Pergamon

Journal of South American Earth Sciences, Vol. 10, Nos. 5-6, pp. 389-402, 1997

Printed in Great Britain
0895-9811/98 $19.00 +0.00

PII:S0895-9811(97)00028-X

Late Paleozoic transpression in Buenos Aires and northeast Patagonia ranges, Argentina

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Abstract — Paleozoic sediments are present in three regions in eastern central Argentina: (1) the Sierras Australes of Buenos Aires, (2) Sierras Septentrionales of Buenos Aires and (3) Northeast Patagonia. All of these deposits share a common deformational imprint imparted by late Paleozoic Gondwanan deformation. Exposures of these rocks are scattered, variably deformed, and isolated by younger sediments deposited in basins related to the Mesozoic through Tertiary opening of the South Atlantic such as the offshore Colorado Basin.

The Sierras Australes of Buenos Aires outcrops are the best preserved. They are mostly located along the Sierras Australes foldbelt, with minor outliers distributed in the adjacent Claromec-basin. The Tunas Formation (early-early late? Permian) is the uppermost unit of the Pillahuincó Group (late Carboniferous-Permian) and is crucial to the understanding of the tectono-sedimentary evolution of the region during the late Paleozoic. The underlying units of the Pillahuincó Group (Sauce Grande, Piedra Azul and Bonete Formations) exhibit a depositional and compositional history characterized by glaciomarine sedimentation and postglacial transgression. They are also characterized by rather uniform quartz-rich compositions indicative of a cratonic provenance from the La Plata craton to the NE. In contrast, the sandstone-rich Tunas Formation has low quartz contents, and abundant volcanic and metasedimentary fragments; paleocurrents are consistently from the SW. Glass-rich tuffs are interbedded with sandstone in the upper half of the Tunas Formation.

The age of the deformation in the Sierras Australes is Permian and early-middle Triassic. This is based on metamorphic events indicated by formation of illite at 282 ± 3 Ma, 273 ± 8 Ma, 265 ± 3 Ma, and 260 ± 3 Ma (K/Ar illite) in the Silurian Curamalal Group. Evidence of syntectonic magmatism is provided by a radiometric date of 245 ± 12 Ma (K/Ar hornblende) for the López Lecube Granite, immediately west of the Sierras Australes.

In the Sierras Septentrionales of Buenos Aires, Precambrian through early Paleozoic deposits of La Tinta, Sierras Bayas, Las Aguilas and Balcarce Formations rest on Precambrian crystalline basement of the La Plata craton. These exposed rocks are affected by subordinate, right lateral wrench faulting; some thrusting indicates tectonic transport toward the NE.

In northeast Patagonia (Sierra Grande region) synkinematic deformation of early Permian (261 ± 5 Ma, Rb/Sr whole rock) age has been identified in Silurian metasediments of the Sierra Grande Formation. Bands of deformation in Sierra Grande quartzites indicate right lateral wrenching in a N-S direction. Contraction in a NE-SW direction is evidenced by folding.

Three stages of tectonic evolution can be discerned for the above regions: (1) Early Paleozoic platform sedimentation, punctuated by episodes of accelerated subsidence during the Silurian and early Devonian, as shown by transgressive episodes, (2) late Paleozoic sedimentation and deformation, and (3) Meso-Cenozoic extensional inversion due to the South Atlantic opening. The late Paleozoic sedimentation and deformation (stage 2) includes late Carboniferous-earliest Permian glacial deposits of the Sierras Australes and Colorado offshore basin, deposited during an initial phase of extension, and cratonward foreland subsidence triggered sedimentation of the synorogenic deposits of the Permian Tunas Formation. Tuffs are intercalated in the upper half of this unit. These tuffs are associated with the silicic volcanism along the Andes and Patagonia (Choiyoi magmatic province) that peaked between the late early Permian and late Permian. Likewise, the first widespread appearance of tuffs in the Karoo basin is in the Whitehill Formation, of late early Permian (260 Ma) age.

The deformation described in this paper can be considered as part of a large scale intracontinental deformation in SW Gondwanaland inboard of an Andean-type compressive margin. This deformation is characterized by transpression (right lateral wrenching) combined with overthrusting to the NE and N-S horizontal contraction.

Resumen — Sobre el margen atlántico de Argentina central existen 3 regiones con afloramientos sedimentarios paleozoicos: 1) Sierras Australes de Buenos Aires; 2) Sierras Septentrionales de Buenos Aires y 3) Patagonia Nororiental. Estos afloramientos poseen un estilo tectónico común impreso por la deformación neopaleozoica gondwánica, aunque actualmente están aislados por sedimentos depositados en cuencas meso-cenozoicas relacionadas con la apertura del Atlántico Sur.

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Los afloramientos de las Sierras Australes son los mejores preservados. La Fm. Tunas (Pérmico temprano a tardío temprano) es la unidad superior del Grupo Pillahuincó (Carbonífero superior-Pérmico) y crucial para la comprensión de la evolución tectono-sedimentaria de la región durante el Paleozoico superior. Las unidades infrayacentes (formaciones Sauce Grande, Piedra Azul y Bonete) exhiben una historia depositacional y composicional caracterizada por una sedimentación glaciomarina con una transgresión postglacial con una composición rica en cuarzo bastante uniforme indicativa de una proveniencia desde el Cratón La Plata hacia el NE. En contrastre, la Fm. Tunas, tiene bajos contenidos de cuarzo y abundantes fragmentos volcánicos y metasedimentarios con intercalaciones de niveles tobáceos ricos en vidrio. Las paleocorrientes provienen desde el SO. La edad de la deformación en las Sierras Australes está comprendida entre el Pérmico y Triásico temprano a medio y está basada en eventos metamórficos reconocidos por la generación de illita en metasedimentitas del Grupo Curamalal (Silúrico) cuyas edades son 282 ± 3 Ma, 273 ± 8 Ma, 265 ± 3 Ma y 260 ± 3 Ma (K/Ar). El Granito López Lecube datado en 245 ± 12 Ma (K/Ar hornblenda) evidencia un magmatismo sin a postectónico.

En las Sierras Septentrionales de Buenos Aires, depósitos sedimentarios precámbricos a paleozoicos inferiores (formaciones La Tinta, Sierras Bayas, Las Aguilas y Balcarce) descansan sobre el basamento cristalino precámbrico (Cratón La Plata). Estas rocas acusan fallamientos transcurrentes dextrales con componentes cabalgantes que indican un transporte tectónico hacia el NE.

En la Patagonia Nororiental se identificó una deformación sintectónica pérmica temprana (261 ± 5 Ma, Rb/Sr, roca total) a partir de metasedimentos silúricos de la Fm. Sierra Grande, donde se indican acortamientos sublatitudinales a partir de bandas de deformación transcurrentes dextrales y plegamientos dispuestos submeridianalmente.

Se pueden reconocer dos grandes estadios dentro de la evolución paleozoica tectonosedimentaria de las regiones consideradas: i) plataforma paleozoica temprana asociada a una subsidencia acelerada evidenciada por transgresiones silúricas a devónicas tempranas; ii) sedimentación y deformación paleozoica tardía con depósitos glaciares carboníferos a pérmicos tempranos de las Sierras Australes y la cuenca del Colorado vinculados como una fase inicial de extensión. La subsidencia hacia el antepaís controló la sedimentación sinorogénica de la Fm. Tunas con tobas intercaladas en su mitad superior que pueden ser comparadas con las de la Fm. Whitehill de la cuenca Karoo asignada al Pérmico (260 Ma). Estas tobas están asociadas con el vulcanismo silícico de la provincia magmática Choiyoi de los Andes y Patagonia que se focaliza entre el Pérmico temprano y el tardío.

La deformación descripta en el presente trabajo puede considerarse como parte de una deformación compresiva de tipo andina mayor intracontinental del flanco sudoccidental de Gondwana, caracterizada por transpresión dextral combinada con cabalgamientos hacia el NE con acortamientos horizontales sublatitudinales.

INTRODUCTION

Argentina's central Atlantic coast preserves only three areas with Paleozoic sedimentation and deformation: Sierras Australes of Buenos Aires, Sierras Septentrionales of Buenos Aires, and northeast Patagonia (Fig. 1). These outcrops are isolated in highlands between important Cretaceous-Tertiary extensional basins, such as the Colorado Basin (Zambrano, 1974; Rolleri, 1975; Uliana *et al.*, 1989).

Due to the quality of the outcrops, their location, their well established ages, and the geometry of deformation in the Sierras Australes de Buenos Aires (Cobbold *et al.*, 1991; Buggisch, 1987; Von Gosen *et al.*, 1991; etc.), the Sierras Australes of Buenos Aires constitute a critical element in the study of the South American margin of the Gondwana continent. Structural and sedimentological information can.be extrapolated to the neighboring areas of Sierras Septentrionales and northeast Patagonia, where these aspects of the geological record are covered or poorly documented.

In this work, an integrated structural correlation and Neopaleozoic tectonic interpretation for the three areas is attempted. First, the structure and stratigraphy of the Sierras Australes of Buenos Aires will be reviewed, followed by new observations for the Sierras Septentrionales and northeast Patagonia. Finally, an integrated tectono-sedimentary model will be presented within the framework of the Gondwana continent.

THE SIERRAS AUSTRALES OF BUENOS AIRES

The stratigraphy of the Sierras Australes of Buenos Aires has been described by Harrington (1947, 1980) and by later researchers (e.g., Japas, 1989; Sellés Martínez, 1989; Von Gosen and Buggisch, 1989; Von Gosen *et al.*, 1990; Von Gosen *et al.*, 1991; Cobbold *et al.*, 1991). The description of the Tunas Formation, the youngest unit of the late Carboniferous-Permian Pillahuincó group, will be emphasized since it is associated with the most intense Neopaleozoic compressive events.

The Tunas Formation is a sandstone-rich unit of early to early late (?) Permian age. Sandy portions in the youngest part of the sequence are lower in quartz, and contain higher percentages of feldspar (mainly plagioclase) and lithics (volcanics), than the quartz-rich sandstones of the underlying Sauce Grande, Piedra Azul, and Bonete Formations. This compositional change, which is associated with a reveral of paleocurrent directions and an increase in the grain size upsection, indicates a reactivation of provenance terrains located to the SW. The presence of growth folds (Cobbold *et al.*, 1991; Rossello *et al.*, 1993), indicate that the deformation was, at least in part, contemporaneous with sedimentation. This is in agreement with Permian radiometric ages of tuff horizons from similar levels of equivalent units of the Paraná and Karoo Basins (Visser, 1987; López-Gamundí *et al.*, 1995), and Malvinas-Falkland islands (Marshall, 1994; López-Gamundí and Rossello, 1995). These units constitute the "Samfrau Geosyncline" of Du Toit (1927), along with correlative units from Patagonia and possibly Western Antarctica. The presence of growth folds and the coexistence of magmatism and metamorphism in the early Permian support this observation.

The Sierras Australes of Buenos Aires have a structure typical of a sigmoidal fold and thrust belt (Ramos, 1984;

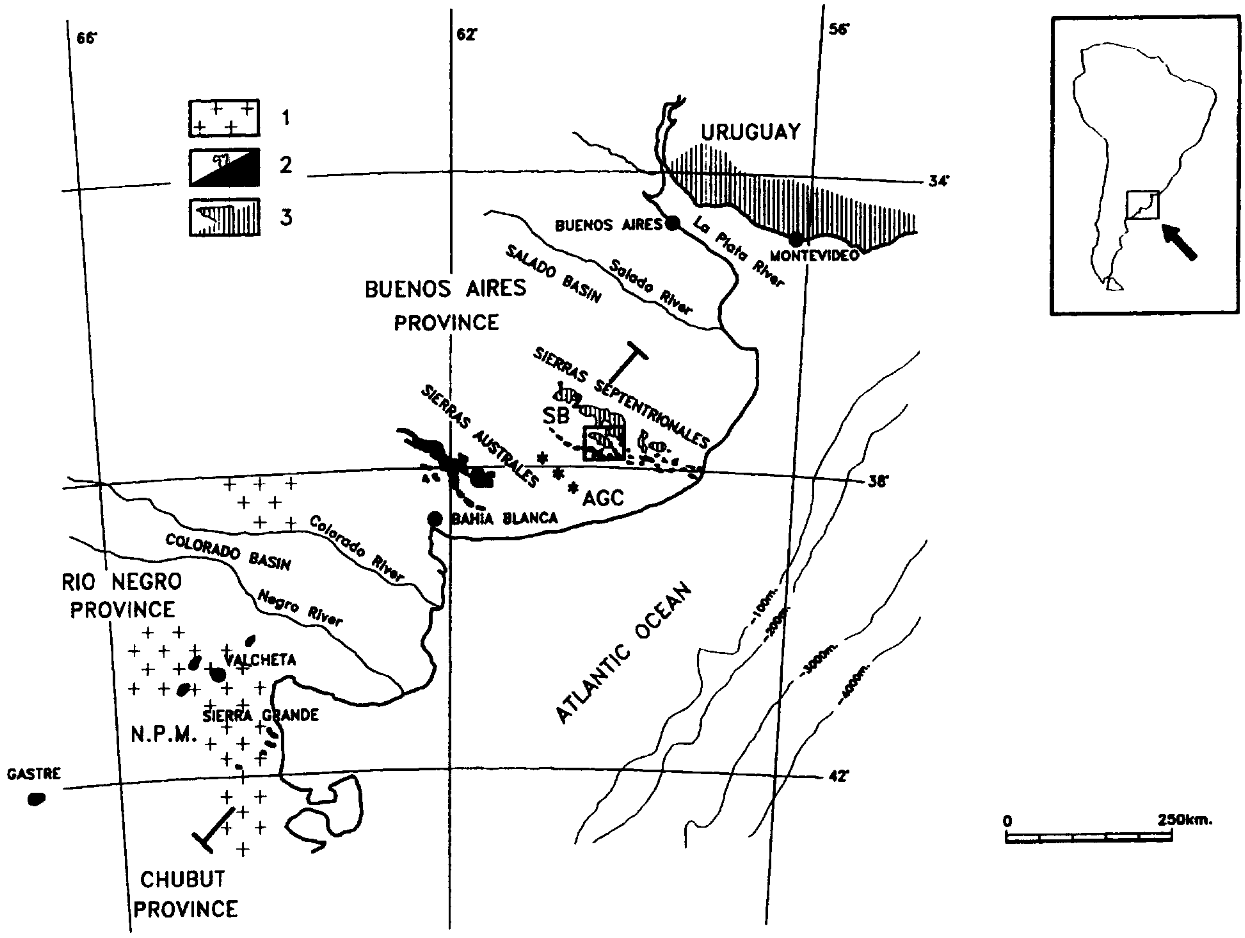

Fig. 1. An geological outline of the centro-Atlantic portion of Argentina with the location of Sierras Australes, Sierras Septentrionales and Northeast Patagonia (Nord Patagonic Massif: **NPM**). Main outcrops of the González Cháves High (**AGC**) which are identified with asterisks (De la Garma, Mariano Roldán, González Chaves and Lumb). **1** indicates the position of the Loma Negra quarry and **2** the position of the LOSA quarry. The quadrate identified with **SB** in Sierras Septentrionales locates Fig. 2. 1: Paleozoic plutonism; 2: sedimentary cover (Precambrian in Sierras Septentrionales, early Paleozoic in Northeast Patagonia and Silurian-Neopaleozoic in Sierras Australes and 3: Precambrian crystalline basement. The position of the sections in Fig. 5, are indicated.

Cobbold *et al.*, 1991) showing a clear and progressive fading of the deformation towards the NE and E (Fig. 2). Harrington (1970), by means of cross-sections, demonstrated this decrease in structural complexity, passing from very tight folds with NE vergence to more open concentric folds (Cobbold *et al.*, 1986, 1991; Japas, 1989). The Pillahuincó Group, near Coronel Suárez city, its base extended on the continental margin and the platform of the Argentine sea, is illustrated in Fig. 1. The regional shape of the outcrops is remarkably triangular, and elongated in the NW–SE direction, parallel to the Sierras Australes and the Sierras Septentrionales ranges, with its base extending towards the Argentine sea platform where it constitutes the "technical basement" of the Colorado Basin (Yrigoyen, 1975; Zambrano, 1980; Frylund *et al.*, 1996).

Towards the the east, the last outcrops of the Sierras Australes dip gradually into the Interserrana or Claromecó Basin (López-Gamundí and Rossello, 1992), where they are covered by Pampean loess; to the west, they dip into the Macachín Basin (Salso, 1966). Some shallow drilling carried out in the surrounding plains detected consolidated rock of Sierras Australes affinity (Harrington, 1970; Zambrano, 1974; Llambías and Prozzi, 1975; Rolleri, 1975). Magnetometric and gravimetric studies (e.g., Kostadinoff, 1993) reveal a deepening of the basement towards the east, although some 80 km away in the same direction it crops out again in the González Chávez, Lumb, Mariano Roldán and De la Garma localities (Harrington, 1970; Terraza and Deguillén, 1973) along the González Chávez High (AGCh in Fig. 1). These different exposures are considered to be parts of a single, major, undulating outcrop, which exposes the older lithologies in the crests, partially covered with modern sediments cemented by epigenic carbonate (*tosca*). From Laprida to the east it deepens regionally, to such extent that in Necochea it reaches a depth of 200 m. Furque (1965), suggested a distribution for these outcrops along a N–NNW/S–SSE line and at a constant distance of the outcrop lines of the Sierras Septentrionales.

Based on their fossil flora and their mineralogic and petrographic features, these rocks may be correlated with the Pillahuincó Group (Llambías and Prozzi, 1975; Terraza and Deguillén, 1973; Arrondo *et al.*, 1982; Andreis

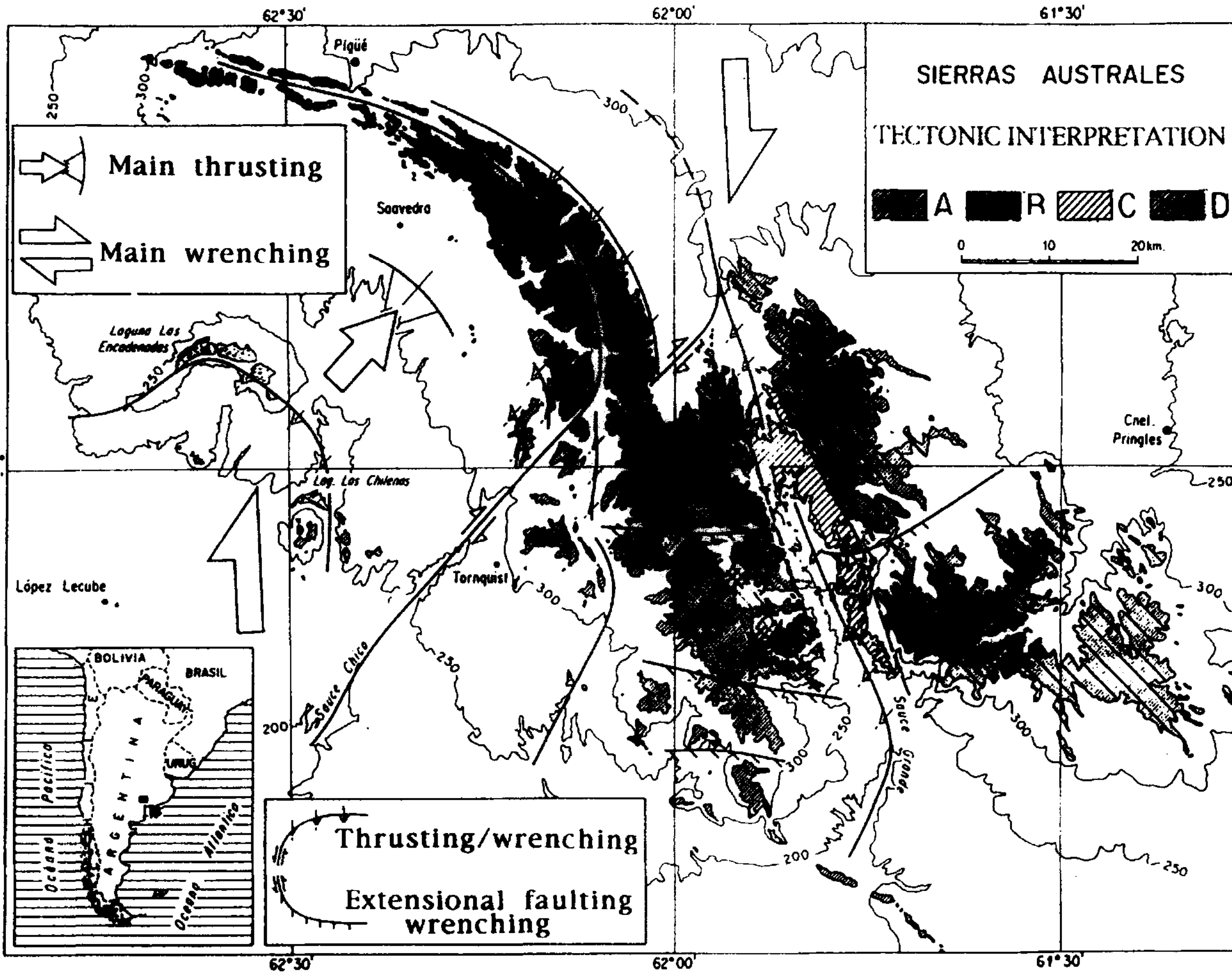

Fig. 2. Geologic map and tectonic interpretation of the Sierras Australes of Buenos Aires. A) Sandstones and quartzites of Curamalal and Ventana Groups; B) Lolén Fm.; C) Sauce Grande Fm., and D) Piedra Azul, Bonete and Tunas Fms. (adapted from Cobbold *et al.*, 1986).

et al. 1987). Ramos (1984); López-Gamundí and Rossello (1992) considered these deposits to be part of the Claromecó foreland basin, which can be correlated with thick Neopaleozoic deposits of the present marine platform, and which constitute part of the tectonic basement of the Colorado Basin (Zambrano, 1974, 1980; Urien, 1981; Arrondo *et al.*, 1982; Andreis *et al.*, 1987). An incipient cleavage, separated by centimeters, oriented N134/150°, subvertical at 84° NE has been recognized in some of these outcrops. Drilling carried out on the marine continental platform and extending south from the Sierras Australes, has demonstrated the presence of Paleozoic rocks related to those of the Sierras Australes. Several wells, particularly the YPF Puelches (59° 18'W and 40° 39'S), have gone through about 250 m (corrected by dip) of black shale interbedded with thin layers of siltstones and sandstones attributed to the Pillahuincó Group (Archangelsky and Gamerro, 1979; Zambrano, 1980; Mainardi *et al.*, 1979; Lesta *et al.*, 1980; Andreis *et al.*, 1987; Archangelsky, 1996). On the other side, Zambrano (1974); Mainardi *et al.* (1979), based on the seismic surveys carried out by YPF, Phillips, and Hunt oil companies, indicate the presence of Upper Paleozoic sediments under the angular unconformity which marks the Cretaceous-Tertiary filling of the Colorado Basin (Frylund *et al.*, 1996). Regarding the age of the main structure of the Sierras Australes, the growth folds of the Tunas Formation show that deposition was contemporaneous with development of a mountain front to the west (López-Gamundí and Rossello, 1992).

Based on these correlations, and data from the Cape Belt (South Africa), the Tunas Formation can be considered to have been deposited at least in part contemporaneously with the compressive event dated at 258 ± 2 Ma (2nd paroxysm or Outeniqua folding of Hälbich *et al.*, 1983). The development of metamorphism (probably late–early Permian) in the westernmost portion of the Sierras Australes (Varela *et al.*, 1985; Buggisch, 1987) can be connected to the deformation phase of similar age, as shown by the isotopic reequilibration of Proterozoic phyllites and graywackes exposed on the interior basement in Capetown (Gresse *et al.*, 1992).

Investigations of illite crystallinity (using the Weaver and Kubler indexes, Lluch, 1976) and clay minerallogy demonstrate that metamorphism and diagenesis is less intense along the eastern margin (Andreis *et al.*, 1989; Cobbold *et al.*, 1991; Zabala *et al.*, 1995; etc.). Illite crystallinity increases to the west, along with dynamometamorphic transformations. Sediments of the Silurian

Curamalal Group show sintaxial growth, wavy extinction, and in some cases with intracrystalline deformations and clast rotation, under greenschist facies metamorphism. Sediments of the Pillahuincó Group show little or no textural changes (the clastic limits are preserved).

Metamorphic illites developed along cleavage planes related to this deformation (Buggisch, 1987; Von Gossen *et al.*, 1991) render K/Ar ages of 273 ± 8 Ma, 265 ± 32 Ma, and between 260 ± 3 Ma and 282 ± 3 Ma (Varela *et al.*, 1985; Buggisch, 1987). The syntectonic López Lecube Granite has an intrusion age of 245 ± 12 Ma (K/Ar hornblende; Llambías *et al.*, 1976) or 227 ± 32 Ma (Rb/Sr whole rock; Cingolani and Varela, 1973). On the other hand, rhyolites of the La Hermita and La Mascota Formations rendered ages of 317 to 348 Ma by Rb/Sr of whole rock (Varela, 1973) and 221 ± 6 Ma and 249 ± 8 Ma (Varela and Cingolani, 1975; Varela *et al.*, 1990).

These ages demonstrate that since the beginning of sedimentation of the Pillahuincó Group during the late Carboniferous (Sauce Grande Formation), a new tectonosedimentary cycle started which culminated with the syntectonic sedimentation represented by the upper half of the Tunas Formation (Kungurian-Kazanian) and according to paleomagnetic evidence it is pre-Tartarian (López-Gamundí *et al.*, 1995).

THE SIERRAS SEPTENTRIONALES OF BUENOS AIRES

The Sierras Septentrionales of Buenos Aires extend over 300 km, trending NW–SE from Mar del Plata to Quillalauquén, with highs between 50 and 315 m above sea level (Fig. 1). A topographic cross-section shows a rather steep escarpment towards the NE border named *Costa de Heuser* by Nágera (1919, in Teruggi and Killmurray, 1980), and a SW border showing a landscape of gentle hills that deepen into the modern sediments (named *Costa de Claraz*). In the central zone, this scheme is duplicated by the existence of a depression between the Tandil Block and the Sierra de la Tinta, with smooth slopes to the SW and a steep front to the NE.

There are several recent works summarizing the geology of the Sierras Septentrionales (e.g., Teruggi and Killmurray, 1980; Dalla-Salda *et al.*, 1988; Iñíguez *et al.*, 1989), although early descriptions of Paleozoic compressive structures have not been substantially enlarged (Nágera, 1919; Schiller, 1930, 1938; Harrington, 1940). Recently, Massabie (1993); Massabie *et al.* (1992) note the presence of wrench tectonics in the Precambrian crystalline basement (La Plata Craton), 150 m of quartzites, dolomites, illite shales, black and red limestones, and marls attributed to the upper Precambrian (La Tinta, Sierras Bayas and Las Aguilas formations), and quartzites of the Balcarce Formation, considered Ordovician (Zalba *et al.*, 1988). The Balcarce Formation is separated from the Precambrian rocks by a regional uncorformity (Zalba *et al.*, 1988).

The Balcarce Formation comprises about 90 m of orthoquartzites and oligomictic orthoconglomerates with scarce, thin pelitic horizons showing a wide dispersion of paleocurrent directions from east to southwest, with a predominance of SSW orientations (Zalba *et al.*, 1988). The Balcarce Formation contains abundant organic structures of the epichnia type corresponding to *Didymaulichnus*, and a wide association of ichnofossils belonging to the *Cruziana* and *Skolithos* biofacies, which allows correlation with similar deposits of this area and suggests an (early?) Ordovician age. This age is limited by the presence of diabase dikes with ages from 450 to 490 Ma (Rapela *et al.*, 1974).

A description of three key areas which preserve kinematic structural relations shows that sediments covering the La Plata Craton were affected by transpressive tectonics prior to the development and filling of the Cretaceous-Tertiary Colorado and Salado basins:

1) Cuchilla de las Aguilas hills (Bárker): Leveratto and Marchese (1983), Manassero (1988); Zalba *et al.* (1988) surveyed faults with WNW–ESE strikes similar to those in the Sierra de la Tinta, Cuchilla de las Aguilas, and Arroyo Calaveras (Fig. 3). All of these structures present their downthrown side to the NE. Structural studies carried out in the Cuchilla de las Aguilas support a thrusting behaviour (Fig. 4). This is also supported by evidence from old kaolin mines (Fig. 5), where kinematic indicators have been found suggesting a direction of tectonic transportation towards the NE.
2) Loma Negra quarry (Sierras Bayas): Massabie *et al.* (1992) have determined that transcurrent faulting occurred on a sequence of La Tinta Formation, which crops out homoclinally in a quarry about 15° to the SW. These rocks show tectonically induced pelitic diapirs (Fig. 6) associated with two subvertical fault sets with a strike of N290° and N320°. The last one cuts the first one and shows a larger extent and relevance. Nágera (1919) provides excellent examples of compressive structures in the Providencia, Mina de la Pintura, and Boca de la Sierra quarries. Also, González Bonorino (1954) surveyed major folds with their axes oriented ESE–WNW and faults with homologous arrangements.
3) LOSA quarry (Sierras Bayas): Codignotto (1969) describes faulting in the LOSA quarry as a scissor-type fault. Later studies (Massabie, 1993) indicate a N130° strike, subvertical, and with a main dextral displacement associated with reverse faults (Fig. 7).

NORTHEAST PATAGONIA

In northeast Patagonia (Northpatagonian Massif), several isolated outcrops of silici-clastic sediments have been recognized that can be correlated to the Sierra Grande Formation (Fig. 1). The Sierra Grande Formation (Stipanicic and Methol, 1980), with a thickness varying between 900 and 1100 m, is located near the town of Sierra Grande, next to the margin of the San

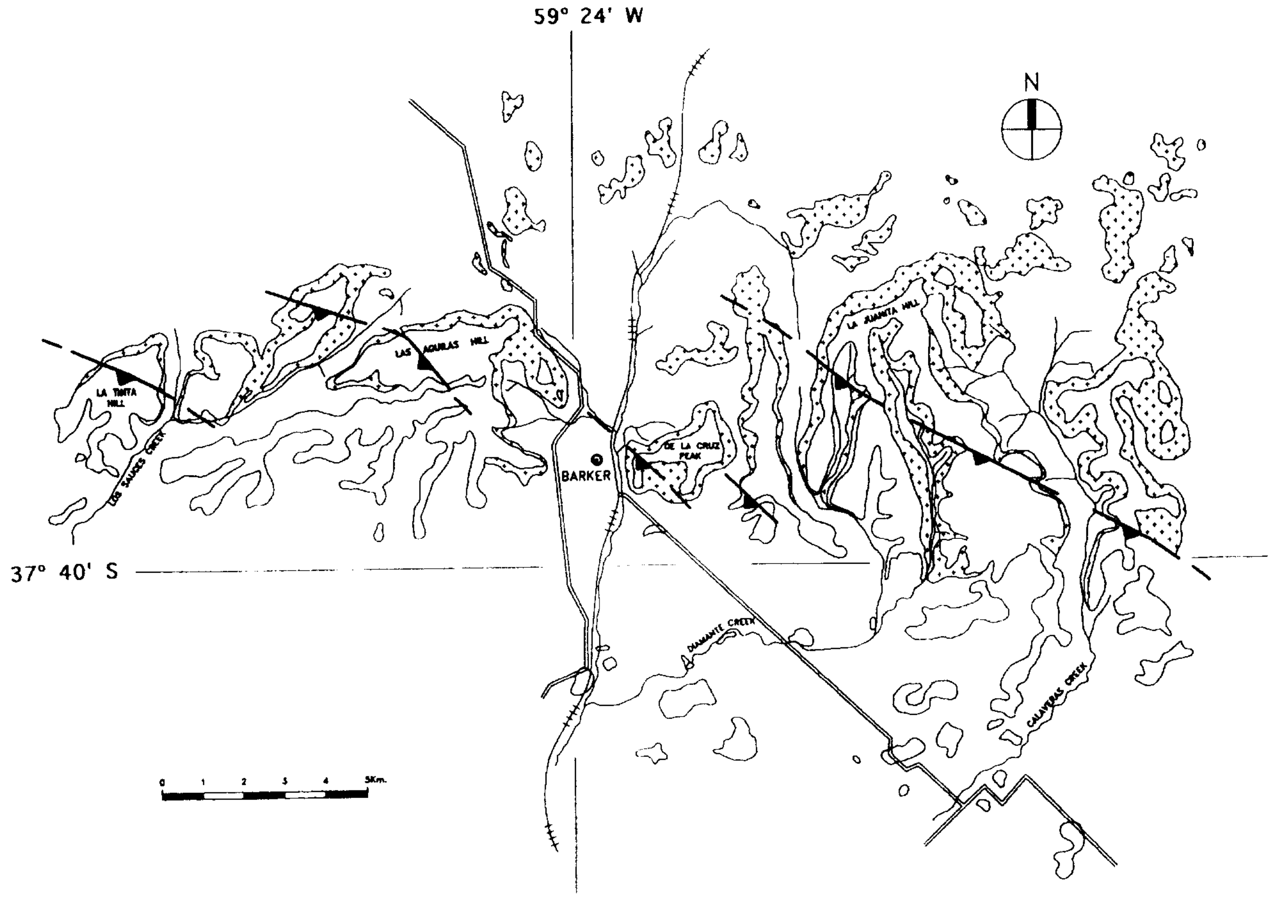

Fig. 3. Simplified geologic map of the Bárker area in the Sierras Septentrionales of Buenos Aires (adapted from Leveratto and Marchese, 1983; Manassero, 1988; Zalba *et al.*, 1988). Outcrops areas with crosses indicate Precambrian crystalline basement, dashed areas Precambrian and Eopaleozoic sedimentites and clear modern sedimentary cover. The position of some thrusts with dextral transpressive and NE vergence are shown.

Matías Gulf (Punta Pozos and Punta Sierra capes), on the border between the Provinces of Rio Negro and Chubut (Fig. 8). Manceñido and Damborenea (1984) mention a sedimentation cycle beginning in the Silurian and possibly reaching the early Devonian. The age of the Sierra Grande Formation can be determined by correlation with radiometrically dated igneous units. Thus, the Sierra Grande Formation was deposited unconformably on the Isla de los Pájaros or Punta Sierra Formation (450 Ma, K/Ar, Núñez *et al.*, 1975) prior to the intrusion of the Sierra Grande Granite dated as early Permian (261 ± 5 Ma, Rb/Sr, Halpern, 1972). These Eopaleozoic and Mesopaleozoic elements allow both lithostratigraphical and environmental correlation with the Curamalal group of the Sierras Australes of Buenos Aires (Cuerda, 1971).

Northwest from Sierra Grande, in sites located near the Valcheta, Rincón del Salado, and Las Salinas del Gualicho areas (Cortés *et al.*, 1984), other outcrops have been recognized, some as large as the above-mentioned but less thick and, in general, more poorly exposed. These units have not rendered fossils, but their lithological resemblance and stratigraphic relations (quartzitic benches unconformable over the plutonic basement), associate them tentatively with the Sierra Grande Formation. In Gastre, the presence of dikes from the Permian Lipetrén Formation within orthoquarzites of the Gudiño Formation show that these sediments are pre-Permian in age (Cortés *et al.*, 1984).

The Sierra Grande Formation, in its type locality, presents folds more than 5 km of extent and a variable wave-length of 1 to 5 km (Zanettini, 1981). Their axes are oriented N or NNW, dipping preferably to the south and southeast. In the Lomas de Manocchio (Fig 8), some deformation bands developed on quartzitic benches have been described showing kinematic features indicating dextral transcurrent components. The axial planes dip to the east and east-northeast. Ramos, and Cortés (1984) interpreted thrust faults dipping to the east. Although the type of deformation for the rest of the outcrops is not known in detail, the Sierra Grande Granite shows synkinematic structural features.

INTEGRATED MODEL OF PALEOZOIC TECTONIC EVOLUTION

This section will be divided into the following sections: (1) Early Paleozoic Platform; (2) Neopaleozoic deformation event and syntectonic sedimentation; (3) Later inversion (Fig. 9).

A

Fig. 4. A submeridianal panoramic view of the quartzites of the La Tinta Fm. west of Los Sauces creek and Cuchilla de las Aguilas hill (La Tinta hill, Fig. 3), which shows a northeast vergin thrust with a decametric vertical displacement (arrows over the horizon), and in a first plane some sedimentites with folding parallel to the thrust.

Fig. 5. Striae detail plunging 40°/185°, formed over fault slickensides of thrust shown in Photograph A which is exposed in the old kaolin mine localized at the northern top of Cuchilla de las Aguilas hill (Fig. 3).

(1) Early Paleozoic Platform: Early Paleozoic sedimentation in the areas studied began with a transgression over the extensive platform of the La Plata Craton, due to a general subsidence. This transgressive event was characterized by the settling of wide, shallow, and stable platforms (Curamalal Group, Sierra Grande Formation, and Balcarce Formation), increasing both their vertical and horizontal development towards the S and SE. The absence of Silurian or Devonian granitic belts in this portion of the South American paleomargin suggest that the subduction processes were not very active, although Dalla-Salda *et al.* (1993) postulate an important continental collision to the west (on the westernmost border of Patagonia). A younger transgressive event, related to the sinking of the depositional basin and the displacement of its axis to the east, is associated with the deposition of the Ventana Group. Thus, the whole of the Sierras Australes and Sierras Septentrionales, the resulting

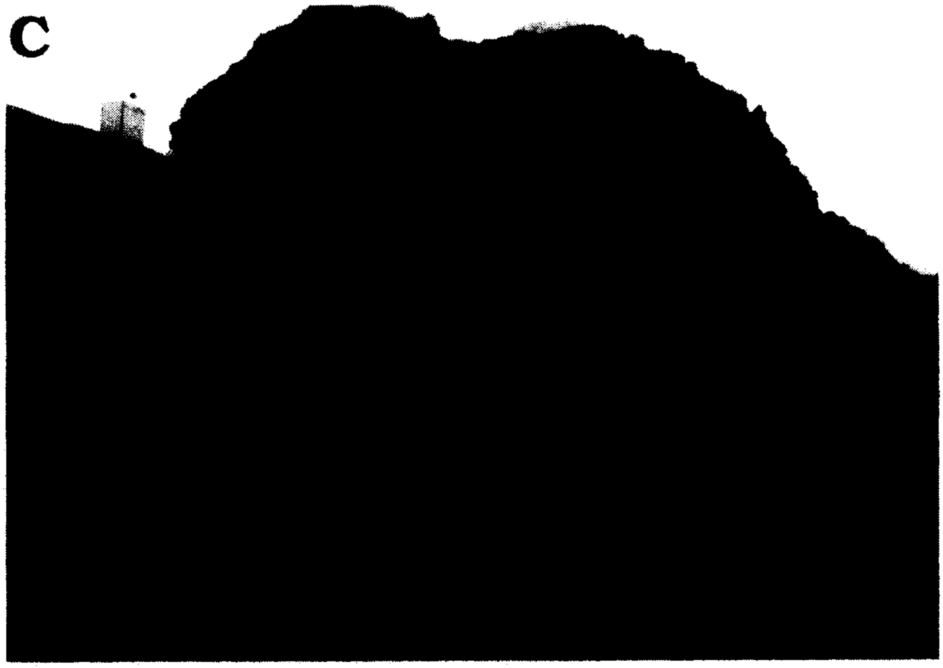

Fig. 6. Parallel strike view of wrenching faulting affecting limestone of the La Tinta Fm. in Loma Negra quarry (1 in Sierras Septentrionales of Buenos Aires, Fig. 1). Note the formation of mesoscopic tectonic induced pelitic diapirism from underlying reddish pelitic beds.

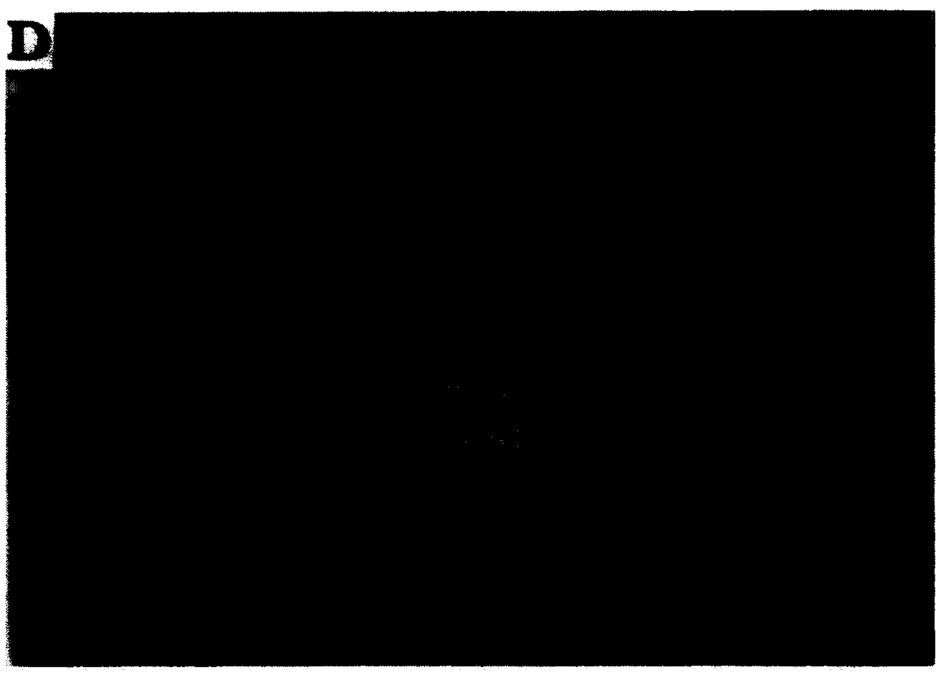

Fig. 7. View of a mesoscopic northeast verging thrust in the southwest flank of the LOSA quarry (2 in Sierras Septentrionales of Buenos Aires, Fig. 1), which was formed in pelitic levels of the La Tinta Fm. (bar is one meter).

intermediate link of the González Chávez High, and portions of northeast Patagonia, were a single major platform (Cuerda, 1971) showing progressively more magmatic activity towards the west.

(2) Neopaleozoic deformation and syntectonic sedimentation: Evidence for Neopaleozoic deformation is widely recorded in Argentina, as in the southern part of the South American plate (Cobbold *et al.*, 1992). West of the study area, Neopaleozoic deformation is widely recognized in the Patagonian Cordillera, where thick turbiditic sequences, probably Silurian to Devonian in age (Hervé, 1988), indicate the presence of an emerging continent with active erosion and transportation of sediment to the ocean. Later, Permo-Carboniferous sediments of the Tepuel Basin are correlated with the Hercynian folding and uplift of the Patagonian Andes (Miller, 1984). The Hercynian deformation is associated with late Paleozoic subduction from the west, and with accretion related to the consumption of the proto-Pacific plate. Thus, a pelagic sequence with clearly oceanic rocks was accreted to the continent after the early Permian in austral Chile, during

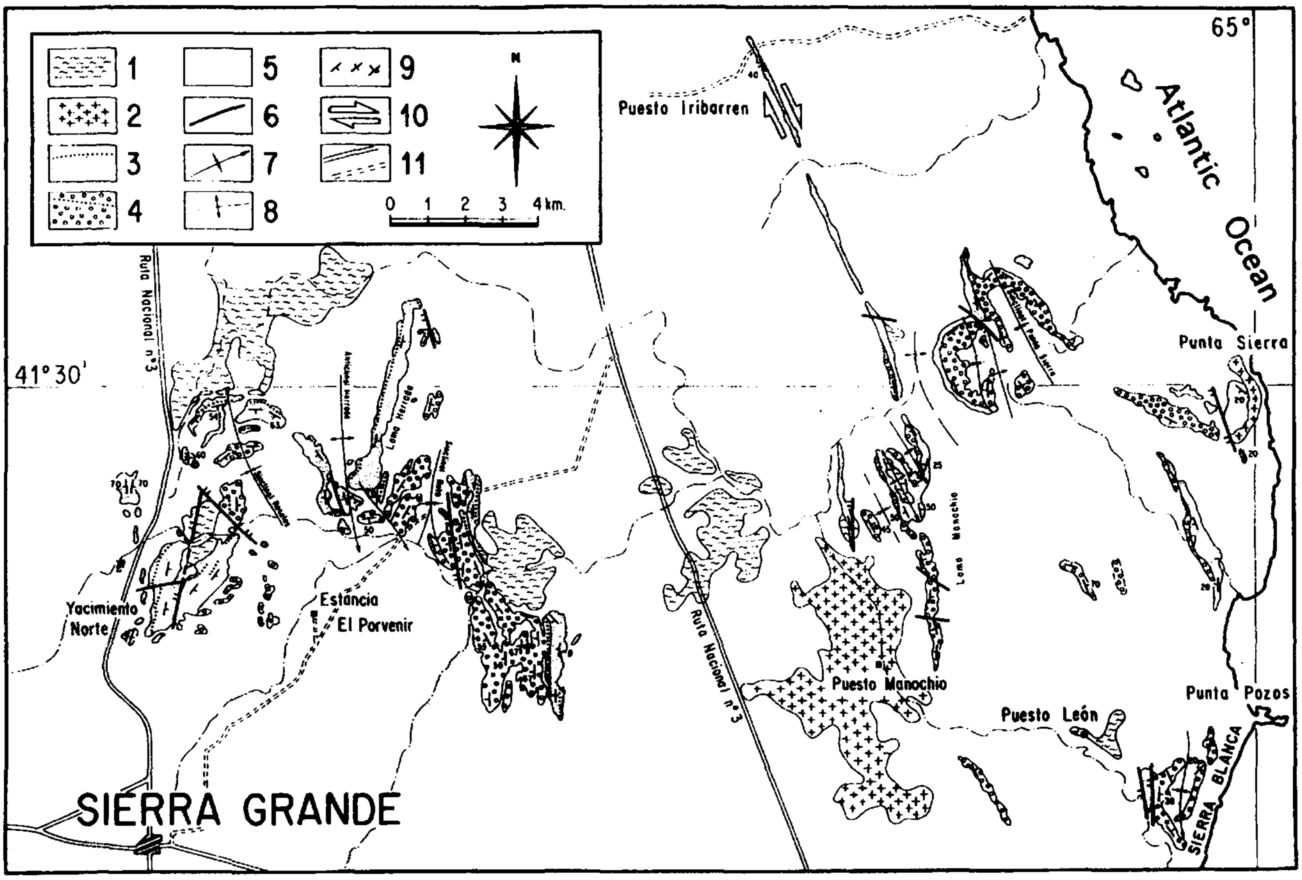

Fig. 8. Geologic sketch of the northeast portion of Sierra Grande hill (modified from Zanettini, 1981). 1: ectinitic basement; 2: Punta Sierra granodiorite, 3: Sierra Grande Fm. (San Carlos Mb. with Rosales ferriferous horizon indicated with dotted line), 4: Sierra Grande Fm. (Herrada Mb. with Alfaro horizon in dotted line), 5: Meso and Cainozoic sedimentary cover; 6: Main faults; 7: Plunging sincline axis; 8: Anticline axis; 9: Bedding attitude; 10: Dextral wrenching kinematic evidences an 11: main and local roads.

a constructive phase of the accretionary prism (Hervé, 1988).

According to the data available for the Sierras Australes of Buenos Aires (López-Gamundí *et al.*, 1995), the deformation responsible for the thrust and fold belt would have been contemporaneous with the deposition of the upper half of the Tunas Formation (Kungurian-Kazanian). Tuff horizons from this section, interpreted as ash fall (Iñíguez *et al.*, 1989), can be correlated in other basins along the Gondwana margin (Veevers *et al.*, 1994, 1995; França *et al.*, 1995). Similar ages and compositions between volcanics of the Choiyoi Formation and its Patagonian equivalents (Rapela and Kay, 1988; Pankhurst, 1990), the rhyolitic ignimbrites of Lihuel Calel (Linares *et al.*, 1980; Sruoga and Llambías, 1992), and volcanic horizons present in the Paraná, Sauce Grande-Colorado, and Karoo Basins suggest a genetic relationship between all these events. Thus, Forsythe (1982), Uliana *et al.*, (1989); López-Gamundí *et al.* (1994) relate this magmatic activity and deformation of the Sierras Australes to the presence of an Andean-type margin with an extensive magmatic arc and a back-arc system. The kinematics of this deformation is consistent with the structural pattern for the Gondwana continent during the later Paleozoic-early Mesozoic (Fig. 10), which was affected by subduction and accretion from the south (de Wit and Ransome, 1992).

In response to these movements, the Eopaleozoic-Mesopaleozoic sedimentary evolution was interrupted by deformation and uplift, generating a regional unconformity (Massabie and Rossello, 1984; López-Gamundí and Rossello, 1993), enhanced in the Sierras Australes area by rhyolitic volcanism (La Hermita, La Mascota). On the Argentine Atlantic Margin, the Pillahuinc-Group is exposed only in the Sierras Australes and its eastern continuity in the González Chávez High. These sedimentites were deposited in a basin elongated in the NW–SE orientation (Suero, 1972) which deepened to the SE (Andreis *et al.*, 1987). Its elongated shape reveals the influence of dextral transpressive tectonics developed internal to the active margin (Cobbold *et al.*, 1986; 1991).

Converging lines of evidence confirm an increase in tectonic activity during the deposition of the Pillahuincó Group and suggest that sedimentation of the Tunas Formation was syntectonic (López-Gamundí *et al.*, 1995). Sandy portions near the top of the sequence show lower contents of quartz and high percentages of feldspars and lithics (volcanics) compared to the more quartzitic composition of the set formed by the Sauce Grande-Piedra Azul-Bonete Formations. This compositional change, associated with an inversion of paleocurrent directions and an increase of grain size toward the youngest layers, are indicative of a reactivation of

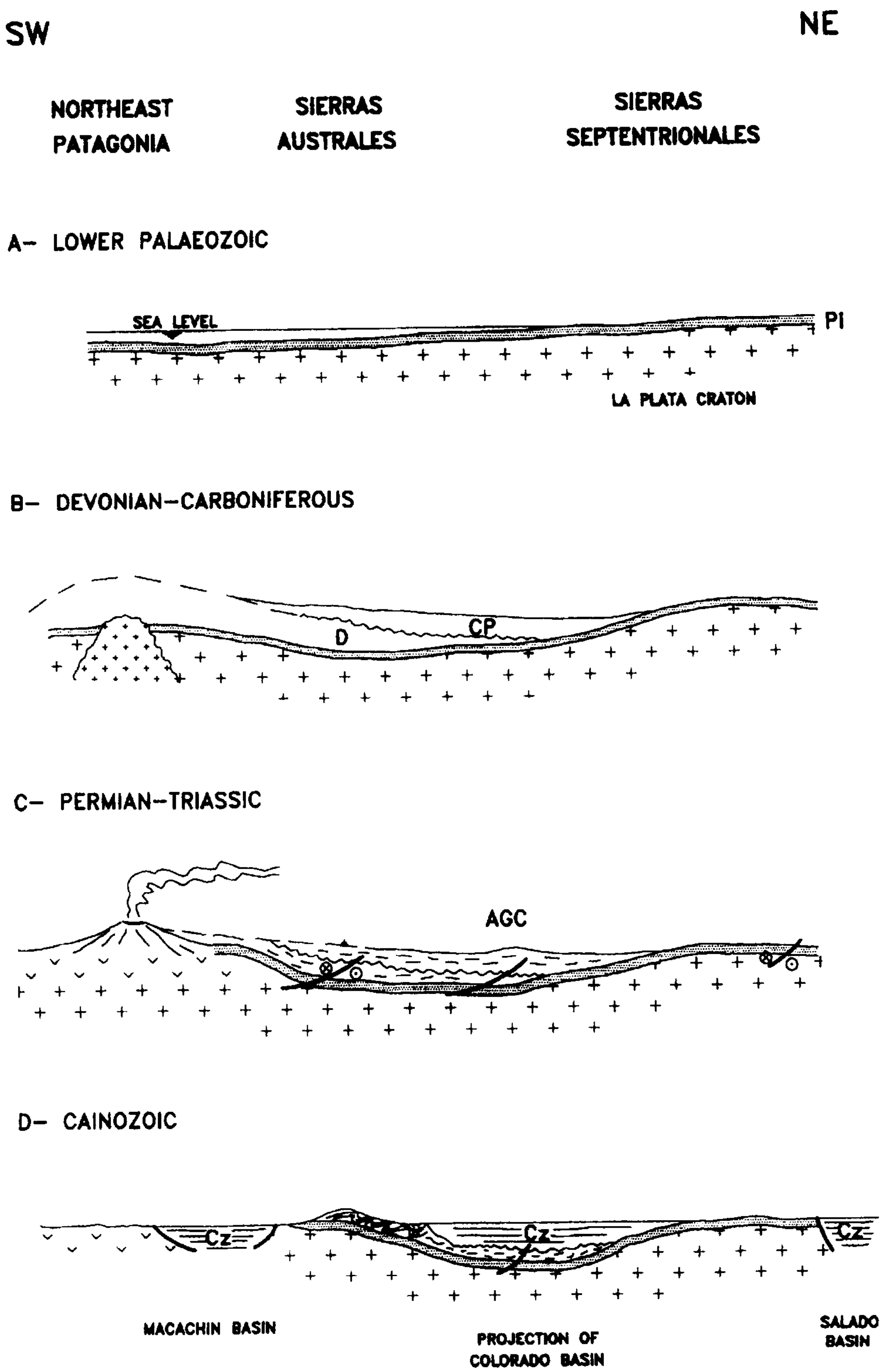

Fig. 9. Evolutive tectonic interpretation based on a crosscutting section to the Sierras Septentrionales of Buenos Aires, Sierras Australes of Buenos Aires and Northeast Patagonia (see location in Fig. 1). A: Development of the Eopaleozoic platform over the La Plata craton; B: Devonian (D) and Carboniferous-Permian (**CP**) sedimentation; C) Neopaleozoic sinsedimentary deformation in Sierras Australes of Buenos Aires, Gonzalez Chaves High (**AGC**) and its presence in Sierras Septentrionales of Buenos Aires and D) Cainozoic sedimentation (**Cz**) showing tectonic inversion in the Salado Basin.

provenence terrains located to the SW. The presence of growth folds (Cobbold *et al.*, 1991; Rossello *et al.*, 1993) indicate that the deformation was, at least partially, contemporaneous with sedimentation of Tunas Formation. This is in agreement with the early Permian radiometric ages of the tuff horizons, which correlate with equivalent units from similar levels of the Paraná and Karoo Basins (Visser, 1987; López-Gamundí *et al.*, 1995) and the Malvinas/Falklands (Marshall, 1994; López-Gamundí and Rossello, 1995, 1996).

The age of this event is well determined in northeast Patagonia, where sediments of the Sierra Grande Formation are deformed and intruded by the synkinematically

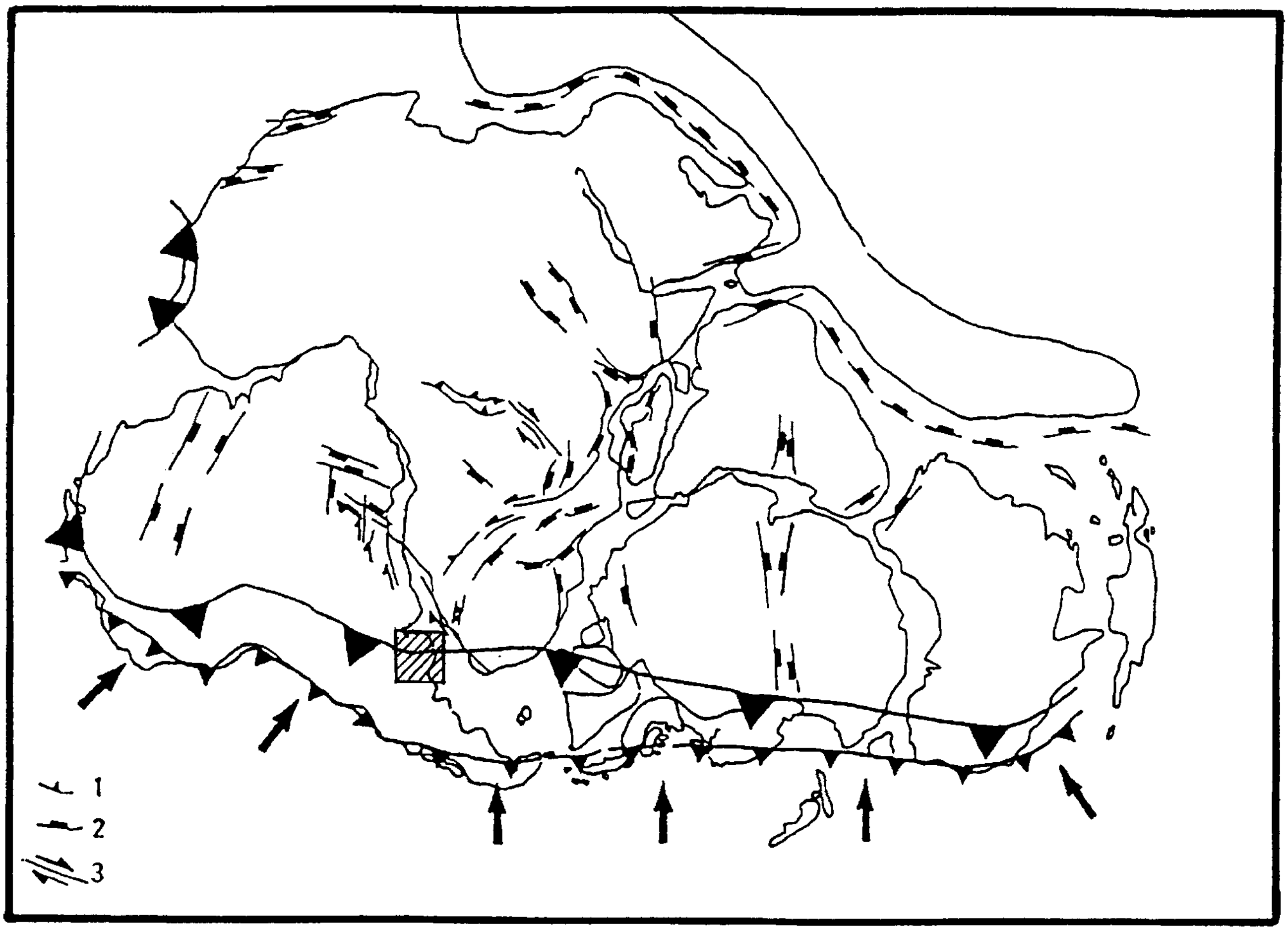

Fig. 10. Tectonic sketch showing the fractures of the Gondwana lithosphere during late Paleozoic-early Mesozoic (250 ± 50 Ma), due to a tectonic convergence along its southern margin (arrows) generated by accretion and/or subduction (taken from Wit and Ransome, 1992). 1) Thrusts; 2) Extension faulting, and 3) Wrenching. The inlet indicates the position of the studied areas in Fig. 1.

deformed Sierra Grande Granite with an age of 261 ± 5 Ma (Rb/Sr, Halpern, 1972).

The age of the deformation that affected the Sierras Septentrionales with tangent compressive movements is only constrained by the age of the youngest rocks affected (Ordovician) and by the late Jurassic-Cretaceous age of the extensive Atlantic Salado and Colorado basins. Nevertheless, the strong similarity to structures of the Sierras Australes allows us to draw a parallel regarding the tectonic transportation vectors, spatial position, and type of transpressive deformation in the Sierras Septentrionales, which can be correlated with the main compressive events of the Sierras Australes.

(3) Mesozoic-Cenozoic inversion: As a consequence of the opening of the South Atlantic ocean, an extensive environment was developed that generated the Salado Basin (Zambrano, 1974; Yrigoyen, 1975; Introcaso and Ramos, 1984), and Colorado Basin (Zambrano, 1980), which isolate the present Paleozoic outcrops of the Sierras Australes, Sierras Septentrionales and northeast Patagonia. Thus, the Paleozoic rocks constitute the tectonic basement of these basins, and they form the highs that limit them.

CONCLUSIONS

The Ordovician-Devonian sedimentary record of the Argentine central-eastern marginal allows us to reconstruct a SW-deepening transgressive platform environment developed on the Precambrian crystalline basement (La Plata Craton). This scenario changes radically during late Carboniferous-Permian times with the more areally restricted sedimentation of the Pillahuincó Group. In particular, sedimentation of the Tunas Formation took place in a foreland setting with the episodic deposition of ashes from a contemporaneous volcanic arc situated to the SW, as suggested by the regional distribution of paleocurrents and volcanic-rich sands. Besides, due to its proximity to the magmatic and orogenic environment developed along the Pacific paleomargin, sedimentation stopped in the Sauce Grande-Colorado Basin after the deposition of the deltaic sands of the Tunas Formation. Sedimentation proceeded through the Triassic in the Paraná and Karoo basins, where the effects of the tectonic activity along the Pacific margin were more subtle.

The late Paleozoic structures affecting the Sierras Australes of Buenos Aires, Sierras Septentrionales of Buenos Aires, and even northeast Patagonia show a transpressive nature comparable at geometrical, kinematic, and genetic levels. These facts widen considerably the belt affected by late Paleozoic deformation, with deformation becoming more intense towards the SW. This variable deformation intensity is shown by the fact that in the Sierras Australes sedimentation took place in a foreland basin environment, and was only affected by minor uplift and strike-slip deformation. In contrast, plutonism and collisional orogeny are evident in parts of northeast Patagonia (Sierra Grande, Gastre).

Acknowledgements — The present work was financed by a scientific cooperation agreement between the CNRS (France) and the CONICET (Argentina). The Buenos Aires University provided the support through grants UBACYT Ex. 217 and Ex. 003. We are thankful to comments by Dr. V.A. Ramos and R.W. Allmendinger. C. Bordarampé translated an early version of the draft.

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