Tectonophysics 604 (2013) 41–50

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

The Scotia Sea gateway: No outlet for Pacific mantle

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ARTICLE INFO

Article history:
Received 24 March 2012
Received in revised form 6 August 2012
Accepted 15 August 2012
Available online 23 August 2012

Keywords:
Dynamic topography
Asthenosphere
Lithospheric cooling models
Plate reconstructions

ABSTRACT

The Scotia Sea in the South Atlantic holds a prominent position in geodynamics, because it has been proposed as a potential outlet of asthenosphere from under the shrinking Pacific into the mantle beneath the opening Atlantic. Shear wave splitting and geochemical studies have previously tested this hypothesis. Here, we take a different approach by calculating present-day dynamic topography of the region in search for a systematic trend in dynamic topography decreasing from west to east in response to a flow-related pressure gradient in the sublithospheric mantle. To this end, we reconstruct the kinematic history of the Scotia Sea, which is characterized by complex back-arc spreading processes active on a range of time scales. Our plate reconstructions allow us to derive an oceanic age-grid and to calculate the associated residual (dynamically maintained) topography of the Scotia Sea by comparing present-day isostatically corrected topography with that predicted from our reconstruction. The results provide no indication for a systematic trend in dynamic topography and we conclude that the material needed to supply the growing subatlantic mantle must be derived from elsewhere.

1. Introduction

According to Alvarez (1982) the isolation of Antarctica by opening of the Drake Passage in the Scotia Sea (Fig. 1) had profound consequences for the global mantle circulation system by establishing subsurface mantle flow from under the Pacific into the Atlantic Ocean domain. As he conceived continental roots and subducting slabs as effective barriers to lateral mantle flow from under the Pacific into the Atlantic hemisphere, he proposed the newly formed seaway as an outlet for flow within the asthenosphere and a potential mechanism to establish mass balance between the shrinking Pacific and the growing Atlantic mantle reservoirs.

The notion of an asthenosphere has a long history in the geophysics, dating from 19th century investigations of isostatic support of mountain belts (see Watts, 2001 for a review). Early on in the 20th century, geodynamicists conjectured it provides a zone of weakness over which plates glide easily (Chase, 1979). Modern geophysical evidence for an asthenosphere comes in the form of geoid and postglacial rebound studies (Hager and Richards, 1989; Mitrovica, 1996), supported by investigations into global azimuthal seismic anisotropy (Debayle et al., 2005), and seismic (Grand and Helmberger, 1984) and mineralogical (Stixrude and Lithgow-Bertelloni, 2005) work on the properties of the low seismic velocity zone found at a depth of between 100 and 400 km beneath oceanic and tectonically active regions. 3-D spherical mantle convection models are consistent with the view of a weak upper mantle. The models show that a low-viscosity asthenosphere has a profound effect on convection by promoting a long-wavelength convective planform with only a few large elongated mantle convection cells (Bunge et al., 1996), comparable to the long wavelength pattern that characterizes global mantle flow. The dominant influence of the asthenosphere on the convective planform has also been inferred from analytic fluid dynamic considerations (Busse et al., 2006), and it has been proposed that the existence of an asthenosphere is essential in stabilizing the unusual plate tectonic style of convection that prevails on Earth (Richards et al., 2001).

Complementary to the mobility of the asthenosphere are mechanically stable keels, termed tectosphere, which may exist beneath old portions of the continental lithosphere (Jordan, 1978). Such keels are presumed to pierce through the entire asthenosphere, promoting coupling between continents and the deeper mantle, and restricting the asthenosphere to the subsurface beneath oceanic realms (Conrad and Lithgow-Bertelloni, 2006).

Here we revisit the hypothesis of Pacific-to-Atlantic asthenosphere flux around the tip of South America. The Scotia Sea provides an ideal location, as noted by Alvarez (1982), to explore the pattern of upper mantle flow, as no continental roots or an active subduction zone provide a barrier to asthenospheric flow. By reconstructing the

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http://dx.doi.org/10.1016/j.tecto.2012.08.023

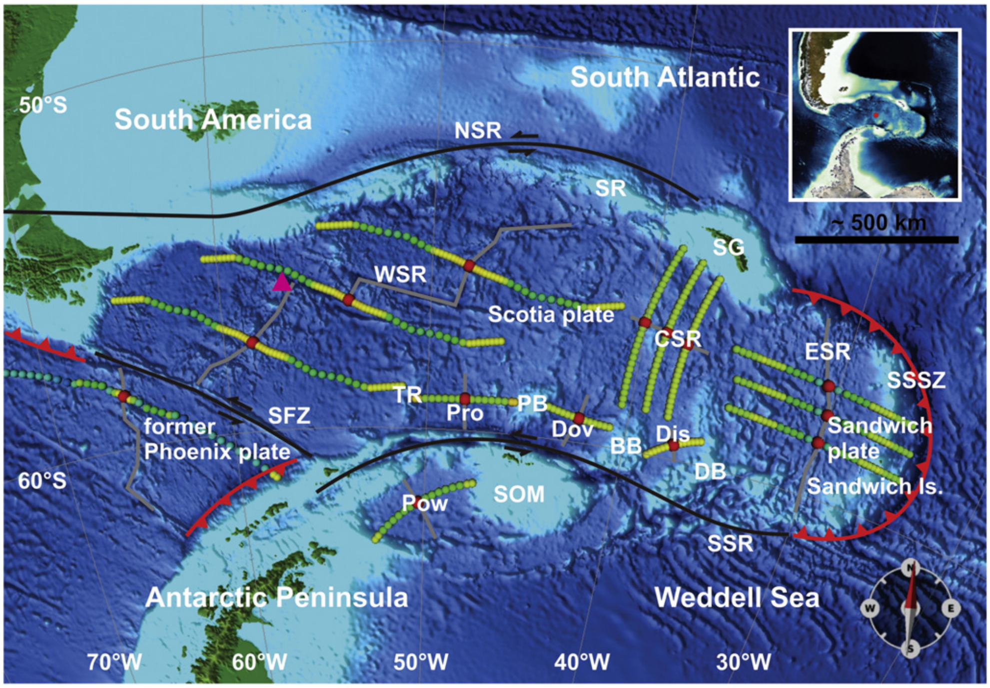

Fig. 1. View of Scotia Sea consisting of the Scotia and Sandwich plates, located in between the Antarctic Peninsula and South America (see also insert map, where the red dot indicates the center of the top view map). The region is framed by transform boundaries in the north (North Scotia Ridge (NSR)), south (South Scotia Ridge (SSR)), west (Shackelton Fracture Zone (SFZ)), and the South Sandwich subduction zone (SSSZ) in the east. Other features are Shag Rocks (SR), South Georgia (SG), and the South Orkney Microcontinent (SOM). Flowlines displaying motion paths of different continental fragments are shown in green. Active spreading (East Scotia Ridge (ESR)) exists in the East Scotia Sea. Extinct spreading ridges are found in the West Scotia Sea (West Scotia Ridge (WSR)), Central Scotia Sea (Central Scotia Ridge (CSR) which remains controversial; see Subsection 2.2) and in the Protector (Pro), Dove (Dov), and Discovery Basins (Dis), respectively, which are bounded by presumably — as some discussion on their origin persists — South American continental fragments (Terror Rise (TR), Pirie Bank (PB), Discovery Bank (DB)). Extinct ridges are also found on the boundary between the Antarctic plate and former Phoenix plate as well as in the Powell Basin (Pow). Location of the dredge sample with Pacific mantle type signature (Pearce et al., 2001) [see discussion] is marked by a triangle.

plate kinematic history of the Scotia Sea we present a geodynamic approach that allows us to detect a dynamically maintained component of topography associated with viscous stresses created by upper mantle flow via Drake Passage through the Scotia Sea, rather than by thermal subsidence related to cooling within the oceanic lithosphere (Braun, 2010).

Our paper is organized as follows: we begin with a general estimate on the pressure gradient required to generate sufficient Pacific mantle flow through the Scotia Sea to achieve mass balance in the Atlantic. Thereafter, we describe the applied dynamic topography deconvolution method, which is followed by a results section and a discussion.

2. Methodology

2.1. Asthenosphere flow estimates

We begin this section with a simple scaling argument, under the assumption that the mass balance required to accommodate Atlantic opening is purely achieved through Pacific mantle flow through the Scotia Sea. We estimate the volume growth rate (Q) of the South Atlantic to be ~ 50 km^3/yr, for which we assumed a length of 10.000 km and a full-spreading rate of 2.5 cm/yr of the South Atlantic mid-ocean ridge system, respectively, as well as a 200 km thick asthenosphere directly under the ridge.

Based on this rate, the pressure difference (Δp) between the western and eastern ends of the Scotia Sea required to compensate the Atlantic growth by Pacific-to-Atlantic mantle flow can be estimated from a simple Poiseuille flow, viewing the Scotia Sea as a channel with thickness h = 200 km (i.e. asthenosphere thickness), width $\Delta y = 1000$ km, and length $\Delta x = 3000$ km. The pressure difference is given by:

$$\Delta p = \frac{Q * 12\mu * \Delta x}{\Delta y * h^3} \tag{1}$$

Assuming an asthenospheric viscosity (μ) of 10^{19} Pa*s, we arrive at $\Delta p \sim 600$ bar, so that the expected dynamic topography in the West Scotia Sea is about 1800 m, large enough to be detectable, although we note that major uncertainties exist regarding the thickness and viscosity of the asthenosphere.

2.2. Dynamic topography deconvolution method

The dynamic component of the actual bathymetry can be unraveled by calculating the difference between the expected bathymetry based on standard cooling models and the isostatically corrected, observed ocean depth (Kido and Seno, 1994). A precise age-grid is therefore crucial, which can be derived from plate reconstruction models which are typically based on magnetic anomaly interpretations. To this end we developed a reconstruction model of the Scotia Sea by using 4DPlates (Clark et al., 2012), a new software package developed by Simula Research Laboratory and Statoil. Deriving an age-grid for the Scotia Sea directly from magnetic lineations is difficult. Indeed various magnetic lineations have been discovered on the ocean floor of the Scotia Sea, but most of them can be correlated to multiple sections of the magnetic reversal