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Constraints on deformation of the Southern Andes since the Cretaceous from anisotropy of magnetic susceptibility

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ABSTRACT

The southernmost segment of the Andean Cordillera underwent a complex deformation history characterized by alternation of contractional, extensional, and strike-slip tectonics. Key elements of southern Andean deformation that remain poorly constrained, include the origin of the orogenic bend known as the Patagonian Orocline (here renamed as Patagonian Arc), and the exhumation mechanism of an upper amphibolite facies metamorphic complex currently exposed in Cordillera Darwin. Here, we present results of anisotropy of magnetic susceptibility (AMS) from 22 sites in Upper Cretaceous to upper Eocene sedimentary rocks within the internal structural domain of the Magallanes fold-and-thrust belt in Tierra del Fuego (Argentina). AMS parameters from most sites reveal a weak tectonic overprint of the original magnetic fabric, which was likely acquired upon layer-parallel shortening soon after sedimentation. Magnetic lineation from 17 sites is interpreted to have formed during compressive tectonic phases associated to a continuous ~ N-S contraction. Our data, combined with the existing AMS database from adjacent areas, show that the Early Cretaceous-late Oligocene tectonic phases in the Southern Andes yielded continuous contraction, variable from ~ E-W in the Patagonian Andes to ~ N-S in the Fuegian Andes, which defined a radial strain field. A direct implication is that the exhumation of the Cordillera Darwin metamorphic complex occurred under compressive, rather than extensional or strike-slip tectonics, as alternatively proposed. If we agree with recent works considering the curved Magallanes fold-and-thrust belt as a primary arc (i.e., no relative vertical-axis rotation of the limbs occurs during its formation), then other mechanisms different from oroclinal bending should be invoked to explain the documented radial strain field. We tentatively propose a kinematic model in which reactivation of variably oriented Jurassic faults at the South American continental margin controlled the Late Cretaceous to Cenozoic evolution of the Magallanes fold-and-thrust belt, yielding the observed deformation pattern.

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1. Introduction

The Andean Cordillera is considered the archetype of non-collisional orogens, as it formed above a subduction zone consuming oceanic lithosphere of the Nazca (Farallon), Phoenix (Aluk), and Antarctic plates below the South American plate (e.g., Jordan et al., 1983; Ramos, 1999; Ramos et al., 2014). This process resulted in an orogenic system 200 to 700 km wide, spanning the South American continent from ~7°N to ~56°S. The present-day tectonic setting of the Andes is characterized by mainly eastward verging basement thrusts in the hinterland that transfer shortening to the fold-and-thrust belt (e.g., Espurt et al., 2011). In the central and southern sectors of the Cordillera two regional-scale orogenic arcs occur, identified by a significant curvature of the main structural trends. The northern one (14°-26°S), known as the Bolivian Orocline (e.g., Eichelberger et al., 2013; Isacks, 1988), is a secondary orocline (sensu Weil and Sussman, 2004) formed by opposite-sense vertical-axis rotation of the two limbs (e.g., Eichelberger et al., 2013; Maffione et al., 2009; Prezzi et al., 2014). More controversial is the tectonic history and style of deformation that controlled the origin of the orogenic re-entrant named as the 'Patagonian Orocline' by Carey (1958) at the southernmost tip of the Andean Cordillera (Fig. 1). Here, the ~ N–S-trending southern Patagonian Andes and the ~ ESE–WNW-trending Fuegian Andes define an orogenic curvature with an interlimb angle of ~110° (Kraemer, 2003). Source of uncertainty on the tectonic evolution of the Southern Andes is due to multiple interaction, where the South American plate underwent convergence with the Antarctic, Phoenix, and Nazca plates to the south and west, and divergence with

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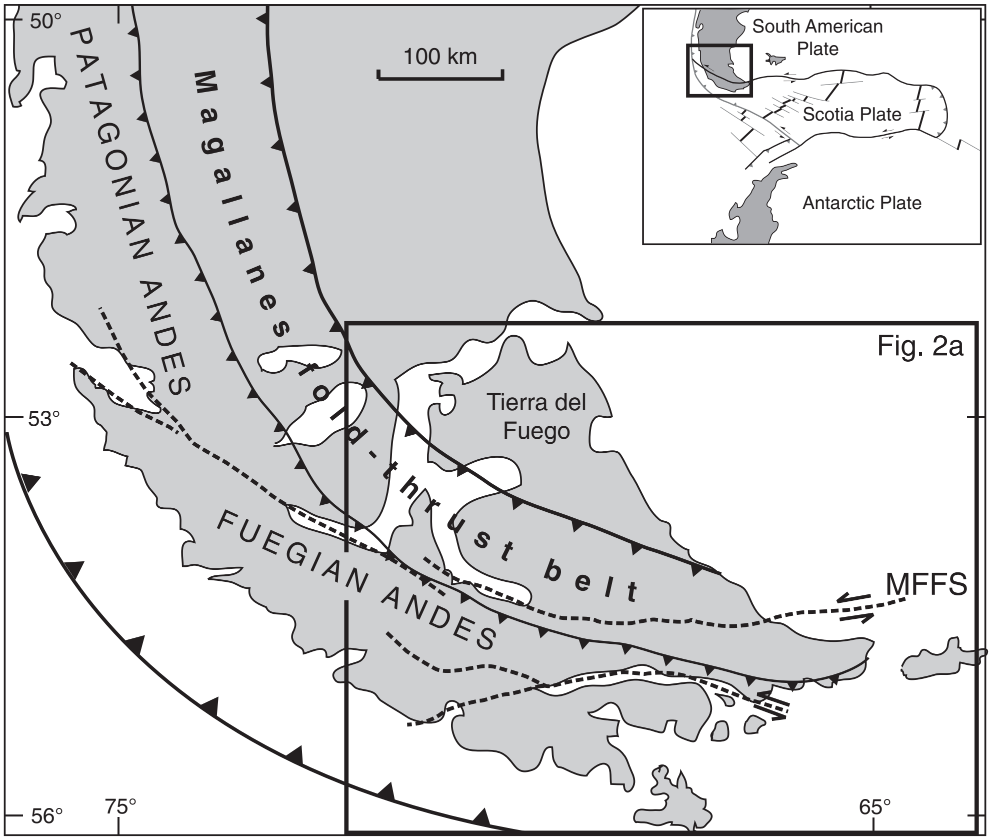

Fig. 1. Simplified tectonic setting of the Southern Andes showing the main tectonic features and structural domains.

the Antarctic and, later, the Scotia plate in the southeast. This complex geodynamic setting yielded alternation of extensional, strike-slip, and compressive events from the Jurassic until the late Cenozoic (Klepeis and Austin, 1997).

Early models considered the curved segment of the Southern Andes as a true orocline (*sensu* Weil and Sussman, 2004), interpreting its formation as due to bending of an originally straight orogen accompanied by large-scale counterclockwise rotation of the southern limb of the arc throughout the Cretaceous and Cenozoic (e.g., Carey, 1958; Dalziel et al., 1973; Kraemer, 2003). Other models explained the curvature of the Southern Andes by invoking strike-slip and transpressional tectonics (Cunningham, 1993) segmenting the southern tip of the Andean cordillera since the Late Cretaceous but without producing significant tectonic rotations. Other authors suggested that oroclinal bending occurred during the initial (Cretaceous) tectonic phases of the Andean orogeny associated with the closure of the Rocas Verdes marginal basin, but it ceased afterwards (Burns et al., 1980). More recently, a primary origin of the curvature of the Southern Andes has also been proposed (Ramos and Aleman, 2000), and was partially validated by lithospheric-scale analogue experiments by Diraison et al. (2000). Whether the Late Cretaceous orogeny involved oroclinal rotation or not is hard to discern from present paleomagnetic data (Rapalini et al., in press), but it clearly produced the consolidation of the basement domain by latest Cretaceous time (Cunningham, 1995; Kraemer, 2003). Afterwards, the basement formed a curved rigid indenter that produced the compressional pattern observed in the Magallanes fold-and-thrust belt, as shown by sand-box models (Ghiglione and Cristallini, 2007). Latest models proposed a two-stage evolution of the curvature of the Southern Andes consisting of a Late Cretaceous phase of oroclinal bending during closure of the Rocas Verdes basin, followed by formation of the primary curvature of the Magallanes fold-and-thrust belt during the Cenozoic (Poblete et al., 2014).

The poorly constrained kinematic evolution of the Southern Andes is also reflected into the debated origin of the Cordillera Darwin metamorphic complex (hereafter referred to as 'Cordillera Darwin') exposed near the hinge of the curvature at ~55°S (Fig. 2). Although several Paleozoic to Mesozoic metamorphic complexes are exposed in the Patagonian Andes to the north (Hervé et al., 2008), the processes for the exhumation of Cordillera Darwin remains the most debated (Cunningham, 1995; Dalziel and Brown, 1989; Klepeis, 1994; Kohn et al., 1995; Maloney et al., 2011). Cordillera Darwin exposes Paleozoic basement rocks metamorphosed under upper amphibolite to greenschist facies conditions (7-11 kbar, 580-600 °C) (Klepeis et al., 2010; Kohn et al., 1993, 1995; Nelson et al., 1980). Kohn et al. (1995) proposed an initial rapid exhumation at 90-70 Ma driven by extension (or transtension), while more external sectors were under compression. Similarly, Dalziel and Brown (1989) argued that the exhumation began at ca. 70 Ma in a localized extensional setting within a developing transform zone between the South American and Antarctic plates. On the other hand, several models were proposed by Cunningham (1995) who related the exhumation to (i) erosional denudation within a restraining bend setting, (ii) transtension, or (iii) erosion and/or extension following isostatic rebound. The most broadly accepted model for the uplift of Cordillera Darwin considers thick-skinned compressional tectonics coupled with widespread erosion (Barbeau et al., 2009; Gombosi et al., 2009; Klepeis, 1994; Klepeis and Austin, 1997; Klepeis et al., 2010; Maloney et al., 2011; Torres Carbonell and Dimieri, 2013).

Understanding the tectonic regime at the Southern Andes during the Late Cretaceous and Paleogene is therefore key to untangle the evolution of the Patagonian Orocline and the exhumation history of Cordillera Darwin. In this study, we reconstruct the nature and orientation of the strain field at the Southern Andes from the Cretaceous throughout the Oligocene using both new and published anisotropy of magnetic susceptibility (AMS) data from the Magallanes fold-and-thrust belt.

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