The Scotia Arc:

An International Geological Laboratory

by Ian W.D. Dalziel

The Scotia arc is the eastward closing loop of mountains, submarine ridges and islands that joins South America to Antarctica. This review of the geology of the region, as established through recent national and international programs, demonstrates the potential of the Scotia arc for furthering understanding of geological processes and the evolution of the southern continents and oceans.

Introduction

The narrow, partly emergent submarine ridge known as the Scotia arc joins the southernmost Andes to the Antarctic Peninsula. It is one of the most fascinating physiographic features of our planet (Fig. 1), and is analogous to the

Caribbean arc that links North and South America. Since there is no equivalent here to the Central America land bridge, the eastward flowing Circum-Antarctic current passes virtually unimpeded through the narrow 600 km gap between Cape Horn and the South Shetland Islands, climatically isolating the Antarctic continent. This circum-polar current is deflected by the complex submarine physiography of the arc, seeking, for example, the still narrower gaps around and between the active volcanic islands of the South Sandwich arc that closes off the discontinuous submarine ridge in the east (Fig. 1).

The political geography of the arc is perhaps equally complex. The southern limb of the arc (southern Scotia Ridge and Antarctic Peninsula) lies within the area covered by the Antarctic Treaty. However, the northern limb (northern

Scotia Ridge and southernmost Andean Cordillera) lies within Chile and Argentina, or else is disputed territory, like the South Sandwich Islands (Islas Sandwichs del Sur) that close off the arc in the east. Despite this complexity, the intense political interest in the region has probably resulted in more logistic support for scientific activity being available than would otherwise have been the case. It has certainly resulted in considerable interaction and cooperation between scientists of many nations separated widely in both the geographical and political sense.

For example, the small Elephant Island in the South Shetlands (Fig. 1) has been studied over the past decade by geologists from Brazil, Chile, the Soviet Union, the United Kingdom, the United States, and West Germany (Figs. 2, 3). Argentine, Australian, Italian, Polish, and Spanish scientists have also worked recently in the Scotia arc, and a New Zealand expedition is planned. This is in addition to Belgian, French and Scandinavian expeditions of the past. Argentina and Chile both have geological surveys with activities in their South American territories, and the British Antarctic Survey that operates mainly south of 60°S has also been active on South Georgia and in the South Atlantic.

Much of this scientific work and some of the cooperative programs began in the International Geophysical Year (1957-58) and now takes place under the aegis of the ICSU Scientific Committee for Antarctic Research (SCAR), which advises the governments of Antarctic Treaty nations. Other cooperative ventures have taken place, and are continuing, under the auspices of such programs as the International Decade of Oceanographic Exploration, the Deep Sea Drilling Project, the new Ocean Drilling Program, the International Geodynamics Project, and the International Lithosphere Program. Less formal arrangements include the cooperative surveys of the United States Antarctic Research Vessel *Hero* in South American and Antarctic waters. Argentine, British, Chilean, Swiss and Ugandan scientists have all participated in cruises organized by the author in various areas around the Scotia arc.

Regional Geological Framework

The southern limb of the Scotia arc was the first part of the Antarctic continent to be sighted. Within two decades it had been suggested that the Andean Cordillera, which disappears at the eastern tip of Tierra del Fuego (Fig. 1), reappears in the Antarctic Peninsula (Barrow, 1931). Hence the name "Antarctandes" was applied to the West Antarctic Cordillera. The informal name "Scotia arc" came into existence after the pioneering bathymetric studies of W.S. Bruce's Scottish National Antarctic Expedition (1902-1904) aboard the brig "Scotia," showed the essential continuity of the submarine ridges joining the Andes to the Antarctic around the Scotia Sea. The term South Sandwich arc is applied to the young (<10 Ma), currently active volcanic arc that closes off the eastern end of this loop. Apart from one

Figure 3: British Antarctic Survey "Twin Otter" aircraft against background of Upper Jurassic strata of the Fossil Bluff Formation, Alexander Island. (Photograph, P.J. Butterworth).

volcano in the Bransfield Strait and one in the southernmost Andes (Monte Burney), these are the only active volcanoes of the region south of 50°S (Fig. 1).

The broad aspects of the evolution of the Scotia arc are now generally accepted by the international community, though there are, of course, areas of disagreement and controversy. Over the years, some scientists have, like Barrow, emphasized the geologic similarities between the southern Andes and the Antarctic Peninsula (e.g. Matthews, 1959; Hawkes, 1952; Dalziel and Elliot, 1983). Others have stressed the differences, and some have rejected as misleading the term "Antarctandes" (e.g. Katz, 1973). In fact a knowledge of the similarities and the differences is essential both to an understanding of the geologic evolution of the region, and to an appreciation of its significance as a laboratory for the study of tectonic processes.

The easterly swing of the Patagonian Andes into the Andes of Tierra del Fuego at the latitude of the Strait of Magellan (54°S) has been called the Patagonian Orocline by Carey (1958). The Fuegian Andes "disappear" into the sea at the eastern end of the Argentine island of Isla de los Estados, clearly continuing as the submarine Burdwood Bank (Fig. 1). Although the eastern part of the northern Scotia Ridge is topographically complex, the Black and Shag Rocks, Clerke Rocks, and particularly the island of South Georgia (Islas Georgias) are unquestionably continental in character, having geologic affinities with the Pacific side of the southernmost Andean Cordillera. South Georgia, it is widely accepted, was once situated south of Isla de los Estados and the Burdwood Bank and immediately east of Isla Navarino in southern Chile (Dalziel et al., 1975; Tanner, 1982).

Figure 2: Brazilian geologists on Elephant Island, South Shetland Islands. (photo courtesy of R. Trouw).

Figure 4: Interpretation of the Gondwanaland margin in the Scotia arc region prior to break-up.

Figure 5: Blocks of white massive fusulinid limestone of Late Pennsylvanian to Early Permian age in a megamélange with a graywacke-shale matrix. Madre de Dios Archipelago (50°S latitude), southern Chile; part of pre-Late Jurassic subduction complex. Vertical heights of limestone blocks about 300m.

Similarly on the southern Scotia Ridge (Fig. 4), the South Orkney Islands are of continental affinities and have long been known to consist of rocks indistinguishable from those forming the easternmost islands of the South Shetland Islands off the tip of the Antarctic Peninsula (Tyrrell, 1945). In former times the South Orkney Islands were thus probably situated east-southeast of the tip of the Antarctic Peninsula in what is now the oceanic Powell Basin (Dalziel, 1984a). In contrast, the South Sandwich Islands that close off the eastern end of the Scotia arc are wholly volcanic, consisting of primitive oceanic arc-type lavas. The oldest known rocks here have been dated at 4 Ma (Baker, 1968), and the age of oceanic crust immediately west of the volcanic arc suggests the igneous activity there may be as old as, but not much older than, 8 Ma (Barker, 1972). Hence, the South Sandwich arc is like a more primitive equivalent of the Lesser Antilles arc (Baker, *ibid*).

Figure 6: Clastic dike cutting flat-lying Upper Cretaceous strata, Argentine coast, Tierra del Fuego (photograph Anne Grunow).

There is evidence that both the northern and the southern limbs of the Scotia arc were parts of the Pacific margin of Gondwanaland before break-up of the supercontinent in the late Mesozoic (Fig. 4). Subduction complexes there (Fig. 5) are unconformably overlain by Upper Jurassic to Lower Cretaceous volcanic and sedimentary sequences in Tierra del Fuego (Fig. 6) and the South Orkney Islands (Dalziel, 1982a; Forsythe, 1982). The exact configuration of this margin is, however, one of the unsolved puzzles of Gondwanaland geography. Standard procedures of reconstruction (e.g. Norton and Sclater, 1979) still lead to a seemingly unacceptable overlap (Fig. 7) between the Antarctic Peninsula and the (Falkland) Malvinas Plateau (Dalziel and Elliot, 1982).

The main difference between the geologic evolution of the northern and southern limbs of the Scotia arc came in the late Mesozoic. At this time an intra-arc or back-arc marginal basin opened along the Pacific margin of South America south of 50°S (Fig. 8; see Dalziel, 1982b, for review). It was floored at least partially by quasi-oceanic crust now preserved as ophiolitic (gabbro-sheeted dyke-pillow lava) bodies in several places. The depth, width and proportion of mafic to continental rocks on the floor of this basin are still unknown, and likely to remain so because the basin was destroyed in a major episode of compressional tectonics, the mid-Cretaceous Andean orogeny, (approximately 100 Ma ago). This episode resulted in intense deformation of all the rocks in the southern Andes (Fig. 9) including the pre-Late Jurassic crystalline basement and the Gondwanaland margin subduction complexes (Nelson et al., 1980).

In contrast, the southern limb of the Scotia arc has no ophiolitic bodies of late Mesozoic age and did not suffer penetrative deformation in any way comparable to that of southern South America. The importance of variation in the state of stress with time and place along the continental margins is demonstrated by the presently active back-arc rifting beneath Bransfield Strait, which separates the South Shetland Islands from the Antarctic Peninsula, and its southerly continuations along the Gerlache Strait and King George VI Sound (Fig. 1). There is no comparable active rift in South America.

Both limbs of the Scotia arc are thus the products of long-lived, if discontinuous, subduction along different segments of what was originally the Pacific margin of Gondwanaland. Fore-arc accretionary wedges (subduction complexes and trench, trench-slope, and fore-arc basin deposits), arc rocks (including the enormous deep-seated Patagonian and Antarctic Peninsula batholiths, see Fig. 10), and back-arc basin deposits constitute most of the southernmost Andean, and Antaretandean Cordilleras (Dalziel and Elliot, 1973; Escobar, 1980; Thompson et al., 1983; Barker et al., *in press*).

It has long been known that Drake Passage and the Scotia Sea, which reach depths in excess of 4,000 m, are floored by oceanic crust. It was suggested early on that this crust, like that of the Caribbean Sea, is part of the floor of the Pacific Ocean. Indeed, Wilson (1966) suggested that the Caribbean and the Scotia arcs formed by a process analogous to that of "ice rafting" with left and right lateral transform faults, on their northern and southern limbs respectively. These faults were regarded as transforming east-dipping subduction zones along the Pacific margins of North America, South America and Antarctica to west-dipping subducting zones beneath the Lesser Antilles and South Sandwich arcs.

Analyses of marine geophysical data (see Barker and Dalziel, 1983) and first-motion studies of earthquakes (Forsythe, 1975) have, however, revealed that the Scotia arc developed in a different way. A northeast-trending center of spreading opened Drake Passage between South America and the Antarctic Peninsula over the past 30 million years (Barker and Burrell, 1977), but this spreading center has ceased to be active over the past 4 Ma (Barker and Dalziel, 1983). A north-south spreading center has also formed behind the South Sandwich arc over the past 8 Ma, giving rise in the east

to a new D-shaped Sandwich plate and leaving behind a complex of one or more remnant arcs in the central Scotia Sea (Barker, 1972; Barker and Hill, 1981).

While motion on the northern Scotia Ridge transform fault is clearly left lateral, that on the southern Scotia Ridge transform also appears to be sinistral, but slower (Forsyth, 1975). Hence, South America is moving left-laterally with respect to Antarctica, as shown also by the relative motions calculated from the South America-Africa and Africa-Antarctica poles of rotation. Thus the tectonics of the Scotia arc are largely controlled by the relative motion of the South American and Antarctic plates as they move west relative to a fixed African plate, this having been one of left-lateral extension over the past 30 million years. The problem is similar to that of the western Mediterranean, where tectonic activity is controlled by the relative motion between the African and European plates as they both move east relative to a fixed North American plate.

Looking back in time the situation may have been more complex, or at least different, prior to 30 Ma, because relative motion seems to have occurred between the Antarctic Peninsula and the East Antarctic craton (Dalziel and Elliot, 1982; Dalziel, 1983). The virtual cessation of spreading in Drake Passage over the past 4 Ma may presage a new regime. The present northeast directed compression across the Scotia plate (Forsyth, 1975) could, if strong enough and if continued, convert the Shackleton fracture zone between Cape Horn and Elephant Island (Fig. 1) into a convergent plate boundary. This might initiate an equivalent of the Central America land bridge by subduction-related volcanism between South America and the Antarctic Peninsula.

The separations of the South Georgia and South Orkney microcontinents from South America and the Antarctic Peninsula respectively result, presumably, from the left-lateral motion on the northern and southern Scotia Ridge transform fault and spreading in the Powell Basin (Fig. 1) in the mid-late Cenozoic. The precise plate kinematics are as yet, however, not understood (Barker and Dalziel, 1983).

Geologic Evolution

Two aspects of the geology of the Scotia arc make its geologic evolution particularly important. The first is that the

Figure 8: ▲ Interpretation of the tectonics of the Pacific margin of southernmost South America in the Early Cretaceous. Crosses represent the Patagonian batholith beneath its volcanic suprastructure, relicts of which are exposed near Cape Horn. The batholith intrudes the South American basement (vertical wiggly lines). The volcaniclastic infilling of the marginal basin (stippled) rests on an ophiolitic floor (black). Cordillera Darwin is seen as a remnant volcanic arc.

Figure 7: Illustration (Dalziel, 1984) of the problem with regard to Antarctica-South America "overlap" in Gondwanaland reconstruction. West Antarctic "microcontinents": A - Antarctic Peninsula; E - Ellsworth Mountains-Whitmore Mountains; M - Marie Byrd Land; T - Thurston Island-Eights Coast.

earlier (pre-Late Jurassic) history has a bearing on the evolution of the Pacific margin of Gondwanaland as a whole. Indeed, study of the rocks in the older subduction complexes of the region is the only way that information can be obtained about the subducted floor of Panthalassa. Brazilian, British, Chilean and U.S. geologists are currently carrying out such studies.

The second aspect concerns the significance of the Scotia arc region with regard to oceanic circulation, climate, and the dispersal of biota. Cold Antarctic bottom water is currently generated in the Weddell Sea basin from whence it flows north into the South Atlantic Ocean. Opening of Drake Passage approximately 30 Ma ago permitted the development of a complete circum-polar current. This event may have been

Figure 9: Cross-section of South Georgia (Allardye Range to Barff Island) and Isla de los Estados illustrating effects of mid-Cretaceous compressional deformation on Upper Jurassic silicic volcanic rocks of continental margin (dashes) and Lower Cretaceous volcaniclastic infilling of marginal basin (various stippled symbols indicate variations in texture and detritus). (after Dalziel et al., 1975 and Tanner 1982).

Figure 10: Granitic stock of Cerro Paine (12Ma) with walls and roof of black Upper Cretaceous turbidites, Andean fold-thrust belt, Chilean Patagonia (photograph Anne Grunow). Photo shows some 9,000 feet of relief.

at least partly responsible for the climatic deterioration which led to glaciation. Together with the separation of Australia from East Antarctica, it certainly resulted in the biologic isolation of the continent in terms of the land animals involved. Thus the stratigraphic and paleontologic records contained in the upper Mesozoic and Cenozoic strata from the Scotia arc region are particularly important.

Unusually complete stratigraphic sequences are preserved in the James Ross Island-Seymour Island (Isla Vicecomodoro Morambio) area off the eastern tip of the Antarctic Peninsula (Rinaldi et al., 1978; Fig. 1). The recent discovery of marsupial remains there has accentuated the significance of these deposits (Woodburn and Zinsmeister, 1984), and additional studies both on land, and of cores collected at sea, can be expected to yield a rich harvest of material of global significance. Leg 114 of the Ocean Drilling Program is planned for the Weddell Sea in 1987.

Figure 11: View NW along Strait of Magellan. Geologists are standing on the Scotia plate looking across the valley to the South America plate, Chilean Tierra del Fuego.

Tectonic Processes

First of all, there is the major question of why the supercontinent of Gondwanaland began to break up approximately 150 Ma ago after existing as a continental entity for at least 350-400 millions of years. A clue to this may lie in the igneous activity that was penecontemporaneous with break-up. The products of this activity include both rocks of silicic-intermediate composition near the Pacific margin (e.g. Dalziel et al., 1974; Caminos and Nullo, 1979) and the Serra Geral-Karoo-Ferrar mafic intrusions and extrusions of South America, Africa and Antarctica respectively.

Could there be some relation between the Pacific margin, presumably subduction-related, igneous activity and the mafic rocks of the continental interiors? Could such a relationship reflect an even more fundamental causal relationship between Pacific margin tectonism and continental break-up? Answers to these questions demand an international effort spread over all three continents. There may, for example, be a relationship between the above-mentioned igneous activity and the widespread Gondwana peneplain that du Toit (1937) and King (1962) correlated between Africa and South America and which is now also recognized in Antarctica (Dalziel and Elliot, 1973; Dalziel, 1982a).

A second type of tectonic process that can be very profitably studied in the Scotia arc region is the evolution of subduction complexes. It is now widely accepted that such assemblages ranging in age from mid-Paleozoic to Cenozoic occur along the margins of South America, West Antarctica and New Zealand. In the Scotia arc region, some of the complexes are older than Late Jurassic, while others may be as young as Cenozoic (Dalziel, 1982a and 1984a; Tanner et al., 1982).

Two striking features of the subduction complexes in the Scotia arc region make them worthy of study. First, many of the rocks that are of oceanic affinities (mafic lavas, chert, calc-silicate, argillite) are polyphase-deformed tectonites rather than mélanges (Dalziel, 1984a). They appear to have been deformed under considerable cover in a zone of "underplating" beneath an accretionary fore-arc wedge, rather than at the toe of the wedge where deformation is seen to occur in modern fore-arcs. Second, the subduction complexes at three localities, the Islas Diego Ramirez (southwest of Cape Horn), Smith Island and the northern part of the Elephant Island group (South Shetland Islands) are all located where fracture zones intersect convergent margins (Fig. 1). Thus, there may be a relationship between uplift and the interaction between fracture zones and subduction zones. Whatever the cause of uplift, the presence of young blueschist tectonites at the continental margin close to a trench is an ideal situation to explain the enigmatic so-called "knockers" of blue-schist in the Franciscan mélanges of California (Karig, 1980). Islands such as Smith Island could readily be shedding blue-schist erosional products into the adjacent but currently inactive trench where they could later become incorporated in a mélange to be exposed as "knockers" upon subsequent uplift.

A third type of tectonic process that can be studied in the Scotia arc region is the evolution of Cordilleran-type mountain belts and their associated fold-thrust belts. Of particular importance here is the east-west trending part of the Andean Cordillera in Tierra del Fuego and along the northern Scotia Ridge to South Georgia. This is the zone in which the Early Cretaceous marginal basin appears to have been widest and deepest (Dalziel, 1982b; Tanner, 1982). It is also where the mid-Cretaceous deformation was most intense. This resulted in structural reactivation of the preLate Jurassic basement in a manner reminiscent of the reactivation of the pre-Triassic Hercynian basement of the Pennine zone during the latest Mesozoic and Cenozoic Alpine orogeny (Nelson et al., 1980).

Following on the mid-Cretaceous event, a foredeep developed on the Atlantic side of the southernmost Andean Cordillera,

and this was deformed during the Late Cretaceous and Cenozoic to form a foreland fold-thrust belt (Winslow, 1982). Thus, although the arc that "collided" with the South American continent to close the marginal basin was not allochthonous, the collision resulted in the initiation of the tectonic uplift of the Andean Cordillera. It appears that this was merely the most intense deformational effect of a mid-Cretaceous compression along the entire length of the Andean Cordillera (Dalziel, 1984b). Cordillera Darwin, the highest part of the Andes in Tierra del Fuego, displays high-grade (amphibolite facies) metamorphic rocks and migmatites. It is similar to some of the "core complexes" of the North American Cordillera (Coney et al., 1982) and provides an unrivalled laboratory for studying the tectonic evolution of the Cordillera.

Finally, it should be noted that the southernmost Andes, from the Strait of Magellan south and including the northern Scotia Ridge, provide the only opportunity to conduct marine geophysical traverses across the entire width of the western Cordillera of both of the Americas (Fig. 11). A series of deep seismic reflection profiles, comparable to the MOIST line obtained by the British Institutions Reflection Profiling System across the northwest Caledonian front (Brewer and Smyth, 1984), could shed considerable light on the deep structure and evolution of cordilleran mountain belts as well as the processes of arc-continent collision and ophiolite obduction. A similar study of the southern Scotia Ridge from the inactive trench across the mid-late Cenozoic volcanic arc of the South Shetland Islands, and the active back arc basin marked by the Bransfield Strait, could also make a major contribution to the processes of development of subduction complexes and marginal basins.

Conclusions

The Scotia arc has already proved to be an unusually productive laboratory for the study of geologic history and tectonic processes. It has enormous potential for future work with significance far beyond the confines of the region

itself. The work to date has been undertaken by groups of scientists from both eastern and western nations, and from both industrial and developing countries.

Major endeavours for the future, such as multi-channel seismic profiling through the southernmost Andes and across the northern and southern Scotia Ridges, can only take place with close international cooperation. Global resource problems, recent and on-going international disputes north of 60°S, and the forthcoming 30th anniversary of the Antarctic Treaty, have all led to an intensification of political maneuvering south of this latitude.

The highly productive cooperative science of the International Geophysical Year led directly to the successful negotiation of the Antarctic Treaty, and efforts of the same type could have a positive influence today. There is reason to believe that cooperation by earth scientists of various countries, as well as yielding data relevant to the solution of important problems in the earth sciences, could also help to relieve tension in the region, and even contribute significantly to ensuring its long-term peaceful availability for study by scientists of all disciplines.

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