1. Introduction

The Andean retroarc zone between 35° and 40°S (Fig. 1), and particularly between 36°30′ and 39°S where the Loncopué Trough is developed, constitutes an outstanding site to address non-steady mountain building since the Andean phase of deformation started some 100 Ma ago. Here we present field and geophysical data from that specific site to exemplify extensional reactivation of the fold and thrust belt that have produced substantial topographic losses.

The Southern Central Andes (28–40°S) can be divided in two sectors based on their evolution during the last 17 Ma. Since that time, the northern region between 28° and 33°S has experienced the Pampean flat subduction associated with basement foreland uplifts. It is limited eastward by a neotectonic compressional front located some 750 km from the trench (Fig. 1) (Costa and Vitasoli, 1996; Ramos et al., 2002). Seismic tomographies at those latitudes show fast P wave-velocities implying a cold setting above a southern segment between 35°S where the Loncopué Trough (Fig. 1) shows large subcrustal low-velocity arrivals interpreted as mantle melts and/or volatiles and (ii) an attenuated lower crust. This scenario has been interpreted as derived from asthenosphere injection in a broadened asthenospheric wedge more than 400 km away from the trench in the retroarc area, triggering extensional deformation at the upper crust (Fig. 2B) (Folguera et al., 2007, 2008). A 2D preliminary electrical resistivity model at 36.5°S shows an “uprising highly conductive plume” with geometry compatible with the asthenospheric anomaly modeled from gravity data (Folguera et al., 2007). The inferred extensional deformation in this segment would have expanded to the east, defining a Quaternary deformational front (Figs. 1 and 2B) where previous compressional structures would be partly collapsing diachronically since ~5 Ma (Folguera et al., 2006a). This scenario has been discussed and even contradicted by other studies, the main discrepancies based only on surficial data (Lavenu and Cembrano, 1999; Backé et al., 2006; Melnick et al., 2006a,b; Rosenau et al., 2006; Galland et al., 2007). This work, through interpretation of reprocessed seismic lines and field work, proposes a crustal-scale extensional nature of one of the main less than 5 Ma depocenters in the southern Central Andes, as well as its polyphasic nature, indicating repeated instability of the orogenic wedge through time. Finally, its origin is discussed in light of current tectonic models discussed for this Andean segment during the Neogene.
Fig. 1. Southern Central and Northern Patagonian Andes and location of the present Pampean flat subduction zone and the Late Miocene Payenia shallow subduction zone to the south, proposed by Kay et al. (2006a). The neotectonic front is also indicated as well as its variable mechanics. The two dashed lines indicate transects along which abnormally heated mantle and crustal attenuation processes have been identified.

Fig. 2. (A) Late Miocene tectonic setting for the area between 33° and 41° S, with locations of easternmost arc-related rocks (after Kay et al., 2006a), synorogenic depocenters, and contractional structures developed at that time (Ramos and Folguera, 2005). (B) Extensional deformation developed after 5 Ma in the same area controlling emplacement of intraplate series and location of the Loncopué Trough and the adjacent Agrio fold and thrust belt.
2. Retroarc geological setting

The eastern slope of the Andes between 36° and 39°S is formed by the main Andes, the product of Late Miocene tectonic inversion of the 27–17 Ma Cura Mallín basin (Jordan et al., 2001; Burns, 2002; Radic et al., 2002; Melnick et al., 2006a,b) and the Agrio fold and thrust belt to the east (Fig. 3). The latter constitutes a Late Early Cretaceous to Eocene fold and thrust belt mildly reactivated at the time of basin inversion in the west (Groeber, 1929; Zamora Valcarce et al., 2008) (Fig. 2). The Late Early Cretaceous to Eocene contractional deformational stage and consequent uplift at these latitudes is determined from (i) fission track data yielding an age between 70 and 50 Ma (Kay et al., 2006b; Zamora Valcarce et al., 2008), (ii) zircon detrital provenance data from the hinterland in synorogenic depocenters dated at <97 Ma (Ramos et al., 2008), (iii) dating of postdeformational intrusives (<105 Ma) (Zamora Valcarce et al., 2006), and (iv) a regional unconformity between Latest Cretaceous to Paleocene sequences and Early Cretaceous strata (Groeber, 1929; Llamblías and Rapela, 1989; Franchini et al., 2003). The Cura Mallín basin is interpreted as formed by a series of synextensional and diachronous depocenters (Burns, 2002; Radic et al., 2002; Utgé et al., 2009), inverted since 17–18 Ma as determined by fission track data (Spikings et al., 2008) and field studies (Utgé et al., 2009). These have been unconformably overlain by the Mid to Late Miocene Trapa–Trapa and Mitrauquén Formations, interpreted as synorogenic deposits (Melnick et al., 2006a,b). Both the Cura Mallín basin inversion and late reactivation of the Agrio fold and thrust belt in Late Miocene times have been related to a shallow subduction regime (Payenia shallow subduction zone), as evidenced by contemporaneous eastward arc expansion (Kay et al., 2006a,b).

3. Early Pliocene to Quaternary extensional deformation in the Loncopué Trough

The Loncopué Trough is on the eastern flank of the highest Andes (Main Andes) between 36°30′ and 39°S (Fig. 3), although its maximum topographic expression lies between 38° and 39°S. The axial part of the trough is marked by a series of low residual gravity anomalies in contradistinction to the Agrio fold and thrust belt to the east and the main Andes to the west, where higher values of residual gravity are reached (Fig. 3). Moreover, the entire area occupied by the Loncopué Trough and the Agrio fold and thrust belt is characterized by strong isostatic anomalies coincident with the area of crustal attenuation (Yuan et al., 2006), indicating that it could be subcompensated.

On the basis of morphological observations, Muñoz and Stern (1985) suggested that the axially depressed sector of the Loncopué Trough is bounded by two N–S fault systems, controlling Early Pliocene to Quaternary monogenetic alkaline basaltic eruptions. Basal Loncopué Trough sequences that were dated in the northern part of the trough at 4 ± 0.5 Ma, culminate in a lava plateau of 1.7 ± 0.2 Ma sparsely covered by 1.4 ± 0.4–1.2 ± 0.1 monogenetic eruptions (Folguera et al., 2004). In the southern and middle sections of the trough, similar basal ages up to 5–6 Ma were
Fig. 4. Western Loncopué Trough system at 38°S where a series of half-grabens of less than 100 m across affect Late Pliocene to Quaternary lava flows (see location in Fig. 3).

Fig. 5. Neotectonic deformation in the western Agrio fold and thrust belt. This occurred previous to 105 Ma, the age of postdeformational dykes (A). This rapid and young event is not related to stacking of thrust sheets east of the fold and thrust belt, which would require another uplift mechanism. (A) DEM of the Agrio fold and thrust belt and its main features. (B) Detail of the area of neotectonic deformation. (C) Structural profile (see location in (A)).

reported for the plateau sequences (Linares and González, 1990). At about 39°S, monogenetic centers range between 2.30 ± 0.3 and 0.47 ± 0.2 Ma (Linares and González, 1990) on the axial part of the trough, while on its western boundary they have been dated from 1.6 ± 0.2 to 0.9 ± 0.3 Ma (Muñoz and Stern, 1985, 1988). Youngest volcanic activity is concentrated at around 38°S in the axial trough, where basaltic flows interfinger with postglacial lacustrine deposits (Grobeber, 1928). A poorly evolved alkaline magmatism, together with low 87Sr/86Sr initial ratios near 0.7040, relates this volcanic field to an extensional regime (Muñoz Bravo et al., 1989).

The youngest tectonic activity in the Loncopué Trough is dated by scarp affecting lava flows at the central part of the trough.
interfingered with postglacial lacustrine sediments (Rojas Vera et al., 2008, 2009). Maximum depocenters belonging to this Pliocene to Quaternary stage are 1500–1900 m thick, with an average value of 1000 m, exposed by exceptional glacial activity in the main Andes.

The two Loncopué fault boundaries and their nature (Fig. 3) were determined by field observations, where Quaternary sequences are extensionally displaced (Figs. 4 and 5), exhibiting linear topographic breaks tens to more than one hundred kilometres long, facing the axial low. The western boundary fault zone is formed at the surface by a series of halfgrabens less than 100 m across, associated with east-facing scarps affecting Quaternary lavas (Fig. 4). The eastern boundary fault zone represents a series of west- and east-facing normal fault scarps affecting Quaternary lavas and previously deformed Mesozoic strata (Figs. 5 and 6). The Mesozoic strata were folded previously at 105 Ma, the age of postdeformational dykes intruded into the compressional structure (Fig. 6) (Zamora Valcarce et al., 2006). Therefore, extensional deformation affecting Quaternary rocks is not likely related to the contractional phenomena.

Even though extension is (i) registered at both trough boundaries, leaving a symmetrical trough in between, (ii) affecting Pliocene to Quaternary rocks, and (iii) temporally unconnected with contractional phases determined at these orogenic sections, its identified short wavelength allows alternative explanations. These structures could be associated with superficial extension of deeper contractional structures active in the Andean foothills. However, our interpretation is that their length, for individual segments of the order of 20 km and for fault systems around 40–60 km, corresponds to rather deeply rooted structures.

4. Late Oligocene to Early Miocene extensional deformation in the Loncopué Trough

Strata of 27–17 Ma age in the Cura Mallín basin are unconformably overlain by Early Pliocene sequences in the main Andes between 36° and 39° S (Fig. 3) (Suárez and Emparán, 1995; Jordan et al., 2001; Burns, 2002), and in the axial part of the Loncopué Trough north of 37° 30′ S (Fig. 3). Late Oligocene to Early Miocene strata are systematically exposed on the western side of the Andes between 38° and 39° S (Fig. 3) and on both sides of the Andes north of 38° S (Folguera et al., 2006b; Melnick et al., 2006a,b). The mechanics of subsidence has been discussed extensively in the last decade, revealing two opposing points of view. On the one hand, Cobbold et
Fig. 7. 2D W–E oriented seismic line across the axial part of the southern Loncopué Trough at 38° S, where a wedge-like depocenter thickens towards the eastern main fault boundary and is characterized internally by minor extensional structures; registered times for the deepest reflectors would imply a maximum infill of the order of 1400 m, considering an interval velocity derived from stacking velocities of 2800 m/s. See location with respect to the axial Loncopué Trough in Fig. 3. Ages of units rely on correlations and are not determined directly. (A) Seismic line. (B) Interpretation of (A) superimposed on it. (C) Complete interpretation.

Fig. 8. (A) 2D W–E oriented seismic line across the axial part of the northern Loncopué Trough at 37° S, where a series of wedge-like depocenters thickens to the west; registered times for the deepest reflectors would imply a maximum infill of the order of 1100 m, considering an interval velocity derived from stacking velocities of 2800 m/s. See location with respect to the axial Loncopué Trough in Fig. 3. (B) Interpretation of (A). Ages of units rely on correlations and are not determined directly.
al. (2008) suggested that those sequences constitute a typical foreland basin associated with the steady uplift of the Andes from Late Cretaceous to Neogene times. On the contrary Spalletti and Dalla Salda (1996), Suárez and Emparán (1995), Jordan et al. (2001), Radic et al. (2002) and Burns (2002), among others, suggest that those depocenters were part of an intra-arc extensional basin. Most of the evidence favoring each hypothesis was based on sedimentological studies, regional basin studies, supposed progressive unconformities, and analyses of low quality 2D seismic lines. Figs. 7 and 8 show reprocessed seismic lines where wedge-shaped depocenters 1100–1400 m thick with variable polarity and dimensions are recognized. Particularly in Fig. 7, halfgrabens are controlled by west-dipping high-angle faults. These are characterized internally by a series of narrower wedges which truncate each other by erosional surfaces (referred as synrift 1–4). These wedges are associated above with anticlines suggesting that related normal faults were partly inverted (Fig. 7) before Pliocene times (the oldest nonfolded rocks in the area). Onlapping reflectors on top of the inverted synrift wedges support the idea that synorogenic sedimentation took place at the time of inversion in the Loncopué Trough, presumably in late Miocene times. This series of halfgraben depocenters is located across the axial part of the southern Loncopué Trough, and seems to be associated with a west-dipping main fault boundary, where strata reach their maximum thickness. This is coincident at the surface with the western fault boundary zone indicated in Figs. 3 and 5. Synrift packages are correlated with the Cura Malín strata outcropping immediately to the west in the main Andes (Fig. 3), while onlapping sequences are assigned to the Trapa–Trapa and Mitrauquén Formations following the same criteria.

The seismic line in Fig. 8 is interpreted as a series of halfgrabens controlled by east-dipping normal faults. These seem to be mildly inverted judging by the presence of broad anticlines developed on top of the thickest sedimentary columns. Contrasting, in the seismic line in Fig. 7, no onlapping unit is distinguishable. This is explained by a deeper level of erosion, where Late Oligocene to Early Miocene units are exposed at the surface (Fig. 3). This contrasts with interpretations published by Jordan et al. (2001) from the same original data, where they infer a western master fault controlling the depocenter. This different interpretation is attributable to the quality of information. While Jordan et al. (2001) dealt with originally processed seismic data, we have used recently reprocessed data that reveal features hidden in previous lines.

5. Discussion and conclusions

Extensional depocenters of 27–17 and 5–0 Ma age inferred from seismic information and confirmed by field studies, separated by foreland sequences, could be superimposed in the Loncopué Trough, having produced locally the sinking of the westernmost section of the Late Cretaceous to Eocene fold and thrust belt. Therefore, a long controversy regarding the mechanics of subsidence in the Loncopué trough could be saved: these foothills have acted alternatively as a foredeep and a retroarc basin. To the east, remnants of these Cenozoic extensional collapses constitute the Agrio fold and thrust belt (Fig. 9), emerged mainly in Late Cretaceous to Eocene times as revealed by dating based on fission track and synorogenic sedimentation. A broad isostatic anomaly (with a maximum of 40 mGal) (Fig. 9) coincides at the surface.
with the Loncopué Trough. At a broader scale the isostatic anomaly shows two peaks that define an amplitude compatible with the area of crustal attenuation described by Yuan et al. (2006) (Fig. 9). Hypothetically, this scenario would point to the permanence of the youngest proposed extensional phenomena that would have started some 5 Ma ago. Orogenic uplift in the southern Central Andes could have been interrupted at least two times through the development of normal faults associated with sedimentation in the hinterland zone. Subsequent periods of contractional deformation would only have incorporated Paleogene extensional depocenters into the orogenic wedge, while a less than 5 Ma extension would not have been inverted yet in the area. Non-steady mountain growth and extensional deformation could be common processes during the evolution of the southern Central Andes at the latitudes of the Loncopué Trough. Finally, as stated before, different hypotheses have been proposed to explain Quaternary extension in the area: (i) as associated with local and surficial minor extension related to deeper compressional structures; (ii) as generated in strike-slip or low-partitioned strain settings, coexisting with compressional and/or transpressional structures (Lavenu and Cembrano, 1999; Backé et al., 2006; Rosenau et al., 2006); and (iii) as related to Andean-scale axial synorogenic collapse, coexisting with contractional behavior in the foothills (Melnick et al., 2006a,b). The Early Pliocene to Quaternary extensional stage could also be the immediate reaction (slab steepening) to the 18–6 Ma Payenia shallow subduction zone (Yuan et al., 2006) that affected the Loncopué Trough area. This hypothesis is based on the fact that the area of extension less than 5 Ma old coincides with the area of eastward expansion of the arc in Late Miocene times. Causes of Late Oligocene to Early Miocene extension in the area are still being debated.

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