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Late Oligocene–Early Miocene compressional tectosedimentary episode and associated land-mammal faunas in the Andes of central Chile and adjacent Argentina (32–37°S)

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Abstract

A reassessment of the geologic and land-mammal fossil evidence used in attribution of a tectosedimentary episode in the Andes between 32 and 37°S to the Middle Eocene "Incaic tectonic phase" of Peru indicates that the episode occurred during Late Oligocene–Early Miocene times (~ 27–20 Ma). From west to east, three structural domains are recognized for this time span in the study area: a volcanic arc (Chile); a thin-skinned, E-verging fold-thrust belt (Cordillera Principal, Chile–Argentina border strip); and a foreland basin (Argentina). Initiation of thrusting in the Cordillera Principal fold-thrust belt produced the coeval initiation of sedimentation in the foreland basin of adjacent Argentina. This onset of foreland deposition postdates strata bearing a Divisaderan Land Mammal Age fauna (i.e. ~ 35–30 Ma) and is marked at ~ 36°30′S by the base of the "Rodados Lustrosos" conglomerates, which are conformably overlain by sedimentary rocks containing a Deseadan Land Mammal Age fauna (i.e. ~ 29–21 Ma). Geologic relationships between the thick volcanic Abanico (Coya–Machalí) and Farellones formations also demonstrate that this tectosedimentary episode practically ended at ~ 20 Ma at least in the volcanic arc, and was therefore roughly coeval with the major tectonic crisis (~ 27–19 Ma) known in northwestern Andean Bolivia some 1500 km to the north. This strongly suggests that a long, outstanding tectonic upheaval affected at least an extended 12–37°S segment of the Andean margin of South America during Late Oligocene and Early Miocene times.

1. Introduction

Compressional deformation of an active margin produces crustal shortening and thickening, and creates a tectonic load which causes the passive continental crust to flexure and a foreland basin to appear (e.g., Flemings and Jordan, 1989). The reliefs produced by the shortening and thickening are submitted to erosion and provide sediments which accumulate in neighbouring basins, particularly in the foreland. Thus, onset or reactivation of compressional deformation is recorded by onset or reactivation of foreland sedimentation. Tectonic quiescence may be like-

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wise recorded by the foreland basin stratigraphy (e.g., Flemings and Jordan, 1990). In a volcanic arc setting, postdating of structures by subhorizontal volcanic rocks also records termination or quiescence of deformation.

Traditional interpretations (e.g., Sébrier et al., 1988) envision that the Andean tectonic evolution was controlled by long extensional periods, during which strata accumulated, and short compressional tectonic pulses, during which they were rapidly deformed. New interpretations (e.g., Jordan et al., 1983; Jordan and Alonso, 1987; Sempere et al., 1990a; Sempere, 1991) favor that formation and infill of Cenozoic Andean basins were controlled by compressional and/or transcurrent tectonics, and that these deformations developed during substantial amounts of time, implying that the beginning and end of deformational episodes may be significantly different in age.

Although a still poorly known deformation, involving thrusting, of probable Late Cretaceous age was described in the Aconcagua region (Vicente, 1972, in press; Vicente et al., 1973), the first major Cenozoic deformations of the Andean orogeny in cordilleran central Chile and adjacent Argentina (32–37°S, Fig. 1) have traditionally been correlated with the Middle Eocene "Incaic phase" of Peru (e.g., Charrier and Vicente, 1972; Yrigoyen, 1976; Ramos, 1988). In this paper we present a new interpretation of the biostratigraphic and structural data, which demonstrates that the 32–37°S Andean segment was submitted to a major compressional deformation between approximately 27 and 20 Ma. Our reassessment of the geologic and land-mammal fossil data upon which the "Incaic" correlation was made, along with incorporation of recent information, shows that the first major Cenozoic orogenic development in this area began in fact in Late Oligocene times. The relationships between the deformed volcanic Abanico (= Coya–Machalí) and the overlying subhorizontal Farellones formations, which are usually unconformable north of 34°S (Rivano et al., 1990), also demonstrates that compressional deformation noticeably decreased in the volcanic arc domain, and possibly adjacent areas, by ~20 Ma. This deformation is apparently coeval with the major tectonic crisis evidenced in the Bolivian Andes about 1500 km to the north (Sempere et al., 1990a; Sempere, 1991).

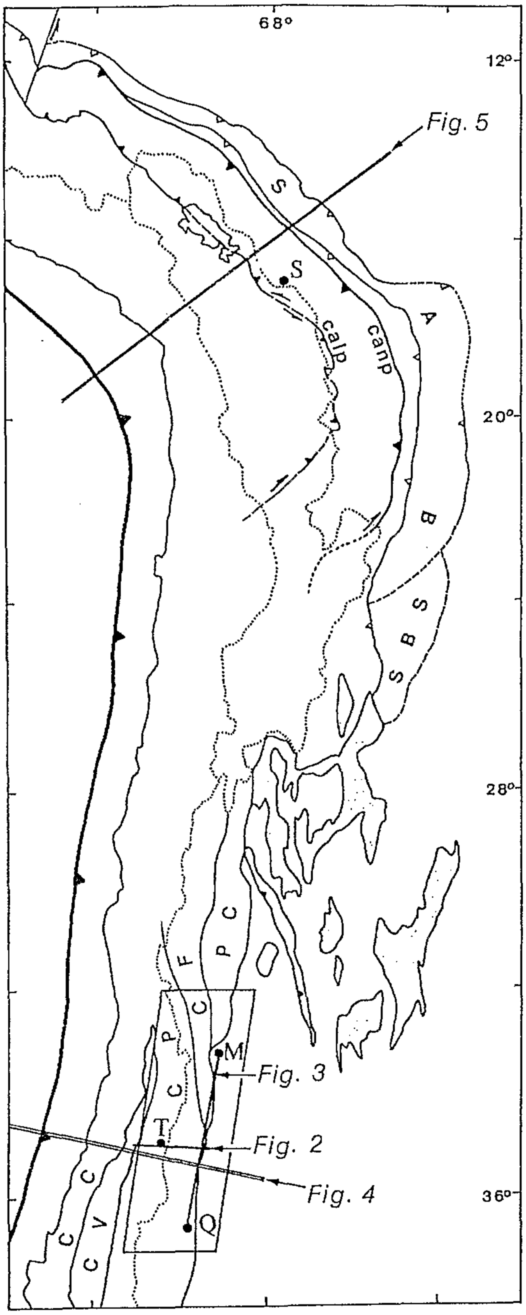
2. Calibration of Deseadan and Divisaderan South American land-mammal ages (SALMAs)

2.1. Absolute age of the Deseadan

Rich Deseadan faunas, which occur in association with radioisotopically dated volcanic units, are known from Salla (Bolivia) and the Chubut Province (Argentina).

MacFadden et al. (1985) provided a magnetostratigraphic and radioisotopic study of the ~540-m-thick Salla beds in the Cordillera Oriental southeast of La Paz (Bolivia). They concluded that these rocks and the associated Deseadan land-mammal faunas span a time interval from ~28.5 to ~24.0 Ma. Naeser et al. (1987) published additional fission-track and K-Ar dates on four ash levels in the lower part of the Salla beds and concluded that the principal fossil horizons range from 27 to 24 Ma, while the complete section ranges from ~28 to 22 Ma. McRae (1990) and Sempere et al. (1990a) reinterpreted the geochronologic data of MacFadden et al. (1985) and suggested that the section may be 3 to 4.5 Myr younger than believed by those workers, possibly because of their dating of partly reworked material. Based on the last two studies, the Deseadan fauna from Salla ranges from ~24 to ~21 Ma. The base of the 20–150-m-thick Luribay conglomerates, which conformably underlie the Salla beds and unconformably overlie pre-Eocene rocks, postdates the onset at ~27 Ma of a major tectonic episode in Bolivia (Sempere et al., 1990a).

In the Chubut Province (southern Argentina), K-Ar dates on basalts and tuffs (which belong to the Plateau Basalt Series, see below) associated with Deseadan land-mammal faunas indicate that at Scarritt Pocket the fossils are bracketed between 23.4 and 21.0 Ma, while at the Gran Barranca and Valle Hermoso the fossils occur below a basalt dated at ~29 Ma (Marshall et al., 1986). The Deseadan fauna at Pico Truncado occurs in a slump block below a basalt dated at 27.6 Ma (Marshall and Sempere, 1993) and is not related with the flow dated at 33.6 Ma as previously believed (e.g., Marshall et al., 1977, 1986).



The dated Deseadan faunas in southern Argentina thus range from ~29 to ~21 Ma, which is consistent with the age of the dated fauna in Bolivia (~24–21 Ma). Deseadan land-mammal faunas thus encompass Late Oligocene–Early Miocene times (~29–21 Ma) and not Early Oligocene time as was long believed (e.g., Pascual et al., 1965; Gorroño et al., 1979; Pascual, 1984).

2.2. Absolute age of the Divisaderan

Before the discovery of the fauna from Termas del Flaco in central Chile (see below), Divisaderan land mammals were known only from Divisadero Largo in the Mendoza Province, Argentina (Simpson et al., 1962; Pascual et al., 1965; Marshall et al., 1983). The regional stratigraphic data summarized below, along with reported "faunal links" between early Deseadan and Divisaderan taxa at Salla in Bolivia (MacFadden et al., 1985), and the radioisotopic dates on Deseadan faunas in Bolivia and Argentina (see above), resulted in subsequent placement of Divisaderan in the Early Oligocene (i.e. ~36–30 Ma; Marshall et al., 1986).

The land-mammal fauna of Divisaderan aspect recently collected from what is apparently the middle or upper part of the Coya–Machalí Formation at Termas del Flaco, central Chile, is associated with volcanic rocks (flows) which yielded ages of ~35 to ~31 Ma (K-Ar, whole rock), with ages of ~31.5 Ma (Ar-Ar, single minerals) at the fossiliferous level (Wyss et al.,

Fig. 1. Map of southwestern South America showing areas discussed in text [modified from Jordan et al. (1983) and Sempere et al. (1990b)] and locations of Figs. 2–5. Framed—area of interest. Fine dot lines—drainage divides; south of lat. 28°S, it coincides with the Argentine–Chilean borderline. The thick thrust line in Pacific Ocean is the trench. Main localities cited in text: *M* = Mendoza (Divisadero Largo); *Q* = Quebrada Fiera de Malargüe; *S* = Salla; *T* = Termas del Flaco. Abbreviations: *CC* = Coastal Cordillera; *CF* = Cordillera Frontal, *CP* = Cordillera Principal; *CV* = Central Valley; *PC* = Precordillera; *SBS* = Santa Bárbara system; *SAB* = Subandean belt; *calp* = Main Altiplanic thrust; *canp* = Main Andean thrust. Dotted pattern = Sierras Pampeanas.

1990, 1992; Charrier et al., 1990). These dates agree with the 36–30 Ma age for the Divisaderan as conceived by Marshall et al. (1986), the fauna is of Divisaderan aspect, and it is cautiously assigned to this SALMA (Marshall and Sempere, 1993). These conclusions agree with those of Pascual and Ortiz-Jaureguizar (1990), who, based on stage of evolution of the type Divisaderan fauna, regard it as probable Early Oligocene age.

The fossils at Termas del Flaco are of Divisaderan aspect and thus certainly younger than the Mustersan SALMA, which is regarded as equivalent to Middle Eocene times (see Marshall and Sempere, 1993). The fossils are embedded in a thick volcaniclastic sandstone, within a mainly volcanic and volcaniclastic sequence (Charrier et al., 1990), which evidences that volcanic activity was important at the time of sedimentation.

3. Stratigraphic and structural data

A structural system composed of: (1) a western volcanic arc; (2) a thin-skinned, E-verging, complex fold-thrust belt; and (3) an eastern foreland basin, is recognized in the area of interest (Fig. 2).

3.1. Chilean side: the volcanic arc

At Termas del Flaco (35°S), a fining- and thinning-upward sequence made up of conglomerates, sandstones and red mudstones, traditionally assigned to the Colimapu Formation (Klohn, 1960), overlies the Tithonian to early Valanginian-age, carbonate-dominated Baños del Flaco Formation with a sharp lithologic discontinuity. Here, bones of dinosaurs occur 65–70 m above the base of this red beds sequence, whereas remains of teiid lizards and a crocodile were recovered 20 m higher in the same stratigraphic unit. These teiid lizards are very close to two extant genera (Valencia et al., in press), and, because of their association with dinosaurs, the base of the red bed sequence, at that locality, is thus certainly Cretaceous but might well be only Late or latest Cretaceous. Furthermore, association of fining-upward red beds and dinosaur remains is reminiscent of the Senonian-age "Estratos con Dinosaurios" (Neuquén Group) of nearby Argentina (see Zambrano, 1981; Legarreta et al., 1989).

Immediately north and south of the Termas del Flaco valley, these red beds ("Colimapu s.l." Formation) and/or older units are tectonically

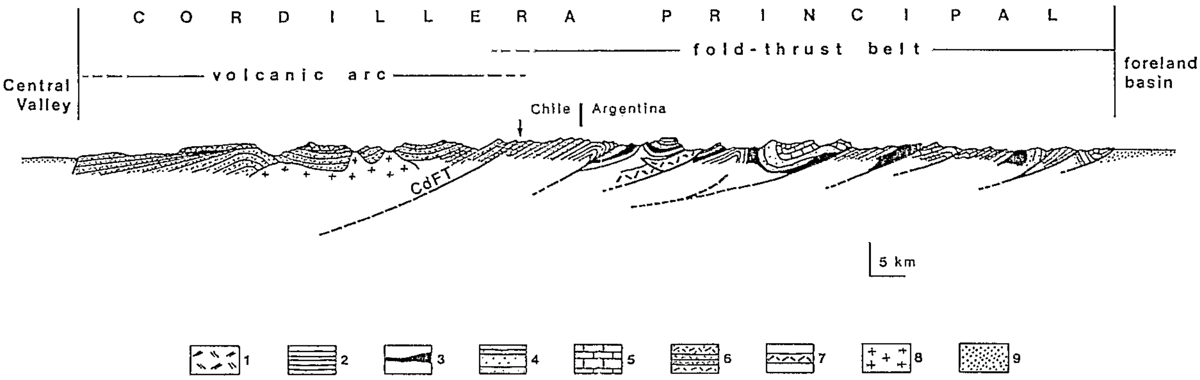


Fig. 2. General present-day cross section at ~35°S [modified from Davidson and Vicente (1973) and Arcos (1987)]. Section is located in Fig. 1. Vertical arrow shows location of the Termas del Flaco mammal-bearing locality. *CdFT* = Cajón del Fierro thrust. *1* = Permo-Triassic Choiyoi Group (acidic volcanics); *2* = pre-Oxfordian Jurassic (shales, marls and limestones); *3* = Oxfordian gypsum; *4* = Kimmeridgian coarse- to fine-grained clastics; *5* = Tithonian and Cretaceous strata (mainly carbonates and shales); *6* = Paleogene (to earliest Miocene?) volcanics (Coya–Machalí or Abanico formations); *7* = late Early Miocene and younger volcanics (Farellones Formation and younger units); *8* = Andean granitoids; *9* = Neogene sedimentary deposits.

overlain by the Coya–Machalí Formation (and not by the "middle and upper members of the Colimapu", as otherwise stated; e.g., Arcos, 1987) by means of the out-of-sequence Cajón del Fierro thrust (Davidson, 1971; Davidson and Vicente, 1973; Godoy and Palma, 1990; Godoy, 1991). The thickness of the part of the Coya–Machalí Formation located above the thrust hanging wall is 2000–3000 m (Arcos, 1987). At Termas del Flaco, mammals of Divisaderan aspect occur a few tens of meters above the sole of the Cajón del Fierro thrust (Charrier et al., 1990), in what appears to be the middle or upper part of the Coya–Machalí Formation, and volcanic rocks associated with these fossils were dated between 35 and 31 Ma (Early Oligocene; Wyss et al., 1990; Charrier et al., 1990; and see above). The Coya–Machalí Formation there dips about 30–50° to the west (Fig. 2; Arcos, 1987; Charrier et al., 1990).

The Coya–Machalí Formation is widely regarded as a lateral equivalent of the Abanico Formation (e.g., Drake et al., 1982), which crops out over large areas in central Chile. The Coya–Machalí and Abanico formations are at least 3000 m thick and consist of intercalations of volcanic, mostly pyroclastic, rocks, and, locally, red to purple continental sedimentary rocks reworking volcanic material (Klohn, 1960; Charrier, 1981; González and Vergara, 1982; Malbrán, 1986; Arcos, 1987); the proportion of volcanics in the unit seems to increase upwards and eastwards. The age of the initiation of accumulation of the Abanico Formation is controversial, especially where the Colimapu (s.l.) red beds are lacking or where deposition of the Tithonian–Neocomian limestones was impeded by widespread coeval volcanism. However, it is tentatively estimated to be mainly late Early to early Late Cretaceous (Drake et al., 1982; Godoy et al., 1988). The available geochronologic data agree to suggest that the Abanico Formation is older than ~24–23 Ma, that its base is older than ~62 Ma, and that it was deformed prior to 20–14 Ma (Drake et al., 1982; Munizaga and Vicente, 1982).

The Abanico or Coya–Machalí formations conformably overlie the Colimapu (s.l.) Formation, and are unconformably overlain by the volcanic Farellones Formation north of 34°S. The accumulation of the Farellones Formation lasted from ~20 Ma till ~7 Ma (Vergara et al., 1988), although a basal age of ~25 Ma for the Farellones Formation has also been proposed north of 32°S (Munizaga and Vicente, 1982). The contact between the Farellones and Abanico (Coya–Machalí) formations is usually an angular unconformity, but conformable contacts are locally known (Rivano et al., 1990; Thiele et al., 1991). The lithologies of the Farellones closely resemble those of the Abanico (Coya–Machalí), and the two formations are sometimes difficult to distinguish. However, the Abanico Formation includes a lesser amount of ash flows and tuffs (Thiele et al., 1991) and yielded older ages on single minerals (SerNaGeoMin, unpublished data).

These chronological data suggest that much of the ~3000-m-thick Abanico (Coya–Machalí) Formation accumulated during the ~35 to ~20 Ma interval, and thus that contemporaneous accumulation rates must have been relatively important. The Farellones Formation, the base of which is now at ~3500 m of altitude in the northern half of the area, was uplifted by at least ~2000 m after the Late Miocene (Pons and Vicente, 1985), and so were the underlying rocks. Thus, subaerial accumulation of ~2000–3000 m of volcanic rocks during Oligocene and earliest Miocene times (middle to upper Abanico and Coya–Machalí formations) did not produce an elevation increase higher than 1500 m of altitude, and some subsidence has to be invoked to explain accumulation. It results from these data that the thickness of the part of the Coya–Machalí Formation located above the Early Oligocene mammal-bearing level at Termas del Flaco, which thus spans no more than the Early Oligocene–Early Miocene interval (i.e., 15 Myr), is 2000–3000 m, and that accumulation rate during this time span was at least 140 m/Myr and may be as high as 300 m/Myr.

The style of deformation of the Abanico and Coya–Machalí formations mostly consists of vertical to inclined folds with hectometric to kilometric wavelengths and some limbs dipping 45° or more, whereas the Farellones Formation is generally subhorizontal and thus postdates deformation of the Abanico and Coya–Machalí (Rivano et al., 1990; Thiele et al., 1991). Relationships between the Farellones and Abanico formations, which are, respectively, ~2500 and ~3000 m thick, have been recently discussed (Vergara et al., 1988; Rivano et al., 1990; Thiele et al., 1991). These studies note that the base of the Farellones Formation shows an apparent trend to younger ages toward the south. Some authors stress that "no generalization can be made about the contact relationship between the two formations (which) are locally separated by a distinct unconformity, in other places by a pseudoconformity, and in still others by N-striking normal faults or fault systems (...)" (Thiele et al., 1991). However, Rivano et al. (1990) showed that, between 32 and 34°S, an unconformity is clearly visible between the Abanico and Farellones formations.

All these facts suggest that the Abanico (Coya–Machalí) and Farellones formations accumulated in a volcanic arc setting during a practically continuous time interval (namely at least Oligocene and Miocene times, ~35 to ~7 Ma), with the particularity that deposition of the upper part of the Abanico (Coya–Machalí) took place while compressional deformation, and thus erosion, were active, whereas deposition of the Farellones occurred after deformation had reached a somewhat quiescent stage in the area. It is noteworthy that Thiele et al. (1991) furthermore suggest on independent bases that the Farellones Formation ash flows were extruded during the transition from a compressional to an extensional regime. This would imply an age of ~20 Ma for the finalization of compressional deformation of the Abanico (Coya–Machalí) Formation. Given the thickness (2000–3000 m) of the deformed strata of the Coya–Machalí Formation above the Early Oligocene mammal level at Termas del Flaco, it may be proposed that deformation started several million years after 31 Ma, possibly around the Early Oligocene–Late Oligocene boundary (~27 Ma).

3.2. Argentine–Chilean border strip (Cordillera Principal): the fold-thrust belt

This area is occupied by the E-vergent Cordillera Principal, the eastern rim of which is called the Aconcagua fold-thrust belt (Ramos, 1988; Mpodozis and Ramos, 1989). The younger Cordillera Frontal and Precordillera structural systems extend east of it (Fig. 1). Cenozoic clastic deposits occur between the three cordilleras. The Precordillera only extends north of 33°S, and its frontal (eastern) part is currently active (Aubouin et al., 1973; Davidson and Vicente, 1973; Jordan et al., 1983; Ramos, 1988). South of 35°S, the Cordillera Frontal dies out and only the Cordillera Principal is recognized (e.g., Jordan et al., 1983; Ramos, 1988). In the Cordillera Principal, the main décollement levels used by thrusting are located in the Abanico (Coya–Machalí) formations (see above) in its westernmost part, mainly in Middle to Late Jurassic gypsum and marls, and, locally, in late Paleozoic rocks (Fig. 2; Davidson, 1971; Davidson and Vicente, 1973; Aubouin et al., 1973; Ramos, 1988). In the Cordillera Frontal, the décollements would occur in late and early Paleozoic rocks, whereas in the Precordillera they would be mainly located in Cambrian–Ordovician carbonate strata (Ramos, 1988). However, J.C. Vicente (pers. commun., and in press) cautions that the respective structures of the Cordillera Frontal and Precordillera are mainly of the thick-skinned type.

Godoy and Palma (1990) and Godoy (1991) showed that the Cajón del Fierro thrust (Davidson, 1971; Davidson and Vicente, 1973) is a Late Oligocene–Early Miocene out-of-sequence thrust and a dominant structure of the western part of the Cordillera Principal fold-thrust belt. This thrust extends north of the Cachapoal valley (34°20′S), where it had previously been mapped as an unconformity (Godoy, 1991). The maximum age of this thrust is constrained by the K-Ar dates of 35–31 Ma associated with the Divisaderan land-mammal fauna from the upper plate Coya–Machalí Formation at Termas del Flaco (Wyss et al., 1990; Charrier et al., 1990; Godoy, 1991). Its minimum age is constrained by the nearby subhorizontal Farellones Formation volcanics which have ages not older than 14 Ma in the area, and basal ages of ~20 Ma more to the north (Vergara et al., 1988; Rivano et al., 1990; Godoy, 1991). South of 35°S, the Cajón del Fierro fault is one of the many thrusts which participated in the structuration of the Chile–Argentina border fold-thrust belt (Davidson, 1971; Davidson and Vicente, 1973), and the major out-of-sequence one. If it were only of local importance at Termas del Flaco, as it was implicitly suggested by some mappings and interpretations, then an extreme condensation of the Mesozoic sequence, for which there is no justification in the Neuquén basin, should be assumed at this locality. We therefore favour the view that the Cajón del Fierro thrust is a continuous, major thrust which extends at least from 34°20′ to 35°15′S, through the Termas del Flaco area.

The eastern outcrops of the Coya–Machalí Formation, which occur within the Cordillera Principal fold-thrust belt located along the border zone between Chile and Argentina, demonstrate that the eastern part of the Oligo-Miocene volcanic arc was deformed during its tectonic transportation toward the east as the upper part of the sedimentary pile overlying the décollement level(s) used by the thrusts. This implies that the Coya–Machalí was deformed during the structuration of the internal (i.e., western) strip of the fold-thrust belt. This tectonic activity of the western part of the belt thus started after the Early Oligocene and had considerably decreased by the beginning of accumulation of the Farellones Formation (older than 14 Ma at the latitude of Termas del Flaco, or as early as at ~20 Ma according to the data from more to the north). This does not preclude that thrust deformation might have gone on more to the east after ~20 Ma.

Translated, Ramos et al. (1991) state that "the acquisition of the structure of the Aconcagua fold-thrust belt began prior to the Farellones Formation (±20 Ma)", and they furthermore consider that the main stage of acquisition of the structure of the eastern part of the Aconcagua fold-thrust belt at ~33°S occurred only after 8.9 Ma, i.e., much later and thus possibly after a relatively quiescent period. However, more detailed data are needed from this area in order to clarify this.

Furthermore, recent work by one of us (E.G.) suggests that, south of 34°S, a large amount of the observable deformation took place after Middle Miocene times, involving both edges of the Farellones volcanic arc. A major reactivation of out-of-sequence thrusting in that area is thus thought to have occurred in the Middle to Late Miocene.

3.3. Argentine side: the foreland basin

Onset of foreland sedimentation in central Andean Argentina is marked by the initiation of deposition of conglomeratic and clastic strata such as the "Conglomerado Violáceo" (33°S) and the "Rodados Lustrosos" (36°30′S), which lie east of the high Andes and are interpreted to be roughly stratigraphic equivalents (Groeber, 1951; Gorroño et al., 1979), and, possibly, the undated lower part of the Santa María Conglomerates, which crops out between the Cordillera Principal and Cordillera Frontal (Schiller, 1912; Vicente, 1972; Yrigoyen, 1976, 1979; Ramos, 1988). Because precise onset of deposition is likely to have been diachronous, we stress that what is correlated here is the unconformity surface, and that we are not attempting at neither precisely dating the conglomeratic beds nor refinedly correlating them, but at constraining in age the onset of the functioning of central western Argentina as the regional Andean foreland basin.

At Quebrada Fiera de Malargüe (Fig. 1), the "Rodados Lustrosos" overlie Paleocene and/or earliest Eocene rock units (Gorroño et al., 1979; Legarreta et al., 1989), and form the basal part of the Agua de la Piedra Formation, which yielded ~37 m above its base a fauna securely assigned to the Deseadan SALMA (i.e., Late Oligocene–Early Miocene, see above) (Gorroño et al., 1979; Marshall et al., 1983, 1986). The "Conglomerado Violáceo" overlies, near the city of Mendoza (Fig. 1), the Divisadero Largo Formation, which is ~70 m thick and bears ~35 m below its top the type fauna of the Divisaderan SALMA (i.e., Early Oligocene, see above) (see Barrionuevo de Arce et al., 1988). The "Conglomerado Violáceo" is gradationally overlain by the Palomares Formation, which correlates with the Agua de la Piedra Formation (Pascual and Odreman-Rivas, 1973; Yrigoyen, 1976, 1979).

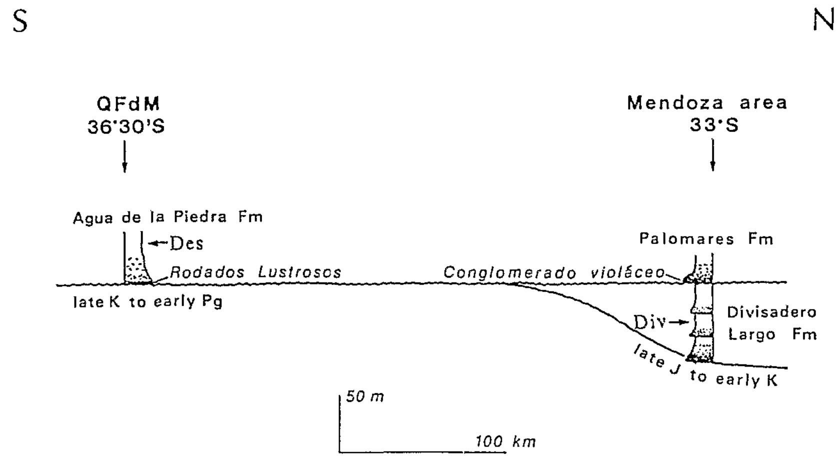


Fig. 3. Synthetic geometric and stratigraphic relationships in the Argentine Andean foothills between 33° and 36°30'S (location in Fig. 1). Ages of underlying units from Gorroño et al. (1979) and Kokogián and Mancilla (1989). Stratigraphic locations of Divisaderan (*Div*) and Deseadan (*Des*) faunas are indicated. Abbreviations: *Fm* = Formation; *J* = Jurassic; *K* = Cretaceous; *Pg* = Paleogene; *QFdM* = Quebrada Fiera de Malargüe.

The sharp lithologic disconformity at the base of the conglomerates east of the high Andes is thus bracketed by Divisaderan and Deseadan faunas, respectively, below and above (Fig. 3). In the southern part of the region dealt with, this disconformity also marks resumption of continental sedimentation after erosion and/or non-deposition during the Early Eocene–Early Oligocene time span, and thus resumption of subsidence. On the basis of the sequential-facial foreland-type signature of the overlying strata (see Groeber, 1951; Yrigoyen, 1976, 1979; Ramos, 1988), this subsidence is interpreted to be of tectonic origin, i.e., to have been generated by some tectonic loading to the west, probably in the Abanico (Coya–Machalí) volcanic arc and in (part of) the Cordillera Principal fold-thrust belt.

The geometry of the Divisadero Largo Formation in map view (Barrionuevo de Arce et al., 1988) provides evidence that the Mendoza area did not function as a foreland basin during Divisaderan times, mainly because Divisadero Largo strata were onlapping toward the west (Barrionuevo de Arce et al., 1988), and not toward the east as it is expected in any Andean foreland basin, and because the Divisadero Largo basin had a roughly E–W-striking well-defined southern boundary, thus perpendicular to the Andean trend.

Other conglomeratic strata attributed to the Early Miocene crop out between the Cordillera Principal and Cordillera Frontal, and between the latter and the Precordillera (Ramos, 1988), i.e., in presently "piggyback" settings. Although the Santa María Conglomerates are overlain by volcanic rocks with K-Ar dates of 8.9 and 8.1 Ma (which are related to flows in the Farellones Formation; J.C. Vicente, pers. commun.), it is thought that their deposition initiated at least in Early Miocene times (Ramos et al., 1990). The lower member of this unit, which crops out between the Cordillera Principal (Aconcagua) fold-thrust belt and the Cordillera Frontal, is thus probably partly equivalent to the "Rodados Lustrosos" of Gorroño et al. (1979), whereas its uppermost member might be related to the "Quechua" tectosedimentary episode which began at ~ 10 Ma (Ramos et al., 1990).

Stratigraphic relations and geometries thus suggest that the unconformity at the base of the "Conglomerado Violáceo", "Rodados Lustrosos" and their equivalents records the initiation of foreland conditions in the corresponding areas. This unconformity therefore marks onset of tectonic loading of the local South American lithosphere, and thus onset of an episode of crustal shortening. It postdates a Divisaderan fauna and predates a Deseadan fauna. Strictly speaking, this chronologic datum only indicates that initiation of foreland conditions occurred in that area after the beginning of the Divisaderan (~ 35 Ma) and before the end of the Deseadan (~ 21 Ma), which is consistent with the data obtained in the volcanic arc and fold-thrust belt more to the west.

4. Discussion

4.1. Summary: regional overview

In central Chile and adjacent Argentina, a Neogene structural system comprising a volcanic arc, a fold-thrust belt and a foreland basin can be recognized. The available chronological data indicate that a major deformation started in the volcanic arc and Cordillera Principal fold-thrust belt several million years after 31 Ma and had practically terminated by 20 Ma at least in the west, and that initiation of foreland conditions occurred between 35 and 21 Ma. Several lines of data thus coherently agree to roughly date the initiation of this structural system to near the Early Oligocene–Late Oligocene boundary (~ 27 Ma). Information from the volcanic arc suggests that deformation in this western belt reached a somewhat quiescent state by 20 Ma (or slightly later, according to the areas).

Accumulation of a very thick pile of mostly volcanic rocks in the arc (~ 2000–3000 m in less than 15 Ma, which is about 200 m/Myr or more) implies a relatively high subsidence rate, even if this accumulation provoked by itself an elevation of altitude by vertical accretion. However, altitude was mainly acquired after the Late Miocene, since about 2000 m of uplift have been demonstrated in the Aconcagua Andes (Pons and Vicente, 1985).

4.2. Comparisons with other central Andean regions

Chronology of deformations in the Andes is a debated and crucial issue. Literature on Andean geology classically uses an implicit catalogue of "diastrophic phases", and now contains a plethora of named "phases" which may at times appear confusing. In reality, the "diastrophic phases" may refer indistinctly to magmatic pulses, uplift or subsidence processes or "pulses", directly observable deformational structures (compressional or extensional), deformations inferred from angular unconformities (too frequently interpreted as marking "tectonic pulses"; see Sempere, 1991), non-angular unconformities, mere disconformities, or, in some cases, simple facies changes. Furthermore, the unconformities which are used to identify these phases may have resulted from tectonism, eustatism and even diapirism (see Sempere, 1991). Correlation between distinct "diastrophic" phenomena chiefly relies on apparent or inferred rough synchroneity, which can unfortunately result in ready use of the same name for phenomena that may not be geographically, genetically and even chronologically related. The only way to resolve the confusing intricacy of present nomenclature and correlations of Andean "diastrophic phases" is to document in each case what occurred, and when and where it occurred. Obviously, secure correlations are possible only when they are based on firm radioisotopic, magnetostratigraphic and/or biostratigraphic data, and discrimination between structural, magmatic and sedimentary phenomena is absolutely needed for precise interpretation of objective regional data. Secure knowledge of the timing of "phases" is what is important and not their names. Liberal application of phase names to uncalibrated deformations, which is presently widely done in South America, gives a false impression of knowledge of geological processes that can lead to erroneous interpretations (Marshall and Sempere, 1993).

The results obtained by this study demonstrate that a major tectonic episode started in central Chile and adjacent Argentina around ~ 27 Ma (Fig. 4) and that this episode had practically ended in the volcanic arc domain of central Chile by ~ 20 Ma. Most strikingly, this Late Oligocene–Early Miocene tectosedimentary episode which affected the Andes between 32 and 37°S was apparently coeval with the major tectonic

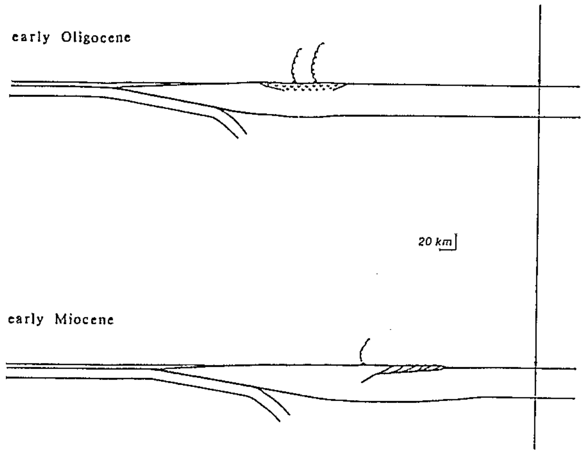


Fig. 4. Schematic cross sections showing tectonic evolution between Divisaderan (Early Oligocene) and late Deseadan (Early Miocene) times in central Chile and adjacent Argentina. Section is located in Fig. 1. The Early Miocene external foreland basin is the only synorogenic basin figured (fine dots). V-pattern = thick volcanics (Abanico and Coya–Machalí formations). Scale is only indicative.

episode recently evidenced in the Bolivian orocline area, i.e., between 12 and 22°S (Fig. 5; Sempere et al., 1989, 1990a; Sempere, 1991), suggesting that they are genetically related. The Bolivian episode has been linked to a marked increase in plate convergence velocity between the South American and Nazca plates (Pilger, 1984; Pardo-Casas and Molnar, 1987; Sempere et al., 1989, 1990a), and the same interpretation seems valid for the tectonic episode evidenced in this paper.

The unconformities at the base of the Luribay, Coniri and Petaca formations in Bolivia (see Sempere et al., 1990a), of the "Gravas de Atacama" (Mortimer and Saric, 1975; Naranjo and Paskoff, 1980) and their equivalents in northern Chile, of the "Rodados Lustrosos", "Conglomerado Violáceo" and their equivalents in Argentina, and of many other central Andean units (see Sempere, 1990, 1991, for Bolivia), appear to be rough temporal equivalents. This equivalence is particularly based on the occurrence of Deseadan land-mammal faunas in conformably overlying rocks at Salla (~ 17°S) and at Quebrada

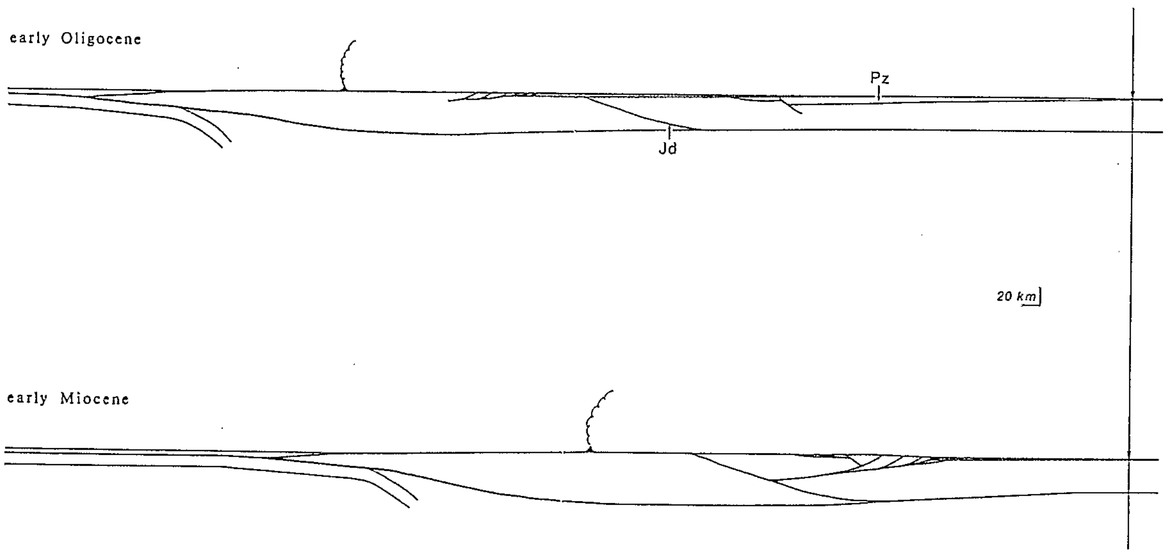


Fig. 5. Cross sections showing tectonic evolution between Divisaderan (Early Oligocene) and late Deseadan (Early Miocene) times in northernmost Chile and Bolivia (in part modified from Sempere et al., 1990a). Section is located in Fig. 1. The external foreland basins are the only synorogenic basins figured (fine dots). Scale is only indicative. *Jd* = Jurassic detachment as proposed by Oller and Sempere (1990); *Pz* = thick infill (predominantly shales) of Paleozoic basin, above relatively thinned crust (see Sempere et al., 1989).

Fiera de Malargüe (~ 36°30′S), and the fact that the Deseadan in both Bolivia and Argentina is constrained between ~ 29 and ~ 21 Ma. The fact that post-unconformity stratigraphic and faunal context at both localities are remarkably similar strongly suggests, on its own, that the basal unconformities are equivalent. Thus, the age of these rocks and faunas are apparently Late Oligocene–Early Miocene and not Early Oligocene as long believed (see above).

In the Andes of central Chile and adjacent Argentina (30°–33°S), this conspicuous regional unconformity was traditionally assigned to the "Incaic phase" (Yrigoyen, 1976, 1979; Ramos, 1988). This decision was based solely on knowledge of an "Early Oligocene" land-mammal fauna reported by Gorroño et al. (1979) and of the associated unconformity below the "Rodados Lustrosos". As the unconformity occurs below what was thought to be an "Early Oligocene" fossil level, Ramos (1988, p. 48) proposed that its age "might be dated as pre-Late Eocene" but cautioned that the age of this unconformity was poorly constrained at these latitudes. These conclusions were based on the belief that the Deseadan SALMA was Early Oligocene and the Divisaderan SALMA Late Eocene (see above).

On the basis of the facts and observations presented above, we assign the unconformity below the "Rodados Lustrosos" to ~ 27 Ma. This age assignment is consistent with the fact that the Cordillera Principal fold-thrust belt corresponds to the "Incaic orogenic front" of Ramos (1988) and had a Late Oligocene–Early Miocene activity. The tectonic and faunal evidences from the contemporaneous deformed area and foreland basin are complementary. It thus appears that this major Andean tectonic episode in central Chile and adjacent Argentina was, as in Bolivia, long confused with the Middle Eocene age "Incaic phase" defined in Peru (see Sempere et al., 1990a).

Yrigoyen (1979) defined a "Pehuenche" diastrophism, which he assigned to the latest Oligocene, on the basis of an unconformity between the Agua de la Piedra Formation (see above and Fig. 3) and the overlying Domuyo–Palaoco Group and Butaló (= Collón Curá) Formation (see also Groeber, 1951). However, according to the presently available chronological data, this unconformity is now at ~ 17 Ma. For this reason, the term "Pehuenche" cannot be applied to the Late Oligocene–Early Miocene deformation dealt with in this paper.

5. Conclusions

There is increasing evidence that the increase in the rate of convergence between the Nazca and South American plates at ~ 26 Ma (Pilger, 1984; Pardo-Casas and Molnar, 1987) had major tectonic, magmatic and sedimentary repercussions on the central Andean margin. In northern Patagonia (45°S), the peak of activity, at about ~ 27–25 Ma, in the Plateau Basalt Series associated with Deseadan land-mammal faunas (see above), was also coeval with this increase in the normal component of convergence (Cande and Leslie, 1986; Rapela and Kay, 1988). Most of this volcanism occurred at ~ 26 Ma, when there was minimal volcanism in the arc to the west (Kay et al., 1990).

More geochronologic studies are clearly needed to better calibrate this tectosedimentary episode in the Andes of central Chile and adjacent Argentina. Although the conclusions of this paper should be regarded as tentative, the available data suggest a remarkable parallel in the orogenic history between the Bolivian Andes (12–22°S) and the Andes of central Chile and adjacent Argentina (32–37°S). At the very least, the data reviewed in this paper demonstrate that the time span between 30 and 25 Ma was a turning point in the tectonic, magmatic, depositional and land-mammal history of South America.

The new data and interpretations from central Chile and adjacent Argentina provide additional evidence for a Late Oligocene–Early Miocene (~ 27–20 Ma) compressional episode in the Andes. This tectosedimentary episode is apparently the same as the one recognized by Jordan and Alonso (1987), beginning at ~ 25 Ma, in northwestern Argentina. All these data suggest that this episode was triggered by a higher convergence rate between the Nazca and South American plates, and that it affected the Andean belt at least between 12 and 37°S. Furthermore, because initiation of major thrusting in the Cordillera Oriental of Colombia likewise occurred at ~ 30 Ma (e.g., Bourgois, 1989), it is likely that this tectonic upheaval occurred also north (and probably south) of this 2800-km-long segment. It would not be surprising if this were to be demonstrated in the forthcoming years by new field studies and by critical revisions and reinterpretations of published information.

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