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Reply to the comment by R. A. Astini and F. M. Dávila on "The West Andean Thrust, the San Ramón Fault, and the seismic hazard for Santiago, Chile"

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1. Introduction

[1] We have proposed earlier a new tectonic model for the evolution of the Andes mountain belt as a bivergent orogen. Here, to reply to a comment by *Astini and Dávila* [2010], we discuss briefly the protracted diachronic evolution (over tens of million years) by propagating deformation at the large-scale (over 10^2–10^3 km), its influence on basin formation in the back-arc region (retroarc foreland basin), and the mechanical implications of the bivergence in the tectonics of the fore-arc region, particularly the possible effects of the underthrusting of the coastal crustal-scale rigid block (the Marginal Block) beneath the West Andean Thrust.

[2] The comment by *Astini and Dávila* [2010] criticizes our new model presented by *Armijo et al.* [2010] suggesting that the Andes is a fundamentally bivergent (or doubly vergent) orogen and defends the conventional model of Andean orogeny, which we think obsolete, involving crustal shortening only by development of retroarc thrusts in the back-arc region (e.g., as discussed, among many others, by *Isacks* [1988]). Our model is based on the structural study of the San Ramón Fault system and the Principal Cordillera at the front of the western flank of the Andes, which is used to characterize the crustal-scale West Andean Thrust (WAT), a major fold-thrust system in the fore-arc region, synthetic to the subduction zone. Astini and Dávila raise cursorily a large number of important questions, which cannot be fully addressed in this reply.

[3] To summarize the main argument: (1) Astini and Dávila think that according to the critical taper wedge model [e.g., *Davis et al.*, 1983], the dominant thrusting of the Andes cannot have shifted from an initial westward vergence to an eastward vergence, as we propose; (2) they claim that the well-known eastward (cratonward) migration of thrusting associated with foreland basin formation in Argentina cannot be explained if the initial dominant thrusting of the Andes was in the fore arc, with westward directed vergence; and (3) Astini and Dávila argue that no continental block in the fore-arc region, as the Marginal (or Coastal) Block that we have defined, can be considered as a western foreland of the Andes because there is no well-developed western foreland basin. The miscellaneous final remarks by Astini and Dávila express their doubts that our model may fit currently accepted models of mass transfer, sediment flow across orogens, and tectonic-climatic forcing because according to our model, a major topographic slope would have been created to the west of the Andes (a feature that as anyone can check is not hypothetical, but a matter of fact). Last (but not least), the Andes at 33.5°S latitude would not be in an early stage of its evolution (as we claim) because sediments in the Argentinean foreland record its development since more than 20 Ma. Our reply, intended to identify first-order conflicting issues, is as follows:

2. Possible Evolution of the Andean Bivergent Orogen

[4] That the Andes have grown in a bivergent tectonic framework is evident (see discussion by *Armijo et al.* [2010]). If our work may innovate, it is by suggesting the importance and possible mechanical role of crustal-scale thrust structures on the west flank of the Andes, in the fore-arc region and synthetic with the subduction zone, which have for long been neglected (we have designated this feature as the WAT). According to our observations and the conceptual framework used for this kind of tectonic problem [*Malavieille*, 1984; *Willett et al.*, 1993; *Beaumont et al.*, 1996; *ten Brink et al.*, 2009], the Andes would be a bivergent crustal wedge. There appears to be no mechanical obstacle for an Andean orogenic growth with two main stages: a first stage characterized by the dominance of a fore-arc thrust belt (prowedge) and a second stage characterized by development and eventual dominance of a back arc thrust belt (retrowedge), and with formation of a conspicuous retroarc foreland basin [*DeCelles and Giles*, 1996]. Both the fore-arc thrust belt and the back-arc thrust belt would have formed as a response to block uplift of the central region bounded by two conjugate step-up shear zones (proshear and retroshear) forming a triangle [*Willett et al.*, 1993; *Beaumont et al.*,

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0278-7407/10/2010TC002692

1996]. According to sandbox kinematic experiments by *ten Brink et al.* [2009], a broad retrowedge would develop only if the central region (the arc) behaves relatively rigidly, acting as a backstop that transmits compressive stress into the back-arc region. In turn, according to numerical experiments by *Beaumont et al.* [1996], this would be achieved only if a buoyant slab has moved into the subduction system (simulating continental collision). As mentioned below, west of the Andes we find an equivalent underthrusting buoyant block (the Marginal Block). So, in contrast with the opinion expressed by Astini and Dávila, we think the currently accepted conceptual framework is appropriate to analyze and test our Andean tectonic scenario.

3. Development of the Eastern (Retroarc) Foreland Basin: Southward and Eastward Propagation of Andean Deformation

[5] The tectonic section of the Andes that we describe at 33.5°S (see structural maps and sections in the work by *Armijo et al.* [2010]) appears to display mostly the effects of the first stage of Andean deformation, but immediately north of 33.5°S the effects of the second stage become more evident, and with dramatically growing evidence, farther north (into the region to which Astini and Dávila mostly refer), for the dominance of a back-arc thrust belt and a retroarc foreland basin. Like others authors [e.g., *Giambiagi et al.*, 2003], we interpret this feature to reflect southward propagation of the Andean deformation. The Andes would be more evolved, with progressively greater cumulative shortening, to the north of 33.5°S [e.g., *Kley et al.*, 1999; *Ramos et al.*, 2004], and less evolved (or incipient) in our section at 33.5°S, where we find a modest overall cumulative shortening of 35–50 km throughout the Andes and probably no more than ~10 km shortening associated with retroarc thrusting (inconsistent with the assertion by Astini and Dávila). We think that the dramatic north-south gradient in the Andean deformation is a first-order feature that should not be ignored.

[6] The foregoing evolution is consistent and complementary with the evolution of the Andean (Altiplano) Plateau (18°S–24°S), by eastward propagation from the Western Cordillera to the Subandean Belt, of east vergent thrusts since ~70 Ma (Cretaceous to early Palaeocene time) [*Sempere et al.*, 1997; *Horton et al.*, 2001; *DeCelles and Horton*, 2003; *McQuarrie et al.*, 2005]. The age of the early Andean compressional structures and exhumation at 18°S–24°S in the western flank of the Andes, i.e., the present-day arc to fore-arc region (Western Cordillera and Chilean Precordillera) is reportedly of "Incaic" age (~38 Ma [*Scheuber et al.*, 1994; *Allmendinger et al.*, 1997; *Maksaev and Zentilli*, 1999]) or perhaps older (Late Cretaceous and Paleocene [*Arriagada et al.*, 2006; *Amilibia et al.*, 2008]). It seems clear that the first structural reliefs of the Andean orogeny were created at this latitude in the area now occupied by the Western Cordillera and Chilean Precordillera. Those ages are significantly older than the 20–25 Ma age of the initial Andean compressional deformation (by basin inversion [e.g., *Charrier et al.*, 2002]) along the same western flank of the Andes at 33.5°S in the Principal Cordillera (consistent with the ages mentioned in the last assertion by Astini and Dávila). Therefore, the Andean deformation along the western flank of the Andes (in the present-day arc to fore-arc region) appears also (as in deformation in the back-arc region) to have propagated southward, along the WAT. So we find that the Andean orogen is characterized by important deformation gradients and a protracted diachronic evolution, which are both indicative of propagating deformation at the large-scale (10^2–10^3 km). Elaborating forward this evolutionary view would probably respond satisfactorily to concerns on details of ages and amounts of deformation reflected by retroarc basin formation in Argentina as expressed by Astini and Dávila.

4. Mechanical Role of the Marginal Block: Significance of Basins in the Fore-Arc Region

[7] Geographically and structurally, the continental basement block located to the west of the western flank of the Andes Mountains is a western foreland. We have designated that western foreland, which is ~200 km wide horizontally (the distance separating the WAT from the subduction zone), Marginal (or Coastal) Block. That configuration appears determinant for the Andean mountain building process because the rigid, eastward dipping Marginal Block appears to act as a balance between forces applied by the Andes across the WAT (load of the Andes) and the subduction zone (associated with the buoyancy of the subducted slab, plus those associated with accretionary or subduction erosion processes, if any). So, these appear to be first-order boundary conditions for the Andean orogeny.

[8] However, it is difficult to classify the basins of different size and nature found on top of the Marginal Block. Just to the west of the WAT is the Central Depression, which may be considered as a modern terrestrial fore-arc basin [*Allmendinger et al.*, 1997; *Horton et al.*, 2001; *McQuarrie et al.*, 2005]. However, *Dickinson* [1995] does not classify the Central Depression as fore-arc basin and instead considers as modern examples of fore-arc basin in the Andean continental margin a string of basins located offshore on a fringe of continental basement. Chilean examples would be the offshore Arica, Iquique, and Valparaíso basins, located at depths of 1500 to 2500 m [*Coulbourn and Moberly*, 1977; *Laursen and Normark*, 2003]. The Central Depression has also been interpreted as an underfilled foreland basin [*Victor et al.*, 2004]. The Central Depression contains a variable thickness of Cenozoic sediments, reaching a maximum thickness of 4 km at 41°S [*Scholl et al.*, 1970]. We conclude, however, that the Central Depression is mostly an underfilled basin at 33.5°S (consistent with the inference by *Farías et al.* [2008], see discussion by *Armijo et al.* [2010]). If it should be classified as a "peripheral" foreland basin or as a terrestrial fore-arc basin (according to the classifications given by *DeCelles and Giles* [1996] and by *Dickinson* [1995]) appears secondary. More importantly, however, it is likely that the Central Depression and the 12 km thick Andean Basin of Early Jurassic to Cenozoic age beneath it together form a specific kind of basin development, which is in need of

further study. The Andean Basin is by far the largest and most impressive basin on top of the Marginal Block basement, dipping consistently eastward with that basement for many thousands kilometers along the strike of the central Andes. Our study at 33.5°S (see structural maps and sections in the work by *Armijo et al.* [2010]) shows, however, that the eastern half of that basin has been deformed, uplifted to high elevations and incorporated to the west vergent Principal Cordillera fold-thrust belt. The upper part of the Cenozoic sequence in the western Principal Cordillera (Farellones Formation) appears to have been syntectonically deposited in a piggyback configuration and transported westward by motion on the basal detachment of the WAT, probably by kilometers, much like wedge-top deposits in a foreland basin system [*DeCelles and Giles*, 1996]. Probably the tectonic role of the Cenozoic deposits found atop the Andean Basin should be reexamined. Given the foregoing, the preliminary modeling results obtained by Astini and Dávila seem interesting and promising, but the conventional elastic flexure modeling approach for foreland basins does not seem appropriate to take into account the specific very compelling boundary conditions under which the Marginal Block has evolved.

5. Final Remarks

[9] One of the most exciting issues of mountain building processes studied in the last decade are the combined effects of tectonics and the creation of topography, the consequent development of orographic barriers that alter atmospheric circulation, which ultimately affect the erosion, sediment transport regimes and the landscape evolution. A review of the Andean tectonic/climatic evolution has been presented by *Strecker et al.* [2007]. The results of our work appear consistent with the main described effects and especially with those concerning precipitation south of 27°S, where the moisture-bearing winds (the Southern Hemisphere westerlies) cause high rainfall on the western flank of the Principal Cordillera and semiarid conditions in the lee of the ranges, an asymmetry (creation of topography associated with the tectonic activity of the Andes, which has produced an efficient barrier at its western flank) that is also reflected in differences in weathering, erosion, and sediment transport rates on opposite sides of the orogen [*Strecker et al.,* 2007].

[10] Finally, the popular concept of Chilean mode of subduction defined by *Uyeda and Kanamori* [1979] where the strong coupling, the high seismic activity, and the uplift and the compresssion of the leading edge of the South America continent are explained by the buoyancy of young subducted lithosphere has evolved gradually into the idea that crustal shortening in an Andean-type orogen can only be achieved by development of retro-arc thrusts in the back arc region [see, e.g., *Stern,* 2002]. So there should be no proarc thrust in Andean-type fore arcs. A complementary idea is that fore arcs built on continental lithosphere (Andean-type arcs) are classified as nonaccretionary [*Stern*, 2002]. In a similar way, the study of retroarc foreland basins closely associated with the development of orogens has apparently given rise to the idea that the existence of orogens and large continental thrusts should remain doubtful until a well-developed foreland basin has been found. Our work is challenging those ideas. For the case of the south central Andes, we have shown evidence demonstrating that the high topography at its western flank (Western Cordillera, Chilean Precordillera, Principal Cordillera) and the major crustal-scale structure that mechanically sustains it (the WAT) are first-order early features of the orogen evolution. So, (1) there is an important fore-arc thrust belt synthetic with the subduction zone; (2) the eastward underthrusting of the Marginal Block demonstrates a specific Andean kind of crustal-scale accretion; and (3) the boundary conditions governing the dynamics of the Marginal Block determine specific conditions for land uplift and subsidence and sediment transport and deposition across the fore-arc region, ultimately in the trench. We agree with Astini and Dávila that all those new issues should now be worked out.

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