The Scotia Arc tectonics project, 1969-1975

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The region of the Drake passage and the Scotia Sea in which R/V *Hero* has operated since her first cruise late in 1968 has long been of interest to earth scientists. Charles Darwin made the first geologic observations in the region from aboard HMS *Beagle* during the 19th century (Darwin, 1846). Earlier, in the time of the original *Hero,* it was first suggested that the Andean Cordillera, which disappears into the waters of the Scotia Sea at the eastern tip of Tierra del Fuego, reappears in the Antarctic Peninsula and its offshore islands (Barrow, 1831). In fact, the voyages of Nathaniel Palmer and others were instrumental in the recognition of the "Antarctandes." Subsequent work at sea, including that of the brig *Scotia* of the Scottish National Antarctic Expedition (Bruce, 1906), led to the discovery of a discontinuous submarine ridge—the Scotia Ridge—joining the Andes to the Antarctandes in the eastward-facing loop that has come to be known as the Scotia Arc (figures 1 and 2).

The Scotia Arc region, which is here taken in a broad sense to extend from latitude 46°S. in Chile (where the Chile Rise intersects South America) to the base of the Antarctic Peninsula (figures 1 and 2), is still of outstanding geologic significance. Global problems relevant to research in this region were recently identified by the International Geodynamics Commission and by the geology and geophysics panel of the Committee on Polar Research, U.S. National Academy of Sciences:

(1) The boundary between two of the half-dozen or so major lithospheric plates into which is divided the world's 100-kilometer-thick, rigid outer shell passes through the region. The boundary between the American plate and the antarctic plate extends from the Chile Rise south to the tip of Tierra del Fuego, along the north Scotia Ridge, south around the active South Sandwich volcanic arc, and eastward along the South Sandwich Fracture Zone to the Mid-Atlantic Ridge. However, as shown in figure 1, the boundary is poorly defined by earthquakes between the Chile Rise and the northern end of the South Sandwich arc.

(2) Not only is the region situated along a presently active plate boundary, but it also has been an active plate boundary for over 200 million years; hence it is an excellent place to study tectonic and igneous processes.

(3) While the geologic relations of Africa and South America, and of Australia and Antarctica, are well established in the reconstruction of Gondwanaland, the former positions of the "eastern" (Antarctica-Australia) and "western" (Africa-South America) parts of the ancient southern supercontinent relative to one another and to India are still uncertain. The Scotia Arc region is the key to this puzzle.

(4) The timing of events during the breakup of Gondwanaland in the Scotia Arc region is crucial to several important developments in earth history (*e.g.,* the migration of marsupials from South America to Australia and the inception of a full circumpolar current with its effects on global climate).

Modern U.S. involvement in the terrestrial geology of the region, and the current Scotia Arc tectonics project, began in the early 1960s when Robert H. Dott, Jr., University of Wisconsin, initiated a program funded by the National Science Foundation to study in greater detail than ever before the geologic relationship of South America and the Antarctic Peninsula. The work of Kevin Scott, U.S. Geological Survey, and the initial work of Martin Halpern, University of Texas at Dallas, were part of this program (see bibliography). In 1963 it became apparent to Professor Dott and me that the geology of South Georgia Island at the eastern end of the North Scotia Ridge was critical in understanding the geologic relationship between South America and the Antarctic Peninsula. It was not possible to visit the island at the time; in fact, it was not until 1973 that a detailed comparative geologic study of South Georgia and southernmost South America was undertaken. With the onset of R/V *Hero* cruises late in 1968, the well exposed but previously inaccessible rocks of the Scotia Arc region were finally reached for study and the potential of this remarkable laboratory of tectonic and igneous processes began to be realized. The use of inflatable boats launched from *Hero* and from temporary camps ashore finally enabled landings to be made virtually anywhere in the region.

Scientific achievements

Scientists involved in the Scotia Arc tectonics project have taken a problem-oriented approach to their research. Geologic mapping has been directed toward solving a particular problem rather than covering a given area. The program's achievements thus can best be described in terms of the elucidation of the geologic evolution of the region, particularly as this affects global problems and the understanding of tectonic processes.

"Basement" complexes. The deformed rocks underlying the widespread Upper Jurassic silicic volcanic sequence of the Scotia Arc region (table) are here referred to as "basement." They have been studied extensively during the project in the South Shetland Islands, the South Orkney Islands, the Antarctic Peninsula, and southern South America. It has been clearly established that the Jurassic volcanic sequence rests unconformably on the basement complex or complexes throughout the region. Comparison of the fossiliferous Upper Paleozoic Madre de Dios sequence with the unfossiliferous

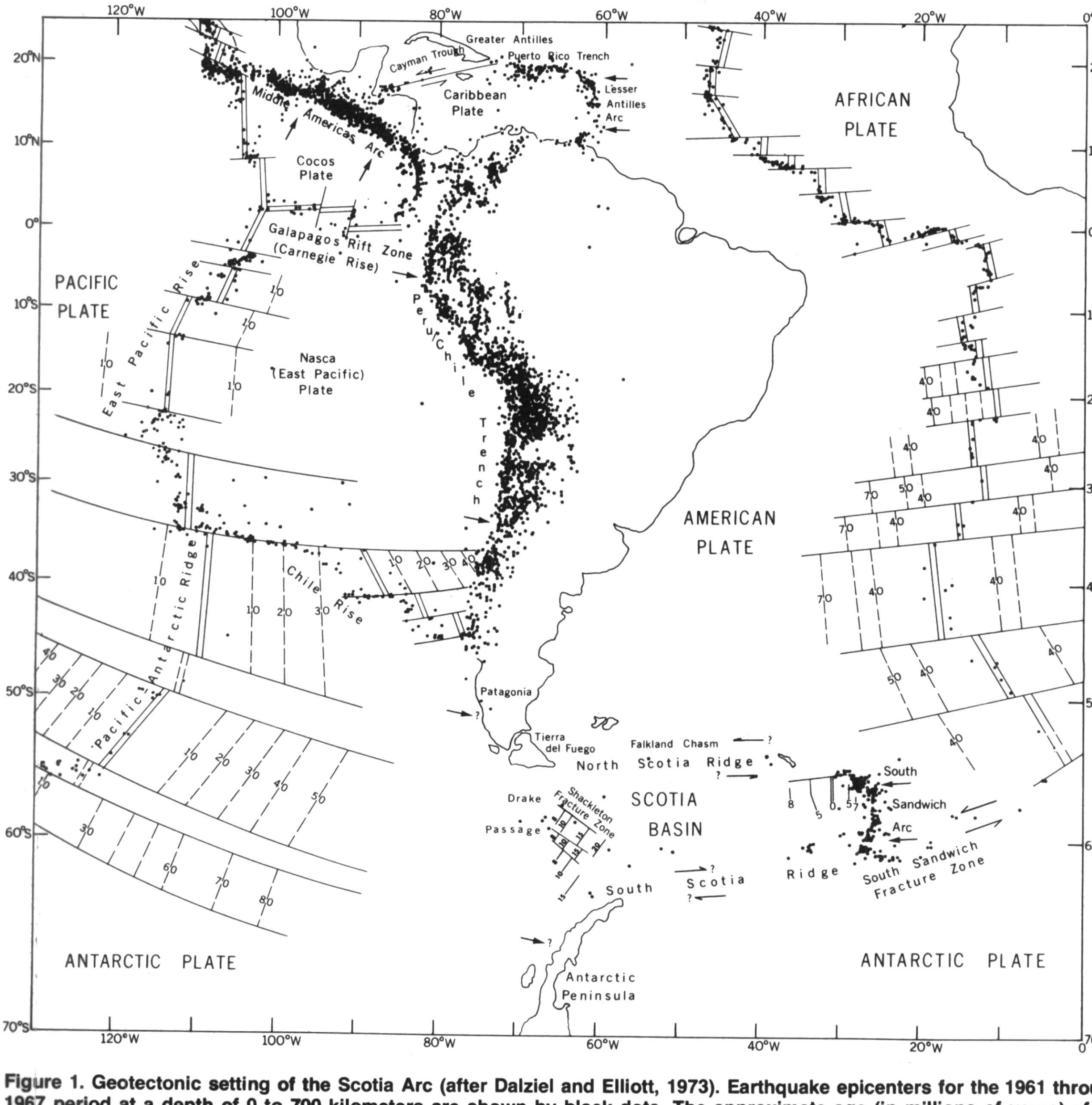


Figure 1. Geotectonic setting of the Scotia Arc (after Dalziel and Elliott, 1973). Earthquake epicenters for the 1961 through 1967 period at a depth of 0 to 700 kilometers are shown by black dots. The approximate age (in millions of years) of the floor of the Atlantic and Pacific oceans also is shown. Arrows indicate inferred relative motion of the lithospheric plates on which they are drawn.

rocks elsewhere in the region (including in the Trinity Peninsula "Series" of the Antarctic Peninsula) (Dalziel, 1972) has strengthened the likelihood that these rocks in fact are Late Paleozoic. While relationships in the South Orkney Islands still suggest that part of the basement is older than Upper Paleozoic (Dalziel, 1974), two sequences previously assigned to the basement (Adie, 1964) are now believed to be younger. Dr. de Wit's recent observations of the rocks at Marguerite Bay indicate that they probably form the roots of an early Mesozoic calc-alkaline volcanic arc or chain; the Sandebugten graywacke and shale sequence of South Georgia is now believed, on structural and sedimentologic grounds, to be Lower Cretaceous (Dalziel *et al.*, in press).

The structure of the basement complex or complexes has an important bearing on the reconstruction of Gondwanaland in the South Atlantic region where the "fit" has never been well established (Smith and Hallam, 1970; Dietz *et al.*, 1971), and also on the nature and plate tectonic implications of the early Mesozoic Gondwanian orogeny that resulted in the deformation of the Upper Paleozoic sedimentary sequences of the Sierra de la Ventana (Argentina), the Cape Fold belt (South Africa), the Ellsworth and Pensacola mountains (Antarctica), and the Scotia Arc region. The basement of the Scotia Arc region seems to have been first deformed during the Gondwanian orogeny and in many places reactivated during the main (mid-Cretaceous) Andean orogenesis. Recent work

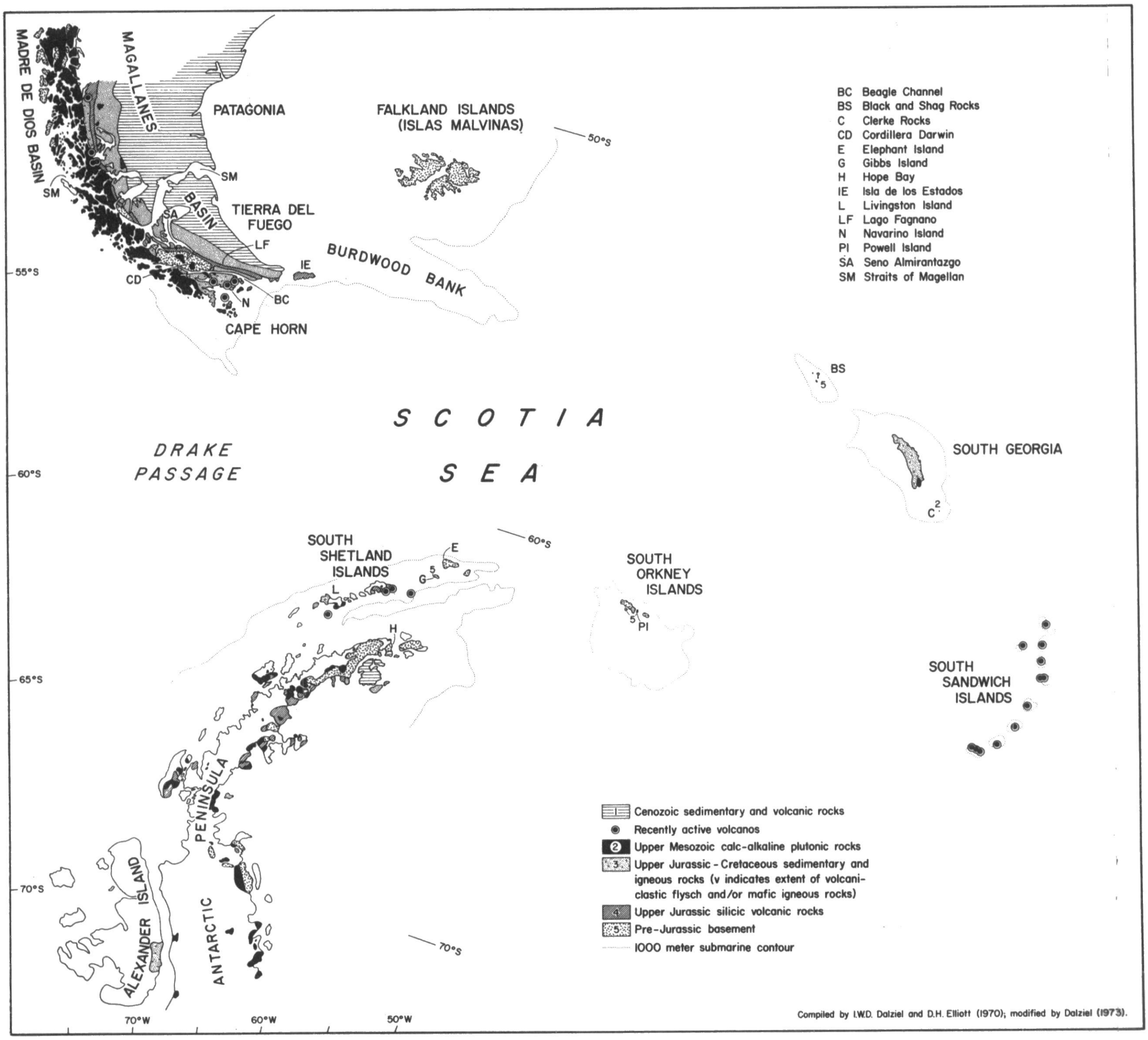
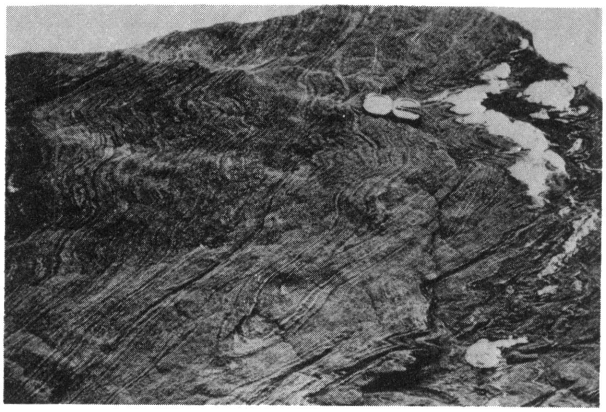


Figure 2. Geologic and location map of the Scotia Arc (after Dalziel, 1974).

has shown that the ultramafic rocks of Gibbs Island in the South Shetland Islands were likely emplaced during the Gondwanian orogeny, possibly in the trench environment. Work undertaken during this project is helping to establish the nature of the Gondwanian orogeny. It appears to have resulted either from the collision of an island arc with the main part of Gondwanaland, or from subduction beneath the margin of the supercontinent.



"Refolded" folds in the metamorphic rocks of Elephant Island, South Shetland Islands. The tight early folds may have resulted from the early Mesozoic Gondwanian orogeny, and the more open (later) folds from the late Mesozoic Andean deformation.

Upper Jurassic volcanic sequence. Silic volcanic rocks of Upper Jurassic age have long been known to occur widely in the Scotia Arc region. Recent work in the Antarctic Peninsula and in South America make it clear that most of these volcanics are related to Late Mesozoic subduction of oceanic crust beneath the South American-west antarctic segment of Gondwanaland. In South America the main outcrop that occurs in a narrow belt along the High Cordillera of the Andes now appears to represent a remnant arc left behind when a small ocean basin opened up during the latest Jurassic

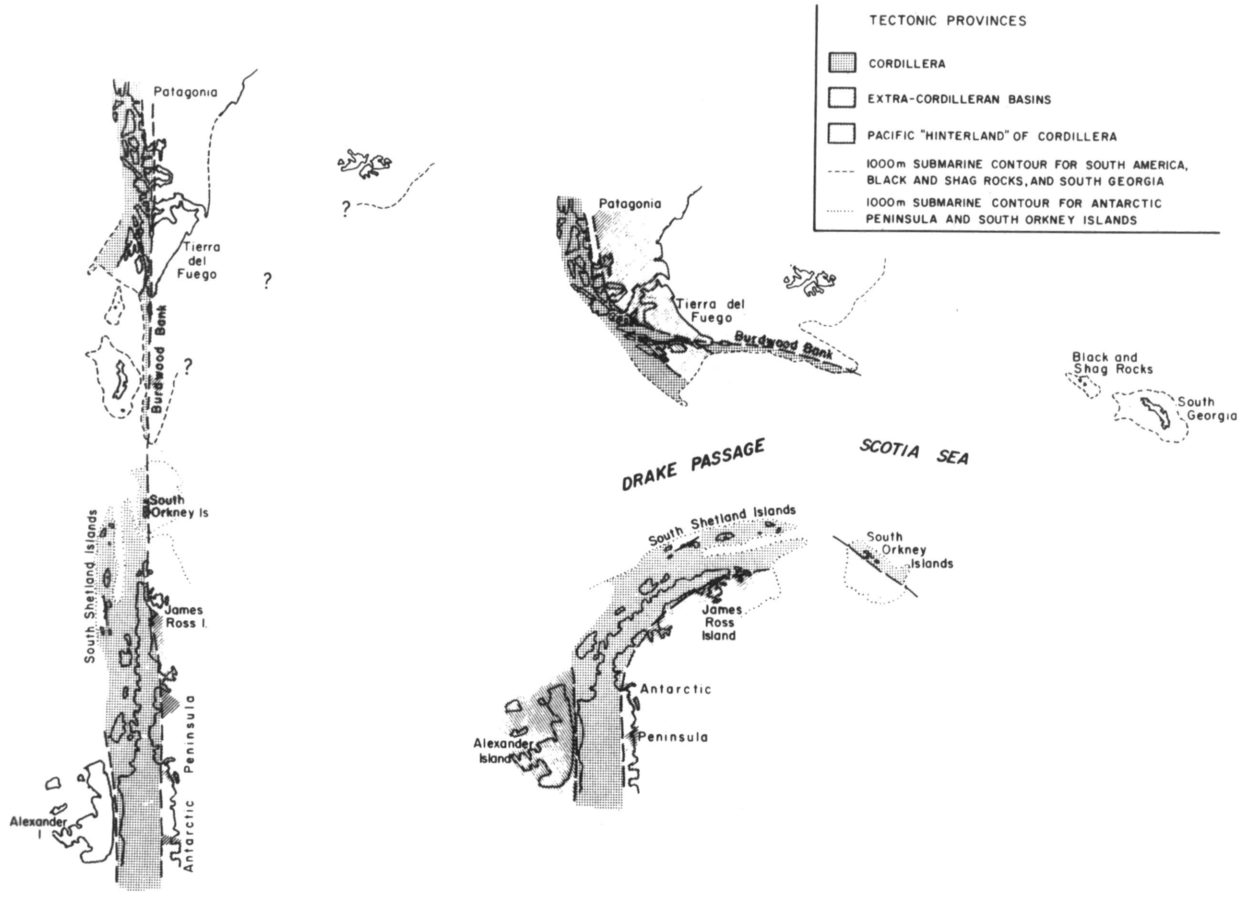


Figure 3. Model for the evolution of the Scotia Arc proposed by Dalziel and Elliot (1973).

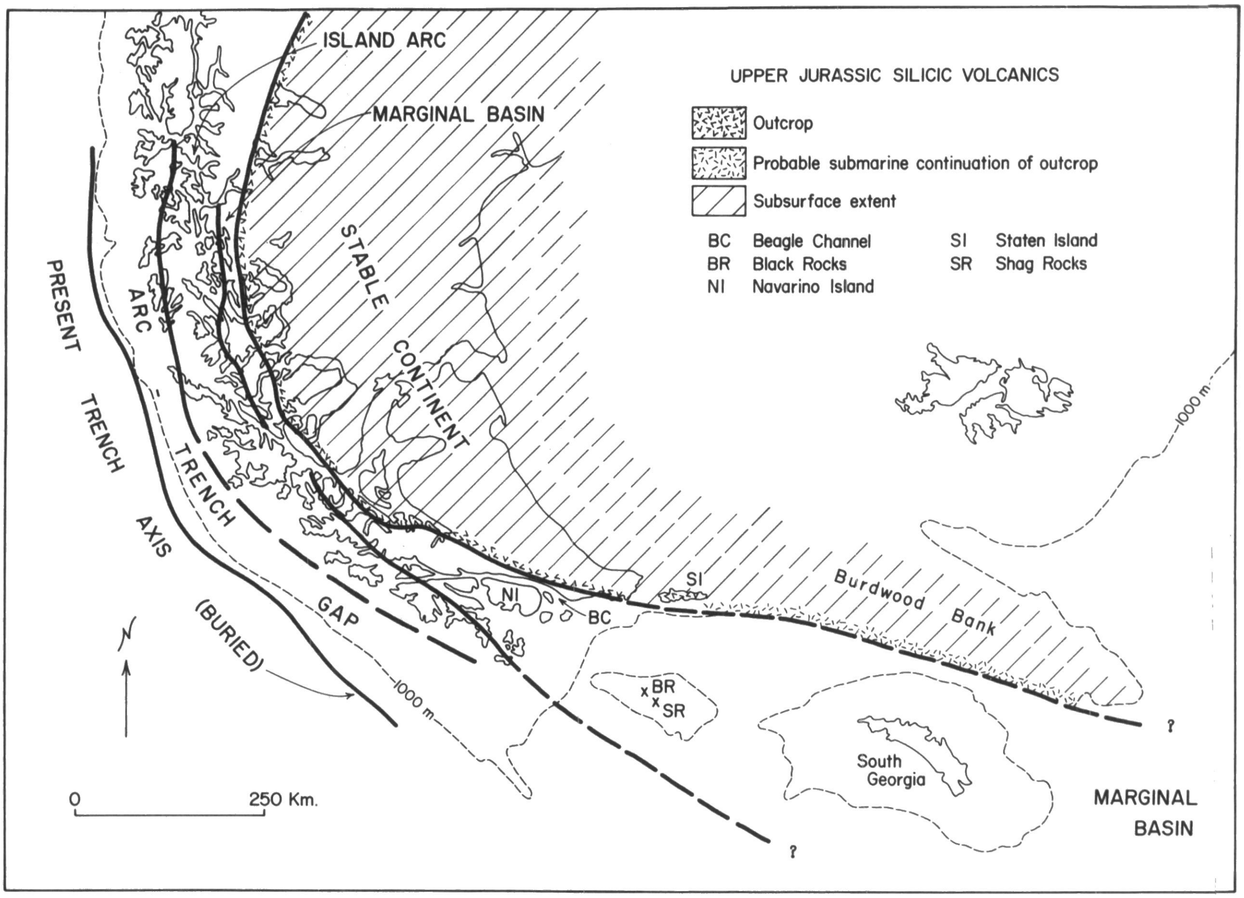
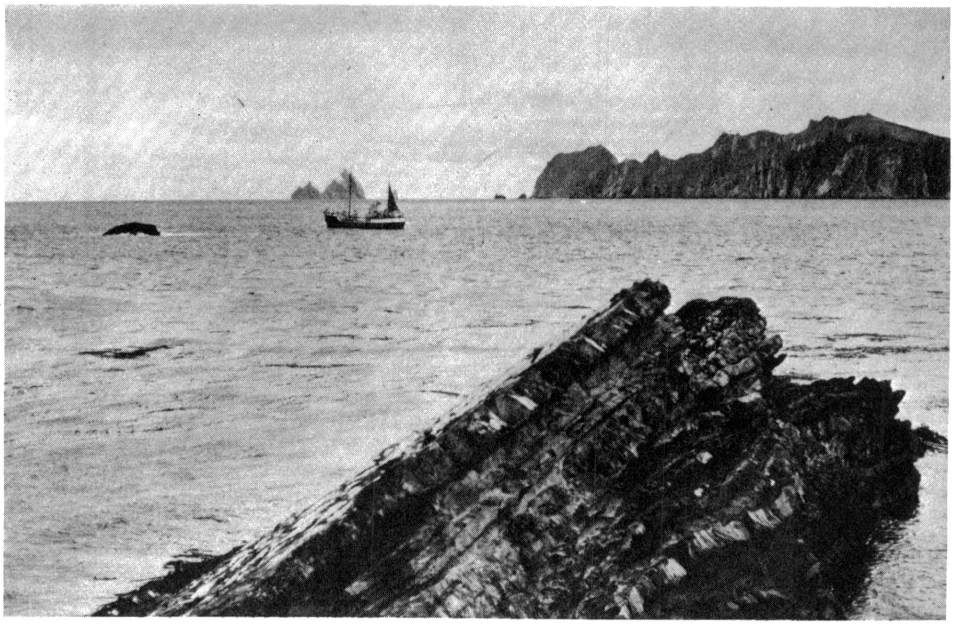


Figure 4a. Reconstruction of north limb of the Scotia Arc (after Dalziel *et al.*, in press).

Principal tectonostratigraphic units and geologic events in the Scotia Arc region.

CENOZOIC	Sedimentary and volcanic sequences (Upper Cretaceous-Cenozoic) with local unconformities		ACTIVE VOLCANISM CENOZOIC VOLCANICITY
CRETACEOUS	u (local) u Sedimentary and volcanic sequences (Lower Cretaceous)	ANDESITIC VOLCANISM AND BATHOLITH EMPLACEMENT (mainly Late Jurassic-Late Cretaceous)	ANDEAN OROGENY (mid-Cretaceous) MAFIC IGNEOUS ACTIVITY (Early Cretaceous: South America only)
JURASSIC	Silicic volcanic and sedimentary sequence (Upper Jurassic)		CALC-ALKALINE VOLCANISM
TRIASSIC	u ~~~~~~~~ u		GONDWANIAN OROGENY Deformation and low-grade metamorphism
PALEOZOIC	Sedimentary sequence(s) (Upper Paleozoic) (?) ~~~~ u ~~~~ u ~~~~ (?) Metamorphic complex (Paleozoic, possible in part Precambrian)		
PRECAMBRIAN	(?) ~~~~ u ~~~~ u ~~~~ (?) ? Metamorphic complex		

u ~~~~ u - unconformity.



Southward-dipping inverted strata on the steep limb of the large synclinal fold affecting the rocks of Isla de los Estados (see figure 5).

within the continental margin calc-alkaline volcanic chain.

Ophiolite complex. Long known by Chilean geologists as the "roccas verdes," the mafic rocks on the Pacific side of the silic volcanic belt in the southern Andes have now been recognized as the upper part of an ophiolite complex representing the floor of a small ocean basin (comparable to the Japan Sea of today) that opened up along the western margin of South America in the Early Cretaceous (figure 4). This is particularly significant since it means that at least this part of the eastern Pacific Ocean margin once looked like the western Pacific margin does today with festoons of island arcs and marginal ocean basins separating the volcanic arcs from the continent proper. It is also significant in terms of mountain building processes: the main uplift of the southern part of the Andean Cordillera occurred at the time when the volcanic arc on the Pacific side of the basin moved back toward South America thus "closing" the marginal basin in an island arc-continent "collision."

Lower Cretaceous sedimentary and volcanic sequences. The most important aspect of these rock sequences is that their recognition in South America as the sedimentary detritus infilling the Japan Sea-like marginal basin has led to a detailed reconstruction of the North Scotia Ridge. It has long been recognized that the rocks of South Georgia are similar to those of Navarino Island in southernmost Chile (Wilckens, 1933; Katz and Watters, 1966). Only recently, however, with the sedimentologic studies of Professor Dott and of Robert Winn, have the details of this comparison been made clear. It can now be appreciated that South Georgia was, until at least the mid-Cretaceous, situated immediately

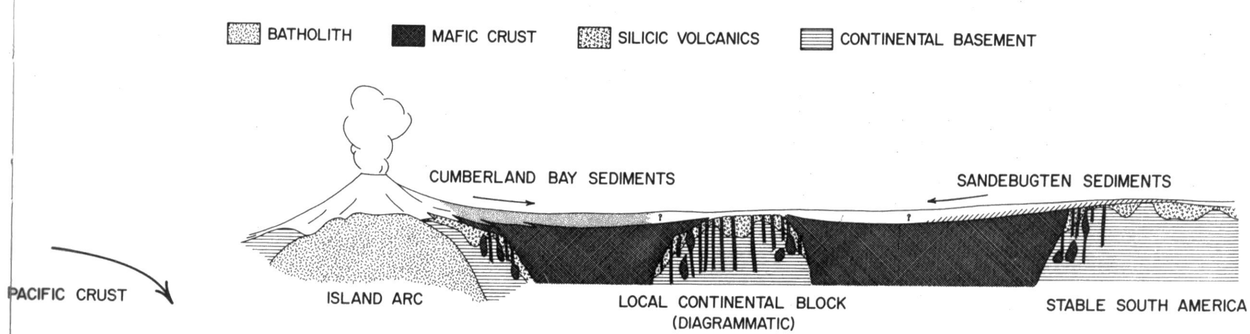


Figure 4b. Interpretative cross section of the northern limb of the Scotia Arc in the Early Cretaceous prior to the opening of Drake Passage and the Scotia Sea (after Dalziel *et al.*, in press).

Participants in the Scotia Arc tectonics project

The scientists listed below, all with interests in the tectonic evolution of the Scotia Arc, have participated in programs either directly or indirectly involving the use of the R/V *Hero* as a base of operations. No attempt has been made here to provide a comprehensive list of individuals interested in the geology of the Scotia Arc region.[1]

Argentina

Servicio Geologico Nacional
Roberto Caminos
Francisco Nullo

Chile

Universidad de Chile
Oscar Gonzalez-Ferran
Estanislao Godoy
Instituto de Investigaciones Geologicas
Riccardo Fuenzalida
Adela Aguilar
Empresa Nacional del Petroleo
Raúl Cortés

Switzerland

ETH Zurich
William Lowrie

United Kingdom

University of Birmingham
John Tarney

United States

Lamont-Doherty Geological Observatory of Columbia University
Ian W. D. Dalziel
Maarten J. de Wit
Charles R. Stern
Keith F. Palmer
Keith O'Nions
Neil Opdyke
University of Wisconsin
Robert H. Dott, Jr.
The Ohio State University
David H. Elliot
University of Texas at Dallas
Martin Halpern

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[1]Such a list is being prepared by the Scotia Arc study group of working group number 2, International Geodynamics Commission: Oscar Gonzalez-Ferran (Chile), chairman; Ian W. D. Dalziel (United States), executive secretary and corresponding secretary for Australia, New Zealand, and the United States; Peter F. Barker (United Kingdom), secretary for the Soviet Union, the United Kingdom, and Western Europe; Roberto Caminos (Argentina), corresponding secretary for Argentina; Riccardo Fuenzalida (Chile), corresponding secretary for Chile.

east of Navarino Island and south of the Burdwood Bank (Dalziel *et al.*, in press) (figure 4).

Andean orogeny. Work undertaken in the course of the Scotia Arc tectonics project has led to a more detailed understanding of the processes involved in the uplift of the southernmost Andes and the Antarctandes. The uplift took place as a result of subduction of the Pacific Ocean floor beneath the South American-antarctic sector of Gondwanaland. In the South American case it took place as a result of the "closure" of the marginal basin in the mid-Cretaceous; this in turn resulted in island arc-continent "collision." The effects of uplift, horizontal shortening, and strike-slip displacement can all be recognized: the floor of the marginal basin (the ophiolite complex) is now up to 2 kilometers above sea level; tight folds (mostly overturned toward the continent) and thrusts striking parallel to the Cordillera are in evidence; large shear zones (including some that are still active such as the Straits of Magellan-Seno Almirantazgo-Lago Fagnano lineament) have been identified. The uplift and horizontal shortening have been shown to result in tectonic thickening of the continental margin, for example on Staten Island at the southeastern extremity of the Andean Cordillera (Dalziel *et al.*, 1974; Dalziel and Palmer, in press) (figure 5). The shears are probably at least in part responsible for the bending of the Andean Cordillera to an east-west trend south of the Strait of Magellan.

Evolution of the Scotia Arc. Early in the project D. H. Elliot and I proposed a model for the evolution of the Scotia Arc that was based on the similarity of the geology north and south of the Drake Passage (figure 3). Subsequent developments, including those outlined above, have shown that this and other recent models (such as that of Barker and Griffiths, 1971, who suggested an eastward-pointing cusp as the original shape of the Andean-Antarctandean Cordillera in the region) are probably highly oversimplified. Specifically, the recognition of the Early Cretaceous marginal basin in the southernmost Andes indicates that the configuration of the South American-Antarctic Peninsula connection at the time could well have been as complex as is today's Alaskan Peninsula-Aleutian Kamchatka connection across the Bering Strait.

Future prospects

The data base and hypotheses that have been generated by the Scotia Arc tectonics project since the inception of R/V *Hero* cruises provide an excellent opportunity for future study, not just of the Scotia region for its own sake, nor even of the region as it bears on global tectonic problems, but as an almost unique laboratory for the study of tectonic and igneous processes. The Mesozoic and

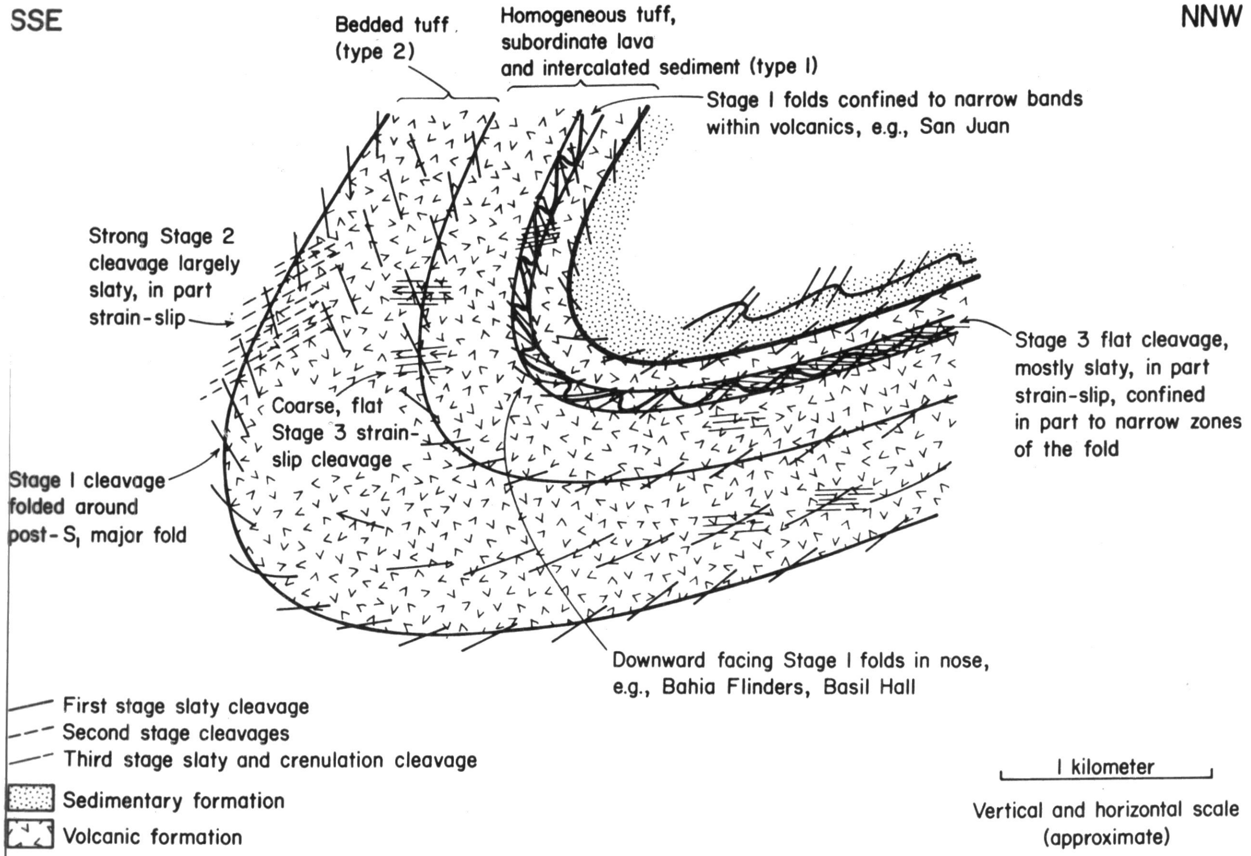
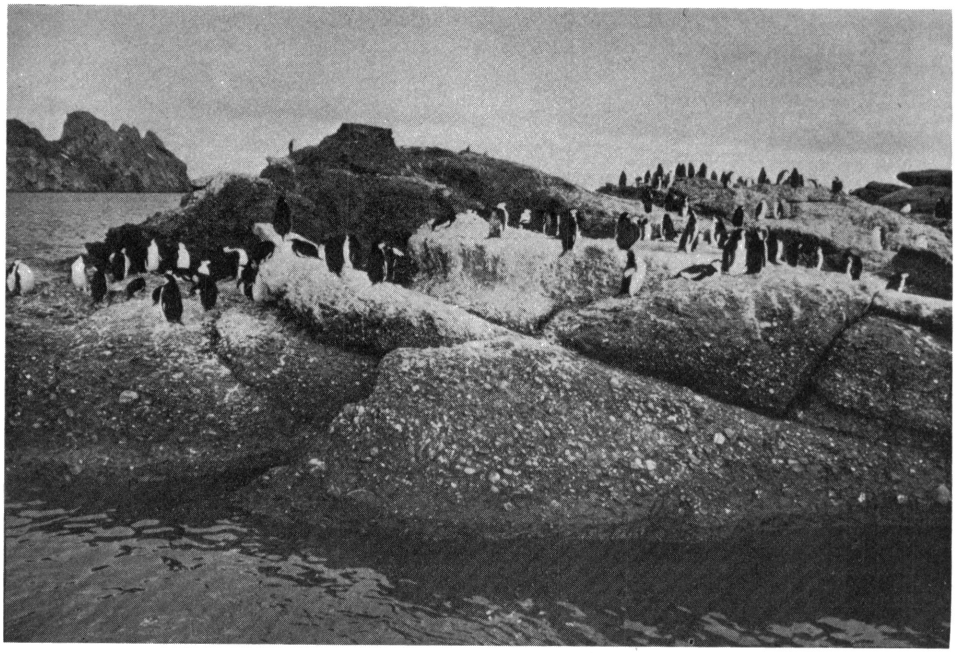
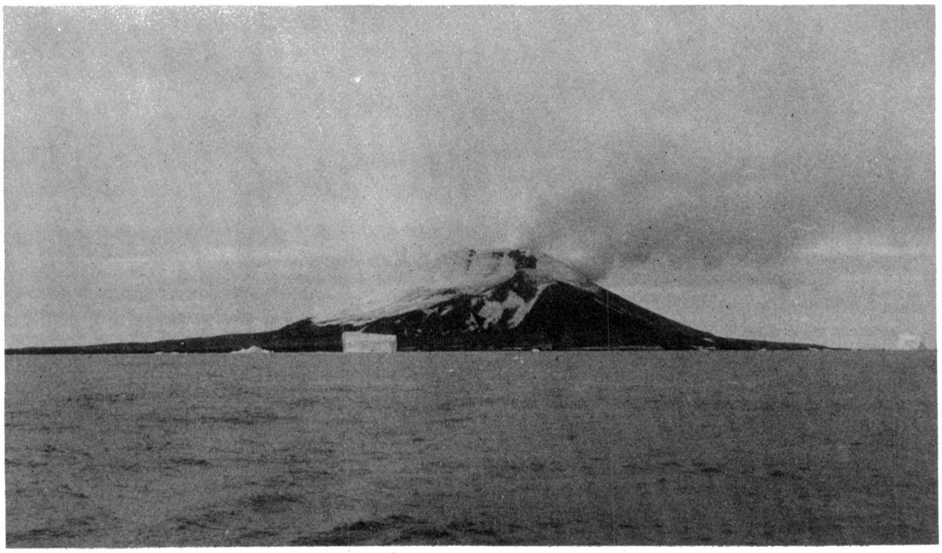


Figure 5. Structural cross section of the rocks of Isla de los Estados, Argentine Tierra del Fuego. The island, which has an elevation of 800 meters, is situated in the core of the fold (after Dalziel *et al.*, 1974a).



Flat-lying undeformed Cretaceous conglomerates in the South Orkney Islands (Powell Island).

The late Miocene (12 million years before present) calc-alkaline pluton of Cerro Paine in the Andean Precordillera north of the Straits of Magellan.



Zavadovski Island, an active volcano northernmost of the South Sandwich Islands (photograph courtesy of Andrew Saunders).

Cenozoic geotectonic setting is clearly established, yet many of the rocks of this age have been uplifted and eroded so that processes currently going on thousands of meters below sea level and up to several kilometers beneath the sea floor can be studied with precision.

Acknowledgments

The Scotia Arc tectonics project has been supported by the Office of Polar Programs and the Office for the International Decade of Ocean Exploration, National Science Foundation. Invaluable logistic support in South America has been supplied by the Departamento de Exploraciones, Empresa Nacional del Petróleo, Chile. The British Antarctic Survey provided transportation to and from South Georgia as well as logistic support on the island.

Special thanks are due to *Hero*'s master, Captain Pieter Lenie, and to former masters Hartschorn, Rogers, Hochban, and Deniston, for their willingness to operate the vessel under difficult conditions, thereby providing us with an unprecedented op-

portunity to study the Scotia Arc region's geology. We also are grateful to the crew of R/V *Hero,* and to the masters and crews of USCGC *Glacier,* USCGC *Edisto,* RRS *Bransfield,* HMS *Endurance,* and the Chilean cutters *Ivan, Viking, Milo, Roca,* and *21 de Mayo.*

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Field activities in the Scotia Arc tectonics project

The following is a resume of geologic field work in the Scotia Arc tectonics project from January 1969 to July 1975 (locations are shown in figure 2):

January-March 1969. Eastern Livingston Island (Hurd Peninsula and False Bay), South Shetland Islands; supported by R/V *Hero* and USCGC *Edisto;* participants from Lamont-Doherty Geological Observatory.

November-December 1969. Northwest Strait of Magellan region, Chile; supported by R/V *Hero;* participants from University of Texas at Dallas, Lamont-Doherty Geological Observatory, Empresa Nacional del Petroleo, Universidad de Chile, and Instituto de Investigaciones Geologicas.

January 1970. Elephant Island and Gibbs Island, South Shetland Islands, and Hope Bay (Antarctic Peninsula); supported by USGC *Glacier;* participants from Lamont-Doherty Geological Observatory.

February 1970. Western Livingston Island, South Shetland Islands; supported by R/V *Hero* and *Piloto Pardo;* participants from Lamont-Doherty Geological Observatory and Universidad de Chile.

July 1970. Cordillera Darwin, Tierra del Fuego, Chile; supported by cutter *Ivan;* participants from Lamont-Doherty Geological Observatory and Empresa Nacional del Petróleo.

January-March 1971. South Orkney Islands; supported by R/V *Hero;* participants from Lamont-Doherty Geological Observatory.

February-April 1972. Tierra del Fuego, Chile; supported by cutters *Ivan* and *Viking;* participants from Lamont-Doherty Geological Observatory and Empresa Nacional del Petróleo.

April-May 1972. Isla de los Estados, Tierra del Fuego, Argentina; supported by R/V *Hero;* participants from Lamont-Doherty Geological Observatory, Universidad de Buenos Aires, and Dirección Nacional de Geología y Minería.

January-March 1973. South Georgia Island; supported by RRS *Bransfield* and HMS *Endurance;* participants from Lamont-Doherty Geological Observatory and University of Wisconsin.

January-March 1973. Northwest Strait of Magellan area, Chile; supported by cutters *Ivan* and *Viking;* participants from Lamont-Doherty Geological Observatory and Empresa Nacional del Petróleo.

April-May 1973. Cordillera Darwin, Tierra del Fuego, Argentina; participants from Lamont-Doherty Geological Observatory and University of Wisconsin.

January-March 1974. Northwest Strait of Magellan area, and Cordillera Darwin, Chile; supported by cutters *Ivan, Rica,* and *21 de Mayo;* participants from Lamont-Doherty Geological Observatory and Empresa Nacional del Petróleo.

May-June 1974. Navarino Island-Cape Horn area, Chile; supported by R/V *Hero;* participants from University of Wisconsin and Lamont-Doherty Geological Observatory.

January-March 1975. Cordillera Darwin, Tierra del Fuego, Argentina and Chile; supported by Chilean navy; participants from Lamont-Doherty Geological Observatory.

January-February 1975. Northwest Strait of Magellan area, Chile; supported by cutters *Roca* and *21 de Mayo;* participants from Lamont-Doherty Geological Observatory, Universidad de Chile, and Empresa Nacional del Petróleo.

February 1975. Tierra del Fuego, Chile; participants from Lamont-Doherty Geological Observatory.

January-March 1975. South Shetland Islands (Gibbs Island and Western Livingston Island), Antarctic Peninsula and offshore islands; supported by R/V *Hero;* participants from Lamont-Doherty Geological Observatory.

June-July 1975. A cruise is being planned for the Chilean coastal cordillera (Punta Arenas-Puerto Montt); supported by R/V *Hero;* participants from Lamont-Doherty Geological Observatory, Universidad de Chile, Empresa Nacional del Petróleo, and Instituto de Investigaciones Geologicas. Also, R/V *Robert D. Conrad* is presently involved in geophysical research in the southeastern Pacific related to the Scotia Arc tectonics project.

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Vegetation of Isla de Los Estados, Argentina

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The primary mission of R/V *Hero* cruise 71-5 was a botanical expedition to Isla de los Estados, Argentina, which is off the eastern tip of Tierra del Fuego and is separated from it by LeMaire Strait. This rugged, mountainous island is about 60 kilometers long, with its long axis running east-west. Both the north and south coasts are much dissected by numerous bays and harbors, many fjord-like.

The itinerary of cruise 71-5 was designed to

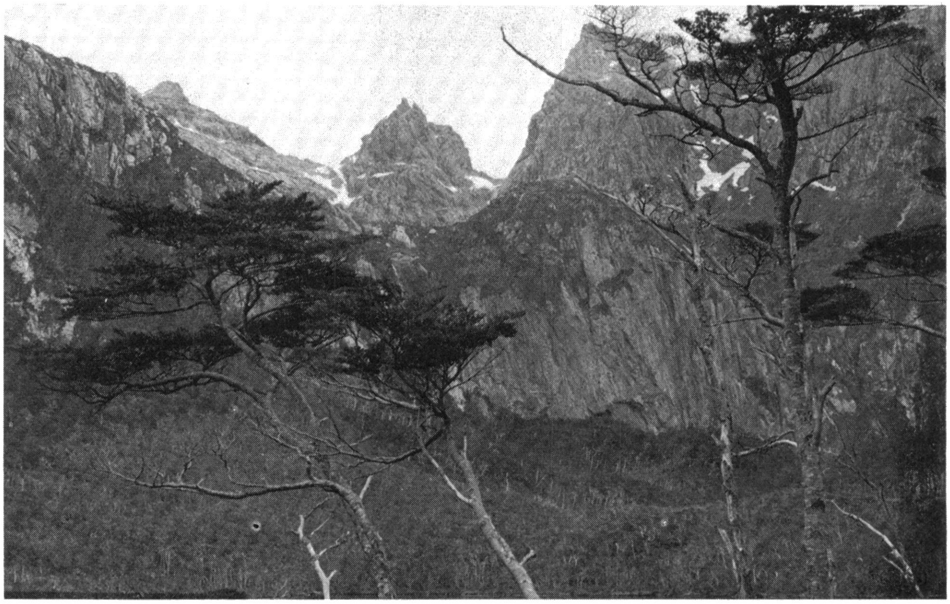

Figure 1. *Nothofagus betuloides-Drimys winteri* association. *N. betuloides* is in the foreground. Location: Puerto Celular.

Photos by author