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Neogene kinematic history of Nazca–Antarctic–Phoenix slab windows beneath Patagonia and the Antarctic Peninsula

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ABSTRACT

The Patagonian slab window is a subsurface tectonic feature resulting from subduction of the Nazca–Antarctic spreading-ridge system (Chile Rise) beneath southern South America. The geometry of the slab window had not been rigorously defined, in part because of the complex nature of the history of ridge subduction in the southeast Pacific region, which includes four interrelated spreading-ridge systems since 20 Ma: first, the Nazca–Phoenix ridge beneath South America, then simultaneous subduction of the Nazca–Antarctic and the northern Phoenix–Antarctic spreading-ridge systems beneath South America, and the southern Phoenix–Antarctic spreading-ridge system beneath Antarctica. Spreading-ridge paleo-geographies and rotation poles for all relevant plate pairs (Nazca, Phoenix, Antarctic, South America) are available from 20 Ma onward, and form the mathematical basis of our kinematic reconstruction of the geometry of the Patagonia and Antarctic slab windows through Neogene time. At approximately 18 Ma, the Nazca–Phoenix–Antarctic oceanic (ridge–ridge–ridge) triple junction enters the South American trench; we recognize this condition as an *unstable quadruple junction*. Heat flow at this junction and for some distance beneath the forearc would be considerably higher than is generally recognized in cases of ridge subduction. From 16 Ma onward, the geometry of the Patagonia slab window developed from the subduction of the trailing arms of the former oceanic triple junction. The majority of the slab window's areal extent and geometry is controlled by the highly oblique (near-parallel) subduction angle of the Nazca–Antarctic ridge system, and by the high contrast in relative convergence rates between these two plates relative to South America. The very slow convergence rate of the Antarctic slab is manifested by the shallow levels achieved by the slab edge (<45 km); thus no point on the Antarctic slab is sufficiently deep to generate “normal” mantle-derived arc-type magmas. Upwelling beneath the region may have contributed to uplift and eastward transfer of extension in the Scotia Sea.

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1. Introduction

The Patagonian and Antarctic slab windows were produced by Late Cenozoic subduction of the Nazca–Antarctic and Phoenix–Antarctic spreading-ridges, respectively (Forsythe and Nelson, 1985; Hole, 1988). These windows – which are gaps in an otherwise continuous slab of subducting oceanic crust in the region – have been linked to a variety of magmatic processes in southern South America and the Antarctic Peninsula, including (1) an interruption of normal calc-alkaline arc volcanism, and (2) widespread eruption of “anomalous” igneous rocks including alkalic plateau lavas and adakitic volcanoes (e.g., Forsythe et al., 1986; Kay et al., 1993; Hole and Larter, 1993; Gorring et al., 1997; D'Orazio et al., 2001; Gorring and Kay, 2001; Bourgois and Michaud, 2002; Guivel et al., 2003; Lagabrielle et al., 2004; Espinoza et al., 2005; Guivel et al., 2006). This connection between slab windows and anomalous magmatism has been documented in slab windows, both modern and ancient, from numerous worldwide localities (Marshak and Karig, 1977; Dickinson and Snyder, 1979; Johnson and O'Neil, 1984; Forsythe and Nelson, 1985; Staudigel et al., 1987; Hole, 1988; Thorkelson and Taylor, 1989; Gorring et al., 1997; Dickinson, 1997; Johnston and Thorkelson, 1997; Bourgois and Michaud, 2002; Breitsprecher et al., 2003; Groome et al., 2003; Haeussler et al., 2003; Sisson et al., 2003; Wilson et al., 2005; Cole et al., 2006; Madsen et al., 2006).

Despite the importance of slab window formation to the geological evolution of Patagonia and the Antarctic Peninsula, a thorough regional depiction of slab window formation has not been previously carried out. In this paper, we provide an integrated geometrical analysis of Nazca–Antarctica and Antarctica–Phoenix ridge subduction, and show how the Patagonian and Antarctic slab windows developed synchronously to produce a pair of large and persistent slab-free regions in Late Cenozoic time. In the process of our analysis

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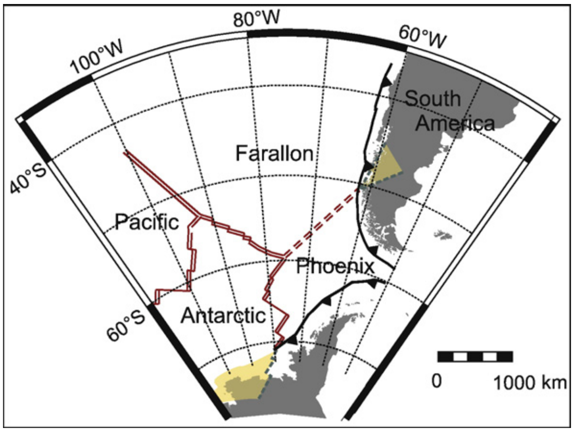

Fig. 1. Possible Eocene configuration of subducting ridges in the southeast Pacific Basin and related slab windows. Plate tectonic models indicate that the Farallon–Phoenix spreading-ridge system intersected the South American trench from Cretaceous to Paleogene time (dashed double red line, e.g. Mayes et al., 1990; Eagles et al., 2004). Note however that both of the triple-junction positions and the configuration and paleo-geometry of the converging spreading-ridge systems are unconstrained by magnetic anomaly data, compared to well-constrained spreading-ridge systems to the south and west (solid red lines). The paleo-position and shape of the concomitant Farallon–Phoenix slab window therefore cannot be constrained. We position the Farallon–Phoenix slab window to coincide with geochemical evidence for it beneath Patagonia of Espinoza et al. (2005), but emphasize the speculative nature of the shape as drawn by the use of dashed lines bounding the slab windows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

we identify an ephemeral quadruple plate junction that was produced by subduction of an oceanic triple junction (Nazca–Antarctic–Phoenix) beneath the South American plate.

2. Overview: ridge subduction in the southeast Pacific Basin

The Patagonian and Antarctic Peninsulas, situated in the south-eastern Pacific Basin, have a long-lived history of ridge subduction involving various pairings of the Pacific, Antarctic, Phoenix (formerly known as the Aluk or Drake), Bellinghausen, Farallon, and Nazca plates. The Pacific–Phoenix spreading-ridge system was subducting beneath the Antarctic Peninsula, and the Farallon–Phoenix spreading-ridge system was subducting beneath Patagonia, as early as the mid-Cretaceous (Barker, 1982; McCarron and Larter, 1998). By the Late Cretaceous, the Pacific–Phoenix spreading-ridge was displaced away from the Antarctic trench by the newly-formed Bellinghausen–Pacific spreading-ridge system, which became the locus of ridge subduction beneath continental Antarctica (Mayes et al., 1990; McCarron and Larter, 1998; Eagles et al., 2004). Although details vary between studies, there appears to be a consensus that the Bellinghausen plate ceased to move independently in Early Paleocene time (~60 Ma), having been transferred to the Pacific and Antarctic plates during a basin-wide plate reorganization event at that time (Mayes et al., 1990; Eagles et al., 2004).

The magnetic anomaly dataset requires a Farallon–Phoenix–South America triple junction throughout the Paleogene, but fails to fully constrain the configuration and paleo-geography of the Farallon–Phoenix spreading-ridge system, including its latitudinal position at the South American trench (Mayes et al., 1990; Ramos and Kay, 1992; McCarron and Larter, 1998; Eagles et al., 2004). Therefore, the shape, position and orientation of the sub-South American slab window cannot be kinematically-defined through this interval (Fig. 1), although geochemical and structural evidence favour a southerly, Patagonian position for it by Eocene time (Espinoza et al. (2005). To the south, the Antarctic–Phoenix spreading-ridge junction with the Antarctic trench is constrained (Mayes et al., 1990), but the paleo-geometry of the previously-subducted sections of the ridge, and thus the shape of the subducted slab edges, is uncertain (Fig. 1). As previously identified by Hole et al. (1991), the Antarctic slab window developed following subduction of a single plate (Phoenix), with the other plate (oceanic Antarctic) remaining fixed to the continent at the trench. Other relevant tectonic events for this interval relate to the connectivity of the Patagonian and Antarctic Peninsulas. The opening of the Drake Passage between the two overriding plates occurred not later than the Early Oligocene (ca. 31 Ma; Lawver and Gahagan, 2003), and possibly as early as Middle Eocene as suggested by micro-basin development in the adjacent precursor to the Scotia Basin (Eagles et al., 2006).

The Neogene magnetic anomaly dataset becomes increasingly robust, such that by Early Miocene time, plate boundaries and relative plate motions for the Nazca, Antarctic, Phoenix, and South American plates are well established (e.g., Shaw and Cande, 1990; Royer and Chang, 1991; Larter and Barker, 1991; Lawver et al., 1995; Tebbens and Cande, 1997; Eagles, 2003; Eagles et al., 2004). Recognition of an Early Miocene breakup of the Farallon plate into the Nazca and Cocos plates (e.g., Hey, 1977; Lonsdale, 2005) led to renaming of the northerly slab (of our study region, Fig. 1) subducting beneath Patagonia as the Nazca slab, rather than the Farallon slab, from that time forward. By 20 Ma, the Nazca–Phoenix–Antarctic oceanic triple junction was within 400 km of the South American trench and migrating towards it, with the Nazca–Phoenix spreading-ridge system having a geographically constrained configuration, and its triple junction with South America situated in the vicinity of the southern Patagonia Peninsula

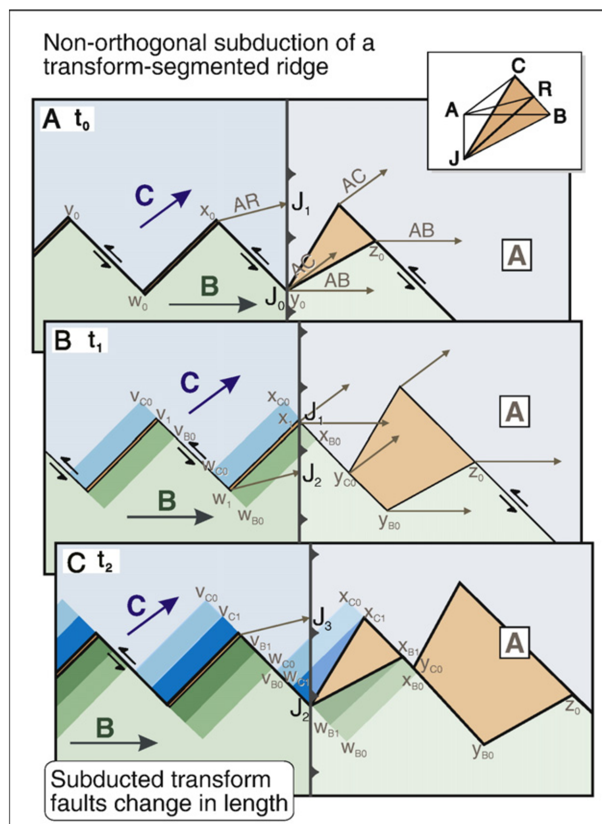

Fig. 2. Geometric method of reconstructing subsurface slab edge geometries from kinematic (plate-rotation pole) dataset in velocity space (modified from Fig. Thorkelson, 1996). This figure demonstrates how points on a slab edge can be tracked from their position in the trench in frame (A) to subsequent times (B, C) in velocity space using the relative motion vector of each oceanic plate relative to a fixed overriding plate. Because the slab edge experiences zero growth after passing through the trench, this time-tracking of velocity-space vectors maps out the edge of the slab over time. The method accurately accounts for transform-faulted slab edge shortening and lengthening which occurs during the subduction of a transform fault segment of the ridge. See text for explanation, or Thorkelson (1996) for detailed discussion.

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