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Thrust-fold belt kinematics and orogenic growth in Tierra del Fuego, Argentina: implications of backthrusting for critical Coulomb wedge development

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Abstract: Analysis of balanced cross-sections and of the chronostratigraphy of the deformed foreland basin successions allows to solve the structural kinematics of the eastern Fuegian thrust-fold belt. Based on the Coulomb wedge theory, we propose a chronologically and geometrically well-constrained growth history for the frontal Fuegian Andes orogen. The mountain front behaved in a critical manner during the Early Eocene, characterized by forward thrusting. The wedge became subcritical after that, until renewed forward propagation of the thrust front in the Early Miocene. The long period as a subcritical wedge enhanced retrodeformation, recorded by out-of-sequence thrusting and backthrusting. We suggest that backthrusts should be considered an important mechanism for accommodating shortening in subcritical orogenic wedges.

Keywords: thrust-fold belt kinematics, orogenic growth, Coulomb wedge, backthrusts, Argentine Fuegian Andes.

The Fuegian thrust-fold belt is the thin-skinned frontal expression of the Andean orogen in Tierra del Fuego, Argentina. Along the Atlantic coast, an almost continuous cross-section of the eastern thrust-fold belt is exposed. The contractional structures affect sedimentary rocks from the Upper Cretaceous to the Miocene, which compose the clastic fill of the Austral-Malvinas foreland basin system (Olivero and Malumián, 2008).

Construction of balanced cross-sections provides useful information for the analysis of the kinematic evolution of the thrust-fold belt. We divided the eastern thrust-fold belt in two sections (Fig. 1), south and north of the Fagnano transform system (the boundary fault between the Scotia and South American plates), which produced a left-lateral offset of almost 50 km to the thrust-fold belt after cessation of thrusting (Torres Carbonell *et al.*, 2008a). According to a well-calibrated chronostratigraphy of the foreland basin sedimentary units and their relationship with the evolution of tectonic structures, we determine age constraints to the kinematics of each cross-section. On the basis of the Coulomb wedge theory, it is possible to infer a chronologically and geometrically well-constrained history of growth of the Fuegian Andes orogen, which enhances the role of backthrusts in mountain building.

Southern cross-section

The unconformity-bounded units involved in the southern cross-section (Fig. 2) include the Upper

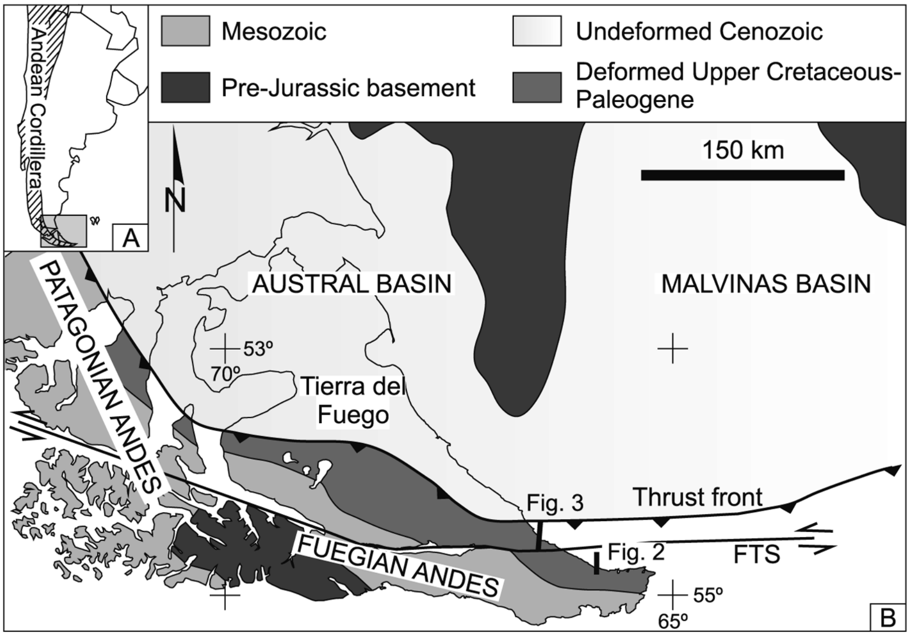

Figure 1. Location map of Tierra del Fuego in South America (A) and its main geological features (B). The trace of the cross-sections of figures 2 and 3 are indicated. FTS: Fagnano transform system.

Cretaceous-Danian (KuD), Upper Paleocene (Pu), Lower Eocene (El), Lower Middle Eocene (Elm), Upper Middle Eocene-Upper Eocene (Emu), Oligocene (O), and Miocene (M). The structures have evolved since the Early Eocene with the formation of a fault-bend in the basal detachment of the thrust-fold belt, which ramps up from a basal flat within Cretaceous units to the upper flat approximately at the KuD-Pu contact. An anticline forms over the detachment ramp in the Cretaceous-Danian rocks, and shortening is accommodated in front of it by the development of a fault-propagation fold (Cabo Leticia anticline), which affects the Pu and El successions.

Partial erosion of the early structures gives birth to an unconformity (*u1*), which is later covered by the Elm. After that, an out-of-sequence thrust forms (Punta Ancla thrust), branching from the basal detachment hinterlandwards from the Cabo Leticia thrust. The Punta Ancla thrust affects the Pu to Elm successions within the back syncline of the Cabo Leticia anticline, uplifting the KuD. This last deformation stage favors the development of a major unconformity (*u2*) on top of which a thick Eml to O succession is deposited. Continued contraction leads to the formation of a S-vergent thrust (Malengüena backthrust) in response to delamination of the Cenozoic sequence (Pu to O) above the basal décollement.

Renewed deformation generates a new thrust splay below the basal detachment, within the Cretaceous-Danian (La Chaira thrust). The splay branches from the lower flat of the Early Eocene ramp in the detachment and rejoins it at the KuD-Pu contact, forming a duplex horse. An anticline is formed above the La Chaira thrust, partially deforming the overlaying sequence synchronous with deposition of the M coarse sediments. The resultant cross-section geometry corresponds to a duplex within the Cretaceous-Danian, and opposing vergence thrusts affecting the Pu-M over its roof thrust.

Northern cross-section

The unconformity-bounded units affected in the northern section (Fig. 3) include the ?Pu, El, Emu, O, and Lower Miocene (Ml). The kinematics of this section start with the deformation of the Pu-El successions (Punta Torcida deformation), which accommodates shortening above the basal décollement blind termination. The folded beds are later covered by the Emu succession after development of a major unconformity (*u2*). A backthrust forms (Campo del Medio backthrust), branching from the basal décollement at the rear of its tip line, folding the Pu-Emu synchronously with the deposition of the basal O succession (Torres Carbonell *et al.*, 2008b). After that, a series of foreland vergent thrusts build up, branching from the blind termination line of the basal detachment and affecting the Pu-El to upper O successions. These thrusts form an imbricate system (Punta Gruesa imbricate fan) coeval with the deposition of the Ml sediments at the thrust-fold belt leading edge (Ghiglione, 2002; Torres Carbonell *et al.*, 2008b).

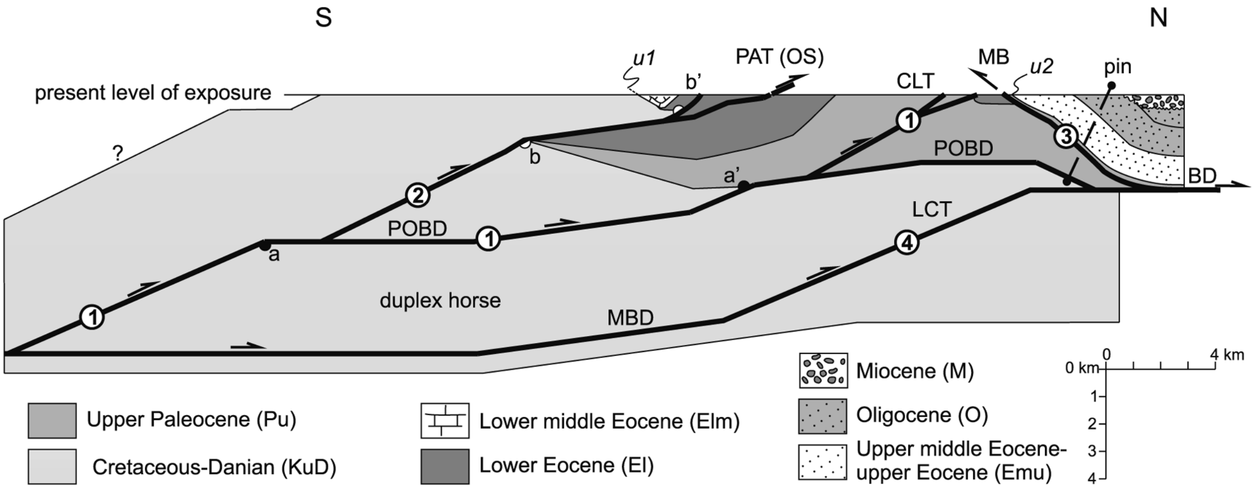

Figure 2. Southern balanced cross-section. Considering its position before the Fagnano fault offset, this cross-section is located 15 km southwards from the northern cross-section. Numbers indicate thrust sequence. Pin line is active only for times of thrust 4. POBD: Paleocene to Oligocene basal detachment; MBD: Miocene basal detachment; CLT: Cabo Leticia thrust; PAT (OS): Punta Ancla thrust (out-of-sequence); MB: Malengüena backthrust; LCT: La Chaira thrust; BD: basal detachment. See location in figure 1.

Orogenic growth history

According to the Coulomb wedge theory (Davis *et al.*, 1983), orogenic wedges are expected to behave cyclically in response to changes in their critical taper angle, which is the sum of the topographic slope α and the basal detachment dip β for given mechanical parameters. The thrust sequence recorded at the studied sections can be summarized as (Figs. 2 and 3): foreland propagation of the basal detachment averaged at the KuD-Pu contact, accommodating thrusting of the Cretaceous-Danian, with coeval foreland vergent thrusting of the Cenozoic above the basal detachment in Early Eocene times (Cabo Leticia thrust); forward propagation of the detachment with a blind termination line (Punta Torcida deformation); out-of-sequence thrusting and uplift of the KuD at the Middle Eocene (Punta Ancla thrust); backthrusting of the Cenozoic during the Oligocene, branching from the basal detachment near its terminal line, and continuing with piggyback propagation in a hinterlandward direction (Campo del Medio and Malengüena backthrusts); and finally foreland and upward propagation of the sole fault and frontal thrusting during the Early Miocene (Punta Gruesa imbricates), possibly coincident with renewed thrusting of the Cretaceous-Danian below the basal detachment (La Chaira thrust).

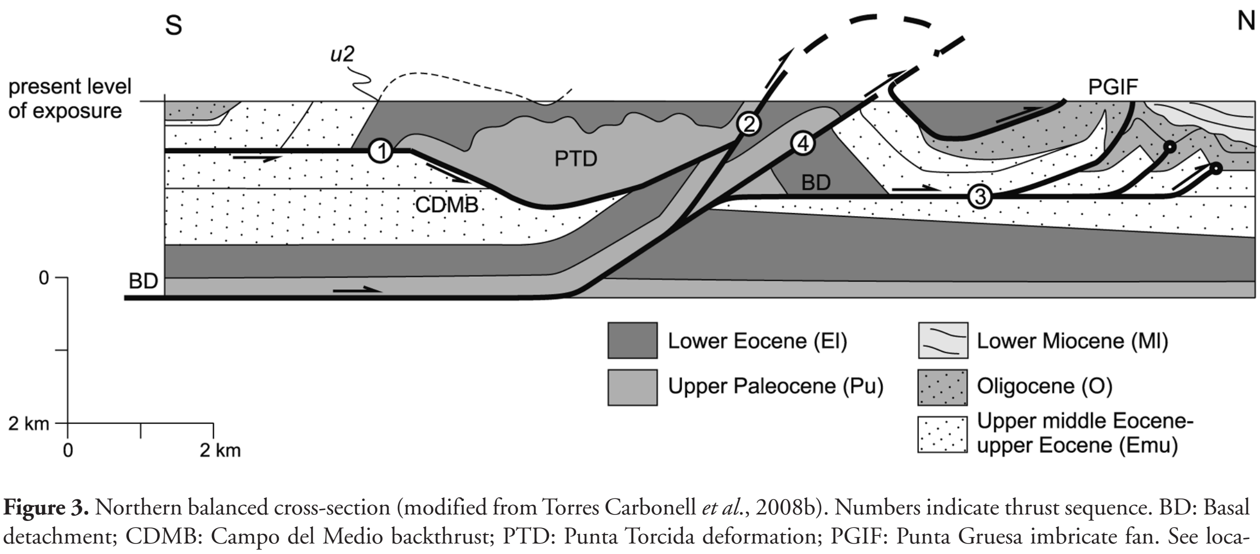

Figure 3. Northern balanced cross-section (modified from Torres Carbonell *et al.*, 2008b). Numbers indicate thrust sequence. BD: Basal detachment; CDMB: Campo del Medio backthrust; PTD: Punta Torcida deformation; PGIF: Punta Gruesa imbricate fan. See location in figure 1.

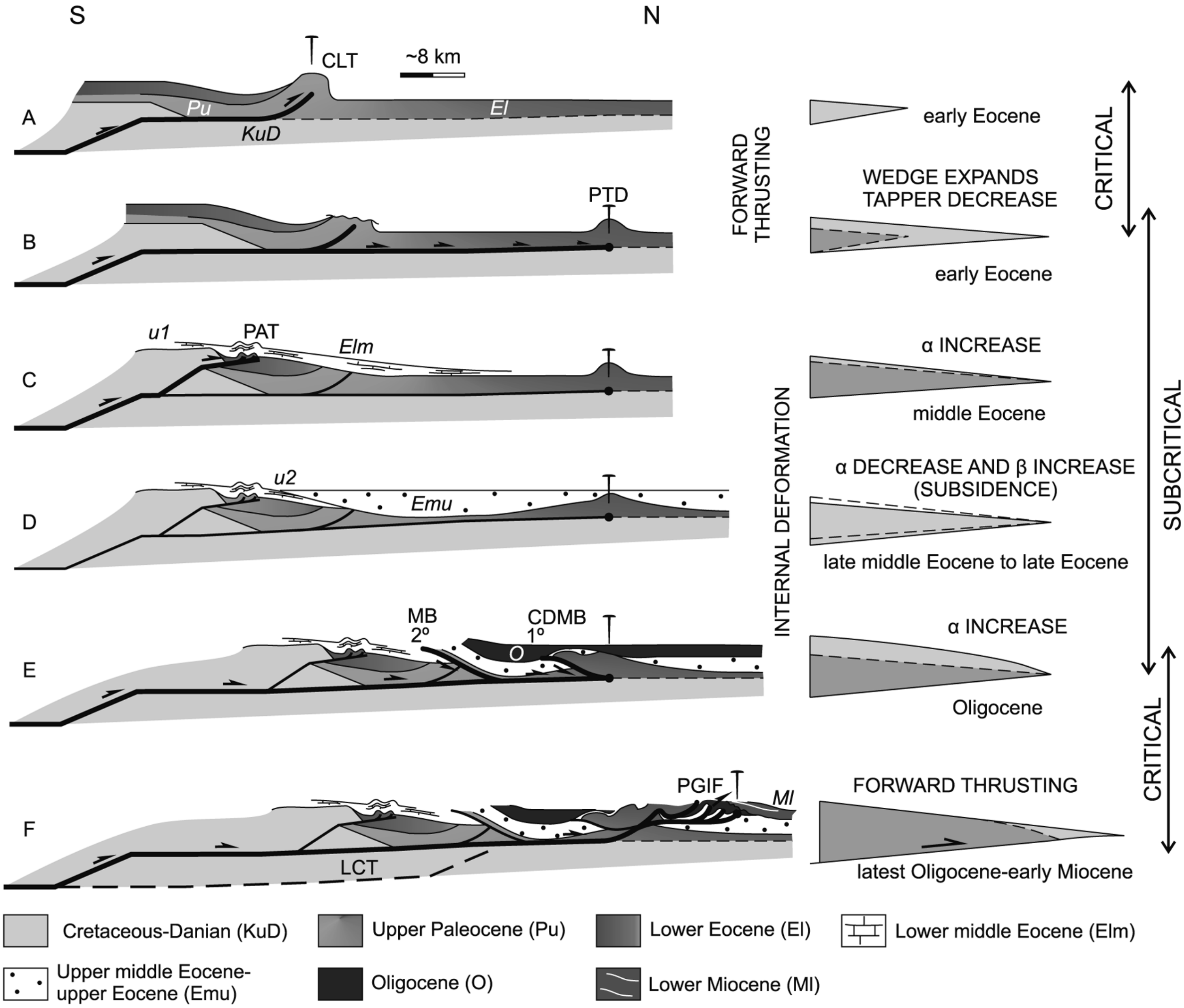

Figure 4. Schematic diagram showing evolution of the orogenic wedge in relation to critical taper, see text for explanation. Heavy lines mark active faults at each stage. Abbreviations are the same as for figures 2 and 3. Schematic wedges are light shaded light for geometry at each stage, while dark shading indicates previous stage geometry. Scale and angular relationships are approximate.

The cyclical behavior of the Fuegian thrust-fold belt can be understood in terms of critical taper mechanics as shown in figure 4. After initial formation of the sole fault and forward thrusting in the Early Eocene (Figs. 4A and 4B), the wedge taper is too low for continued movement over the detachment and further propagation of the thrust front. A higher taper angle is therefore attained by internal out-of-sequence thrusting southwards from the basal detachment tip line during the Middle Eocene (Fig. 4C), simultaneously with the clastic infill of the foreland basin. The tectonic load concentrated at the rear of the wedge leads to subsidence and a slight increase in the detachment slope β towards the south. This is followed by the deposition of a thick sedimentary succession during the Late-Middle to Late Eocene (Fig. 4D). Since the wedge continues to be subcritical, further contraction results in backthrusting (Fig. 4E), which affects the clastic successions during deposition of the Oligocene package. Backthrusting evolves due to delamination above the basal detachment in a piggyback fashion, forming a hinterlandward leading imbricate system. The first structure formed is the Campo del Medio backthrust, which can not accommodate further deformation after its branch line migrates to the basal detachment termination line, thus resulting in the formation of the second structure (Malengüena backthrust). After the Oligocene backthrusting stage, the wedge becomes critical and slides forelandwards with deformation localized at the leading edge. This causes the development of the Punta Gruesa imbricate fan, recorded by syntectonic Lower

Miocene strata (Fig. 4F), and probably related to growth of the wedge with accretion below the sole by emplacement of the La Chaira thrust, as a way of maintaining the taper. This last structural stage enhances erosion and coarse clastic deposition atop the orogenic wedge.

Discussion and conclusions

On the basis of previous work, the Fuegian Andes have been interpreted as evolving in three cycles: Late Cretaceous, Paleocene-Early Eocene, and Middle Eocene-Oligocene, each involving several stages of subcritical, critical and supercritical wedge behavior, with thrusting in the study area limited to the late Paleocene and the Middle to Late Eocene (Ghiglione and Ramos, 2005). We propose here a different model, in the light of our new balanced cross-sections and an improved chronostratigraphy. We found that the frontal part of the Andean orogen at eastern Tierra del Fuego behaved as a critical wedge during the early propagation of the sole detachment, in the Early Eocene. After that, the wedge became subcritical, being affected by internal deformation until the next stage of foreland thrust-front propagation in the Early Miocene. The retrodeformation of the wedge during the subcritical stage is recorded by out-of-sequence thrusting and backthrusting. These structures are strongly linked to thick unconformity-bounded clastic successions deposited within the wedge-top depocenter of the Austral basin (see also Torres Carbonell *et al.*, 2008b).

We highlight herein that backthrusting should be considered a very important way in thrust-fold belts to accommodate internal wedge deformation that, during subcritical stages, cannot be propagated forelandwards. In this sense, backthrusting plays an important role in building up the wedge to acquire a critical taper angle.

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