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Journal of South American Earth Sciences 14 (2001) 707–724

Journal of
South American
Earth Sciences

www.elsevier.com/locate/jsames

Cenozoic tectonic evolution of the Alto Tunuyán foreland basin above the transition zone between the flat and normal subduction segment (33°30′–34°S), western Argentina

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Received 1 March 2000; revised 1 November 2000; accepted 1 April 2001

Abstract

The Alto Tunuyán basin is a Neogene foreland basin located between Cordillera Principal and Cordillera Frontal, from 33°30′ to 34°00′ south latitude. At this latitude, the feature that characterizes the subduction geometry beneath the Andean Cordillera is a transition in the slab dip from nearly horizontal, north of 33°S, to normal dip, south of 34°S. This particular tectonic setting apparently controlled the Neogene tectonic history of the area. The Neogene sedimentary infill of the basin is represented by the Tunuyán Conglomerate and the Palomares, Butaló, and Papal formations. Thrusting and uplift of the Cordillera Principal began during the early Miocene. Deformation and uplift of the volcanic arc, located on the western part of the thrust belt, produced the sediment source for the lower 200 m of the Tunuyán Conglomerate. As deformation migrated progressively eastward during middle Miocene times, it involved the underlying Mesozoic sequences, the erosion of which provided the material accumulated in the rest of the Tunuyán Conglomerate. The Palomares Formation unconformably overlying the former unit reflects the uplift of Cordillera Frontal. Deposition of the Butaló and Papal formations over the partially deformed broken foreland basin reflects accumulation during a period of tectonic quiescence and low rate of erosion in the eastern part of Cordillera Principal and the western part of Cordillera Frontal. The basement uplift of Cordillera Frontal generated a sticking point that prevented the propagation of the thrust belt toward the foreland. Consequently, out-of-sequence thrusts developed in the Cordillera Principal and the basin was partially cannibalized.

Keywords: Foreland basin system; Andean evolution; Transition subduction segment

Resumen

La cuenca del Alto Tunuyán corresponde a una cuenca de antepaís ubicada entre las cordilleras Principal y Frontal, entre los 33°30′ y los 34°00′S. La misma se encuentra sobre el segmento de transición entre una zona de subducción normal y una zona de subducción subhorizontal. Este ambiente tectónico particular controló la evolución de la cuenca durante el Neógeno. El relleno sedimentario neógeno de la cuenca está representado por el Conglomerado Tunuyán y las Formaciones Palomares, Butaló y Papal. Durante el Mioceno temprano comenzó la estructuración de la faja plegada y corrida de la Cordillera Principal, generando una cuenca de antepaís. El levantamiento del arco volcánico primero, y luego el de las secuencias mesozoicas, se ve reflejado en la procedencia de los depósitos sinorogénicos del Conglomerado Tunuyán. Durante el Mioceno medio, un importante evento tectónico afectó al basamento de la cuenca, elevando la Cordillera Frontal. En el sector norte de la cuenca se depositaron los sedimentos de la Formación Palomares, cuyas paleocorrientes indican procedencia desde el noreste evidenciando la estructuración del Cordón del Plata y el sector norte del Cordón del Portillo, en la Cordillera Frontal. El sector sur del Cordón del Portillo se habría elevado con posterioridad y su deformación no habría sido tan importante como en el sector norte. La depositación de las sedimentitas de la Formación Butaló, en el sector norte de la cuenca, y de la Formación Papal, en el sector sur, reflejan un período de quietud tectónica. Posteriormente el levantamiento de la Cordillera Frontal actuó como punto de fijación controlando la generación de corrimientos fuera de secuencia en la faja plegada y corrida y de la cuenca de antepaís.

Palabras-clave: Foreland basin system; Andean evolution; Transition subduction segment

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PII: S0895-9811(01)00059-1

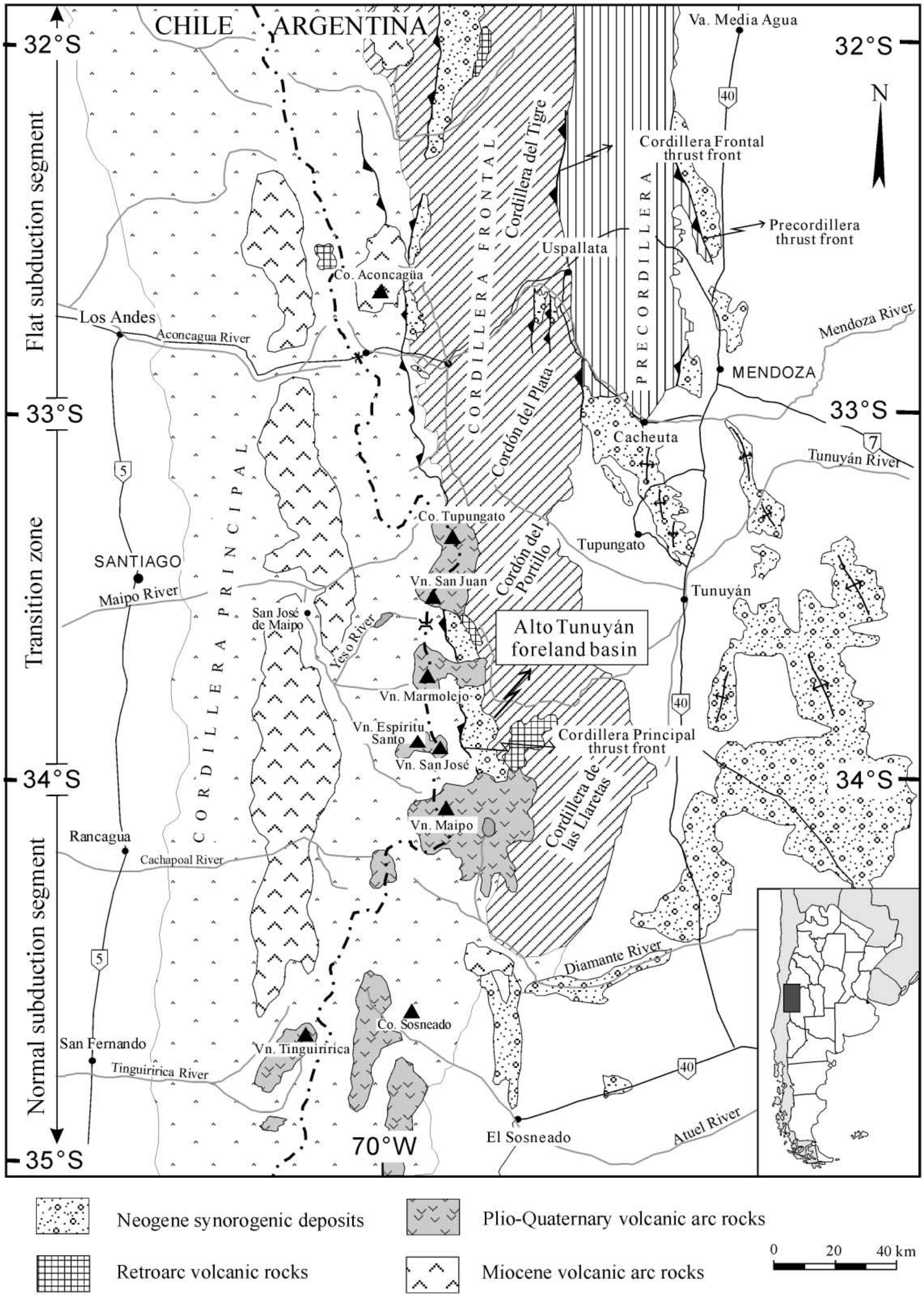

Fig. 1. Morphostructural map of the Andean Mountains between 32 and 35°S, and location of the Alto Tunuyán foreland basin.

1. Introduction

The Neogene foreland basins of Mendoza Province, in western central Argentina, are characterized by a N–S trend, parallel to the main structures of the Andes (Fig. 1). The history of these basins is intimately linked to the Andean tectonic events, which are themselves related to the geometry of the subducted plate. The segment of subducted slab located between 33 and 34°S has been pointed out to be a transition zone between the flat and the normal subduction segments (Cahill and Isacks, 1992). Nevertheless, questions about how it influenced the deformation of this portion of the Andes still persist. The Alto Tunuyán basin is a good example of the interaction between tectonics and sedimentation. It is a Neogene foreland basin located between Cordillera Principal and Cordillera Frontal, from 33°30′ to 34°S. The sedimentary infill of the basin is closely linked to the tectonic development of both ranges, and it is quite different from the foreland basins located to the north, above the subhorizontal subduction segment (Pérez, 1995; Pérez and Ramos, 1996; Jordan et al., 1996), and to the south, above the normal subduction zone (Kraemer and Zulliger, 1994; Zulliger, 1994; Combina et al., 1997; Achilli et al., 1999; Kraemer et al., 1999).

The first observations in the area were made by Darwin (1846), who described the possible provenance of the synorogenic sediments, named by him Tunuyán Conglomerate. Stratigraphic studies were carried out later by Polanski (1957, 1964). However, the characteristics and tectonic setting of the Neogene strata were poorly understood. Studies performed during recent years shed some light on the sedimentary, structural, and tectonic evolution of the region (Ramos et al., 1996b; Pángaro et al., 1996; Pérez et al., 1997; Ramos et al., 1998; Giambiagi, 1999a,c).

Most patterns of synorogenic sedimentation suggest a cratonward progression of thrusting. However, detailed field observations in the Alto Tunuyán foreland basin have led to the conclusion that the generation of the Andean Mountains at these latitudes has a more complex history than a simple foreland progression. The aim of this paper is to propose a model for this tectonic evolution and its relations with the tectonic setting.

2. Tectonic setting

The Andean Mountains develop along the contact between the Nazca Plate and the South American Plate. The distribution of seismicity suggests that the Nazca Plate is characterized by alternating flat and normal segments of subduction (Baranzangi and Isacks, 1976; Cahill and Isacks, 1992). Several anomalous features of the Andes orogenic system appear to correlate with these geometries, such as volcanism and distribution of morphostructural belts (Isacks et al., 1982; Jordan et al., 1983). North of 33°S, a flat subduction segment without arc magmatism underlies the Cordillera Principal, Cordillera Frontal, Precordillera, and Sierras Pampeanas structural provinces since early Miocene. South of 34°S, a normal subduction segment with arc magmatism underlies the Cordillera Principal and the Cordillera Frontal. Neither Precordillera nor Sierras Pampeanas were developed in this segment, because the foreland was not involved in the deformation (Fig. 1). The subducted plate geometry influences foreland deformation; subhorizontal subduction is associated with extended foreland deformation, while in the normal subduction zone the foreland is not involved (Jordan et al., 1983).

The study area is located in the transition between a flat slab to the south of 34°S and a normal slab to the north of 33°S. The transition appears to occur as a smooth flexure of the subducted slab rather than a tear (Cahill and Isacks, 1992), and only the horizontal part of the slab, located north of 33°S, decreases toward the south until it disappears (Fuenzalida et al., 1992).

3. Structural provinces

The Andes Mountains at these latitudes comprise two parallel morphostructural units: Cordillera Principal to the west and Cordillera Frontal to the east. The two ranges are separated by a Neogene foreland basin, named "Depresión intermontana del Alto Tunuyán" by Polanski (1957) (Fig. 1).

Taking into account the degree of basement involved in the deformation, the fold-and-thrust belts of Cordillera Principal have been divided in Mendoza Province by Ramos (1988) and Kozlowski et al. (1993) in two segments: Aconcagua and Malargüe. The Aconcagua fold-and-thrust belt, developed between 32°00′ and 34°15′S (Cegarra and Ramos, 1996) in Cordillera Principal, is characterized by thin-skinned tectonics with detachment in the Mesozoic sequences and low-angle thrusting (Ramos et al., 1996a). The Malargüe fold-and-thrust belt, located between 34°15′ and 38°00′S, is a thick-skinned fold-and-thrust belt formed by tectonic inversion of a Late Triassic–Lower Jurassic rift system during late Cenozoic times (Kozlowski et al., 1993). The Cordillera Frontal, which extends from San Juan Province to Diamante River (34°30′S), is characterized by ample basement block faulting (Polanski, 1964).

4. Timing of deformational events

Deformation within the Andes Mountains appears to have migrated from west to east since the early Miocene. It occurred as a result of the increase in the rate of convergence between the South American and Nazca Plates since late Oligocene times (Pilger, 1981; Pardo Casas and Molnar, 1987). Compressional deformation took place mainly between early Miocene and late Miocene (22–8 Ma) (Ramos et al., 1996a). Irigoyen et al. (1998, 2000) have examined the timing of thrusting in the Aconcagua fold-and-thrust belt at these latitudes through paleomagnetic and chronological studies of synorogenic Neogene strata cropping out in the Cacheuta–Tunuyán area. Deformation of this thrust belt is interpreted to have begun by at least 16 Ma.

The Alto Tunuyán foreland basin was generated by flexure as a response to the thrust-belt load. During the development of the basin, the volcanic arc was active in

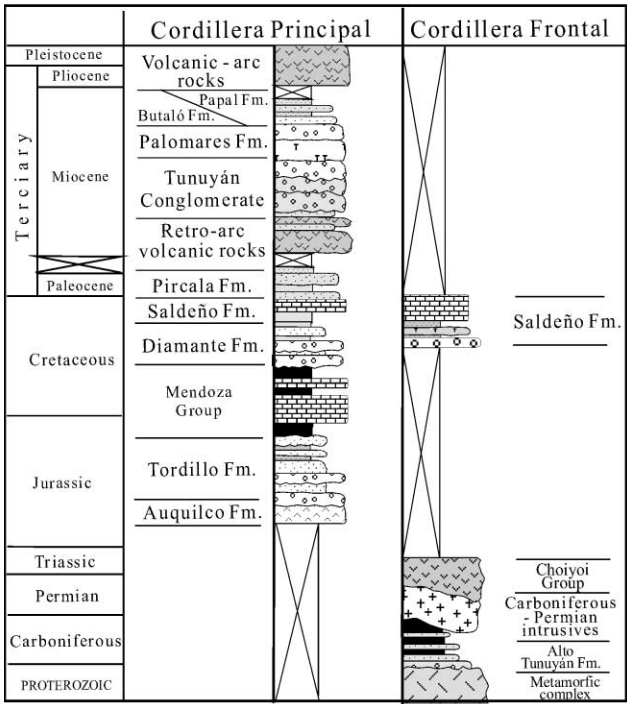

Fig. 2. Generalized stratigraphic column of the units outcropping in Cordillera Principal and Cordillera Frontal between 33°30′ and 34°S.

the Chilean slope of Cordillera Principal, being represented by calc-alkaline andesites and rhyolites of the Farellones Formation, that range in age from 20 to 10 Ma (Drake et al., 1982; Rivano et al., 1990) (Fig. 1). At this time, in the Argentine slope of Cordillera Principal, retroarc volcanism was active (Ramos et al., 1996b). One sample of this volcanism has been dated in 18.3 Ma (Giambiagi, 2000), indicating that the deformation had not taken place by that time.

The Cordillera Frontal basement block probably was not a positive feature at this latitude until after 11 Ma. At that time, deformation of Cordillera Frontal was just beginning. Immediately prior to 9.7 Ma, there was a marked increase in subsidence in the Cacheuta–Tunuyán basin, most likely related to a significant phase of deformation (Irigoyen et al., 1998). By this time, the volcanic activity ceased in the flat-subduction segment and modern tectonic segmentations came into existence (Jordan et al., 1983; Jordan and Allmendinger, 1986; Kay et al., 1987). As was pointed out by Johnson et al. (1986) in the Sierra de Huaco area, at 30–31°S, there was synchronicity between these plate tectonic events and thrusting and uplift of Precordillera. Above the transition segment in the study area, there is evidence of the relationship between this plate tectonic event and the uplift of Cordillera Frontal.

The volcanic arc migrated eastward to its present position in the Argentine–Chilean border by Early Pliocene times, postdating all the thrusts in Cordillera Principal. The eastern anticlines near Tunuyán city mark the edge of the modern deformation front.

5. Stratigraphy

The stratigraphy of the study area, illustrated in Fig. 2, can be divided into five main strata intervals (Alvarez et al., 1999 and references therein; Alvarez, 1997; Ghiglione, 1998), namely: (1) pre-Jurassic rocks of the crystalline basement outcropping in Cordillera Frontal; (2) Upper Jurassic–Lower Cretaceous marine and nonmarine sequences of Cordillera Principal; (3) Upper Cretaceous–Lower Tertiary deposits corresponding to Saldeño and Pircala formations; (4) Tertiary synorogenic foreland basin deposits; and (5) late Miocene retroarc volcanic rocks and Pliocene–Quaternary volcanic arc rocks.

5.1. The Neogene synorogenic deposits

Synorogenic sediments filling the basin are represented by three Miocene formations that record alluvial and fluvial deposition (Giambiagi, 1999a) and one marine unit that records a Miocene ingression (Pérez et al., 1997). Each of these units reflects a major tectonic phase in the basin development.

5.1.1. Tunuyán Conglomerate

The Tunuyán Conglomerate is well developed in the whole basin and crops out in an elongate trough from the Palomares River area to the Papal stream area (Fig. 3). It consists of synorogenic coarse sediments deposited in an alluvial-fan setting, reaching up to 1400 m in thickness in the northern part of the basin and 1100 m in the southern part (Fig. 4). The vertical variation in clast composition of the synorogenic deposits reflects the progressive erosion and unroofing of the Aconcagua fold-and-thrust belt. The clast imbrications, which indicate that paleoflows were to the east, are consistent with this hypothesis (Giambiagi, 2000). The lower 200 m of this unit are made up of clasts derived from the volcanic arc situated in Chile by this time, while the upper member is characterized by clasts derived from both the volcanic arc and the Mesozoic sequences of Cordillera Principal (Giambiagi, 1999c).

The Tunuyán Conglomerate is the western proximal equivalent of the Miocene distal synorogenic deposits known as the Mariño Formation, which crops out to the east of Cordillera Frontal foothills (Fig. 1). These two units should have been deposited in the same foreland basin, being the Tunuyán Conglomerates' coarsest basin facies. Irigoyen et al. (1998, 2000) studied the Mariño and La Pilona formations at Cacheuta–Tupungato area, from 33°00′ to 33°20′S. Magnetostratigraphy, calibrated by ^{40}Ar–^{39}Ar dating of interbedded air-fall deposits, indicates 15.7 Ma for the base of the Mariño Formation and 12.2 Ma for the top. Based on these data, the Tunuyán Conglomerate can be approximately constrained between 16 and 12 Ma (middle Miocene); but its top can probably be younger (approximately 10–9 Ma).

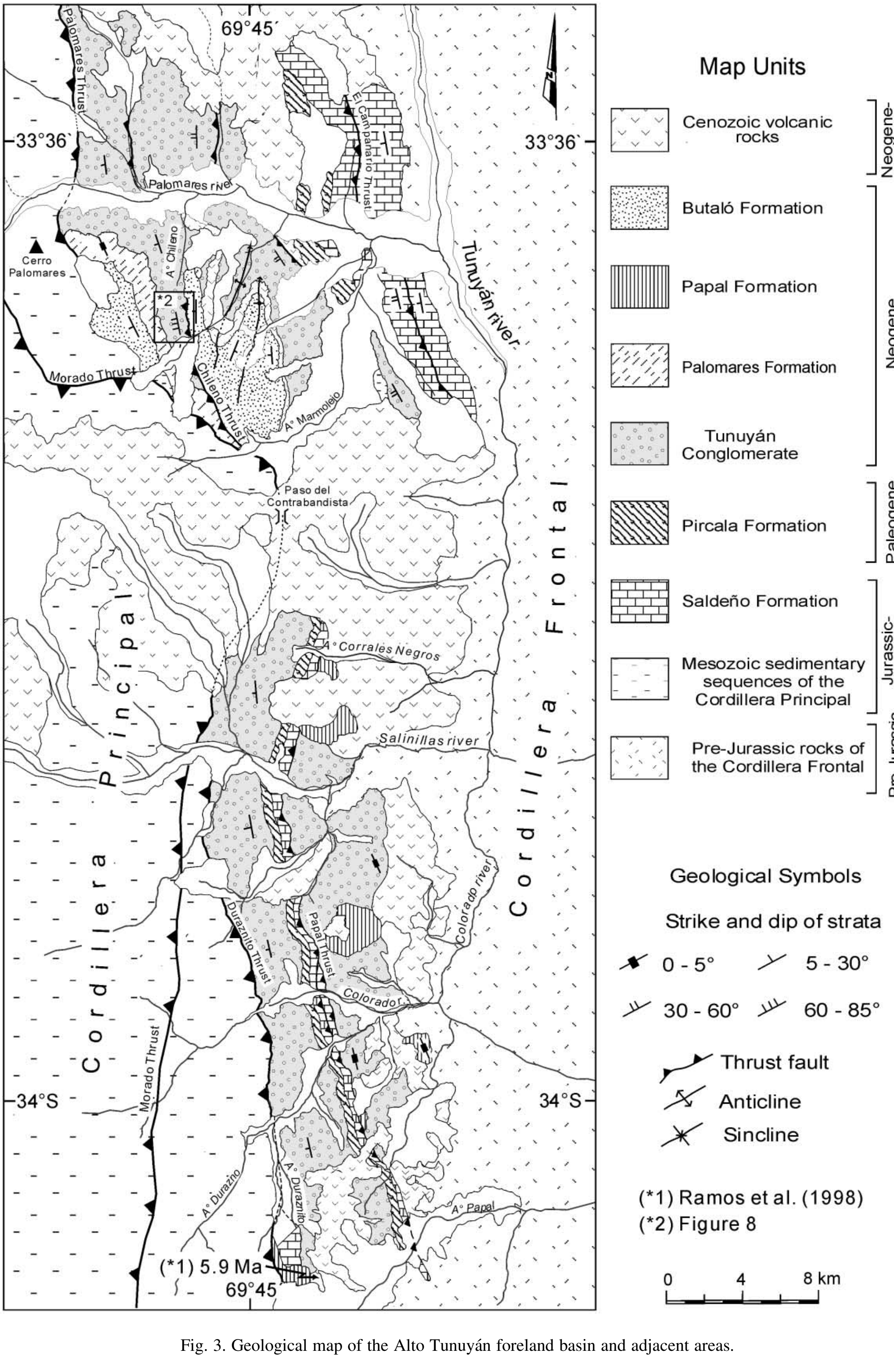

Fig. 3. Geological map of the Alto Tunuyán foreland basin and adjacent areas.

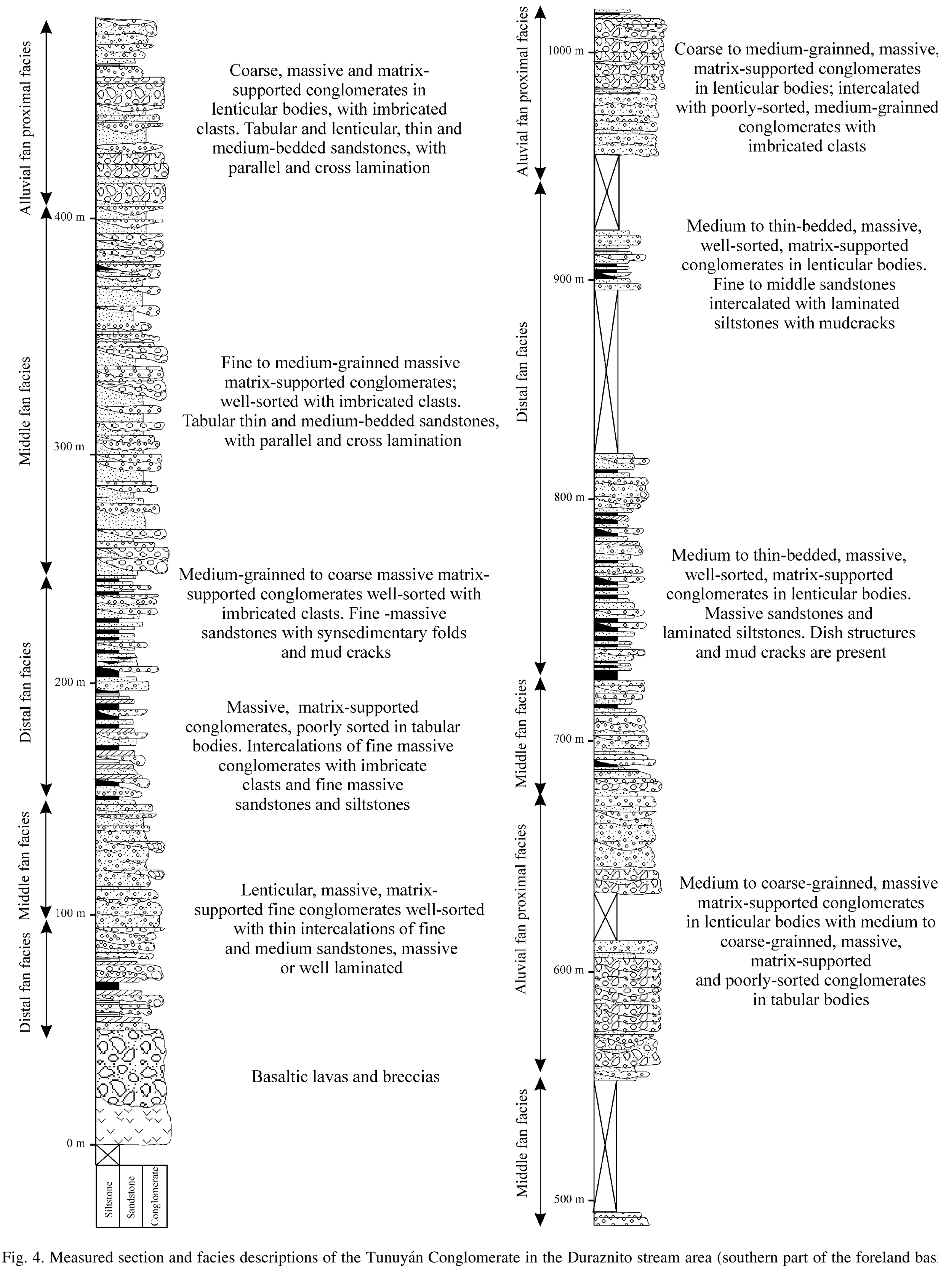

Fig. 4. Measured section and facies descriptions of the Tunuyán Conglomerate in the Duraznito stream area (southern part of the foreland basin).

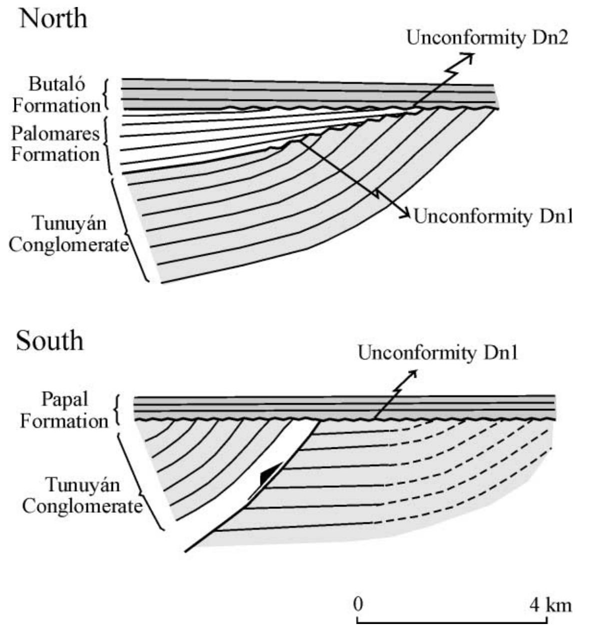

Fig. 5. Schematic diagrams, not to scale, showing: (a) angular unconformity Dn1 and progressive unconformity Dn2 in the northern part of the basin; and (b) angular unconformity Dn1 in the southern part.

5.1.2. Palomares Formation

The Palomares Formation is unconformably overlying the Tunuyán Conglomerate, and it consists of volcaniclastic and clastic sediments deposited in an alluvial-fan setting. It has a maximum thickness of 200 m. The distribution of this unit is limited to the northwestern part of the basin (Fig. 3). South of Paso del Contrabandista, the unit is absent and the Papal Formation unconformably overlies the Tunuyán Conglomerate.

Another unit that records this uplift in the Cordillera Frontal foothills is La Pilona Formation, which crops out eastward of Cordón del Portillo and Cordón del Plata (Fig. 1). Deposition of La Pilona Formation started at or slightly before 11.7 Ma and continued to 9 Ma in the Cacheuta-Tupungato area; sedimentological and paleocurrent studies indicate provenance exclusively from Cordillera del Tigre (Fig. 1) (Irigoyen et al., 1998). This suggests that the Cordón del Plata was not a positive feature at that time. The paleocurrent measurements in the Palomares Formation indicate north-east provenance, revealing the uplift of Cordón del Plata after 9 Ma, during the late Miocene.

5.1.3. Butaló Formation

The Butaló Formation records the final infilling of the intermontane trough between Cordillera Principal and Cordillera Frontal. The distribution of this unit is restricted to the area located between Palomares and Marmolejo rivers (Fig. 3). It reaches a thickness of more than 300 m in the north of the basin and is made up of medium- to fine-grained fluvial and lacustrine deposits bearing fossil plants that corroborate its continental origin (Giambiagi, 1999a). The study of clast provenance allows us to distinguish both Cordillera Principal and Cordillera Frontal as source areas.

5.1.4. Papal Formation

The Papal Formation appears as small outcrops from Corrales Negros stream to Papal stream (Fig. 3). It reaches up to 350 m in thickness south of Cerro Papal, where it was divided by Herrero Ducloux and Yrigoyen (1952) into four members, composed of sandstones, marbles, fine conglomerates, and 100 m of gypsum and siltstones. Pérez et al. (1997) interpreted these sediments as having been deposited in a marine environment.

5.1.5. Correlation between the Papal and Butaló formations

The Butaló Formation has been correlated with the Papal Formation by Polanski (1964), who suggested that they have been simultaneously deposited in unconnected basins. Although the Papal Formation reflects a different environment of deposition from the Butaló Formation, both units have key features in common. First, both overlie the Tunuyán Conglomerate with an angular unconformity that postdates the fault activity in the thrust front of the Aconcagua fold-and-thrust belt (Fig. 3). Second, both units are affected by the Chileno and Papal thrusts, which appear to be coeval. The Papal and Butaló formations are overlaid in angular unconformity by andesitic volcanic arc rocks. On the basis of K/Ar dating of these andesites (5.9 Ma, Ramos et al., 1998), the minimum possible age for these synorogenic deposits is upper-late Miocene.

6. Unconformities separating the Neogene units

Two unconformities separating the synorogenic units have been recognized (Giambiagi, 1999b). In the northern part of the basin, the lower erosive unconformity (unconformity Dn1) separates the Tunuyán Conglomerate and the Palomares Formation. It is a conspicuous angular unconformity in the eastern part and a paraconformity in the western part (Fig. 5a). The onlap relationship between Palomares Formation and the underlying Tunuyán Conglomerate indicates erosion of at least 600 m of sediments and therefore a significant uplift and erosion prior to deposition of the conglomerates. This event is related to the regional uplift of Cordillera Frontal.

In the southern part of the basin, the Papal Formation is separated by the unconformity Dn1 from the underlying Tunuyán Conglomerate and Saldeño Formation. This is a high-angle angular unconformity in the Duraznito stream area and a paraconformity in the Colorado River area (Fig. 5b).

The second unconformity, Dn2, can only be observed in the northern part of the basin. It is angular in the central part and a paraconformity toward the west (Fig. 5a). It outlines the boundary between the growth strata represented by

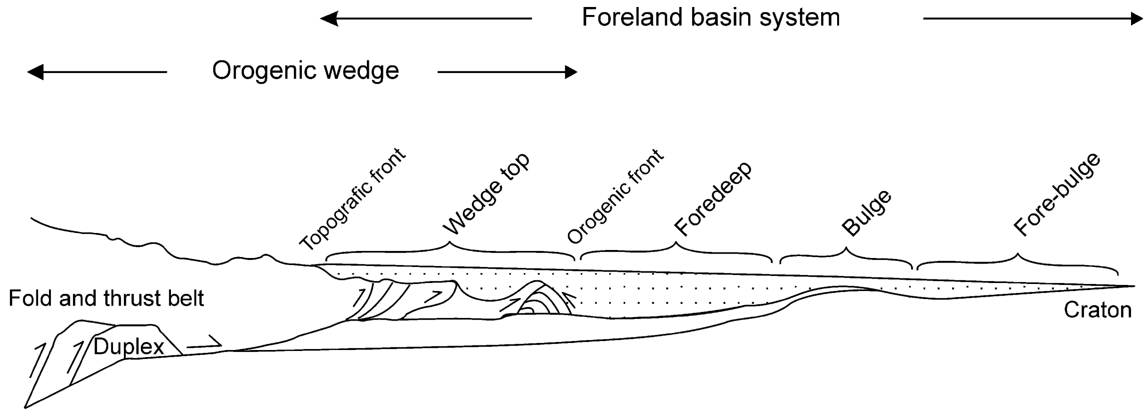

Fig. 6. Foreland basin system divided in four zones of sediment accumulation: wedge-top, foredeep, forebulge, and back-bulge depozones. (From DeCelles and Giles, 1996).

Palomares Formation, which offlap the hanging wall of the deep fault in the basement of Cordillera Frontal, and the deposits of Butaló Formation, which overlap the hanging wall above. The growth strata display a wedge-shaped geometry thinning eastward and decreasing in dip upward. Their geometries are interpreted to be a composite progressive unconformity (Riba, 1976) and indicate progressive limb tilting during sedimentation. In the southern part, this accumulative wedge is absent and there is no evidence of any progressive unconformity (Fig. 5b).

7. The Alto Tunuyán foreland basin system

Many modern and ancient foreland basin systems consist of four zones of sediment accumulation: the wedge-top, foredeep, forebulge, and back-bulge depozones (DeCelles and Giles, 1996) (Fig. 6). The wedge-top depozone overlies the orogenic taper and is characterized by the abundance of progressive unconformities and synsedimentary growth structures developed as the deformation front migrates forward within the subsiding basin and the sedimentary wedge is progressively incorporated in the thrust deformation. The foredeep depozone occurs between the structural front of the thrust belt and the proximal flank of the forebulge, and they typically consist of a thick sedimentary column that has not been affected by deformation during deposition. The forebulge depozone is a region of potential flexural uplift that may be marked by an unconformity or by a zone of thin, highly condensed sedimentation (DeCelles et al., 1998). The back-bulge depozone is the mass of sediment that accumulates in the zone of potential flexural subsidence cratonward of the forebulge.

In order to describe the Alto Tunuyán foreland basin system, the study area has been divided into two regions: the northern part, located in the Palomares River area, and the southern part, between Salinillas River and Papal Stream (Fig. 3).

7.1. Northern part

In this region, the deposits of the foredeep and the wedge-top depozones are juxtaposed vertically in response to a lateral migration during Miocene times (Fig. 7). The lower 1000 m of the Tunuyán Conglomerate represent a wedge of sediment that thickens toward the fold-and-thrust belt and thins cratonward. This wedge was not affected by deformation during the deposition of the conglomerate, and it is interpreted as part of the foredeep depozone fed by tributaries from the thrust belt.

Several syntectonic unconformities are well developed in the proximal alluvial-fan facies of the upper 400 m of the Tunuyán Conglomerate, suggesting a wedge-top depozone environment controlled by local thrust movement (Fig. 7). These features are well developed in the Chileno stream area (Fig. 3). Fig. 8 shows details of the growth strata and the unconformities. The geometry of these strata has been characterized as a cumulative wedge with rotative onlap, which would document a decrease in uplift rate through time (Giambiagi, 1999b). The cumulative wedge system results directly from the uplifting process, and it is developed as a rotative onlap. Beds in the lower part of the conglomerate dip 60°W, but the amount of dip decreases progressively upsection, being only 20–25°W at the top of the section. There are two possible explanations for these unconformities: (1) the migration of the thrust front eastward and emplacement of thrusts within the basin; and (2) the uplift of Cordillera Frontal. As there is no evidence of the uplift of this range at the time of the deposition of the Tunuyán Conglomerate, it is likely that there was deformation within the foreland basin. These syntectonic unconformities record rapid, localized uplift contemporaneous with sedimentation.

These strata covered the frontal part of the Aconcagua fold-and-thrust belt and tapered onto it. The transition from foredeep to wedge-top depozone occurred when the front of the deforming wedge penetrated the basin. After the uplift of Cordillera Frontal and the generation of a broken foreland

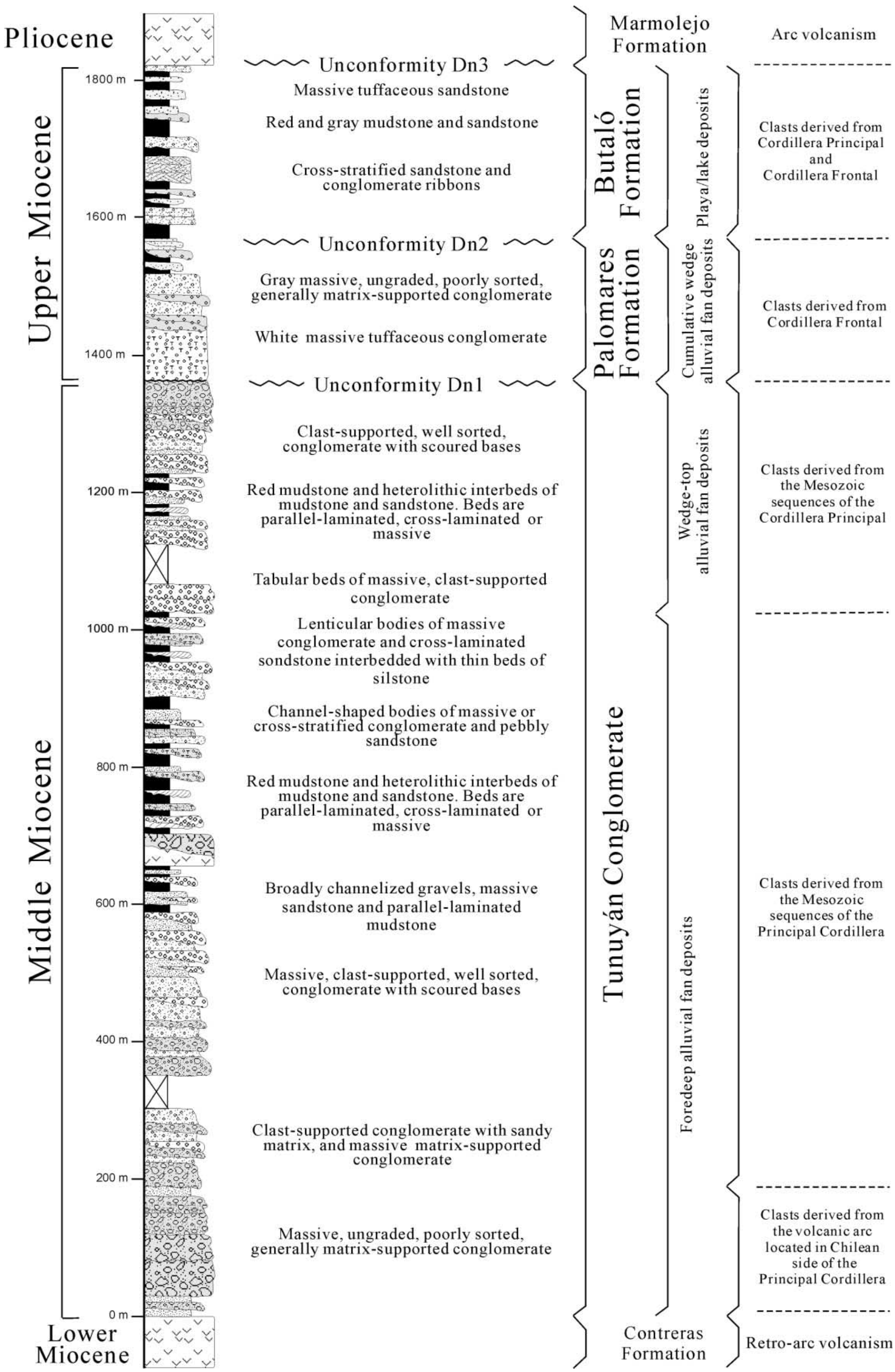

Fig. 7. Representative vertical sedimentary section of the Tunuyán Conglomerate, and Palomares and Butaló formations. Depositional environment and clast provenance are indicated.

Fig. 8. Detail of the syntectonic unconformity in the upper part of the Tunuyán Conglomerate, in the Chileno Stream area (dashed lines). The arrow indicates one of the erosive surfaces within strata.

basin as defined by Jordan (1995), the synorogenic strata represented by the Palomares and Butaló formations were deposited.

7.2. Southern part

In the southern part of the basin, up to 1100 m of synorogenic strata of the Tunuyán Conglomerate were deposited in the foredeep depozone of the foreland basin system. There is no evidence of growth structures or progressive unconformities, indicating that faults within the basin were not active during deposition of this unit. However, the top of the section is cut by the Duraznito thrust, so there is a possibility that the growth strata have been eroded.

The lowest beds of the Tunuyán Conglomerate onlap the crystalline basement of Cordillera Frontal in the north side of Colorado River, indicating deposition against a pre-existing relief. In this area, the foreland basin fill exhibits a major unconformity at the base, where the absence of the Saldeño and Pircala formations represent an important stratigraphic gap. In the Palomares River area there is a paraconformity between Pircala Formation and the synorogenic units. However, in the Marmolejo stream area, the Tunuyán Conglomerate unconformably overlies the Saldeño Formation. Thus the gap is represented by an erosional unconformity with lateral transition to conformity toward the north. This reflects uplift of the southern part of Cordillera Frontal as a forebulge during the first stage of thrusting in Cordillera Principal. This forebulge could have been rapidly buried by sediments shed off from the orogen when the basin became overfilled. Afterwards the Papal Formation was deposited in a broken foreland basin over the previously deformed synorogenic strata.

8. Structure of the Alto Tunuyán foreland basin

The structure of the Aconcagua fold-and-thrust belt is characterized by a series of east-verging NS-trending thrusts that propagate toward the foreland, showing a piggy-back order and out-of-sequence thrusts (Ramos et al., 1996a). These structures deformed Mesozoic and Tertiary sedimentary and volcanic rocks, and were active until Pliocene time. The structures present in the study area are the most external expression of this fold-and-thrust belt.

Six main thrusts deformed the synorogenic sediments: Palomares, Chileno, El Campanario, and Morado thrusts in the northern part of the basin, and Duraznito and Papal thrusts in the southern part (Fig. 3). In the Palomares River area, the thrust front of Cordillera Principal crops out in the Cerro Palomares. The internal structure of this hill is characterized by an imbricate thrust fan with hanging-wall folds, termed here Cerro Palomares thrust system (Figs. 3 and 9). It has previously been studied by Pángaro et al. (1996), who remarked its complex deformation history. In this area, major structures are exceptionally well exposed and detailed mapping revealed a number of features that define the relationships between the structure and the synorogenic sediments. The Cerro Palomares thrust system uplifts the Mesozoic sequences over the upper part of the Tunuyán Conglomerate and the Palomares Formation. It is formed by three main thrusts: I, II, and III, the latter corresponding to the Palomares thrust.

The Palomares thrust is an east-vergent, low-angle reverse fault that splits into two thrusts (thrusts IIIa and IIIb). It is an out-of-sequence thrust because it prograded in the hanging wall of the earlier thrust II, and it cuts previous deformed structures (Fig. 9). The anticline observed in Fig. 9 is interpreted to be a fault-related fold that has been translated along a fault (thrust II) through the anticline forelimb (*hybrid fold* of Mitra, 1986). This fault dies out below the lower member of Palomares Formation. Pángaro et al. (1996) interpreted the Neogene strata observed on top of the frontal limb as a roof sequence detached from the underlying thrust by a roof thrust with backthrust sense. During the foreland thrusting, the roof rocks are uplifted and tilted; however, instead of tilted strata over the anticline, subhorizontal strata are observed. The subhorizontal beds in the Cerro Palomares area indicate that the layers do not predate the folding. The Palomares Formation overlaps the inactive thrust II and the erosional surface that affect the Tunuyán Conglomerate (unconformity Dn1). There are two possible explanations for this geometry: either the sedimentation was coeval with the

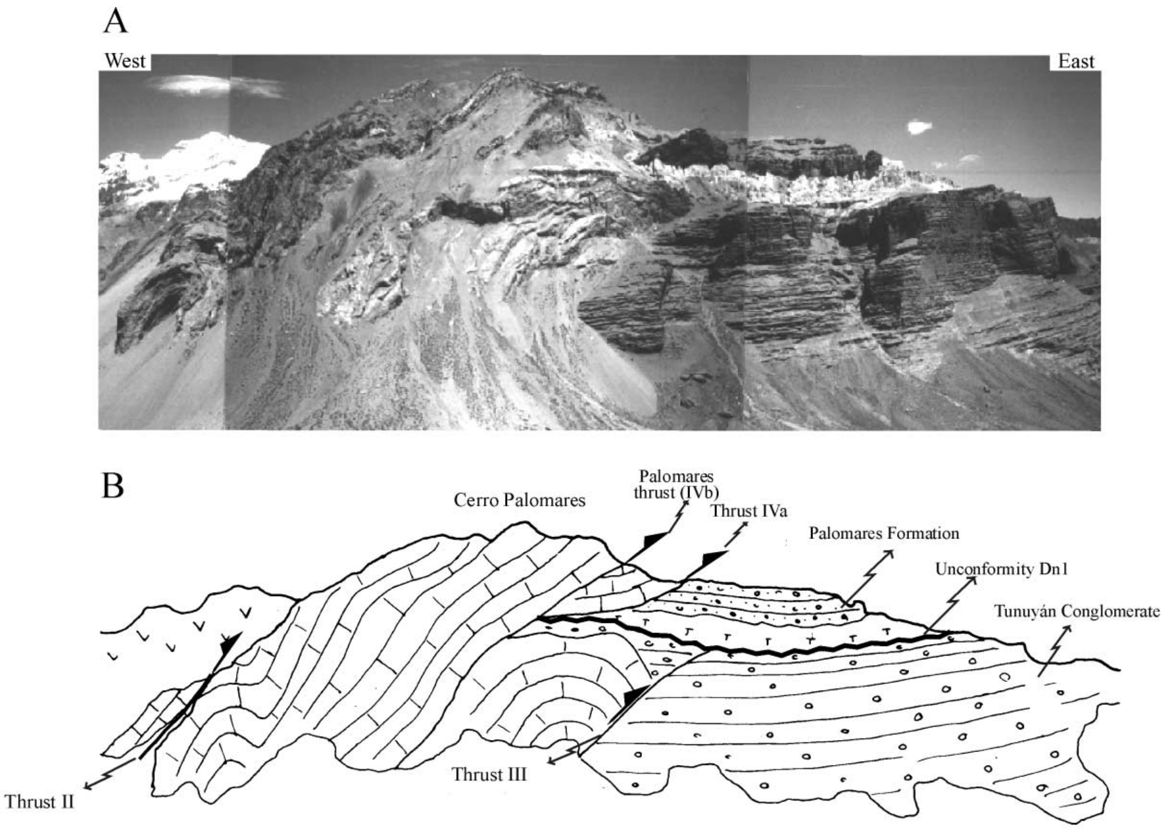

Fig. 9. (a) View of the Cerro Palomares, showing the Palomares thrust system, which uplifts the Mesozoic sequences over the upper part of the Tunuyán Conglomerate and the Palomares Formation. (b) Field sketch of A, showing the relationship between the structures and the synorogenic units.

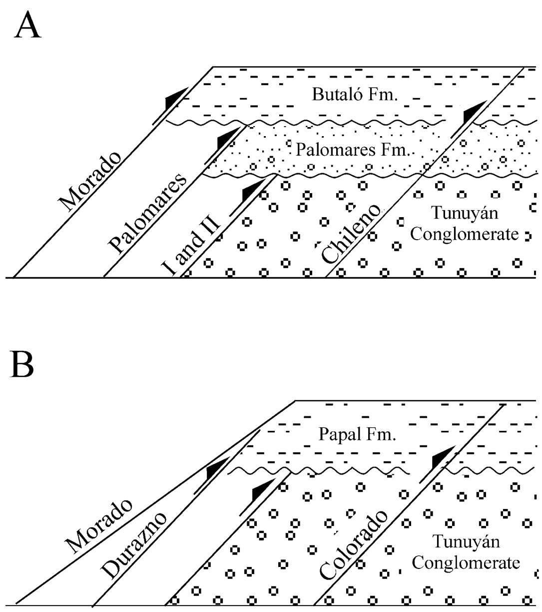

Fig. 10. Schematic cross-sections showing the relationships between thrusts and synorogenic units. (a) Northern part of the basin: Thrust I and II only affect the Tunuyán Conglomerate. Palomares thrust ramps through the Tunuyán Conglomerate and Palomares Formation, and it is covered by Butaló Formation. The Morado and Chileno thrusts affect all the Neogene units. (b) Southern part of the basin: Thrust I only affects the Tunuyán Conglomerate; Duraznito breakthrust cuts Papal Formation, and it is cut by Morado out-of-sequence thrust; the Papal thrust affects all the Neogene units.

folding with a low sedimentation rate relative to the fold uplift rate (Suppe et al., 1992; Zoetemeijer et al., 1993); or the strata were deposited after the generation of thrust II and during the development of thrust I or III (Zoetemeijer and Sassi, 1992). In the eastern flank of Cerro Palomares, this thrust system is covered unconformably by the Butaló Formation (Fig. 3).

The Chileno thrust, located between Palomares and Marmolejo rivers, is detached over the Saldeño Formation and ramped through this unit and the Tertiary strata. The development of this fault is thought to be related to the generation of the syntectonic unconformities registered in the upper 400 m of the Tunuyán Conglomerate. These strata indicate sedimentation above an active thrust, while the lower part of the Tunuyán Conglomerate corresponds to pre-tectonic sedimentation. On the other hand, the Chileno thrust affected the Butaló Formation (Fig. 10). These observations suggest that the fault formed in two stages: an initial stage during the middle Miocene, and a reactivation stage during the late Miocene. This fault loses displacement and disappears toward the north.

The Butaló Formation was folded together with the Tunuyán Conglomerate into an anticline and a syncline in the Palomares River area (Fig. 3). The folds, interpreted to be fault-bend folds, vanish just north of the Palomares River. To the south, in the Arroyo Marmolejo area, they are cut by

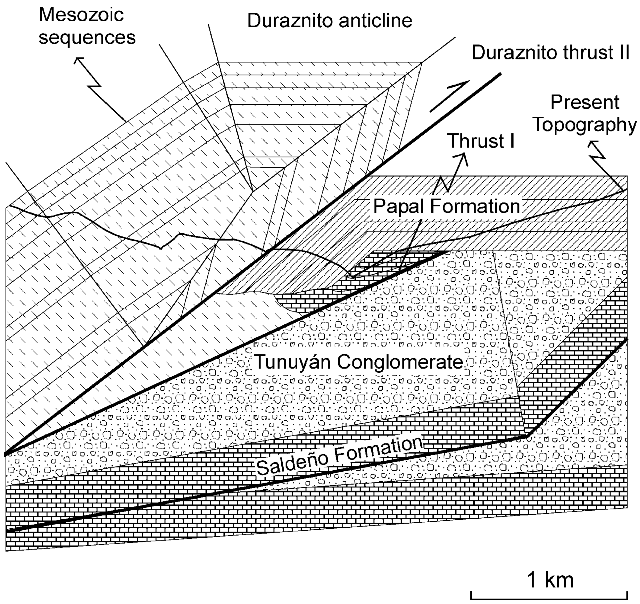

Fig. 11. Detailed geological cross-section of the Duraznito stream area.

Chileno and Morado thrusts. El Campanario thrust, which carries those folds in its hanging wall, emerges eastward near Tunuyán River. There is no evidence of onlap against the folds that seem to be the youngest structures of the area.

South of Paso del Contrabandista, the most outstanding structure is the Duraznito thrust (Fig. 3), which is a breakthrust with a N–S strike and vergence toward the east. This fault developed in two stages, which are documented in the headwaters of the Duraznito stream area by geological relationships (Fig. 11). During the first stage, prior to the deposition of Papal Formation, thrust I developed as an in-sequence thrust, uplifting an anticline of Mesozoic sequences over the Tunuyán Conglomerate. During the second stage, after the deposition of the Papal Formation, the reactivation of this thrust generated a breakthrust, thrust II, which cuts the frontal limb of the anticline and deforms unconformity Dn1. To the east, Papal thrust represents the orogenic front of the Cordillera Principal in this part of the studied area. This fault places Saldeño Formation over the Tunuyán Conglomerate and the Papal Formation.

One of the most laterally extensive structures of the frontal part of the Aconcagua fold-and-thrust belt is a west-dipping out-of-sequence thrust named Morado thrust. This fault cuts off the hanging wall of the Palomares and

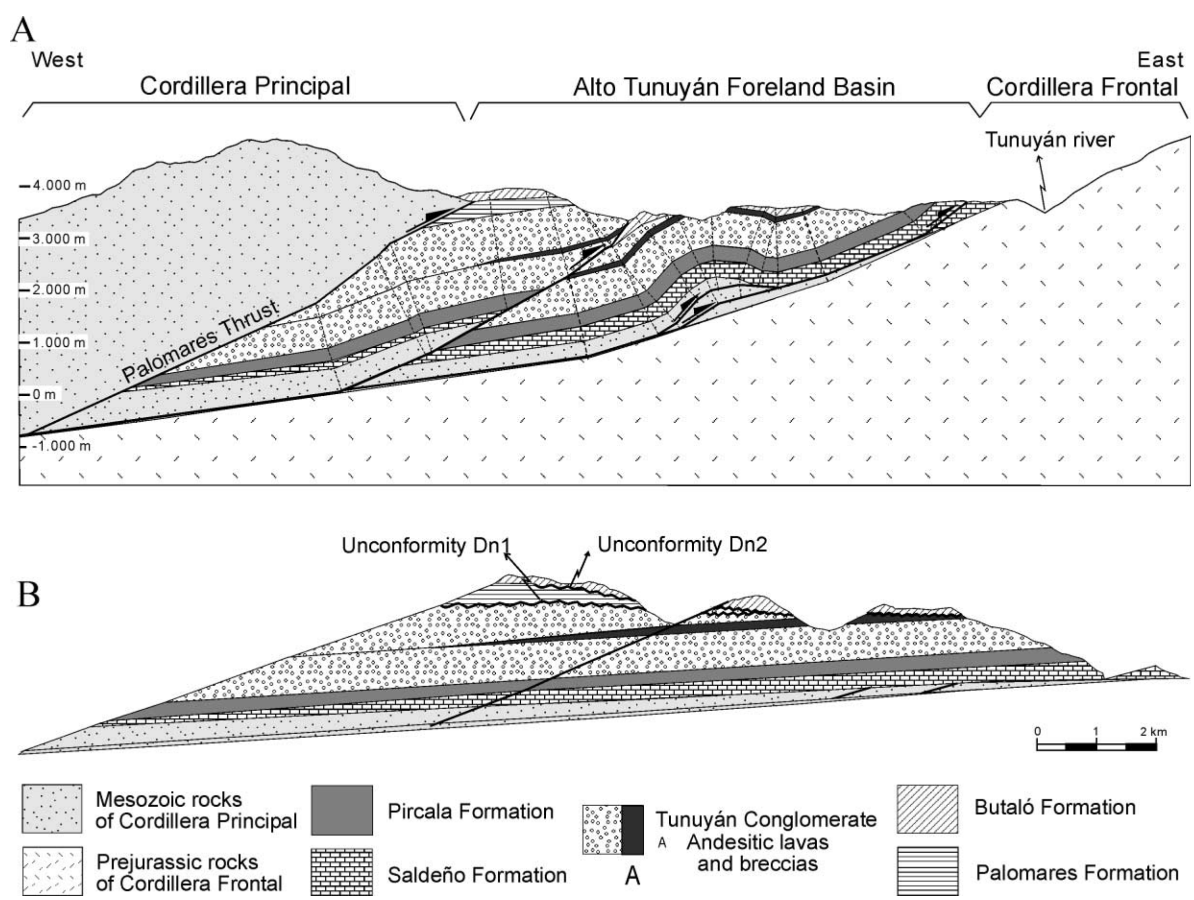

Fig. 12. (a) Balanced structural cross-section of the northern part of the basin. (b) Palinspastic reconstruction showing the unconformities Dn1 and Dn2. (From Giambiagi, 1999c).

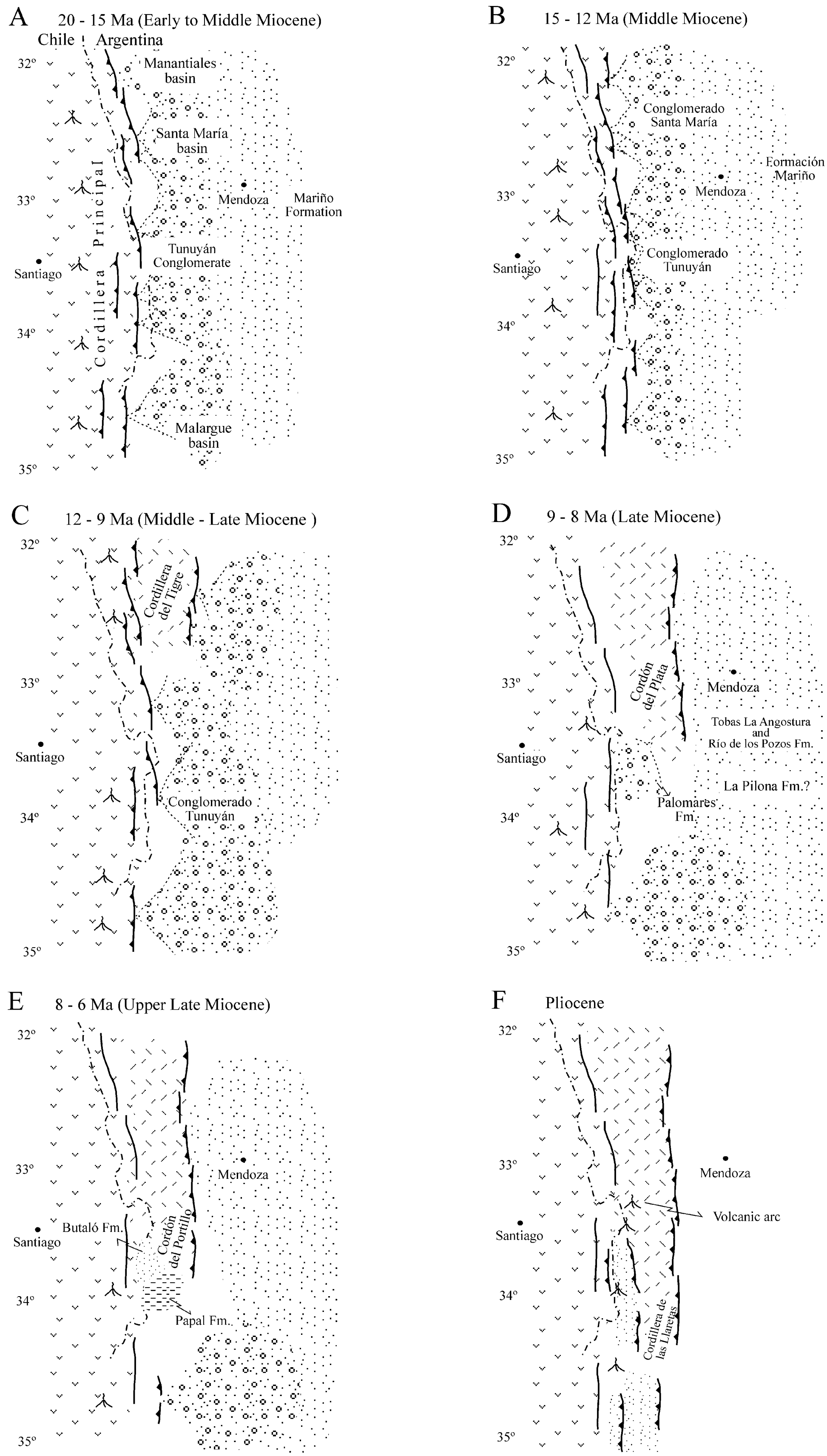

Fig. 13. Series of interpretative maps summarizing the evolution of the Neogene foreland basins, and deformation of the Andean Mountains, along 32°S and 35°S.

Duraznito thrusts, placing the Mesozoic sequences over the Neogene strata in the central part of the basin (Figs. 3 and 10).

Fig. 12 shows a balanced cross-section of the northern part of the basin. The dip of the structural basement is approximately 20°W in the eastern edge of the basin. It is inferred that this angle diminishes toward the west to 12°W and then 5°W. This unusual dip is due to the westward tilting of the Cordillera Frontal block as a result of the uplift in the footwall of a deep fault.

9. Discussion

The Alto Tunuyán foreland basin reveals a complex tectonic history of the Andean Mountains between 33°30′ and 34°S. In order to establish the tectonic evolution of the area, the following tectonic and sedimentary events, as well as the sequence of development, must be discussed.

9.1. Deformation of Cordillera Principal

The westerly derived syntectonic sediments of the Tunuyán Conglomerate and the Mariño Formation suggest that the deformation of Cordillera Principal started in early-middle Miocene times. This uplift began in westernmost areas, involving the volcanic rocks as indicated by the clasts of the first 200 m of the Tunuyán Conglomerate (Fig. 13a).

There is no evidence of deformation within the foreland basin during the deposition of the lower 1000 m of the Tunuyán Conglomerate, during early to middle Miocene times (Fig. 13b). The first episode of movement is documented by the development of Chileno thrust in the northern part of the basin. The synchronism of the movement of this thrust and the deposition of the upper 400 m of the Tunuyán Conglomerate are documented by the progressive unconformities in the hanging wall of the fault. This relationship suggests that the first movement of this fault took place during middle-late Miocene (Fig. 13c).

9.2. Cordillera Principal thrust front

Kinematic studies indicate that the Cordillera Principal thrust front developed in at least three major stages: (1) a piggy-back sequence stage during middle Miocene; (2) a quiescence stage during middle-late Miocene; and (3) a thrust reactivation stage with emplacement of out-of-sequence thrusts during late Miocene. The first stage occurred during the deposition of the upper part of the Tunuyán Conglomerate in the north and after its deposition in the south. In the Cerro Palomares area, thrusts I and II were developed (Fig. 9). Thrust II began to grow as a fault-bend fold simultaneously with the deposition of the upper part of the Tunuyán Conglomerate as growth strata. In the Duraznito stream area, thrust I was emplaced after the deposition of the Tunuyán Conglomerate.

During stage 2, the thrust system became inactive and erosion of the area was responsible for the generation of the unconformity Dn1, which is covered by the Palomares and Papal formations. Because the Tunuyán Conglomerate below the unconformity is middle Miocene in age and the Palomares Formation is likely to be late Miocene in age, this unconformity is thought to be middle-late Miocene.

During the last stage, the thrust system was reactivated and Palomares and Duraznito out-of-sequence thrusts developed. The former involved both Tunuyán Conglomerate and Palomares Formation, but it did not affect the Butaló Formation. The fact that the Butaló Formation unconformably overlain the Palomares out-of-sequence thrust postdates this fault to middle-late Miocene. The Duraznito thrust involved the Papal Formation. If we assume the Papal and Butaló formations to be coeval, then the Palomares thrust should have been developed prior to the emplacement of the Duraznito thrust.

9.3. Uplift of Cordillera Frontal

The shift of the thrust front to the east generated the uplift of Cordillera Frontal, which presents a different structural style, controlled by large-block faulting. This uplift produced a great change in the basin. The structural and sedimentary responses to this situation were: (1) the westward tilting of the structural basement and generation of a broken foreland basin, (2) the generation of the unconformity Dn1, and (3) the deposition of the cumulative wedge system, or progressive unconformity, represented by the Palomares and Butaló formations that lie on the unconformity Dn1. The absence of this cumulative wedge system in the southern part of the basin appears to be caused by two factors. One is a greater uplift of Cordillera Frontal in the north than in the south, as indicated by the exposure of the Proterozoic Complex in Cordón del Plata and the northern part of Cordón del Portillo, which is absent in the southern part of this range. More important, however, could be the effect of diachronous uplift from north to south. Several observations strengthen this hypothesis: Paleocurrent data from the Mariño Formation in the Cacheuta–Tupungato area indicate provenance from the northwest, from Cordillera del Tigre (Irigoyen et al., 1998) (Fig. 13d). Paleocurrent data from the Palomares Formation show that the source area was the northwestern part of Cordón del Portillo and probably the southern part of Cordón del Plata (Fig. 13e). Therefore, it is suggested here that Cordillera del Tigre was uplifted between 12 and 9 Ma and then Cordón del Plata and Cordón del Portillo between 9 and 6 Ma. The last range to be uplifted in Cordillera Frontal was the southern part of Cordón del Portillo and Cordillera de las Llaretas (Fig. 13f).

9.4. Relationship between the evolution of the Cordillera Principal thrust front and the uplift of Cordillera Frontal

The unconformity Dn1 and the deposition of the Palomares Formation document the uplift of Cordillera Frontal. This important event corresponds to the evolutionary stage 2

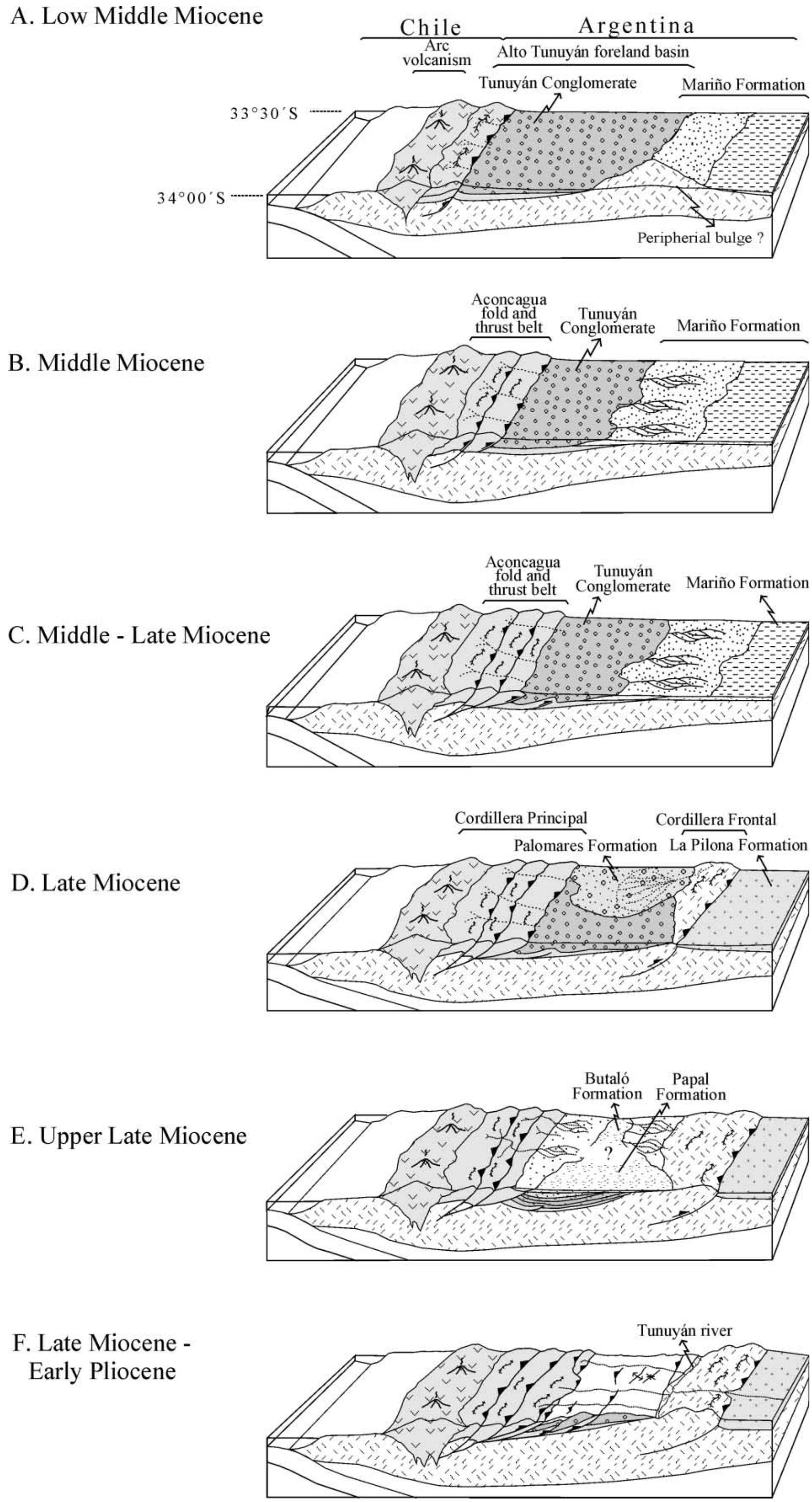

Fig. 14. Schematic block diagrams illustrating the Neogene evolution of the foreland basin. (Modified from Giambiagi, 1999c).

in Cordillera Principal thrust front. In the northern part, this unconformity represents a gap in the Neogene strata from late-middle Miocene to early-late Miocene. In the southern part, however, the unconformity represents a bigger gap because of the absence of the Palomares Formation, from late-middle Miocene to probably middle-late Miocene.

9.5. Final deformation of the foreland basin

After the deposition of the Butaló and Papal Formations, during late Miocene, new structures developed within the basin. It is likely that Chileno thrust is the prolongation to the north of Papal thrust, which developed during this stage. The unconformities Dn1 and Dn2 were folded in an anticline and a syncline, which affected middle-upper Miocene rocks (Fig. 3). The deformation therefore occurred during the late Miocene. The Neogene strata are also affected by the Morado thrust in an out-of-sequence mode. There is, however, no direct evidence to demonstrate the timing of deformation of this structure when compared with the folds of the basin. Both structures developed before Pliocene time, because the Pliocene–Pleistocene volcanic rocks are relatively unaffected by thrusting.

9.6. Comparison with the foreland basins located to the north and south

Between 32–36°S, Neogene foreland basins with similar characteristics to the Alto Tunuyán basin are present to the east of the Cordillera Principal. Two of these basins, the Santa María and Manantiales basins, are located to the north, over the flat-slab subduction zone. Toward the south, the Malargüe basin was developed over the steep subduction zone. The early evolution of the Alto Tunuyán basin is similar to the one registered in the northern and southern basins, mentioned earlier.

Thrusting and uplift of the Andes initially took place toward the west, in the Cordillera Principal, in early to middle Miocene times. This led to the development of a series of basins located between active fold-and-thrust belts and an unbroken foreland. The flattening of the angle of subduction occurred toward the middle-late Miocene in the northern segment. As a consequence, the foreland was involved in the deformation, as is evidenced by the uplift of the Cordillera del Tigre between 12–9 Ma (Irigoyen et al., 1998); and the Manantiales and Santa María basins received no further sedimentation (Pérez, 1995; Cristallini and Pérez, 1996; Jordan et al., 1996).

Toward the south, the Alto Tunuyán basin evolved over the transition segment, characterized by a younger and weaker deformation of the foreland, as indicated by the uplift of the Cordón del Plata and Cordón del Portillo, during 9–6 Ma. The sedimentary record indicates that it continued to receive sedimentary infill with a shift in the source area from west to east. In the south, above the normal subduction segment, the foreland was not involved in the deformation; and the Malargüe basin, unlike the basins to the north, evolved into two piggy-back basins, as deformation progressed eastward (Kraemer and Zulliger, 1994; Achilli et al., 1999).

10. Conclusions

Comparison of the basins located above the subhorizontal slab segment, the transition zone and the normal subduction zone, have led to the assumption that the geometry of the slab intimately controlled the history of these basins. Accurate recordings of surface structural and sedimentological data from the Alto Tunuyán foreland basin have been integrated to show the reconstruction of the Andean deformation of Cordillera Principal and Cordillera Frontal at 33°30′–34°S. Like many other foreland basins, the Alto Tunuyán basin has had a multistage history of evolution, different from the basins located to the north and to the south. Based on stratigraphy and structural geometry, six different major stages of its tectonic evolution have been recognized (Fig. 14).

During early Miocene, thrusting and uplift of the Aconcagua fold-and-thrust belt began in the area today known as Cordillera Principal. This episode of compression was probably related to changes in the rate of plate motion. The Alto Tunuyán foreland basin was formed in response to flexural subsidence driven by the topographic load of the adjacent thrust belt. Folding and thrusting started in the western part of the thrust belt uplifting the volcanic arc during early-middle Miocene. This deformation and uplift generated a sediment source for the lower 200 m of the Tunuyán Conglomerate (Fig. 14a). As the deformation migrated progressively eastward, it involved the Mesozoic sequences, forming a thin-skinned fold-and-thrust belt, the denudation of which provided the material accumulated in the rest of the unit (Fig. 14b and c). The foreland basin system migrated with the edge of the orogenic belt, and the study area became the site of the synsedimentary deformation caused by the Chileno thrust (Fig. 14c) and thrusts I and II located in the Cerro Palomares area (Fig. 9). In the northern part of the basin, the lower 1000 m of the Tunuyán Conglomerate were deposited in the basin's foredeep depozone (Fig. 14b), while the upper 400 m show progressive unconformities recording accumulation in the frontal part of the orogenic wedge (wedge-top depozone) (Fig. 14c).

During the middle Miocene after 11 Ma, a drastic change in the tectonic framework of the basin occurred. The uplift of the crystalline basement of Cordillera Frontal took place. Prior to 9 Ma, thrusting was probably restricted to Cordillera del Tigre. Thereafter, during the late Miocene, the deformation progressed southward, uplifting Cordón del Plata and the northern part of Cordón del Portillo, and then the southern part of this range and Cordillera de las Llaretas. This event took place first in the northern part (33°30′S) and then in the southern part (34°S), and it was responsible for the generation of a broken foreland basin and the development of an erosional surface, which truncates the lower part of the synorogenic strata (Fig. 14d). The angular unconformity Dn1 that separates the Tunuyán Conglomerate from the overlying Palomares, Butaló, and Papal formations records a phase of deformation that is also recorded in the La Pilona–Tupungato area, between the Mariño and La Pilona formations (Irigoyen et al., 1998). The unroofing study of the Palomares Formation demonstrated that during the uplift of Cordillera Frontal there was not any major deformation in Cordillera Principal, meaning a quiescence stage in the Cerro Palomares area. After the deposition of the Palomares Formation and before the sedimentation of the Butaló and Papal formations, during middle-late Miocene, there was a reactivation of deformation in Cordillera Principal. This is observed in the Cerro Palomares area by the development of Palomares out-of-sequence thrust.

By late Miocene times, the basin was characterized by the deposition of fluvial and lacustrine beds of the Butaló Formation and the possible marine sequence represented by the Papal Formation. This deposition took place in a narrow elongate trough over the partially deformed broken foreland basin. It reflects accumulation during a period of tectonic quiescence and low denudation of both Cordillera Principal and Cordillera Frontal (Fig. 14e).

The uplift of Cordillera Frontal generated a sticking point, preventing the propagation of the thrust belt toward the foreland. As a result, the Morado out-of-sequence thrust developed in Cordillera Principal and the basin was partially cannibalized by the reactivation of Chileno and Papal thrusts and the development of the Peñón and Atravesado folds (Fig. 14f).

Acknowledgements

We wish to thank Carla Buono, Sergio Orts, Patricio Vazques Calvo, and Emilio Rocha for their help in the field. This research was supported by grants from the University of Buenos Aires (UBACYT TW87) and CONICET (PIP 4162). Special thanks are due to Victor A. Ramos for his comments and discussions. Reviews and suggested improvements by Gustavo Gonzalez Bonorino, Guillermo Re, and Pablo Kraemer are also greatly appreciated.

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