Tectonic evolution of northern Antarctic Peninsula from brittle mesostructures and earthquake focal mechanisms

A. Maestro[1,2], J. López-Martínez,[2] and F. Bohoyo[1]

[1]Servicio de Geología Marina. Instituto Geológico y Minero de España, Ríos Rosas 23, 28003 Madrid, Spain (a.maestro@igme.es, f.bohoyo@igme.es)
[2]Departamento de Geología y Geoquímica, Facultad de Ciencias, Universidad Autónoma de Madrid, 28049 Madrid, Spain (jeronimo.lopez@uam.es)

Summary Paleostress results derived from brittle mesoscopic structures at locations on the South Shetland Islands, Antarctic Peninsula and Seymour Island and from focal mechanism analysis show a stress field characterized by both extensional and compressional regimes. The scattering of orientations of maximum horizontal stress (σ_1) about NW–SE to N–S and NE–SW trends and of minimum horizontal stress (σ_3) with two main NE–SW and NW–SE modes suggests that two stress sources have been responsible for the dominant directions of maximum and minimum horizontal stress in this area. Compresional structures are related to former Phoenix Plate subduction under the Antarctic Plate in Jurassic to present time and to Quaternary isostatic uplift. Stress states with NW–SE trends of σ_3 are compatible with subduction-related back-arc extension in the eastern Antarctic Peninsula. NE–SW σ_3 orientations are associated with continental fragmentation of the northern Antarctic Peninsula during the Cenozoic.

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Introduction

The stress regime of the Antarctic Peninsula region has remained little known due primarily to the lack of rock outcrop and the scarcity of commercial drilling and recorded seismicity. Stress tectonic studies in this area are key to developing a better understanding of the net effects of plate-boundary and glacio-tectonic forces. Several authors have proposed that the tectonic evolution of this Antarctic Plate sector is profoundly influenced by growth and decay cycles of Antarctic ice sheets through postglacial rebound and uplift/subsidence associated with glacial erosion and surface mass distribution (e.g. Wilson et al., 2002). However, other authors have long maintained that the mass of present Antarctic ice sheets, superimposed on a compressive tectonic stress regime, promotes fault stability and aseismicity by decreasing net differential stress (e.g. Hampel and Hetzel, 2006). Finally, González-Casado et al. (2000), Maestro et al. (2006) and Bohoyo et al. (2007) have related the stress regime during the Cenozoic to present solely to the movement of the various plates that bound the Antarctic Peninsula and tectonic processes developed along and within them.

The main objectives of this study of palaeostresses in brittle mesostructures in Mesozoic-Quaternary rocks are: (i) characterization of the Mesozoic-Recent tectonic stress field in the northern part of the Antarctic Peninsula; and (ii) determination of possible stress sources responsible for the orientation of Mesozoic-Quaternary maximum and minimum horizontal stress.

Results of brittle mesostructures and focal mechanism analysis

Palaeostress analysis was made from fault planes, joints and tension gashes measured at 107 sites in the South Shetland Islands, Antarctic Peninsula and Seymour Island. A total of 137 stress tensors have been obtained (Fig. 1). Orientations of the maximum horizontal stress (σ_1) show three main modes trending NW–SE, N–S and NE–SW, while the minimum horizontal stress (σ_3) direction is NE–SW and NW–SE. The age of the stress tensors has been ascribed to three criteria: 1) the formation age in which the mesostructures have been measured; 2) the similarity distribution of the fault, joint and tension gash planes in rocks of different age; and 3) the relationship of the measured mesostructures with other geological structures (e.g. relationship between the principal stress axes and the bedding plane and cross-cutting relationships among dikes and other dikes or geological features).

The stress state during the Late Cretaceous to Eocene has been determined in two places (Fig. 1C): a) on Hurd Peninsula (South Shetland Islands), where it has been obtained from tension gashes (11 compressive stress tensors with a predominant NNW–SSE direction); and b) on Seymour Island (Weddell Sea), where it has been determined from faults, joints and tension gashes (56 extensional stress tensors with NW–SE orientation).

On the other hand, the stress state during the Neogene to present has been determined from faults in four places (Fig. 1E): a) in the South Shetland Islands (Livingston, King George and Elephant Islands) 28 extensive and 33 compressive stress tensors have been obtained, with N–S and NE–SW σ_1 orientations and NW–SE and NE–SW σ_3 orientations; b) on Deception Island (Bransfield Basin) one compressive and four extensional stress tensors have been determined with NW–SE σ_1 orientation and NW–SE and NE–SW σ_3 orientations; c) in Hope Bay (Antarctic Peninsula) one extensional stress tensor with NE–SW orientation has been obtained; and finally, d) in Seymour Island three compressive stress tensors with NNE–SSW, E–W and NW–SE orientations have been determined. Present-day stress orientation data from earthquake focal mechanisms located in the study area, from the US Geological Survey National Earthquake Information Center (NEIC) and Harvard Seismology Centroid Moment Tensor Catalog (Dziewonski et al., 1981) from 1973 to the present, suggest a NE–SW and ESE–WNW to NW–SE compression and a SE–NW and NNE–SSW extension (Fig. 1G).

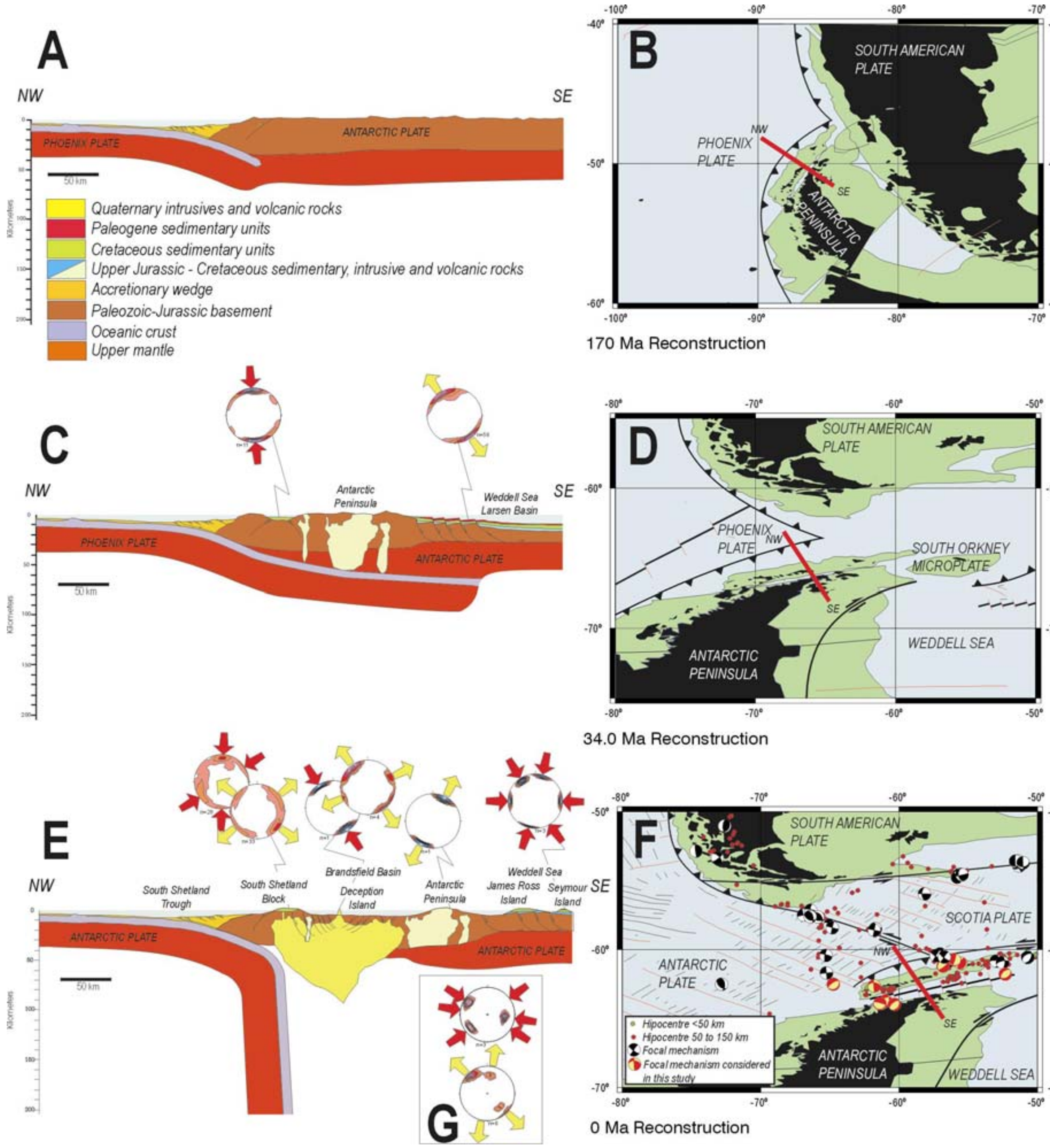

Figure 1. Geodynamic evolution of the northern part of the Antarctic Peninsula in the middle Jurassic (A and B), since late Cretaceous until Eocene (C and D), and during Neogene to present (E and F). Density stereoplots (equal area projection, lower hemisphere) representing extension (σ_3) and compression (σ_1) axes obtained from analysis of brittle mesostructures (C and E) and earthquakes focal mechanisms (G) with yellow and red arrows respectively. Cross sections are represented on the palaeogeographic maps with a red line. Palaeogeographic maps were carried on using ODSN Plate Tectonic Reconstruction Service (http://www.odsn.de/odsn/services/paleomap/paleomap.html). Earthquake focal mechanisms data have been obtained from US Geological Survey National Earthquake Information Center (NEIC) and Harvard Seismology Centroid Moment Tensor Catalog (Dziewonski et al., 1981).

Geodynamic evolution of Antarctic Peninsula from Middle Jurassic to present

The Antarctic Peninsula is an ensialic Mesozoic arc formed on Palaeozoic, or possibly older Gondwana basement from eastward subduction of the proto-Pacific or former Phoenix Plate (Fig. 1A). Prior to mid-Jurassic time, the peninsula formed part of the palaeo-Pacific margin and one of several crustal blocks within Gondwana (Fig. 1B). Subsequently, as subduction continued, it separated from Gondwana by crustal extension and seafloor spreading in the Weddell Sea region, as an independent microplate (Storey et al., 1996).

The subduction of the former Phoenix Plate under the Antarctic Peninsula continued during the Late Jurassic to Early Cretaceous. During this time, an extensional basin with NE-SW direction developed in the western margin of the Weddell Sea called the Larsen Basin (Fig. 1C and D). The Larsen Basin is bounded to the east by the shelf-break beyond which lies the oceanic crust of the Weddell Sea, and to the west by steep faults and the Antarctic Peninsula. Some authors have related the origin of this basin to a major phase of Middle Jurassic to Early Cretaceous dextral transcurrent motion, causing the fragmentation of West Antarctica into crustal blocks separated by pull-apart basins (e.g. Trouw and Gamboa, 1992) (Fig. 1D). We consider that the opening of the Larsen Basin is related to subduction of the former Phoenix Plate under the Antarctic Plate. If we consider studies related to subduction styles depending only on the orientation of the sinking slab (Doglioni, 1995), then it could be determined that the former Phoenix Plate is descending eastwards at a low angle beneath the Antarctic Plate. This style of subduction process does not usually lead to the development of a back-arc basin. However, if the hanging-wall plate is overriding at different displacement velocities it is possible to develop a back-arc basin (Doglioni, 1995). The relative motion of the Weddell Sea and East Antarctica to the NNW and the Antarctic Peninsula to the NW causes different displacement vectors between the hanging-wall plates, resulting in a faster motion of the Antarctic Peninsula northwestward in relation to the Weddell Sea and East Antarctica and being responsible for the extension in between them. This extension may be coeval with compression elsewhere. During the Cretaceous to Paleogene, sinistral movement of the Antarctic Plate relative to the Scotia Plate may have produced oblique NE–SW to ENE–WSW extension along the continental margin of the Antarctic Peninsula. This movement compartmentalized the Antarctic Peninsula and caused the South Orkney Microcontinent to drift from the Antarctic Peninsula during Late Eocene to Early Miocene, leading to the development of the WNW–ESE oriented Powell Basin (Fig. 1D).

The former Phoenix Plate became part of the Antarctic Plate when sea-floor spreading stopped in the Drake Passage at 4 Ma and subduction at the South Shetland Trench thrust terminated (Barker, 1982). Nevertheless, analysis of earthquake focal mechanisms and migrated multichannel seismic reflection profiles across the South Shetland Trench have provided evidence supporting active subduction along the northern margin of the South Shetland Block at the present. The fact that sea-floor spreading has stopped does not necessarily mean the end of subduction because the older and denser oceanic crust of the former Phoenix Plate could be continuing to sink under its own weight. Therefore, the opening of the Bransfield Trough is related to passive subduction of the former Phoenix Plate and roll-back at the South Shetland Trench (Fig. 1E). In addition, taking into account the recent character of the stress field in this area with NE–SW compression between the South American and Antarctic plates, the tectonic structure in the Bransfield Trough and the South Shetland Block could be explained by sinistral movement between the Antarctic and the former Phoenix plates (Fig. 1F; González-Casado et al., 2000; Maestro et al., 2006).

Data comparison and discussion

The geodynamic framework that accounts for the extensional and compressional stresses recorded in the Mesozoic to Quaternary rocks of the northern Antarctic Peninsula is complex. Although both compressional and transcurrent macrostructures are found (South Shetland Trench, Shackleton Fracture Zone, South Scotia Ridge), most of the mesostructures and focal mechanisms of earthquakes show that the general stress regime is extensional. Major NW–SE rifting processes during the Late Cretaceous to Quaternary developed extensional basins in the Antarctic Peninsula area, as follows:

i) Larsen Basin, in the eastern Antarctic Peninsula, has been interpreted as a back-arc basin associated with the NE–SW oriented magmatic arc in the Antarctic Peninsula area. This passive margin is largely related to subduction of oceanic lithosphere below continental masses along the Pacific side of Gondwana. The Larsen Basin sedimentary fill comprises a 6–7 km thick, mega-regressive, clastic sequence of Barremian–Eocene age, derived from the active proximal magmatic arc to the west. Volcanism was intermittent from the Jurassic to Palaeocene or Eocene.

ii) The NE–trending and elongated Bransfield Basin developed at northwestern tip of the Antarctic Peninsula. This basin developed as a back-arc basin that was formed since about 4 Ma as a result of the roll-back associated with the sinking of the former Phoenix Plate under the Antarctic Plate. Seismic reflection studies suggest the presence of an igneous basement, interpreted as thinned continental crust intruded by plutonic dikes and volcanic rocks, a sedimentary basement composed of tectonised sedimentary material, and Pliocene-Quaternary sedimentary cover.

The evolution of these two basins is closely related. During the Mesozoic and most of the Cenozoic the Antarctic Peninsula was an active margin characterised by the former Phoenix Plate subduction eastward under the Antarctic

Plate. This process developed the back-arc Larsen Basin, which opened as a result of NW–SE extension induced by differentially subducted hanging-wall lithosphere. This could explain the lack of evidence of the elevated heat flow typical of most back-arc basins. At about 4 Ma, when the former Phoenix Plate became part of the Antarctic Plate, spreading at the Antarctic–Phoenix Plates had stopped or, if it continued, it did so only very slowly. Although spreading had probably stopped, subduction continued, probably driven mainly by the weight of the subducted slab. According to Larter & Barker (1991), the roll-back effect associated with this sinking plate induced NW–SE extensional stresses in the overlying plate leading to the opening of the Bransfield Basin and the separation of the South Shetland Block. The extensional horizontal stress of the predicted intraplate stress field trends NW–SE, which explains the majority of palaeostress data obtained in this study.

On the other hand, the fragmentation of continental blocks, due to tectonic activity along the former right-lateral transcurrent boundary between the Antarctic and Scotia Plates, which is left-lateral at present, contributed to Cenozoic deformation of the northeastern end of the Antarctic Peninsula. The South Orkney Microcontinent, located at the northeastern end of the Antarctic Peninsula and the largest fragment of continental crust in the South Scotia Ridge, is considered to be an Antarctic Peninsula fragment. This NE–SW extensional stress regime, probably in the Late Eocene to Oligocene, led to NE–SW extension of the South Orkney Microcontinent and Powell Basin break-up.

Compressional stress states established on Deception Island and other islands of the South Shetland archipelago are related to subduction processes of the former Phoenix Plate under the Antarctic Plate, whereas the compressional tensors determined on Seymour Island could be related to uplift associated with Antarctic ice sheet retreat during the Quaternary.

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