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Evolution of the Scotia Sea Region: Relevance to Broad-Band Seismology

P.F. BARKER

British Antarctic Survey, Madingley Road, Cambridge CB3 0ET - UK (pfba@pcmail.nerc-bas.ac.uk)

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Abstract - This paper reports briefly an attempt to examine the tectonic evolution of the Scotia Sea region, in the context of the use of broad-band seismological techniques there. Such techniques can determine present plate boundaries, and examine crustal and upper mantle velocities and velocity anisotropy. Some studies are already under way (*e.g.* Vuan et al., 1999; Mueller, 1999; in press) and additional work is planned. An understanding of Scotia Sea evolution should allow future work to become more focussed.

TECTONIC BACKGROUND

The present Scotia Sea has developed since 40 Ma, essentially in a back-arc extensional environment behind an eastward-advancing subduction zone ancestral to the present South Sandwich subduction zone. The Scotia Sea has a mainly oceanic crustal structure. Several sea-floor spreading regimes have been documented using marine magnetic anomalies, and other oceanic areas have been dated on the basis of heat flow measurements and bathymetry (Fig. 1 and Tectonic Map, 1985; Lawver et al, 1991; Barker, 1995; King et al., 1997; Lodolo et al., 1997; Coren et al., 1997; although ocean floor bathymetry is suspect in the back-arc: Sclater et al., 1976). Yet other areas have most probably a similar, oceanic origin, but may be too small for identifiable marine magnetic anomalies to have been created. Heat flow measurements can resolve some of these uncertainties. Intervening, more elevated areas within the Scotia Sea may be fragments of remnant arc, or of older continent. Provinces have become better-defined in places by use of satellite altimetry-derived gravity and bathymetry (*e.g.* Sandwell & Smith, 1997).

A comparison of the slow rates and directions of separation of the major (South American, Antarctic) plates that surround the Scotia Sea (*e.g.* Barker & Lawver, 1988), with the generally faster rates and discrepant directions of identified spreading inside the Scotia Sea (Tectonic Map, 1985), strongly suggests a back-arc origin for the entire Scotia Sea, so that the excessively rapid spreading may be accommodated by allowing complementary subduction.

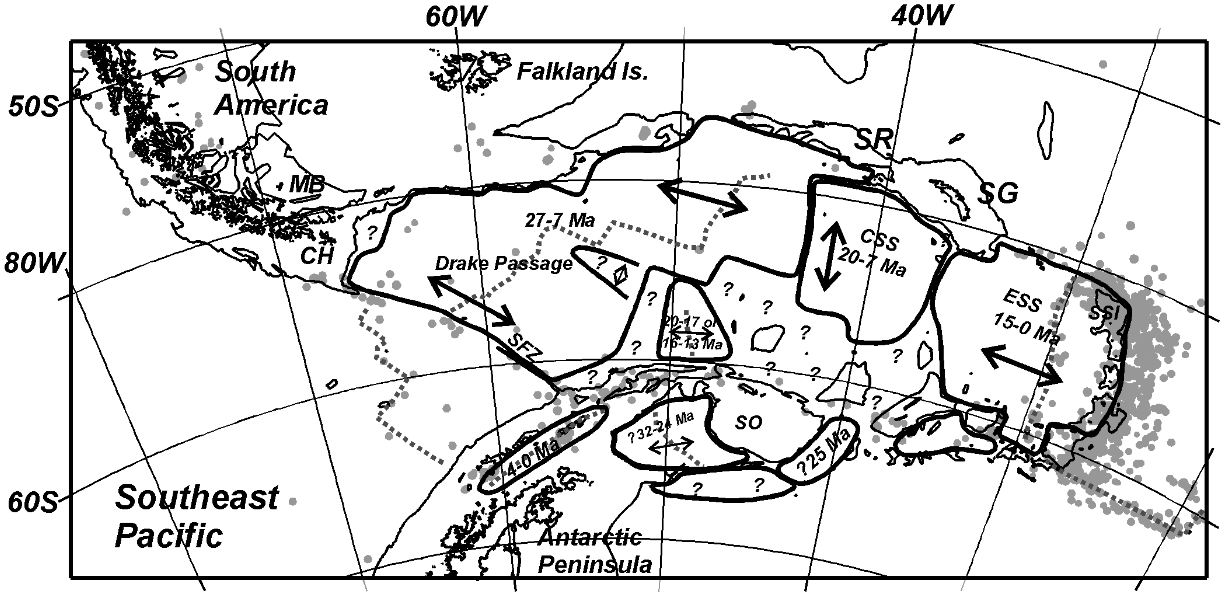

Fig. 1 - Ocean floor ages, and directions of spreading where known, in sea-floor spreading provinces (bounded by solid lines) in the Scotia Sea region. Areas of likely oceanic crustal structure but unknown age denoted by "?". The Scotia Sea is surrounded by the North and South Scotia Ridge and South Sandwich island arc (SSI), delineated by the 2000 m isobath (Tectonic Map, 1985). The North Scotia Ridge extends east from South America (Magallanes Basin MB; Cape Horn CH) through the Shag Rocks (SR) and South Georgia (SG) blocks, to the northern end of the South Sandwich trench. The South Scotia Ridge extends east from the Antarctic Peninsula through the South Orkney microcontinent (SO) to the southern end of the South Sandwich trench. SFZ is Shackleton fracture zone. Earthquake epicentres, which help delineate plate boundaries, are shown as grey dots, and present or abandoned extensional plate boundaries are shown dashed.

The character of back-arc extension worldwide appears to involve jumps of the centre of spreading towards the subduction zone, often to the line of the island arc where presumably lithospheric strength is reduced and rollback-induced stress on the overriding plate is large (*e.g.* Jarrard, 1986). Certainly, the Scotia Sea shows that several different spreading regimes have operated, sometimes simultaneously, and the locus of active extension appears to have migrated eastward with the subduction zone: the oldest coherent spreading, in Drake Passage to the west, stopped several Myr ago (Barker & Burrell, 1977), while the only active extension occurs in the East Scotia Sea close to the present-day trench (Barker, 1995). In the case of the Scotia Sea region, however, an additional factor has operated to influence the mode of back-arc extension, involving ridge crest subduction (Barker et al., 1982). It is notable that nowhere in the present trench is the Antarctic plate being subducted: it appears that, throughout Scotia Sea evolution, each time that the rapidly advancing trench hinge has overtaken a spreading section of the SAM-ANT plate boundary, the plate geometry and mode of extension in the back-arc have changed, so that the newly opposed Antarctic plate was not subducted. Although the difficulty of magnetic anomaly identification in the northernmost Weddell Sea (Hamilton, 1989; Livermore & Woollett, 1993) has so far prevented an exact comparison of collision ages and times of changes in the back-arc, the observed geometric relationships support this hypothesis. The position of the palaeo-subduction zone is known from shipboard and other studies (*e.g.* Maldonado et al., 1998) and provides a constraint for Scotia Sea reconstructions that points to the importance of past northward migration of the northern margin of the Scotia Sea.

The Scotia Sea is bounded on three sides by the Scotia Arc, which to north and south (the North and South Scotia Ridge) is an elevated, fragmented mixture of older continental blocks, accretionary prism and extinct arc volcanoes (Dalziel, 1983; 1984; Barker et al., 1991), and to the east is the active South Sandwich volcanic arc. Along the North and South Scotia Ridge, subaerial outcrop is sparse, but the geology of individual fragments can be assessed from rock dredging, gravity, magnetic and seismic reflection and refraction measurements or long-range sidescan sonar (*e.g.* Ewing et al., 1971; Harrington et al., 1972; Dalziel et al., 1975; Simpson & Griffiths, 1982; Dalziel, 1983; Cunningham et al., 1998). The continental fragments have a geological or geophysical character similar to that of provinces of southern South America and the Antarctic Peninsula, consistent with their formation at a subducting Pacific margin. Northward migration of the Scotia Sea (referred to above) involved development of an accretionary prism on the northern side of the associated North Scotia Ridge (Ludwig & Rabinowitz, 1982; Cunningham et al., 1998), and closure of the Magallanes Basin (*e.g.* Winslow, 1982).

Present relative plate motions along the North and South Scotia Ridge are slow, sinistral and east-west, components of the similar motion of the bounding South American and Antarctic plates (Forsyth, 1975; Pelayo & Wiens, 1989; De Mets et al., 1990; 1994). Although there is minor transtension and transpression along these northern and southern boundaries, subduction is confined to the South Sandwich trench, and extension largely to the East Scotia Sea back-arc. Rapid back-arc extension is enabled by subduction of South American oceanic lithosphere, with rapid eastward roll-back of the hinge of subduction in the hotspot reference frame (Chase, 1978; Jarrard, 1986; Gripp & Gordon, 1990). It seems most probable that the earlier formation of the entire Scotia Sea region was driven by similar subduction of South American oceanic lithosphere and roll-back of the subduction hinge.

The structure and previous evolution of the Scotia Sea region may influence both the geometry of modern plate boundaries and the nature of motion along them, but not always dominantly so. Much of the North Scotia Ridge comprises an accretionary prism, developed during north-south convergence that has now been replaced by east-west sinistral strike-slip motion. However, the present plate boundary does not follow the frontal fold, but where known takes a line much closer to the backstop of the prism (Cunningham et al., 1998). It is important to find out if it runs to north or south of South Georgia. The Shackleton Fracture Zone is now the boundary between Antarctic and Scotia plates, and may be transpressional throughout its length (the present-day situation is uncertain: see Pelayo & Wiens, 1989; Lawver et al., 1995; Kim et al., 1997), but was in part previously a strike-slip boundary between the Phoenix plate and the southeastern Drake Passage ocean floor (see the Tectonic Map, 1985, or Barker et al., 1991). Along the South Scotia Ridge, the plate boundary in the west separates magnetic and non-magnetic continental fragments, but eastward appears to be dissecting a complex palaeo-arc: its precise path here is poorly defined.

RECONSTRUCTIONS - POTENTIAL OF BROAD-BAND SEISMOLOGY

One contribution to lithosphere tectonics that can be made by regional broad-band seismological studies is to help determine the locus of modern plate boundaries, particularly where plate motions are slow and large earthquakes are sparse, by supplementing information derived from global seismology. Secondly, studies of mantle and crustal velocity from Rayleigh wave dispersion provide a useful tool in unknown regions, but become of more limited value as the region becomes better known. Particularly if they involve long propagation paths, they can suffer from limited lateral resolution, that will be significant if those paths cross the boundaries of a tectonic province. It could be important to try to reduce path lengths. Thirdly, broadband seismology has the capability of examining mantle anisotropy by measuring shear-wave splitting. This is of particular importance in the Scotia Sea region, because of the hypothesis of Alvarez (1982) that an imbalance between excess mantle in a shrinking Pacific province and a mantle deficit in an expanding Atlantic-Indian province might be eliminated by shallow eastward sub-lithospheric flow in regions such as the Scotia Sea, where the supposed barriers to shallow flow (sinking slab, deep continental sub-lithospheric root) are absent. Recent measurements of mantle anisotropy off Peru-Chile (Russo

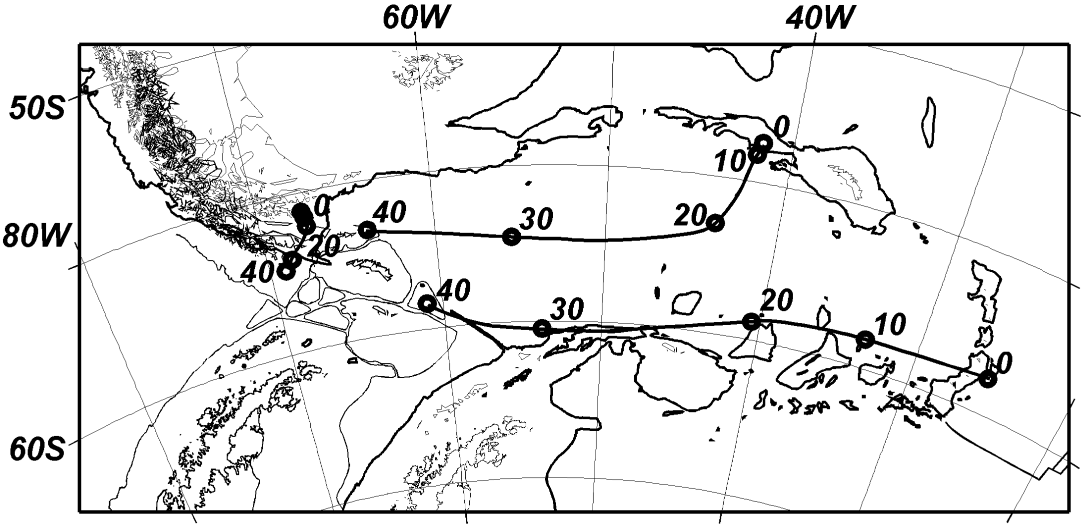

Fig. 2 - Reconstruction of Scotia Sea region to 40 Ma (drawn thin) in coordinates of present-day stable South America, compared with present-day geography (defined by coastline and 2000 m isobath from Tectonic Map, 1985, drawn thicker). Three flow lines (marked at 10 Myr intervals) show the motions since 40 Ma of a point near Cape Horn, a point on the Shag Rocks continental fragment and a point within the present-day South Sandwich fore-arc.

& Silver, 1994) suggest trench-parallel mantle flow, which supports parts of the Alvarez hypothesis. It would be important to see if shallow eastward mantle flow in the Scotia Sea region is taking place now or has taken place in the recent past. An assessment of regional tectonic evolution should contribute to optimal location of additional, discretionary broad-band stations.

Figure 1 shows a summary of spreading directions and durations of coherent spreading regimes in the Scotia Sea region, where known from magnetic anomalies, heat flow or other data. Ocean floor may occur elsewhere, but its age is largely unknown and its spreading direction generally conjectural. Exceptions are Anomaly 10 detected just outside the Drake Passage spreading province of figure 1, off Cape Horn by LaBrecque (1985) and off the South Scotia Ridge by Lodolo et al (1997). These data, and data on major plate motions and the geology of continental fragments, provide the information on which reconstructions can be based. Most recent previously published reconstructions were by Barker et al. (1984; 1991) and the geology of reconstructed continental fragments was shown by King & Barker (1988). A more detailed set of reconstructions than are considered here is being published elsewhere (Barker, in press).

Figure 2 is a reconstruction (in the coordinate frame of stable South America) to Anomaly 18 time (about 40 Ma), at which time the major plates (South America and Antarctica) are close together at the Pacific margin (using the rotations of Barker & Lawver, 1988) and the continental fragments that subsequently dispersed into the North and South Scotia Ridge can be brought together into a compact arrangement that is compatible with their onshore and offshore Pacific margin geology. Magnetic anomaly constraints in the Scotia Sea extend back only to about 27 Ma. Superimposed on this reconstruction are three flow lines that show the paths of particular parts of the present-day Scotia Arc: an old part of the present South Sandwich forearc (Barker, 1995), a point on the Shag Rocks block of the North Scotia Ridge, and a point near to Cape Horn showing slow closure of the Magallanes Basin. The more detailed study of regional tectonic evolution from which these flow lines are derived may be found elsewhere (Barker, in press).

Use of stable South America as a reference frame is partly in recognition that, if shallow mantle flow out of the Pacific has taken place, then the continental lithosphere and subducting Pacific margin of South America make it a useful datum. Also, more “absolute” reference frames, such as the mean hotspot reference frame (Gripp & Gordon, 1990) used in and derived from neotectonics, are of uncertain relevance in “local” cases, and may only be propagated back in time by use of speculative assumptions.

From the point of view of mantle anisotropy studies, the key lesson is most probably that, during Scotia Sea evolution since 40 Ma, the path with the longest (back to 40 Ma) history of creation of ocean floor in the back-arc, and thus the most persistent Alvarez-type gap and eastward flow, is now overlain by the southern Scotia Sea. The northern Scotia Sea now overlies an area which previously saw the northward migration (and eastward elongation) of the North Scotia Ridge behind a rolling-back hinge of South American ocean floor. Only afterward (perhaps only since 10-20 Ma from Fig. 2) would it have experienced eastward sub-lithospheric mantle flow.

There are other considerations (assuming that Alvarez-type sub-horizontal mantle flow has occurred) that govern the selection of broadband seismometer sites:

- a site on ocean floor is preferable to one on continental crust because of the simpler, isotropic crustal structure and absence of a possible deep sub-lithospheric “root”
- a site on older ocean floor will have experienced a longer history of sub-horizontal mantle flow after the possibly confused flow associated with initial formation
- a site on ocean floor that has NOT moved east since 40 Ma will have experienced greater (faster) sub-horizontal mantle flow than a site on ocean floor that HAS moved east.

The last two points are specific illustrations of key generalities: firstly, that anisotropy will result from the differential motion of a lithospheric plate and the underlying asthenosphere, rather than the absolute motion of either, so that an understanding of plate motion is crucial to the correct interpretation of observations of shear wave-splitting. And secondly, anisotropy "frozen-in" to the thickening lithosphere, created by shear stress during its formation, may be different from, but difficult to distinguish from, sub-lithospheric anisotropy caused by present motion (or by motion in the recent past: the "half-life" of anisotropy in the sub-lithospheric mantle, after its cause has ended, is unknown).

There are also considerations of signal-noise ratio at a site, which may depend upon such factors as sediment thickness and ocean bottom current flow and variation. It is therefore not useful here to consider site location in any detail.

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