Have the southernmost Andes been curved since Late Cretaceous time? An analog test for the Patagonian Orocline

Matías C. Ghiglione — Laboratorio de Tectónica Andina, Universidad de Buenos Aires, Ciudad Universitaria, C1428EHA, Buenos Aires, Argentina, and Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Avda. Rivadavia 1917, CP C1033AAJ, Ciudad. de Buenos Aires, Argentina

Ernesto O. Cristallini — Laboratorio de Modelado Geológico (LaMoGe), Universidad de Buenos Aires, Ciudad Universitaria, C1428EHA, Buenos Aires, Argentina, and Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Avda. Rivadavia 1917, CP C1033AAJ , Ciudad. de Buenos Aires, Argentina

ABSTRACT

The kinematic evolution of the enigmatic arc-shaped southernmost Andes of Patagonia and Tierra del Fuego has been a subject of debate for most of the past century. We compared the results from analog sandbox experiments with the tectonic evolution and actual configuration of the mountain chain in order to elucidate whether oroclinal bending took place during the Tertiary, or if the southernmost Andes have been a curved orogen since at least Late Cretaceous time. Experiments simulating oroclinal rotation produced strong along-strike variations in shortening and failed to account for structural data compiled from the Fuegian Andes. Results from experiments simulating an L-shaped, concave-to-foreland indenter were in agreement with the known Tertiary structural evolution of the southernmost Andes. The diachronicity of principal shortening events previously recognized in Patagonia and Tierra del Fuego could only be reproduced by moving the indenter in two successive orthogonal directions: first approximately northward to form the Fuegian fold-and-thrust belt, and then approximately eastward to propagate thrusting in the Patagonian Andes. This two-phase evolution is consistent with a recorded change in the convergence direction of the Farallon-Nazca plate that occurred at ca. 27 Ma.

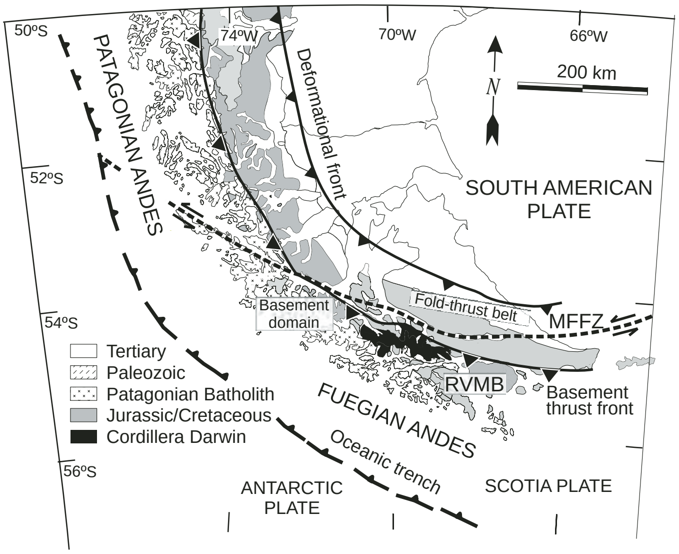

Figure 1. Location map of southernmost Andes showing tectonic plates and main structural domains. MFFZ—Magallanes-Fagnano fault zone; RVMB—Rocas Verdes marginal basin.

Keywords: oroclines, sand analog experiments, arcuate structures, Patagonian Andes, Tierra del Fuego.

INTRODUCTION

One of the most conspicuous and long-debated features of the entire Andean mountains is the progressive change in strike from the N-S–oriented Patagonian Andes to the ESE-WNW–trending Fuegian Andes (Fig. 1). In his classic book, *Origin of Continents and Oceans*, Alfred Wegener (1929) suggested that the arcuate shape of the southernmost Andes formed because South America and Antarctica drifted west with respect to the Scotia arc. Following the same drift concept, Carey (1958) named this bend the "Patagonian Orocline," assuming that the curve was due to oroclinal bending of an originally straight orogen. This hypothesis remained the leading explanation of the curve for many years, although an agreement on the timing of oroclinal bending could never be reached. Indeed, while a majority of researchers subscribed to the idea that substantial continental-scale bending took place during the Tertiary orogeny, following the Late Cretaceous closure of the Rocas Verdes marginal basin (Dalziel et al., 1973; Cunningham, 1993; Kraemer, 2003), Burns et al. (1980) suggested that oroclinal bending took place during marginal basin closure but ceased thereafter.

In recent years, a new hypothesis has emerged that considers the southernmost Andes as a primary bend (Ramos and Aleman, 2000). Diraison et al. (2000) provided evidence for this hypothesis by showing that analog models that had an oceanic plate subducting beneath a continental corner could account for the major elements of the structural pattern observed in the southernmost Andes. The hypothesis was further strengthened by structural and tectonic analyses of the region, relating the episodes of Late Cretaceous to Neogene contractional deformation to changes in subduction direction against a curved orogen (Ramos and Aleman, 2000; Ghiglione and Ramos, 2005).

In the current study, we conducted a series of analog experiments in order to evaluate whether the southernmost Andes underwent oroclinal bending during Tertiary orogeny or if it has been a curved orogen since at least the Late Cretaceous. While thrusting and folding was absent in lithospheric-scale experiments by Diraison et al. (2000), our modeling of the upper crust successfully reproduces the evolution of the thin-skinned fold-and-thrust belt. The tectonic evolution of the structural arc was surveyed by analyzing and comparing the following parameters (according to: Zweigel, 1998; Lickorish et al., 2002; Marshak, 2004; Figs. 2 and 3): (1) particle displacement paths (kinematic data), (2) trend lines of structures, (3) relative convergence directions of tectonic plates, (4) timing of main shortening events, and (5) percentage of shortening.

STRUCTURE OF THE SOUTHERNMOST ANDES

Kinematic analysis of fault-slip data from the southernmost Andes indicates that regional shortening directions vary in trend from ENE in the Patagonian Andes to NNE-SSW in the Fuegian Andes (Diraison et al., 2000; Fig. 2). Two sets of trend lines can be recognized around the bend: (1) In the external part of the arc, trend lines are truncated by regional strike-slip faults. (2) In contrast, trend lines are almost continuous along the inner arc, where they are only offset at their southern end by the Magallanes-Fagnano fault zone (Fig. 2). Each set of trend lines corresponds to a different structural domain: (1) a basement domain on the external arc, composed of the Patagonian batholith and metamorphic basement blocks, and (2) a fold-and-thrust belt on the inner arc, which has

---

Geology, January 2007; v. 35; no. 1; p. 13–16; doi: 10.1130/G22770A.1; 4 figures.

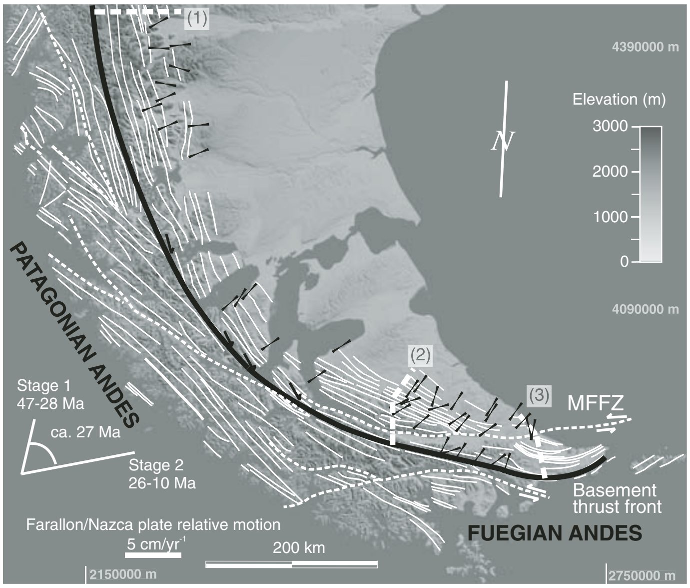

Figure 2. High-resolution topographic map (Mercator projection) from processed National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission data (SRTM) of the southernmost Andes showing trend lines (thin solid white lines), major strike-slip faults (dashed white lines), convergence of trend lines against basement domain (black arrows), and basement thrust front (thick solid line). MFFZ—Magallanes-Fagnano fault zone. Black bars show strikes of shortening axes at 42 localities obtained by fault analysis (from Diraison et al., 2000). Numbered thick dashed white lines indicate position of balanced cross sections from which shortening was constrained as follows: 1—35 km (~30%) from Kraemer (1998, 2003); 2—80 km (~50%) from Alvarez-Marron et al. (1993), Klepeis and Austin (1997), Kley et al. (1999), and Kraemer (2003); 3—70 km (~50%) from Ghiglione (2003) and Ghiglione and Ramos (2005). Farallon-Nazca plate relative motion is from Somoza and Ghidella (2005).

affected Late Jurassic to Tertiary sedimentary sequences (Figs. 1 and 2). The boundary between these two domains is the basement thrust front (Kraemer, 2003; Figs. 1 and 2). The approximate total shortening in the Patagonian external domain is 35 km (~30%) at the northern end of the studied bend (Kraemer, 1998; Fig. 2). An increase in orogenic shortening from that point toward the Fuegian Cordillera has been mentioned (Diraison et al., 2000; Kraemer, 2003), although this variation has not been described in detail. Total shortening through the Fuegian fold-and-thrust belt is 70–80 km (~50%) (Kley et al., 1999; Ghiglione, 2003; Fig. 2).

A compressional event produced the closure of the Early Cretaceous Rocas Verdes marginal basin (Fig. 1) and the ensuing collision of the magmatic arc and ocean floor against the craton during the Late Cretaceous (Klepeis and Austin, 1997). This deformational event involved transpressional deformation that produced the pervasive strike-slip faulting present through the basement domain (Cunningham, 1993; Fig. 2). These processes resulted in the consolidation of the crystalline domain by latest Cretaceous time, before the formation of the thin-skinned fold-and-thrust belt in the early Tertiary (Klepeis and Austin, 1997; Kraemer, 2003). Whereas shortening across the thin-skinned fold-and-thrust belt occurred principally from the middle Eocene to early Oligocene in Tierra del Fuego (Klepeis and Austin, 1997; Ghiglione and Ramos, 2005), deformation and uplift occurred mainly during Miocene time in the Patagonian Andes, although deformation there began during the Eocene (Ramos, 1989; Kraemer, 1998). Furthermore, contractional deformation of the Fuegian Andes stopped during the Oligocene and changed in character to a wrench deformation regime produced by the spread of the transform plate boundary between the South America and Scotia plates named the Magallanes-Fagnano fault zone (Klepeis and Austin, 1997; Figs. 1 and 2). The rapid orogenic front propagation during the middle to late Eocene in Tierra del Fuego coincided precisely with a period of rapid convergence and northward-directed subduction of the Farallon plate (Ramos and Aleman, 2000; Ghiglione and Ramos, 2005; Fig. 4). In contrast, the Patagonian cordillera underwent its principal period of contractional deformation when the convergence vector rotated to a more orthogonal, eastward direction (Ramos, 1989, 2005; Fig. 4).

ANALOG MODELING

In our experiments, we used an ~17 mm layer of well-rounded dry sand, sieved to 0.4 mm, with negligible cohesion, a friction angle of ~29°, and a geometric scale of $\lambda = \sim 2.43 \times 10^{-6}$. These properties make the sand a good analog for the brittle upper crust (Davy and Cobbold, 1991). The displacement paths of points on top of the sand were compared directly with compiled kinematic data (according to Lickorish et al., 2002).

We performed a series of sandbox experiments designed to simulate the push of the basement domain, which we consider as a Late Cretaceous rigid backstop that has collided against the soft sedimentary cover (Fig. 3). The selected experiments presented in this paper are representative of three possible tectonic configurations: (1) a one-phase diagonal indentation, (2) a two-phase orthogonal indentation, and (3) an oroclinal bending of the indenter, followed by orthogonal convergence. The first two experimental setups were designed to test the hypothesis that the southernmost Andes were already a curved orogen in Late Cretaceous time. In these experiments, an "L" shaped indenter with an aperture angle of 107° (i.e., the angle between limbs of the basement thrust front; Fig. 2) was forced into the sand-fill along an orthogonal or diagonal translation path (Figs. 3A–3C). In the last experiment, which was designed to examine the effects of a large-scale oroclinal rotation of the basement, the lower half of a partially curved indenter with an initial aperture angle of 124° was pivoted 17° counterclockwise around a hinge (Figs. 3D–3E). For reference purposes, the left edge of the experimental setup was taken as the N-S direction, the N-S limb of the indenter was called Patagonian limb, and the ~E-W one was called Fuegian limb (Fig. 3).

RESULTS

One-Phase Diagonal Indentation

The indenter collided with the sand-fill in a near-bisector direction, producing simultaneous shortening and laterally continuous arcuate structures along both limbs (Fig. 3A). After a displacement of 15 cm, a shortening value of 54% was measured in the corner region (Fig. 3A). Shortening in the limbs was proportional to displacement direction, and was thus slightly greater in the Fuegian limb than in the Patagonian limb (Fig. 3A). In a similar experiment, not described here, a ratio of shortening of ~2:1 (i.e., ~60% Fuegian limb to ~30% Patagonian limb) was obtained by using a displacement angle of 40° against the Patagonian limb.

This alternative adequately explained the continuity and smooth bending of trend lines, but did not reproduce the distribution of shortening directions around the arc (compare with Fig. 2). Whereas the Patagonian Orocline displays noncoaxial contraction directions (Fig. 2), the displacement paths obtained in this experiment were substantially parallel, even though a gradual convergence toward the center of the arc could be observed in younger thrusts (Fig. 3A).

Two-Phase Orthogonal Indentation

This experiment reproduced the particular sequence of thrusting and shortening found in the southernmost Andes by moving the indenter in two stages: (1) almost perpendicular (80°) to the Fuegian limb and at a 30° angle to the Patagonian limb (Fig. 3B), and (2) almost perpendicular (75°) to the Patagonian limb and parallel to the Fuegian limb (Fig. 3C). To allow comparison with the southernmost Andes, we used the amount of displacement necessary to produce a shortening of ~50 % along the Fuegian limb during stage 1 and ~30% along the Patagonian limb during stage 2.

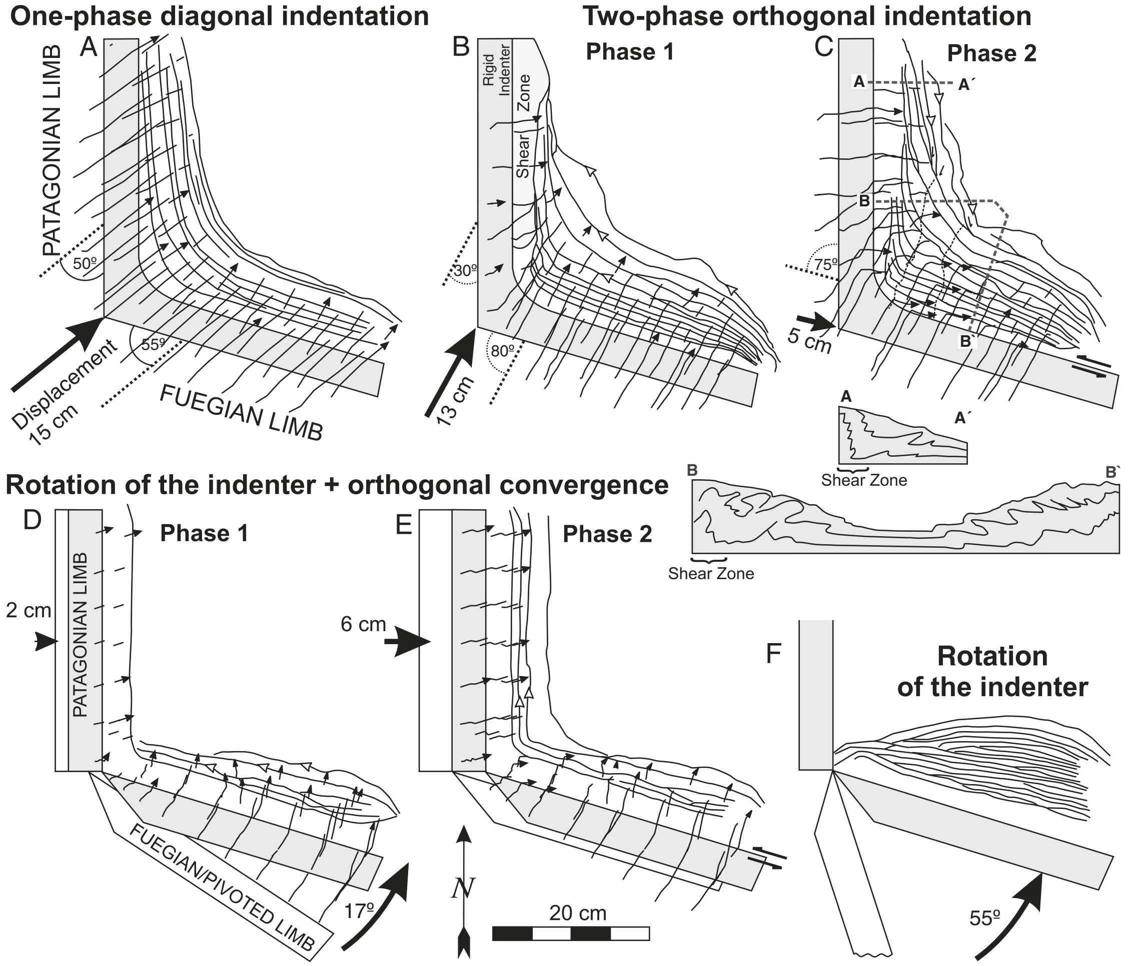

Figure 3. Intermediate and final stages of each of three experiments, showing finite displacement vectors for material points on top of sand (thin solid lines; arrows indicate general vergence) and trend lines. A: Case of concave-to-foreland indenter in one-phase diagonal indentation. B–C: Two-phase orthogonal indentation including two cross sections. D: Oroclinal bending of indenter, followed by (E) orthogonal convergence, and (F) 55° bending of Fuegian limb in accordance with estimations from Kraemer (2003). White arrows indicate lateral direction of thrust propagation.

During stage 1, main thrusts were first generated along the eastern extremity of the Fuegian limb. Next, they advanced to the west and turned around the corner region to end up dying against a shear zone generated along the Patagonian limb (Fig. 3B). In this shear zone, a substantial strike-slip displacement developed. There was also transpressional uplift perpendicular to the Patagonian limb (Fig. 3B).

During stage 2, thrusting occurred along the Patagonian limb belt, increasing its width. The Fuegian limb belt remained stable, and only the sector near the corner region was reached by the advancing Patagonian limb belt (Fig. 3C). The component of strike slip against the Fuegian limb was partitioned along the edge of the indenter rather than being dispersed in the sand wedge (Fig. 3C). In the Patagonian Orocline, this component has been partitioned along the Magallanes-Fagnano fault zone since the Oligocene (Figs. 2 and 4).

One intriguing aspect was the convergence of trend lines that occurred when newly formed thrusts on the Patagonian limb propagated southward until they stopped against previously formed, NW-trending structures (Fig. 3C). We suggest that this behavior is the consequence of using an ESE displacement direction rather than an ENE or E direction. The latter would probably produce a northward propagation of thrusts from the edge of structures formed earlier, as happened in the following experiment (see Figs. 3D–3E), and truncations would not occur.

Thrusting coming from the Fuegian limb during stage 1 produced a southward increase in shortening along the southern Patagonian limb (compare cross sections from Fig. 3C). In nature, although it is not clear at which latitude the Fuegian thrusting begins to have an effect, its influence can explain the southern increase in shortening mentioned for the Patagonian Andes (Diraison et al., 2000, Kraemer, 2003).

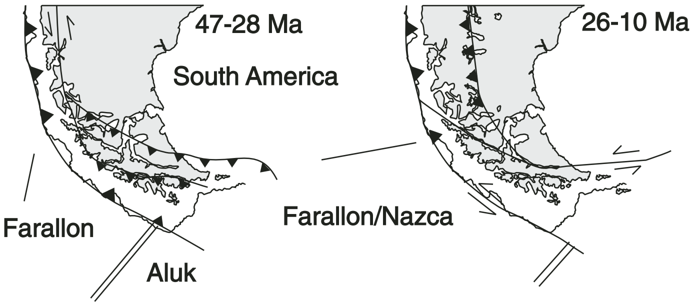

Figure 4. Schematic reconstructions of tectonic evolution of southernmost Andes. Relative plate motions are from Somoza and Ghidella (2005).

This experiment accounts for the direction, distribution, and timing of shortening (Figs. 3B–3C) in both segments of the southernmost Andes (compare with Figs. 2 and 4).

Rotation of the Indenter followed by Orthogonal Convergence

This experiment involved two stages. First, rotation of the Fuegian limb took place synchronously with a small amount of orthogonal convergence in the Patagonian limb (Fig. 3D). Along the Fuegian limb, the arc of rotation, and therefore displacement, shortening, and width of the belt increased with distance to the axis of rotation, and trend lines converged toward the hinge (Fig. 3D). During stage 2, the thrust belt on the Fuegian limb remained stable, and pure strike-slip motion occurred between the sand-fill and the rigid edge (Fig. 3E).

This experiment mimicked the recorded timing of shortening, as well as the continuity of trend lines found in the Patagonian Orocline (Fig. 2). The resulting geometry differed from the actual configuration of the southernmost Andes in that the experiment produced a strong variation in orogenic shortening and in width of the thrust belt along the strike of the pivoted edge (Figs. 3D–3E). A stronger variation was observed when a greater angle of rotation was used in another experiment, shown in Figure 3F.

DISCUSSION

In summary, the series of analog sandbox experiments shows that shortening and width of the thrust wedge across the curving southern tip of the Andean orogen depend on indenter direction and amount of convergence.

Oroclinal bending of the indenter produced a strong variation of shortening along the Fuegian limb and failed to account for the structural data compiled from the Fuegian Andes. The particular strike-slip orocline model from Cunningham (1993) was not reproduced here because it implies a succession of E-W–oriented, left-lateral faults cutting the trend of folds and thrusts transversally to the orogen, and the strike-slip faults recognized so far in the southernmost Andes are orogen-parallel, and faults and folds are continuous along strike (Fig. 2).

An L-shaped indenter explains the structural configuration and the diachronicity of shortening events in the Fuegian and Patagonian Andes, but only when two-phase orthogonal indentation is applied. In such experiments, convergence at angles larger than ~55° produces strong shortening, and angles ranging from ~40° to 0° produced little or no shortening, respectively (Fig. 3). Therefore, two different stages of indentation are proposed: Stage 1—convergence at a direction forming an acute angle larger than ~55° with the Fuegian limb where shortening is maximum, and convergence at a much smaller angle with the Patagonian limb. Stage 2—rotation of the convergence vector clockwise to form an angle of between 50° and 90° with the Patagonian limb, and an angle smaller than ~20° with the Fuegian limb, where the belt remains steady. Significantly, the angles between the calculated convergence directions for the tectonic plates on the Pacific basin and the presently curved southernmost Andes are in a similar range (Figs. 2 and 4). This implies that the northward-oriented convergence vector from 47 to 28 Ma (Somoza and Ghidella, 2005) resulted in an orthogonal indentation along the Fuegian Andes and oblique indentation against the Patagonian Andes, while an eastward convergence vector from 26 to 10 Ma produced the inverse effect (Figs. 2 and 4).

CONCLUSIONS

The present study shows that the distribution of trend lines, particle displacement paths, plate convergence directions, and the variations in amount, relative timing, and direction of orogenic shortening around the southernmost Andes are in agreement with the collision of a rigid, concave-to-foreland indenter against the soft sedimentary cover. Our findings support the idea that the southernmost Andes have been curved since Late Cretaceous time and that oroclinal rotation was not significant in relation with the Tertiary orogenic shortening. These results also open the possibility that these mountains are a primary bend, a fact that should be taken into account in plate tectonic reconstructions of the Scotia Sea region.

The driving force that controlled the movement of the basement indenter was the subduction of oceanic crust on the Pacific side of the orogen. The movement of the basement indenter included two sequential and almost perpendicular phases, which resulted from changes in the subduction direction that occurred ca. 27 Ma (Figs. 2 and 4). These findings show that backarc contraction is strongly affected by the direction and rate of convergence of the subducting plate, which enhances our understanding of deformation at plate boundaries.

ACKNOWLEDGMENTS

This research was supported by the Agencia Nacional de Promoción Científica y Tecnológica (PICT 14144/03), Fundación Antorchas, Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET; PEI 5758/05) and Universidad de Buenos Aires. M.C. Ghiglione was supported by a postdoctoral grant from CONICET. We are grateful to J. Brodeur, V.H. Garcia, C.C. Guzmán, R. Somoza, and D.L. Yagupsky for giving support and advice during experimental setup and manuscript preparation. Ghiglione thanks Victor A. Ramos for guidance during his work in Patagonia and Tierra del Fuego. The reviewers M. Ford, J. Kley, and S. Marshak provided constructive criticism that led to an improved manuscript.

REFERENCES CITED

Alvarez-Marrón, J., McClay, K.R., Harambour, S., Rojas, L., and Skármeta, J., 1993, Geometry and evolution of the frontal part of the Magallanes foreland thrust and fold belt (Vicuña area): Tierra del Fuego, southern Chile: American Association of Petroleum Geologists Bulletin, v. 77, p. 1904–1921.

Burns, K.L., Richard, M.J., Belbia, L., and Channelawn, F., 1980, Further paleomagnetic confirmation of the Patagonian Orocline: Tectonophysics, v. 63, p. 75–90, doi: 10.1016/0040–1951(80)90108–0.

Carey, S.W., 1958, The tectonic approach to continental drift, *in* Continental Drift: A Symposium: Hobart, Tasmania, Geology Department, University of Tasmania, p. 177–355.

Cunningham, W.D., 1993, Strike-slip faults in the southernmost Andes and the development of the Patagonian Orocline: Tectonics, v. 12, p. 169–186.

Dalziel, I.W.D., Klingfield, R., Lowrie, W., and Opdyke, N.D., 1973, Paleomagnetic data from the southernmost Andes and the Antarctandes, *in* Tarling, D.H. and Runcom, S.K., eds., Implications of Continental Drift to the Earth Sciences 1: San Diego, Academic Press, p. 87–101.

Davy, P., and Cobbold, P.R., 1991, Experiments on shortening of a 4-layer model of the continental lithosphere: Tectonophysics, v. 188, p. 1–25, doi: 10.1016/0040–1951(91)90311-F.

Diraison, M., Cobbold, P.R., Gapais, D., Rossello, E.A., and Le Corre, C., 2000, Cenozoic crustal thickening, wrenching and rifting in the foothills of the southernmost Andes: Tectonophysics, v. 316, p. 91–119, doi: 10.1016/S0040–1951(99)00255–3.

Ghiglione, M.C., 2003, Estructura y evolución tectónica del Cretácico-Terciario de la costa Atlántica de Tierra del Fuego [Ph.D. thesis]: Buenos Aires, Universidad de Buenos Aires, 150 p.

Ghiglione, M.C., and Ramos, V.A., 2005, Progression of deformation in the southernmost Andes: Tectonophysics, v. 405, p. 25–46, doi: 10.1016/j.tecto.2005.05.004.

Klepeis, K.A., and Austin, J.A., 1997, Contrasting styles of superposed deformation in the southernmost Andes: Tectonics, v. 16, p. 755–776.

Kley, J., Monaldi, C.R., and Salfity, J.A., 1999, Along-strike segmentation of the Andean foreland: Causes and consequences: Tectonophysics, v. 301, p. 75–94.

Kraemer, P.E., 1998, Structure of the Patagonian Andes: Regional balanced cross section at 50°S, Argentina: International Geology Review, v. 40, p. 896–915.

Kraemer, P.E., 2003, Orogenic shortening and the origin of the Patagonian Orocline (56 degrees S. Lat.): Journal of South American Earth Sciences, v. 15, p. 731–748, doi: 10.1016/S0895–9811(02)00132–3.

Lickorish, W.H., Ford, M., Burgisser, J., and Cobbold, P.R., 2002, Arcuate thrust systems in sandbox experiments: A comparison to the external arcs of the Western Alps: Geological Society of America Bulletin, v. 114, p. 1089–1107.

Marshak, S., 2004, Salients, recesses, arcs, oroclines, and syntaxes—A review of ideas concerning the formation of map-view curves in fold-thrust belts, *in* McClay, K.R. ed., Thrust Tectonics and Hydrocarbon Systems: American Association of Petroleum Geologists (AAPG) Memoir, v. 82, p. 131–156.

Ramos, V.A., 1989, Foothills structure in northern Magallanes Basin, Argentina: American Association of Petroleum Geologists Bulletin, v. 73, p. 887–903.

Ramos, V.A., 2005, Ridge collision and topography: Foreland deformation in the Patagonian Andes: Tectonophysics, v. 399, p. 73–86, doi: 10.1016/j.tecto.2004.12.016.

Ramos, V.A., and Aleman, A., 2000, Tectonic evolution of the Andes, *in* Cordani, U., et al., eds., Tectonic evolution of South America: Rio de Janeiro, Brazil: Proceedings of the 31st International Geological Congress, Rio de Janeiro, Brazil, In-folio Producao Editorial, p. 635–685.

Somoza, R., and Ghidella, M.E., 2005, Convergencia en el margen occidental de América del sur durante el Cenozoico: Subducción de Nazca, Farallon y Aluk: Revista de la Asociación Geológica Argentina, v. 60, p. 797–809.

Wegener, A., 1929, The origin of continents and oceans (4th edition) (Translated from the 4th revision of the German edition by John Biram): New York, Dover Publications, 246 p.

Zweigel, P., 1998, Arcuate accretionary wedge formation at convex plate margin corners: Results of sandbox analog experiments: Journal of Structural Geology, v. 20, p. 1597–1609, doi: 10.1016/S0191–8141(98)00052–2.

Manuscript received 9 March 2006
Revised manuscript received 28 June 2006
Manuscript accepted 1 August 2006

Printed in USA