisian-Ladinian, Middle Triassic). (B) Reconstruction of Patagonia at 225 Ma (Carnian–Early Norian, Late Triassic). CPB = Central Patagonia batholith.

Plate 12. (A) Reconstruction of Patagonia at 150 Ma (Kimmerigian-Thitonian, Late Jurassic).

(B) Reconstruction of Patagonia at 135 Ma (Valanginian-Hauterivian, Early Cretaceous).



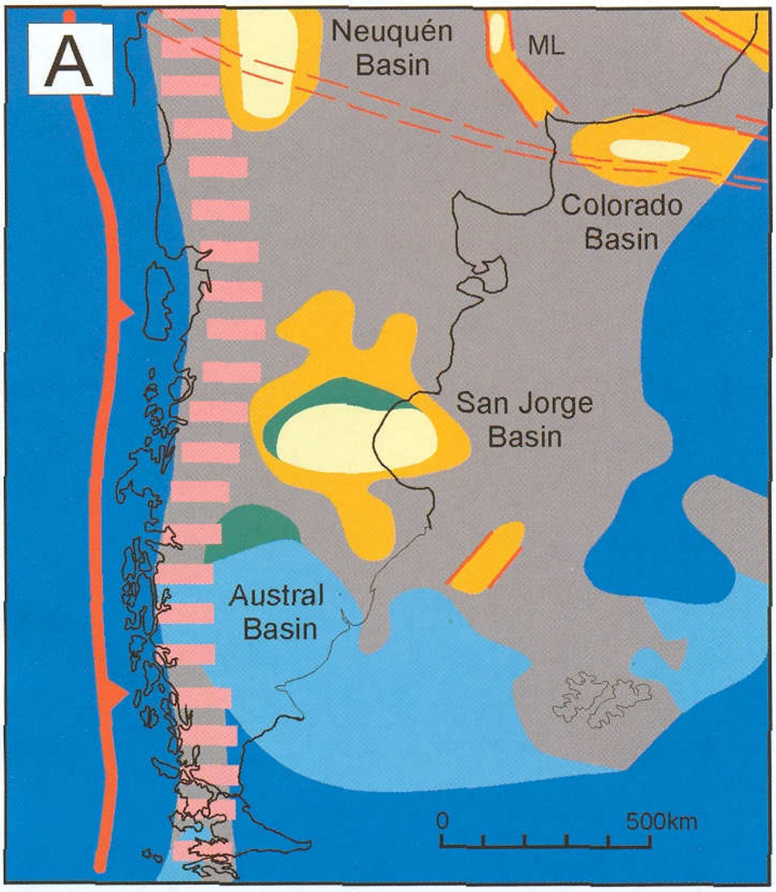
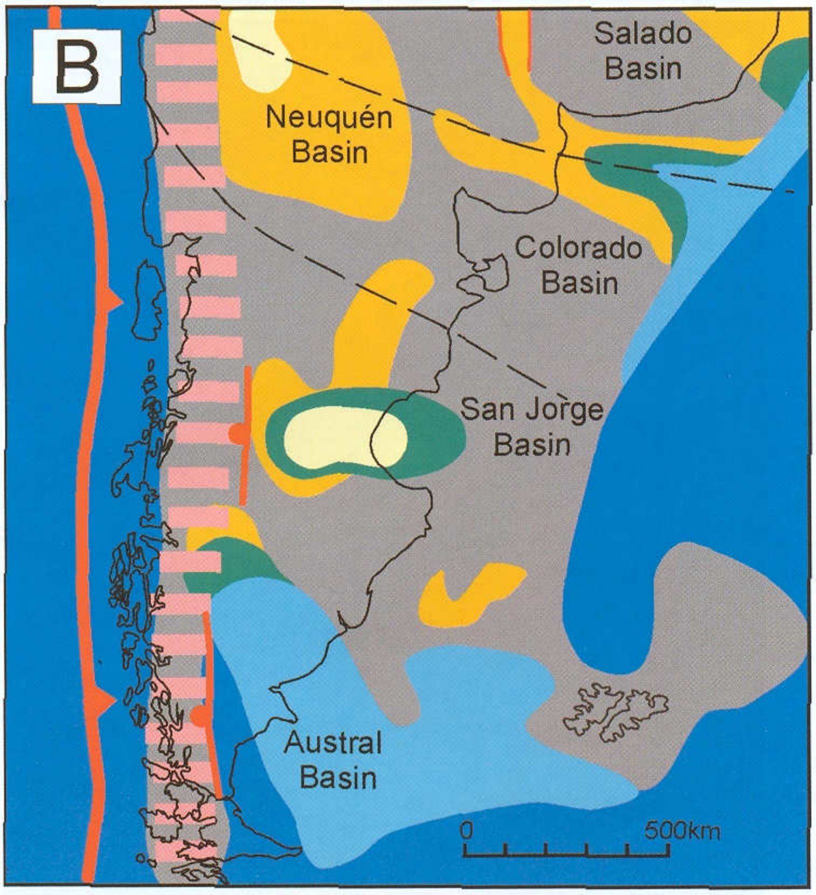
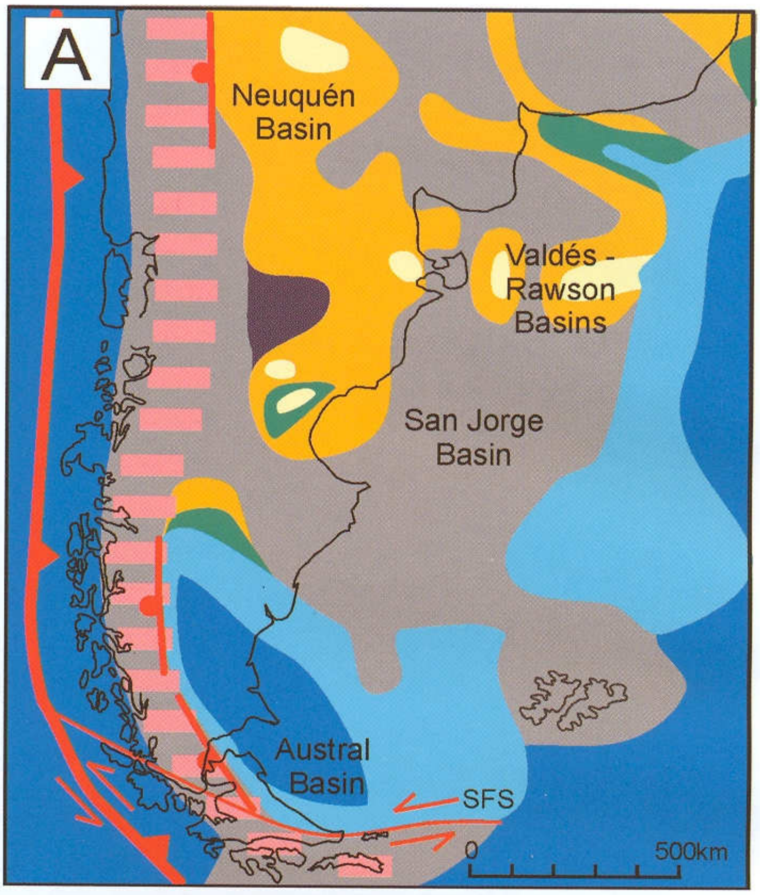


Plate 13. (A) Reconstruction of Patagonia at 120 Ma (Aptian, Early Cretaceous).

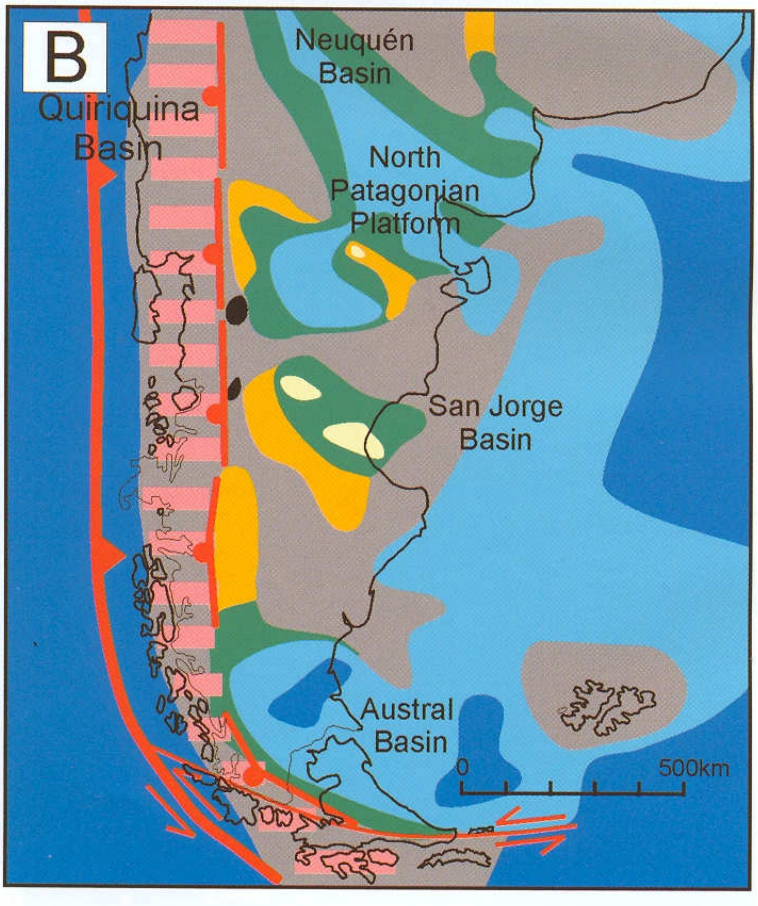


(B) Reconstruction of Patagonia at 105 Ma (Albian, *Early Cretaceous*).
ML = Macachín-Laboulaye rifts.°

Plate 14. (A) Reconstruction of Patagonia at 90 Ma (Cenomanian-Turonian, Late Cretaceous). SFS = Shackleton Fault System.



(B) Reconstruction of Patagonia at 75 Ma (Campanian-Maastrichtian, Late Cretaceous).



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