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Mountain building processes at the orogenic front. A study of the unroofing in Neogene foreland sequence (37ºS)

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ABSTRACT. The orogenic front at 37ºS has been mainly formed through at least two contraccional stages, as inferred from the exhumed major angular unconformities at the Late Eocene and the Late Miocene times respectively. A Late Cretaceous event is restricted to the hinterland zones in the Main Cordillera. A series of syntectonic sedimentary packages, that thin to the east is identified through a detailed description of the cannibalized westernmost Neogene foreland basin associated with the Sierra de Reyes. Their detrital microscopic and macroscopic descriptions reveal that the Neogene basin was fed from the west and particularly from the eastern Sierra de Reyes slope at the time of mountain incision. Detrital composition of the upper section reveals that a metamorphic component is present, implying that a domain further east has been exhumed, and therefore that the westernmost foreland basin has been cannibalized. This also implies that exhumation previous to Miocene times should have been minimum in the area, since the Neogene succession represents a complete unroofing. The structural cross sections show Neogene shortening of about 20%, leaving in comparison Eocene contraction as negligible.

Keywords: Central Andes, Malargüe fold and thrust belt, Foreland basin, Synorogenic deposits, Argentina.

RESUMEN. Procesos orogénicos en el frente Andino. Estudio de una secuencia de destechado correspondiente a la cuenca de antepaís neógena. El frente orogénico a los 37°S ha sido construido por, al menos, dos episodios contraccionales, determinados a partir de discordancias angulares entre los depósitos del Eoceno Superior y del Mioceno Superior. Un episodio contraccional del Cretácico Superior, ampliamente descrito con anterioridad, se encuentra parcialmente restringido a las zonas internas de la Cordillera Principal. A partir de un detallado análisis de la cuenca de antepaís neógena asociada, canibalizada por el frente de levantamiento de la sierra de Reyes, se puede distinguir una secuencia sedimentaria que experimenta una disminución de su espesor hacia el este. Las descripciones microscópicas y macroscópicas de estos depósitos sinorogénicos revelan que la cuenca neógena fue alimentada desde el oeste y en particular desde el flanco oriental de la sierra de Reyes en el momento que esta se levantaba. La composición de los detritos de la parte superior de la cuenca neógena demuestra que existen componentes metamórficos, implicando que sectores del antepaís hacia el este estaban siendo exhumados al momento de su depositación. El hecho de que la sección miocena registre la secuencia de destechado completa de la sierra de Reyes, implica que la fase miocena superior fue la principal en esta zona, y que la fase eocena ha sido relativamente menor a nivel del frente orogénico. El corte estructural demuestra un acortamiento para el Neógeno de 20%, dejando negligible el acortamiento ocurrido para el Eoceno.

Palabras clave: Andes centrales, Faja plegada y corrida de Malargüe, Cuenca de antepaís, Depósitos sinorogénicos, Argentina.

1. Introduction

Even though the Andean cycle of deformation started some 100 Ma ago (Tunik *et al.*, 2010), at the time when the South Atlantic Ocean opened (Somoza and Zaffarana, 2008), mountain building processes associated with this process were not homogeneously distributed through the subduction margin and therefore their inception time and distribution remain one of the most important topics in Andean research.

The eastern Andean slope, corresponding to the Argentinean slope, is formed by a series of fold and thrust belts that differ in mechanics as well as timing along the mountain strike. The Main Andes between 35º and 37.5ºS consists of the Malargüe fold and thrust belt (Kozlowski *et al.*, 1993). This deformational belt has been constructed by tectonic inversion of previous Late Triassic-Early Jurassic normal faults during Late Cretaceous, Late Eocene, and Late Miocene times (Charrier, 1979; Charrier *et al.*, 2007; Cobbold and Rossello, 2003; Orts and Ramos, 2006; Giambiagi *et al.*, 2008) and thin-skinned deformation in sag sequences of Early Jurassic to Early Cretaceous deposits of the Neuquén basin (Zamora Valcarce and Zapata, 2005; Manceda and Figueroa, 1995). Particularly, the orogenic front corresponding to the Malargüe fold and thrust belt at 37ºS deforms Late Triassic rocks up to Neogene levels. This thick-skinned orogenic front is formed at these latitudes by five main basement structures, from north to south: the Palauco, Cara Cura, Sierra de Reyes, La Yesera and Pampa Tril anticlines (Fig.1).

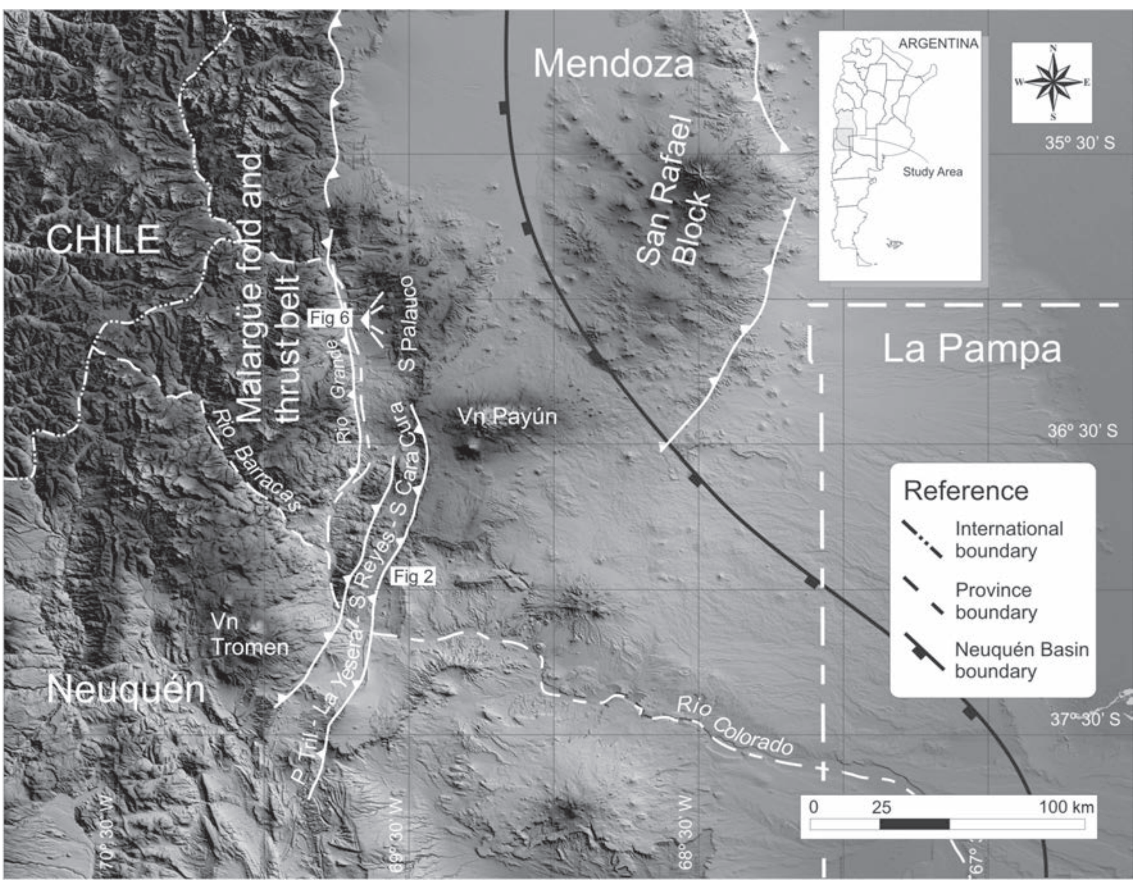


FIG. 1. Digital elevation model of the study area, showing main morphostructural elements: The Malargüe fold and thrust belt is characterized by the presence of a series of basement blocks west of the emergent orogenic front, where the Sierra de Reyes is located.

This orogenic front is spatially linked to Upper Cretaceous and Neogene sedimentary sequences deposited in foreland basins associated with the orogenic wedge at these latitudes (Kozlowski *et al.*, 1993; Vergani *et al.*, 1995; Silvestro and Atencio, 2009; Zamora Valcarce *et al.*, 2009; Tunik *et al.*, 2010): the 97-65 Ma Neuquén Group (Tunik *et al.*, 2010) and a late Miocene succession gathered in the Tristeza Formation. The orogenic front has cannibalized both sedimentary prisms through a succession of contractional stages registered in two angular unconformities, previously not well constrained.

2. Objectives

The focus of this work is the geological study of the eastern slope of the Sierra de Reyes anticline and its associated Neogene foreland basin (Fig. 2). The westernmost Neogene depocenter associated with this basin is preserved in the Pampa de Carrizalito syncline. The age of these deposits is constrained between the underlying Upper Oligocene-Lower Miocene volcanic rocks of the Palauco Formation (~24-18 Ma) (Kay *et al.*, 2006; Silvestro and Atencio, 2009) and Late Pliocene basalts at the base of the Payenia volcanic successions (Ramos and Folguera, 2005, 2010).

The main objective of the present work is to constrain the timing of development of the orogenic front, by **i.** studying the sedimentary Neogene succession at Pampa de Carrizalito in the westernmost foreland basin associated with the Sierra de Reyes, and **ii.** determining the clastic sources in the denuded eastern flank of the hill. The occurrence of different angular unconformities in the region, will be evaluated through the identification of the syntectonic successions. A structural cross section has been surveyed through the eastern slope of the Sierra de Reyes and across the Pampa de Carrizalito Neogene depocenter, combining field data as well as seismic and bore hole data. This section was restored in order to determine the contrasting participation of the basement in the different sections and to define the general structural styles.

In this work we analize in detail the Late Miocene succession exposed at the core of the Pampa de Carrizalino syncline (Fig. 2). First, compositional variations were determined trough field description of their detrital components at the western and eastern syncline limbs. Complemented with the study of thin-sections, six sedimentary units (a to f) have been differentiated in the westernmost profile, being only three traceable to the eastern profile, inferring a pinch-out of some of these packages to the east, through the syncline structure.

Finally, these compositional transitions described in the westernmost foreland basin are compared to lithologies identified in the field over the eastern Sierra de Reyes uplift. The different contractional stages based on the main angular unconformities at the orogenic front were discussed in order to evaluate their relative importance.

3. Geological setting

There are several studies regarding the tectonic evolution of the area, dealing with the early Mesozoic retroarc extension or linked to the tectonic inversion and mountain building episodes. These studies established a geological framework that can be summarized through the following stages: First, during the Late Triassic-Early Jurassic a series of extensional non-connected depocenters affected the western Gondwana margin, not being associated with a subduction setting (Charrier, 1979; Uliana y Biddle, 1987). Second, during the Early Jurassic, extensional deformation affected the arc and the retroarc area, with elongated basin in the SW direction (Vergani *et al*., 1995) that generated a series of retroarc basins, among which the Neuquén basin constituted one o the largest Pacific embayments along the Gondwana margin. This period is represented in the Neuquén basin and particularly in the study area by the marine sandstones and shales of the Bardas Blancas Formation. Lately during Late Jurassic to Early Cretaceous times subsidence was governed by thermal decay and eustatic changes along the western Gondwana margin (Vergani *et al*., 1995). This period is represented in the Neuquén basin at this locality by the Auquilco Formation evaporites, shales and limestones of the Vaca Muerta Formation and shales and sandstones of the Agrio Formation, gathered in the Mendoza Group. During late Early Cretaceous, a compressive stage inverted the previous retroarc basins (Mpodozis and Ramos, 1989). The compressive episode is associated with initiation of the development of the Neuquén foreland basin (Vergani *et al*., 1995; Tunik *et al*., 2010). Latest Cretaceous to Eocene times is characterized by an

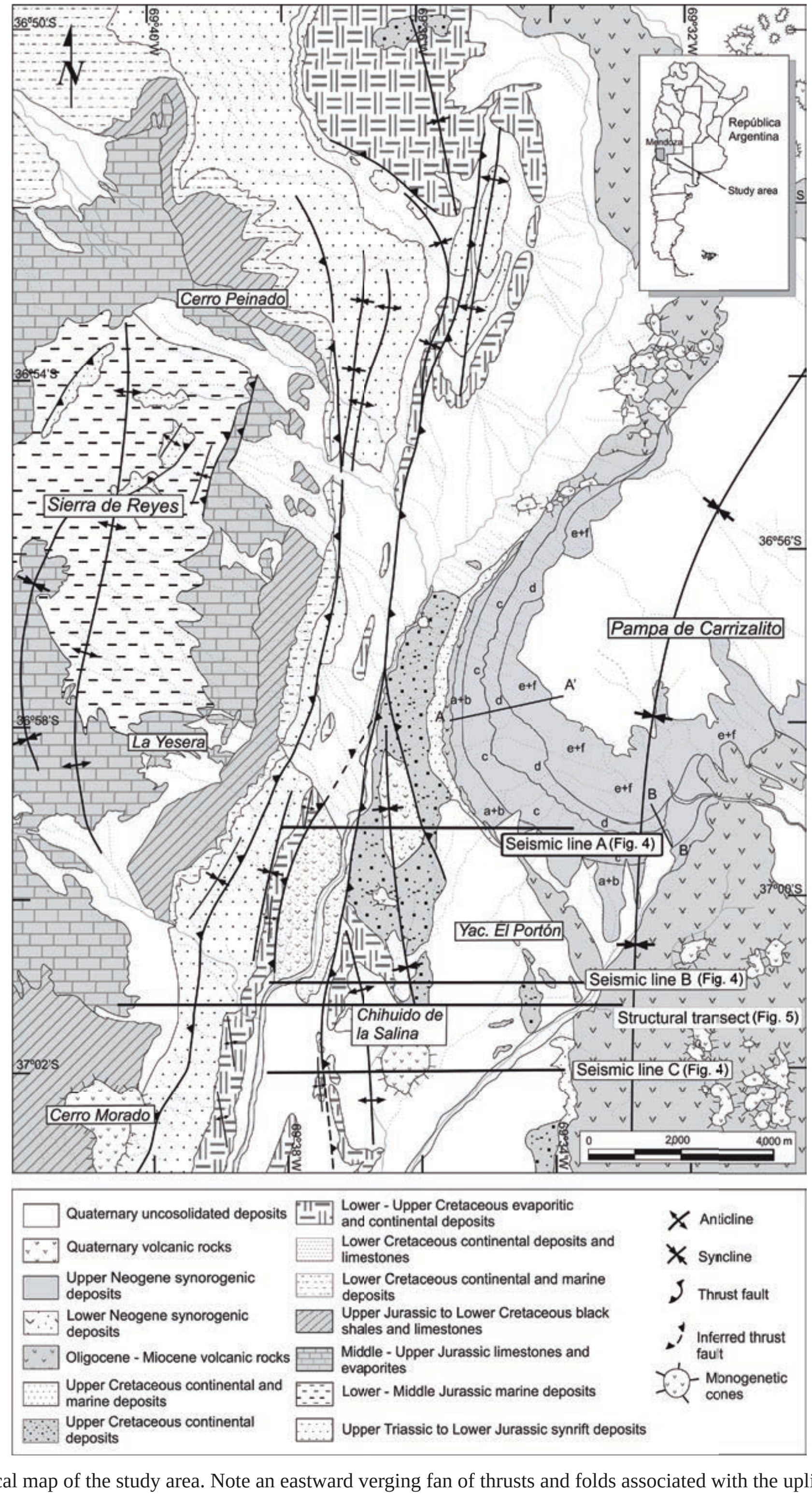


FIG. 2. Geological map of the study area. Note an eastward verging fan of thrusts and folds associated with the uplift of the Sierra de Reyes and the Neogene depocenter located to the east along Pampa de Carrizalito; a-f are the defined units in the sedimentary and petrologic analyses performed in the depocenter.

Atlantic marine ingression controlled by tectonic loading associated with a high-stand sea level represented by the Malargüe Group (Weaver, 1927; Bertels, 1969b; Uliana and Dellapé, 1981; Barrio, 1990). The Principal Cordillera has then been affected at these latitudes by extensional deformation some 27 Ma ago with the development of the Cura Mallín basin (Radic, 2010). These depocenters have been inverted in Late Miocene times, when the arc expanded to the east (Kay *et al*., 2006; Litvak *et al*., 2008, 2009), contemporaneously to the reactivation of Late Cretaceous to Eocene contractional structures in the eastern Malargüe fold and thrust belt (Spagnuolo *et al*., 2008). This arc expansion and consequent contractional deformation has led to the development of a foreland basin in Late Miocene times (Silvestro and Atencio, 2009). The Main Andes between 36º and 37ºS is represented by the Malargüe fold and thrust belt formed by basement rooted faults affecting thick columns of Mesozoic to Tertiary strata (Kozlowski *et al*., 1993; Manceda and Figueroa, 1995; Giambiagi *et al*., 2008), and the San Rafael block to the east, a broken foreland block potentially uplifted during slab shallowing processes in the last 14 Ma (Ramos and Kay, 2006).

4. Structure

The Malargüe fold and thrust belt has been constructed through three main stages, the first in Late Cretaceous (~97-75 Ma), the second in Eocene times (~45 Ma), and the third during Late Miocene times (18-5 Ma) (Groeber, 1933, 1953; Cobbold *et al*., 1999; Cobbold and Rossello, 2003; Orts and Ramos, 2006; Mosquera and Ramos, 2006; Zamora Valcarce *et al*., 2006; Folguera *et al*., 2007; Silvestro and Atencio, 2009; Tunik *et al*., 2010). As mentioned, at this latitudes, it is possible to recognize a series of prominent basement structures produced by tectonic inversion of Late Triassic-Early Jurassic normal faults (Kozlowski *et al*., 1993; Dimieri, 1997; Zamora Valcarce and Zapata, 2005; Yagupsky *et al*., 2007; Zamora Valcarce *et al*., 2008; Giambiagi *et al*., 2009).

Based on the different structural styles the, study region has been divided in three zones (Fig. 3) that present distinctive characteristics from west to east. The most prominent structure in the study area corresponds to the Sierra de Reyes anticline (zone 1), which is a double verging structure associated with exposures of Late Triassic rocks at its core. Our study focuses in the eastern flank of the Sierra de Reyes that is associated with the easternmost basement exposures (Fig. 3). These rocks are covered by marine Lower Jurassic shales and limestones to Upper Cretaceous continental deposits, unconformably overlain by Upper Oligocene volcanic rocks grouped in the Palauco Formation and upper Neogene sedimentary sucessions (Fig. 2). All these deposits are dipping to the east over Lower Cretaceous sequences (Fig. 3). The eastern flank of this anticline, is affected by the north-trending West Aguada de Reyes thrust with a west dipping fault that repeats Lower Cretaceous rocks at the surface. The zone 2 to the east consists of a series of highly discontinuous and narrower north-trending folds (Fig. 3). At its southern part, minor 'échelon' arrangement in associated anticlines, suggests subordinate strike slip mechanisms.

Finally, the zone 3 is represented at the surface by a single smooth feature represented by the Pampa de Carrizalito syncline. Neogene deposits in the entire area are hosted in this structure. In spite of the apparent simplicity of this last area, at depth the structural complexity becomes greater. A series of vertical slices corresponding to a 3D seismic line was analyzed in this area (Fig. 4) in order to determine the transition between zones 2 and 3 at depth (Fig. 3). Then, two décollements were identified beneath the western flank of the Pampa de Carrizalito syncline, the upper located in Lower Cretaceous evaporites of the Huitrín Formation, and the lower in the contact between Upper Jurassic to Lower Cretaceous shales and limestones of the Vaca Muerta Formation and Upper Jurassic evaporites of the Auquilco Formation. The basement anticline exposed at the westernmost zone is inserted in the lower décollement transferring shortening upwardly to the Jurassic and the Neogene cover. A series of duplexes between the two décollements and associated to triangular zone tilt the western flank of the frontal syncline (Fig. 4) (Zamora Valcarce and Zapata, 2005). The upper décollement shows important thickness variation as seen in seismic data (Figs. 4 and 5).

A 20 km long W-E balanced cross section was constructed with the 2D Move software (see figure 2 for location), constrained by surface data all along the study area and seismic information and bore hole

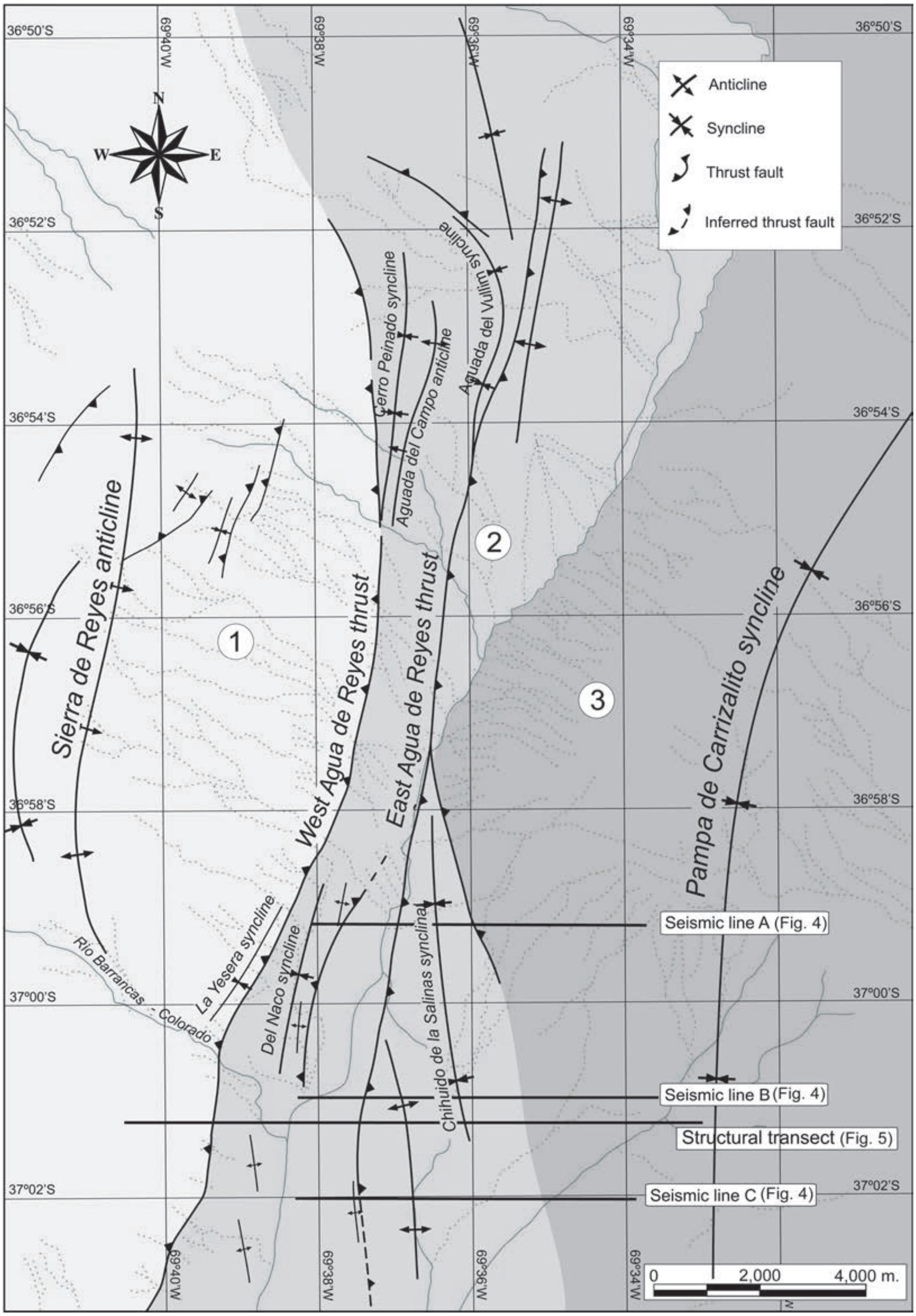


FIG. 3. Main structures described in this work. Note three different zones (1, 2, 3). Zone 1 has a broad discontinuous structure; zone 2 has longer and narrower structures with a shallower décollement; zone 3 is represented by the broad Pampa de Carrizalito syncline. Locations of seismic lines of figure 4 are indicated, as well as structural section depicted in figure 5.

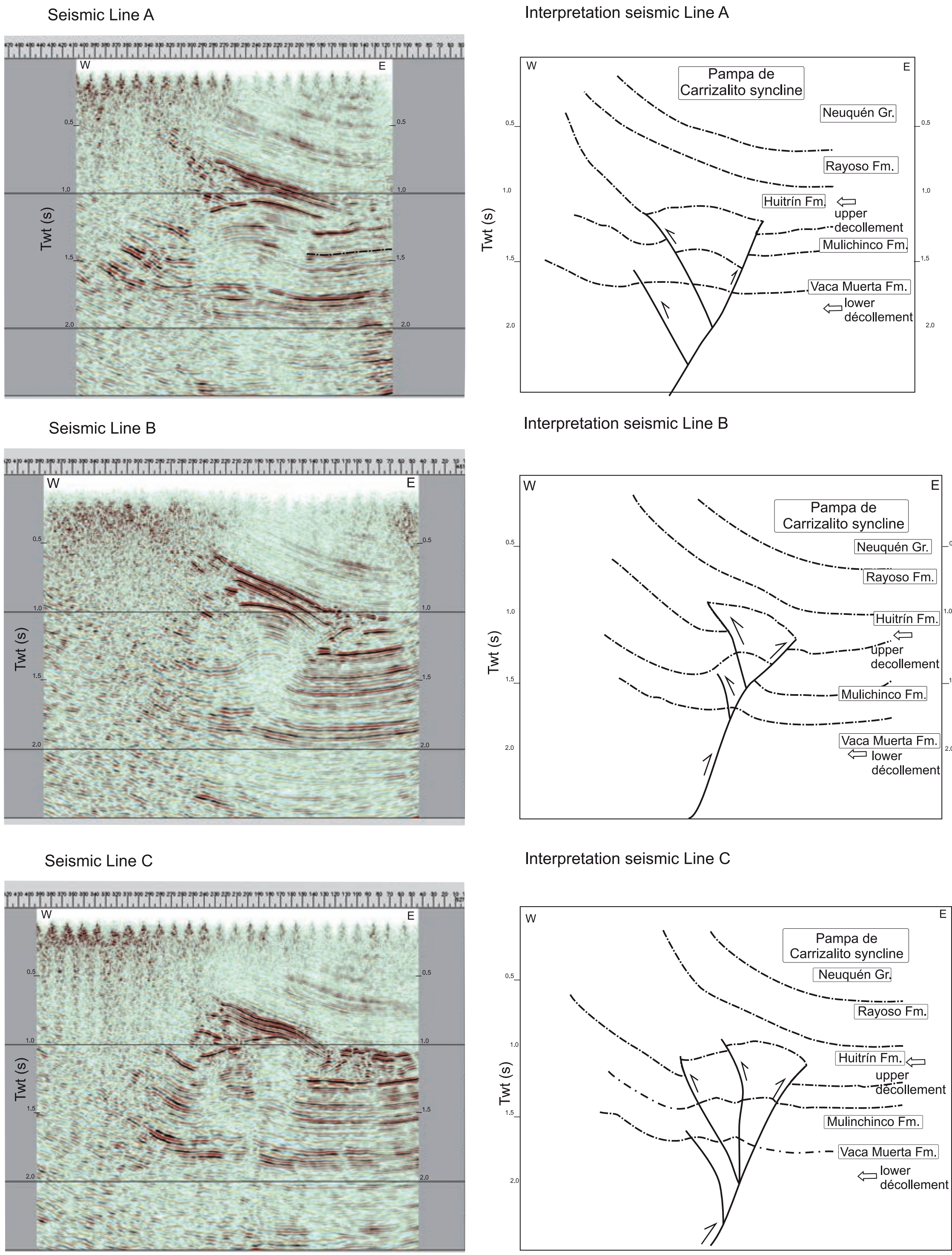


FIG. 4. Vertical slices of 3D seismic lines and corresponding interpretations showing the main structures in the SE sector of the study area. Note the upper décollement corresponding to evaporites of the Lower Cretaceous Huitrín Formation in the Pampa de Carrizalito syncline, that decouples highly deformed lower terms from the upper terms (see location in figure 2).

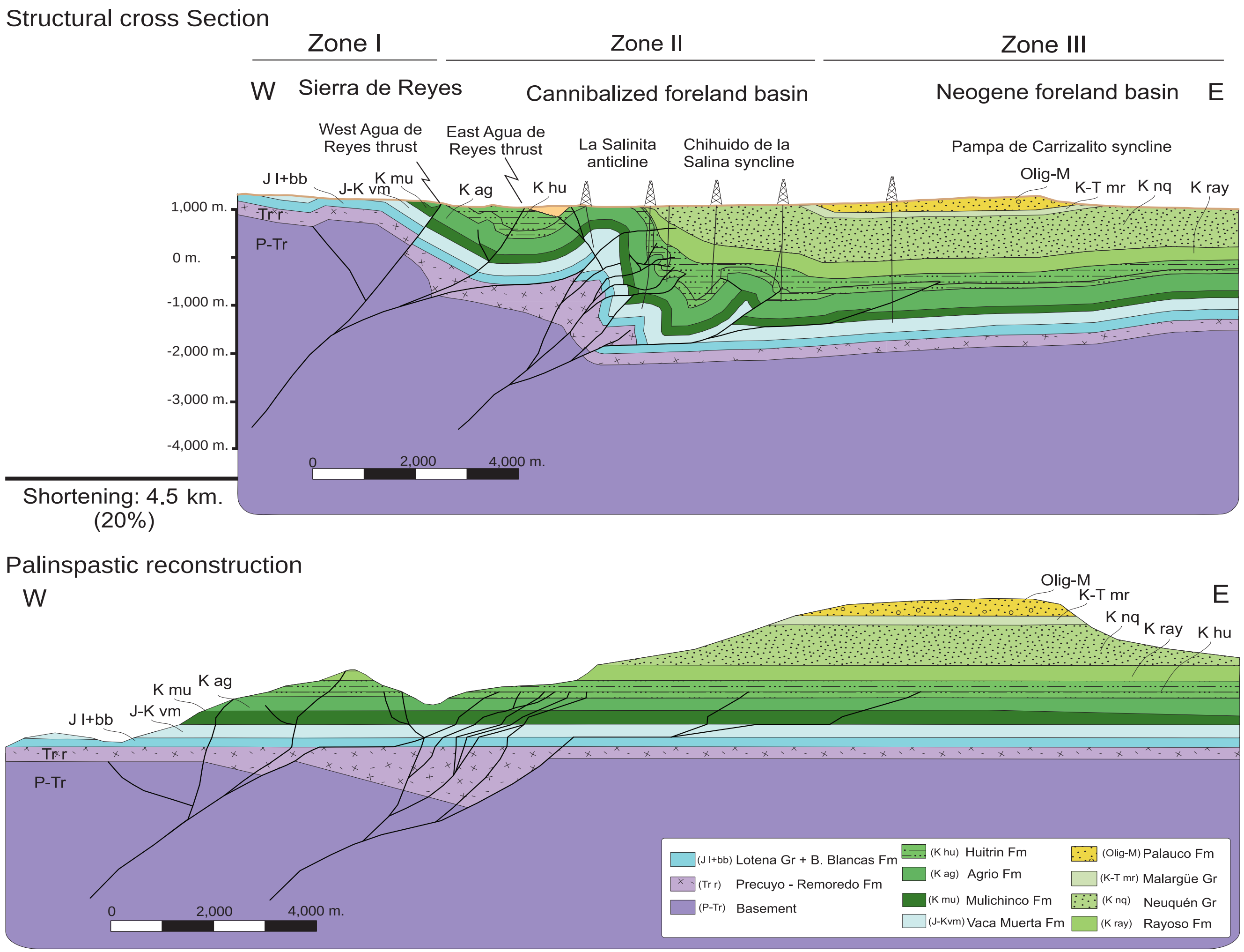


FIG. 5. Structural cross section and palinspastic reconstruction based on field data, seismic lines and bore hole data. Note the two deformational styles: in the west a basement block uplifted by east-verging structures thrust on top of Lower Cretaceous deposits, (Mendoza Group), which have thin-skinned deformation further east (this easternmost section is based on Zamora and Zapata, 2006). See figure 2 for location and references.

data in the easternmost part (Fig. 5). The shortening of the basement together with the Mesozoic cover is about 20% representing approximately 4.5 km.

5. Analysis of the Neogene basin east of the orogenic front at 37ºS

The orogenic front at these latitudes exhumes a lower angular unconformity between Eocene terms of the upper Malargüe Group and Upper Oligocene to Lower Miocene rocks of the Palauco Formation (Fig. 6). An upper unconformity is also denuded between the Palauco Formation and the Neogene sedimentary cover (Fig. 7). We performed a sedimentological and petrographical study through this section along two profiles from the Upper Oligocene to the Neogene succession of the Pampa de Carrizalito syncline in order to constrain the relative importance of these different pulses that formed the orogenic front at this latitude.

The successions hosted in the Pampa de Carrizalito depocenter are assigned to the Late Miocene based on their occurrence on top of the Palauco Formation whose upper part has been dated at 18,12±0,24 Ma (Ar/Ar; Silvestro and Atencio, 2009). The profiles located in both syncline flanks (A-A' and B-B'; Fig. 7, see figure 2 for location) were done in order to describe the geometry of the main sedimentary units, thickness variation next to the orogenic front, and detrital compositional changes. The analyzed deposits could be divided in a series of units characterized by contrasting compositions. The lower units consist of volcaniclastic facies that grade upwardly to clastic wedges whose composition is derived from the erosion of the Jurassic to Cretaceous sequences exhumed in the eastern slope of Sierra de Reyes. In detail, the basal sections are mainly composed of ignimbrites and volcaniclastic beds containing basalt clasts derived from the underlying Palauco Formation (units a and b); then there are deposits with abundant sandstone clasts (unit c) (Fig. 8) on top of the previous units, followed by beds with limestone detritus, then gypsum clasts and finally shale clasts (units d, e, f respectively) (Fig. 9). The uppermost portion contains clasts of polycrystalline quartz that can be associated with a metamorphic source (unit e) (Fig. 10).

This variation in the detrital composition can be related to the different stratigraphic units that have been successively exhumed in the western Sierra de Reyes. The lower sandstones are derived from the erosion of the Neuquén Group, while the

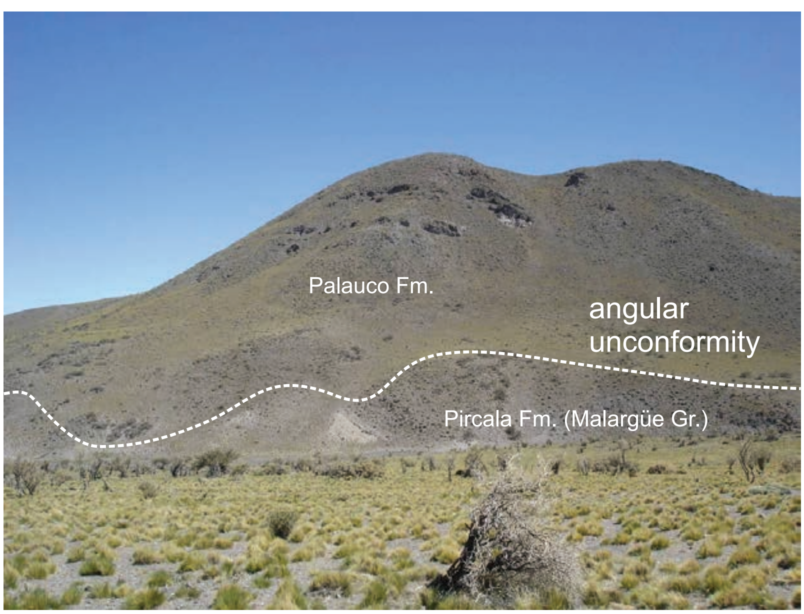


FIG. 6. Angular unconformity between Eocene rocks of the upper Malargüe Group and Late Oligocene to Early Miocene basalts of the Palauco Formation, in the northern part of the study area. This indicates the existence of a Late Eocene uplift in the region (see location in figure 1).

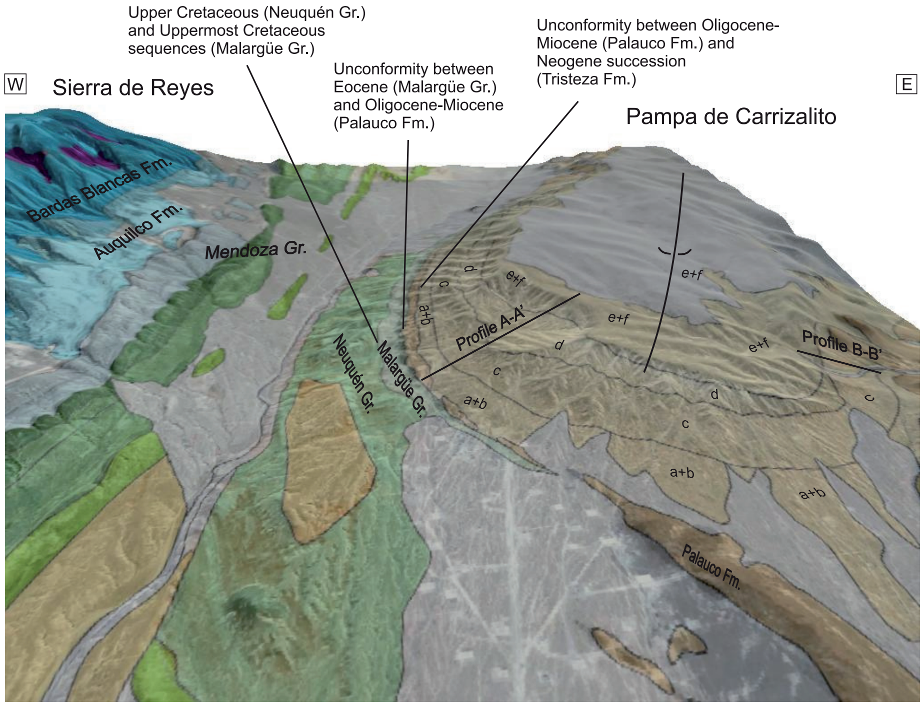


FIG. 7. TM Landsat image and geological map draped over DEM, showing location of section surveyed at the eastern flank of the Sierra de Reyes and the Pampa de Carrizalito depocenter. The angular unconformities are indicated, between Eocene rocks (Malargüe Group) and Oligocene-Miocene basalts of the Palauco Formation and between the last and the Neogene succession (Tristeza Formation). A, b, c, d, e, f are the units recognised in both profiles characterized by contrasting compositions.

limestone fragments are related to the erosion of the Mendoza Group, and the gypsum clasts to the Auquilco Formation. Finally, the shales could be related to the Bardas Blancas Formation. Therefore, clast sources in the lower units are the Upper Cretaceous deposits exposed at the western flank of Sierra de Reyes, while the younger sources are the Lower Cretaceous and Jurassic sequences. Similar variations were also recognized in the eastern profile (B-B'; see figure 2 for location), with the exception of the lowest volcaniclastic unit (a and b) and the unit containing gypsum clasts (unit e) (Fig. 11).

When comparing both profiles, it is evident that: **a.** A conspicuous decrease in clast size from west to east, characterized by dominant conglomerates in the western limb of the Pampa de Carrizalito syncline to units composed mainly of sandstones to the east; **b.** a clear reduction in thickness for most of the identified horizons with the disappearance of the basal and intermediate units to the east (Fig. 12); **c.** the uppermost portion contains clasts associated with a metamorphic source identifying a foreland provenance. NE-SW paleocurrent directions were here determined from channeled deposits from which no perpendicular direction was available and therefore sense was not determined. This implies that the foreland area would be uplifted and exhumed at this time (Fig. 12).

Finally, progressive unconformities were identified at the top of the B-B' profile (Fig. 13). These are indicating that the Neogene depocenter was being cannibalized at this time by structures growing over the Late Jurassic décollement, which steepened the frontal syncline limbs (Fig. 14).

6. Discussion and conclusions

Three angular unconformities are exhumed in the Andes at these latitudes, and particularly, in the eastern slope of the Sierra de Reyes: The unconformities between **i.** Upper Cretaceous and Uppermost Cretaceous sequences (Neuquén and Malargüe Groups); **ii.** Eocene and Oligocene-Early Miocene

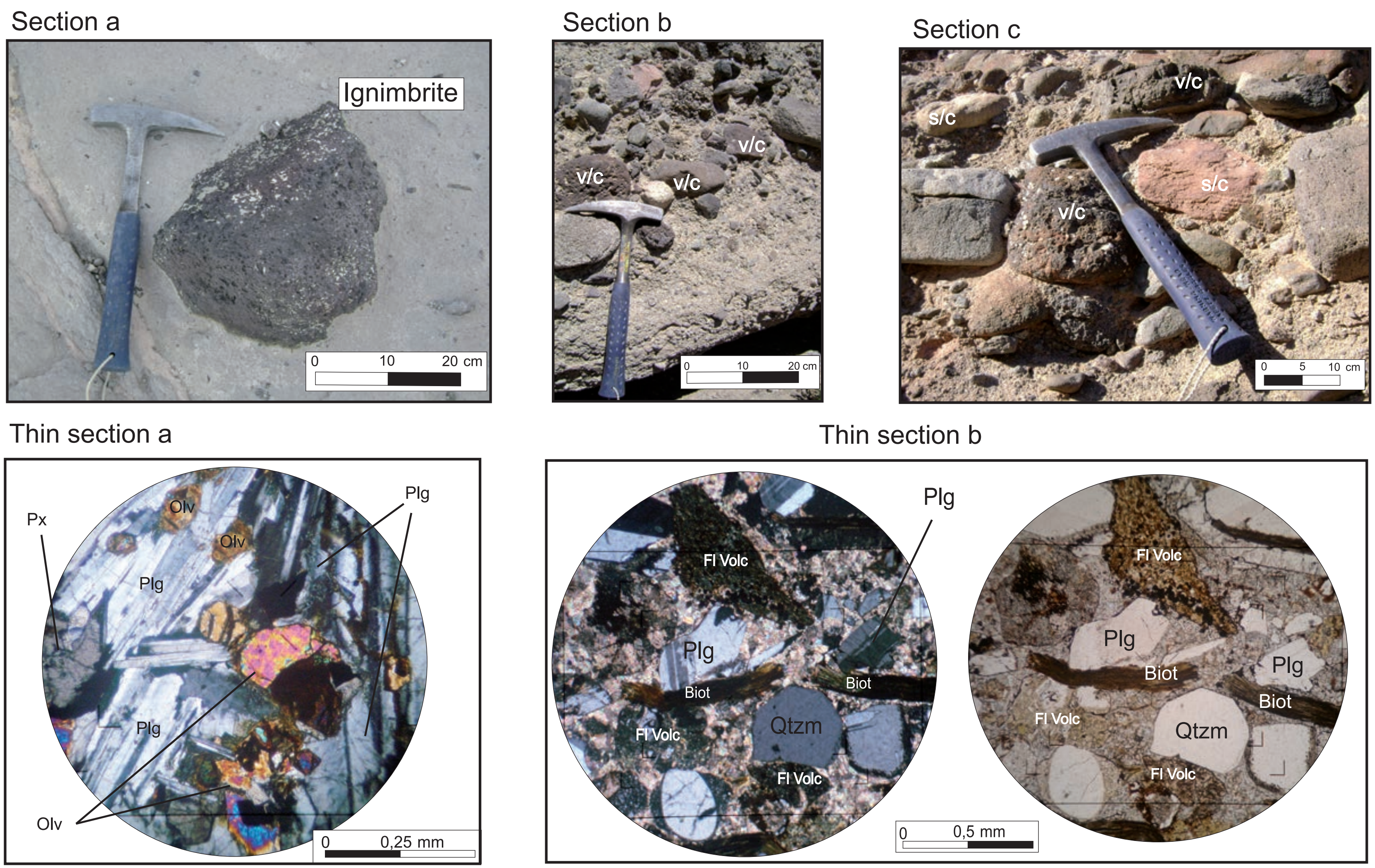


FIG. 8. Outcrop view and thin-sections corresponding to the a, b, c units of the late Miocene succession in the Pampa de Carrizalito. See profile A-A' for location. Note the presence of volcanic clasts (**v/c**) in b unit, and sandstone clasts (**s/c**) in c unit, which are absent in units a and b. (**Olv**: olivine; **Plg**: plagioclase; **Qtzm**: monocrystalline quartz; **Biot**: biotite; **Fl Volc**: volcanic lithic fragments).

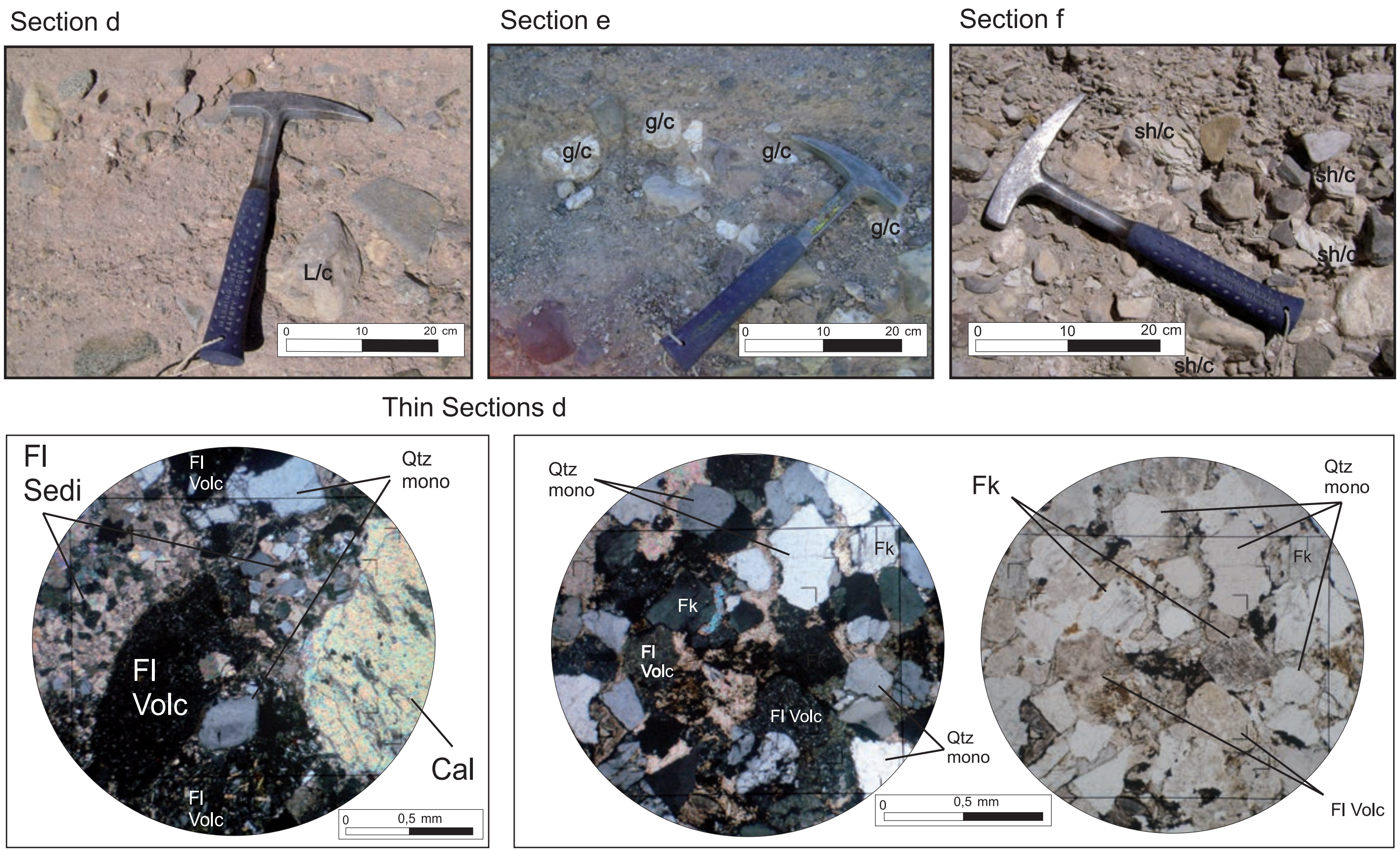


FIG. 9. Outcrop view and thin-sections of the d, e, f units of the Upper Miocene succession in the Pampa de Carrizalito. See profile A-A' for location (Fig. 7). Note the presence of limestone (**L/c**), gypsum (**g/c**) and shale clasts (**sh/c**) progressively increasing upwardly. **Qtz mono**: monocrystalline quartz; **Fk**: Potassic feldspar; **Fl Volc**: Volcanic Lithic fragment; **Cal**: Limestone; **Fl Sedi**: Sedimentary lithic fragments.

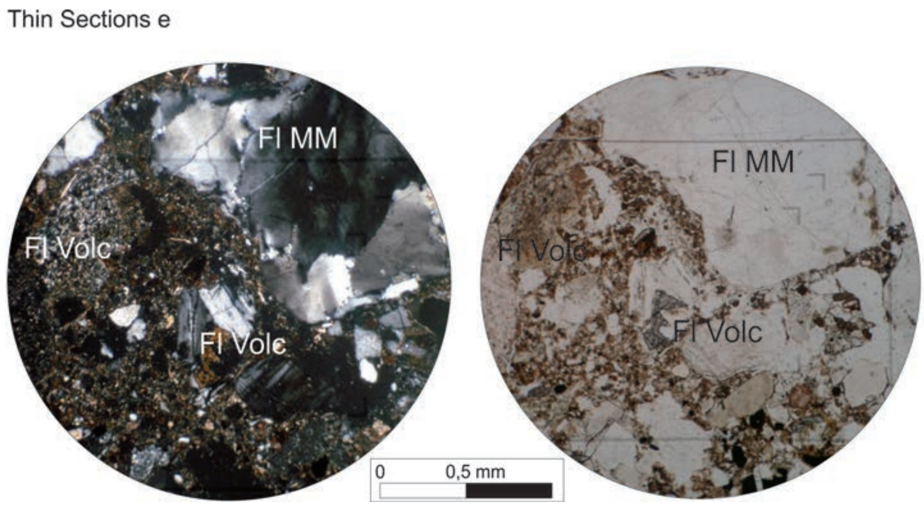
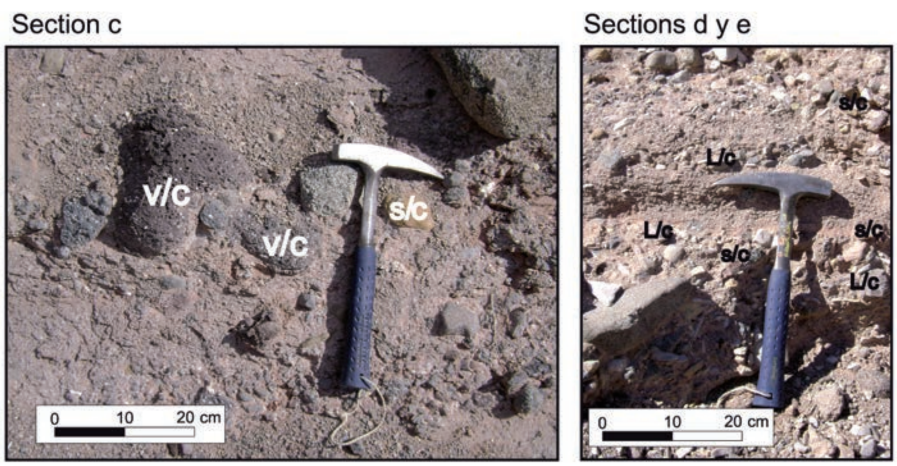


FIG. 10. Thin-sections corresponding to the e unit from Upper Miocene succession in the Pampa de Carrizalito (see figure 9 and figure 7, profile A-A', for location). Note the presence of metamorphic lithic fragments **(Fl MM)**, represented by polycrystalline quartz.



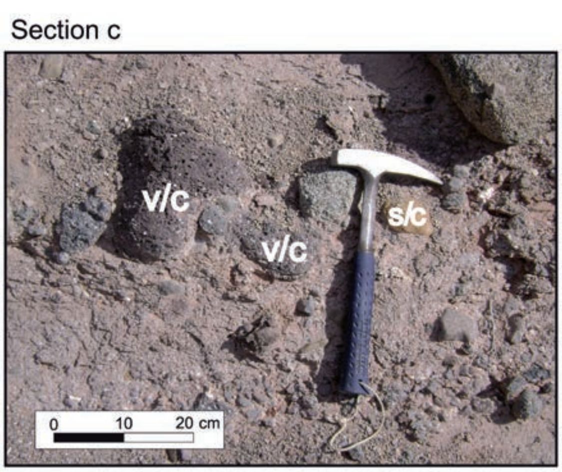


FIG. 11. Outcrop view of c, d y e, f units of Tristeza Formation accumulated in the easternmost Pampa de Carrizalito. See profile B-B' for location. They have the same sources described for the westernmost profile. Note again the appearance of clasts of different compositions resulting from the progressive unroofing of the Sierra de Reyes. **V/c**: Volcanic Clast; **S/c**: Sandstone Clast; **L/c**: Limestone Clast; **Sh/c**: Shale Clast.

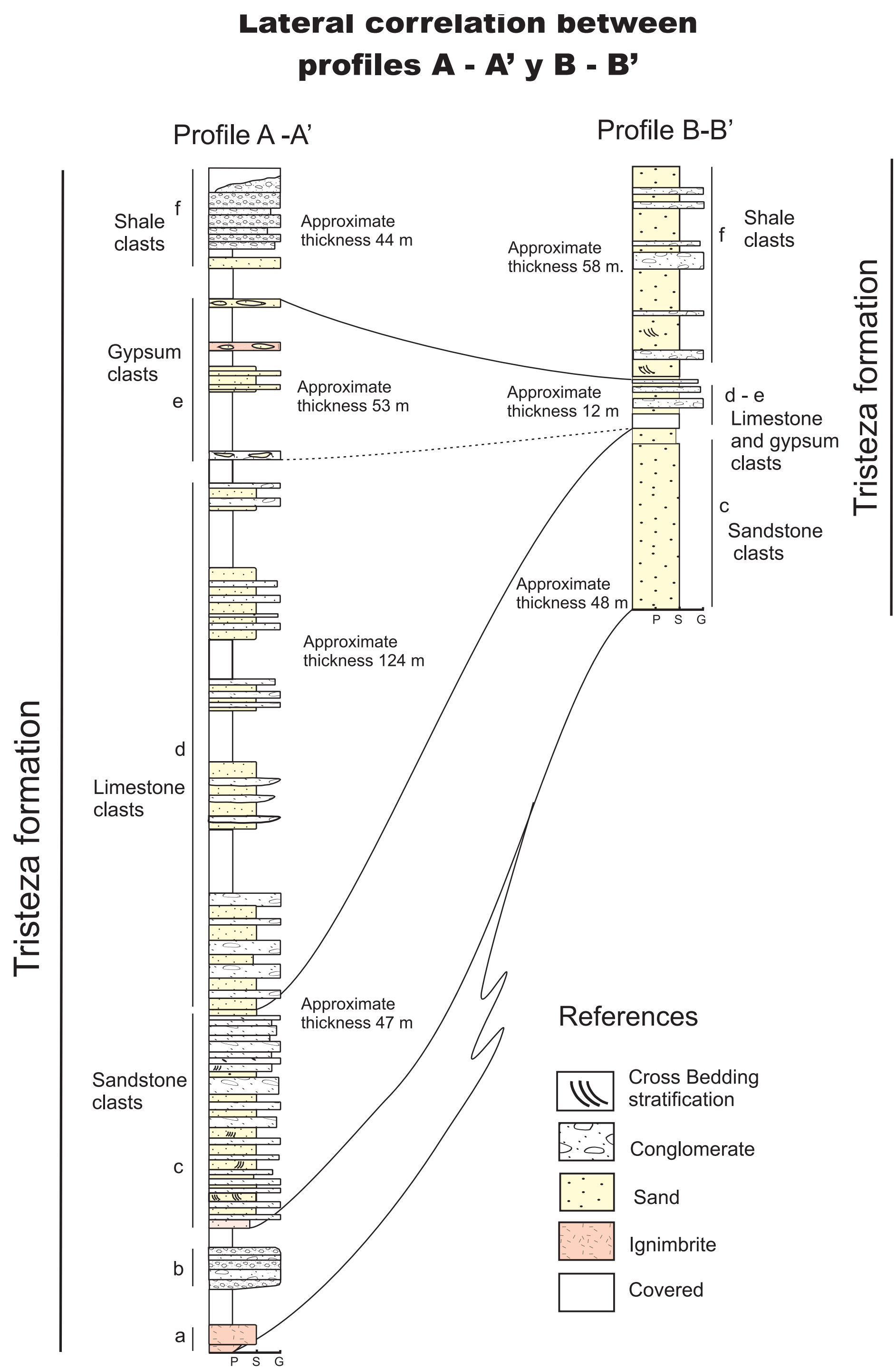


FIG. 12. Lateral correlation between profiles A-A' and B-B' (Fig. 7) based on clast compositions recognized in both sections. Note an eastward wedging of the basal and mid units of the westernmost section of the Tristeza Formation in Pampa de Carrizalito. Apparent pinch-out of f unit at the easternmost section is interpreted as caused by erosion/cannibalization of the upper units. Grain size diminishes eastwards from dominant conglomerates to sandstones. (**P**: means shale size; **S**: means sand size; **G**: means conglomerate size).

FIG. 13. Progressive unconformities and growth strata in the eastern flank of the Pampa de Carrizalito syncline in the uppermost unit f of Tristeza Formation.

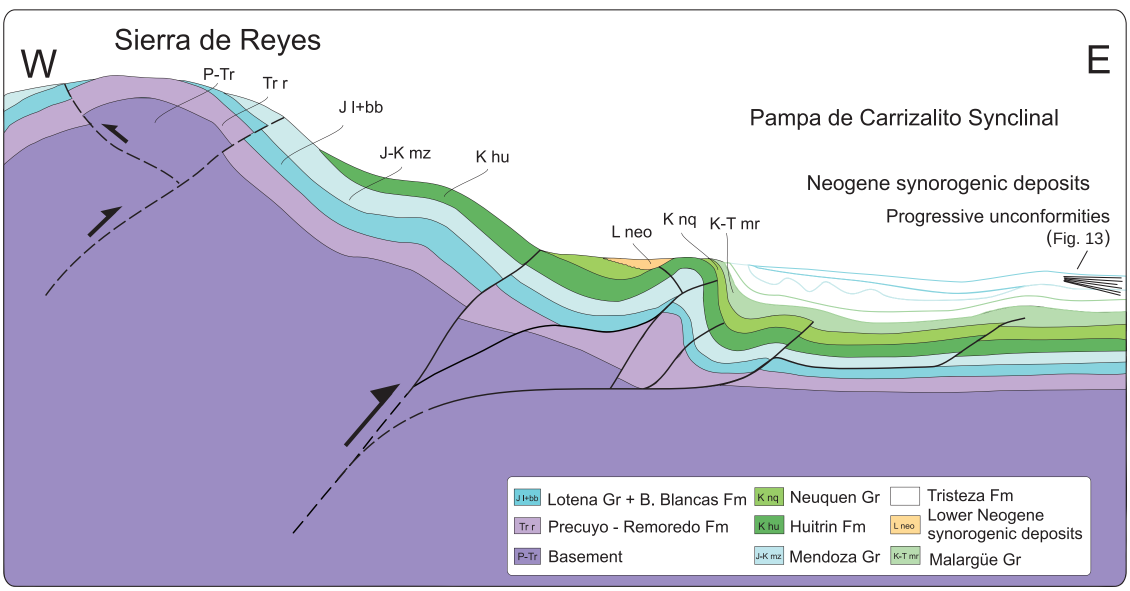


FIG. 14. Last stage of the Sierra de Reyes uplift. Note the decoupling between east-verging inserted wedges of the Sierra de Reyes eastern flank and frontal syncline (Pampa de Carrizalito), where the Neogene succession was accumulated in a foreland depocenter. Progressive unconformities and growth strata, plus an unroofing sequence proves its character. Compartmentalization of this eastern Neogene depocenter is interpreted as caused by the activity of the easternmost thrust cannibalizing the westernmost foreland basin.

sequences (Malargüe Group and Palauco Formation); **iii.** Early Miocene and Upper Miocene sequences (Palauco Formation and Tristeza Formation) (Fig. 7): The first was mentioned earlier in literature. In particular Cobbold and Rosello (2003) claimed that the beginning of the contractional deformation and consequent orogenic uplift in the area, started in late Aptian times (~115 Ma). Tunik *et al.* (2010) based on U-Pb dating on detrital zircons determined that exhumation started around 97 Ma in the hinterland

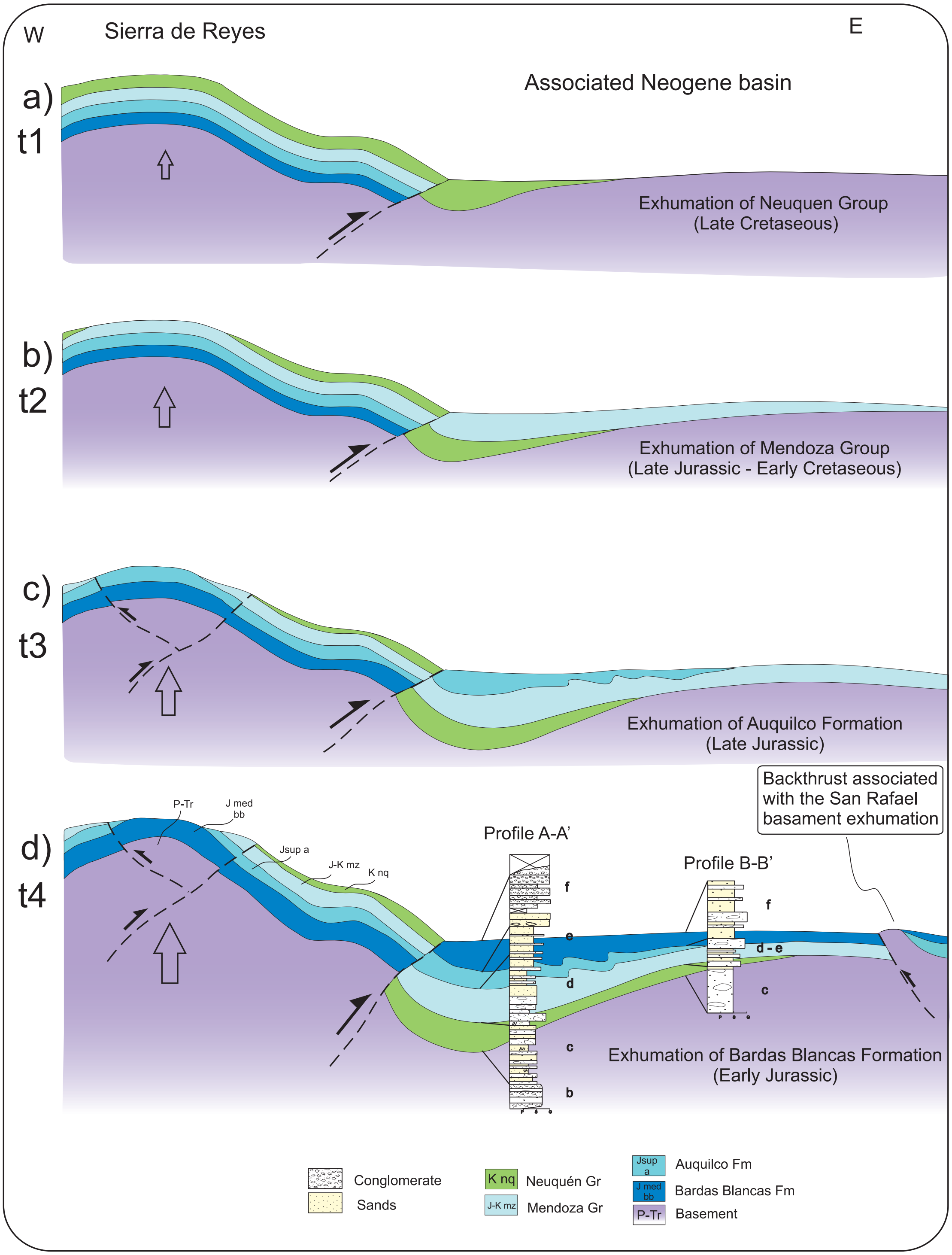


FIG. 15. Four evolutionary stages proposed for the orogenic front at the study area. Different clast provenances are recognized and correlated through the Neogene Pampa de Carrizalito foreland basin. They show progressive exhumation of the eastern flank of the Sierra de Reyes.

zone further to the west, recorded by synorogenic deposits of the Neuquén Group. This age does not necessarily indicate initial uplift which could be older, but exhumation. Based on field data, the Late Cretaceous contractional setting affected more strongly the westernmost zone of the studied area, up to the río Grande valley to the east (Fig. 1) (Folguera *et al.,* 2007). In the study area this deformation was milder defining the mentioned unconformity. The second contractional event had a clear impront in the study area and took place at the present orogenic front, between the Eocene upper Malargüe Group and the late Oligocene volcanic rocks of the Palauco Formation (Fig. 6). This one, is associated with 50-100 m thick synorogenic sequence represented by sandstones and conglomerates of the upper Malargüe Group (Kozlowski *et al.,* 1987). The third mountain building episode registered at the orogenic front developed in Late Miocene times. This is also associated with synorogenic sedimentation represented by the Tristeza Formation (Fig. 7).

Compositional variation of the Eocene-Neogene successions shows that exhumation of the Jurassic and Upper Cretaceous successions occurred in an order, which is reverse to the stratigraphic order at the eastern slope of the Sierra de Reyes. The presence of detrital components eroded from the Mesozoic successions begins with volcaniclastics detritus that are coming from Upper Oligocene to Lower Miocene sequences, followed upwards by sandstone, limestone, gypsum and finally shale clasts, in a reverse order with respect to the stratigraphic succession in the eastern flank of Sierra de Reyes (Fig. 15). This implies that the succession hosted in the Pampa de Carrizalito syncline constitutes a typical unroofing sequence: at the time of uplift of the Sierra de Reyes, fluvial incision led to the deposition of a succession characterized by a variable clastic composition. We found metamorphic fragments in the upper portion of profile B-B' (see figure 2 for location and figure 14). As there is no evidence of this kind of source in the Principal Cordillera to the west, this indicates that the foreland area to the east is uplifted and exhumed at this time, implying the uplift of the San Rafael Block located north-east of the study area and the cannibalization of the here analyzed western foreland basin.

The fact that an entire unroofing sequence is registered in a Neogene depocenter next to the orogenic front implies that a complete exhumation of the Sierra de Reyes started about this time. Therefore previous tectonic phases have not affected substantially the study region. We can conclude that the Neogene contractional stage was responsible for the exhumation of the orogenic front at these latitudes and created the present-day topography. Besides, the provenance study presented herein shows that the wedge top foreland basin was cannibalized during the exhumation of the last stages of the sedimentary record when the San Rafael Block was exhumed to the east (Fig. 15).

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References

Barrio, C.A. 1990. Paleogeographic control of Upper Cretaceous tidal deposits, Neuquén Basin, Argentina. Journal of South América Earth Sciences 3 (1): 31-49.

Bertels, M. 1969b. Mocripaleontología y estratigrafía del límite Cretácico-Terciario en Huantraico, Provincia de Neuquén, Parte II. Ameghiniana 6 (4): 253-278.

Charrier, R. 1979. El Triásico en Chile y regiones adyacentes de Argentina. Universidad de Chile, Departamento de Geología, Comunicaciones 26: 1-37.

Charrier, R.; Pinto, L.; Rodríguez, M.P. 2007. Tectonostratigraphic evolution of the Andean orogen in Chile. *In* The Geology of Chile (Moreno, T.; Gibbons, W.; editors). The Geological Society: 21-114. London.

Cobbold, P.R.; Diraison, M.; Rossello, E.A. 1999. Bitumen veins and Eocene transpression, Neuquén Basin, Argentina. Tectonophysics 314: 423-442.

Cobbold, P.; Rossello, E. 2003. Aptian to Recent compressional deformation in the foothills of the Neuquén basin Argentina. Marine and Petroleum Geology 20: 429-443.

Dimieri, L.V. 1997. Tectonic wedge geometry at Bardas Blancas, southern Andes (36ºS), Argentina. Journal of Structural Geology 19: 1419-1422.

Folguera, A.; Ramos, V.A.; Zapata, T.; Spagnuolo, M. 2007. Andean evolution at the Guañacos and Chos Malal fold and thrust belts (36º30'-37ºS). Journal of Geodynamics 44: 129-148.

Giambiagi, L.; Bechis, F.; García, V.; Clark, A. 2008. Temporal and spatial relationships of thick-and thin-skinned deformation: A case study from the Malargüe fold-and-thrust belt, southern Central Andes. Tectonophysics 459: 123-139.

Giambiagi, L.; Ghiglione, M.; Cristallini, E.; Bottesi, G. 2009. Características estructurales del sector sur de la faja plegada y corrida de Malargüe (35º-36ºS): Distribución del acortamiento e influencia de estructuras previas. Revista de la Asociación Geológica Argentina 65 (1): 140-153.

Groeber, P. 1933. Descripción de la Hoja 31c 'Confluencia de los ríos Grande y Barrancas'. Boletín de la Dirección de Minas y Geología: 38-72. Buenos Aires.

Groeber, P. 1953. Ándico, Mesozoico. *In* Geografía de la República Argentina. (Groeber, P.; editor). Sociedad Argentina de Estudios Geográficos (GAEA): 2 (1): 349-536. Buenos Aires.

Kay, S.M.; Burns, M.; Copeland, P. 2006. Upper Cretaceous to Holocene Magmatism over the Neuquén basin: Evidence for transient shallowing of the subduction zone under the Neuquén Andes (36ºS to 38ºS latitude). *In* Evolution of an Andean margin: A tectonic and magmatic view from the Andes to the Neuquén basin (35º-39ºS) (Kay, S.M.; Ramos, V.A.; editors). Geological Society of America, Special Paper 407: 19-60.

Kozlowski, E.; Cruz, C.; Rebay, G. 1987. El Terciario volcaniclástico de la zona Puntilla del Huincan. Mendoza. *In* Congreso Geológico Argentino, No. 10, Actas 4: 229-232. Tucumán.

Kozlowski, E.; Manceda, R.; Ramos, V.A. 1993. Estructura. *In* Geología y Recursos Naturales de Mendoza (Ramos, V.A.; editor). *In* Congreso Geológico Argentino, No. 12 and Congreso de Exploración de Hidrocarburos, No. 2. Relatorio 1 (18): 235-256.

Litvak, V.; Forguera, A.; Ramos, V.A. 2008. Determination of an arc-related signature in Late Miocene volcanism over the San Rafael Block, Southern Central Andes (34º30"-37º) Argentina: The Payenia shallow subduction zone. *In* International Symposium on Andean Geodynamics, No. 7, Extended abstracts: 289-291. Niza, France.

Litvak, V.; Forguera, A.; Ramos, V.A. 2009. La expansión hacia el antepaís del arco volcánico mioceno al sur de la provincia de Mendoza, Andes Centrales del Sur. *In* Congreso Geológico Chileno, No. 12, Electronic Files. Santiago, Chile.

Manceda, R.; Figueroa, D. 1995. Inversion of the Mesozoic Neuquén rift in the Malargüe fold and thrust belt, Mendoza, Argentina. *In* Petroleum basins of South America (Tankard, A.J.; Suárez S., R.; Welsink, H.J.; editors). American Association of Petroleum Geologists. Memoir 62: 369-382. Tulsa.

Mosquera, A.; Ramos, V.A. 2006. Intraplate deformation in the Neuquén Embayment. *In* Evolution of an Andean margin: A tectonic and magmatic view from the Andes to the Neuquén basin (35º-39ºS lat.) (Kay, S.M.; Ramos, V.A.; editors). Geological Society of America, Special Paper 407: 97-123.

Mpodozis, C.; Ramos, V.A. 1989. The Andes of Chile and Argentina. *In* Geology of the Andes and its relation to hydrocarbon and mineral resources (Ericksen, G.E.; Cañas Pinochet, M.T.; Reinemud, J.A.; editors). Circum-Pacific Council for Energy and Mineral Resources. Earth Sciences Series 11: 59-89. Houston, Texas.

Orts, S.; Ramos, V. 2006. Evidence of middle to late Cretaceous compressive deformation in the high Andes of Mendoza, Argentina. Backbone of the Americas. Abstract with Programs 5: p. 65. Mendoza.

Radic, J.P. 2010. Las cuencas cenozoicas y su control en el volcanismo de los Complejo Nevados de Chillán y Copahue-Callaqui (Andrés del Sur, 36-39ºS). Andean Geology 37 (1): 220-246.

Ramos, V.A.; Folguera, A. 2005. El origen de la Payenia (Mendoza sur y Norte de Neuquén): Evolución estructural y tectonomagmática de los Andes a estas latitudes. *In* Congreso Geológico Argentino, No. 16, Actas 2: 115-126. La Plata.

Ramos, V.A.; Folguera, A. 2010. In Press. Payenia volcanic province in the Southern Andes: An appraisal of an exceptional Quaternary tectonic setting. Journal of Volcanology and Geothermal Research. doi: 10.1016/j.jvolgeores.2010.09.008.

Ramos, V.A.; Kay, S.M. 2006. Overview of the tectonic evolution of the southern Central Andes of Mendoza and Neuquén (35º-39ºS latitude). *In* Evolution of an Andean margin: A tectonic and magmatic view from the Andes to the Neuquén basin (35º-39ºS lat) (Kay, S.M.; Ramos, V.A.; editors). Geological Society of America, Special Paper 407: 1-17.

Silvestro, J.; Atencio, M. 2009. La cuenca cenozoica del Río Grande y Palauco: edad, evolución y control estructural, Faja plegada de Malargüe (36°S). Revista de la Asociación Geológica Argentina 65 (1): 154-169.

Somoza, R.; Zaffarana, C.B. 2008. Mid-Cretaceous polar standstill of South America, motion of the Atlantic hotspots and the birth of the Andean cordillera. Earth and Planetary Science Letters 271: 267-277.

Spagnuolo, M.G.; Folguera, A.; Ramos, V.A. 2008. Linkage between Neogene arc expansion and contractional reactivation of a Cretaceous fold-and-thrust belt (southern Central Andes, 36º-37ºS). *In* International Symposium on Andean Geodynamics, No 7, Extended Abstracts: 513-516. Niza, France.

Tunik, M.; Folguera, A.; Naipauer, M.; Pimente, M.; Ramos, V.A. 2010. In Press. Early uplift and orogenic deformation in the neuquén basin: constraints on the Andean uplift from U-Pb and Hf isotopic data of detrital zircons. Tectonophysics. doi: 10.1016/j.tecto.2010.04.017

Uliana, M.A.; Bidlle, K.T. 1987. Permian to Late Cenozoic evolution of Northern Patagonia: main tectonic events, magmatic activity and depositional trends. *In* Gondwana Six: Structure, Tectonis and Geophysics. American Geophysical Union, (McKenzie, G.D.; editor). Geophysical Monograph 40: 271-286.

Uliana, M.A.; Dellapé, D.A. 1981. Estartigrafía y evolución paleoambiental de la sucesión Maastrichtiano-Eoterciaria del engolfamiento neuquino (Patagonia septentrional). *In* Congreso Geológico Argentino, No 8, Actas 3: 673-711. San Luis.

Vergani, G.D.; Tankard, A.J.; Belotti, H.J.; Welsink, H.J. 1995. Tectonic evolution and paleogeography of the Neuquén basin, Argentina. *In* Petroleum basins of South America (Tankard, A.J.; Suárez, R.; Welsink, H.J.; editors). American Association of Petroleum Geologists. Memoir 62: 383-402.

Weaver, P. 1927. The Roca Formation in Argentina. American Journal of Science 13: 417-434.

Yagupsky, D.; Cristallini, E.; Zamora Valcarce, G.; Varadé, R. 2007. Sistema compresivo sobreimpuesto a un rift oblicuo: Aplicaciones en la faja plegada y corrida de Malargüe, sur de Mendoza. Revista de la Asociación Geológica Argentina 62 (1): 124-138.

Zamora Valcarce, G.; Zapata, T.R. 2005. Estilo estructural del frente de la faja plegada neuquina a los 37ºS. *In* Congreso de exploración y desarrollo de Hidrocarburos. No. 6, Archivos Electrónicos. Mar del Plata.

Zamora Valcarce, G.; Zapata, T.R.; Del Pino, D.; Ansa, A. 2006. Structural evolution and magmatic characteristics of the Agrio fold-and-thrust belt. *In* Evolution of an Andean margin: A tectonic and magmatic view from the Andes to the Neuquén basin (35º-39ºS lat.) (Kay, S.M.; Ramos, V.A.; editors). Geological Society of America, Special Paper 407: 125-145.

Zamora Valcarce, G.; Atencio, M.; Manceda, R. 2008. El Frente de las grandes estructuras de la faja plegada de Malargüe. *In* Congreso Geológico Argentino, No 17, Actas electrónicas, San Salvador de Jujuy.

Zamora Valcarce, G.; Zapata, T.; Ramos, V.; Rodríguez, F.; Bernardo, L.M. 2009. Evolución Tectónica del frente Andino en Neuquén. Revista de la Asociación geológica Argentina 65 (1): 192-203.

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