South Sandwich Slices Reveal Much about Arc Structure, Geodynamics, and Composition

R. D. Larter, E. C. King, P. T. Leat, A. M. Reading, J. L. Smellie, and D. K. Smythe

The simple tectonic history of the South Sandwich island arc, a classic intra-oceanic arc lying in the South Atlantic Ocean, provided excellent opportunities for the Sandwich Lithospheric and Crustal Experiment (SLICE), conducted early in 1997, to investigate how, and at what rates, the Earth's crust is modified by subduction processes. The SLICE investigations of the South Sandwich island arc and the East Scotia Sea back-arc basin (Figure 1) included onshore and offshore recording of controlled-source and earthquake seismic data, establishment of geodetic GPS monuments on two islands, a new geological survey of the islands, and sampling of the islands and sea floor. Knowledge of the structure, geodynamics, and composition of this arc system is important because its simple tectonic history will allow estimation of the rates at which subduction processes modify the crust, and because its intra-oceanic setting makes it ideal for studying the timing and compositions of fluxes from the subducting slab.

Arc Tectonic History

At the South Sandwich Trench (Figure 1), the small Sandwich plate overrides the southernmost part of the South American plate at a rate of 70-85 mm/yr [*Pelayo and Wiens*, 1989]. Earthquake data indicate that the subducted slab dips at 45-55° to a depth of at least 175 km along most of its length and it is tearing beneath the northernmost part of the island arc [*Brett*, 1977]. West of the arc, at around 30°W, the Sandwich and Scotia plates are separating at the East Scotia Ridge (ESR) spreading center. The full spreading rate of the ESR, consisting of 10 main spreading segments (E1-E10, numbered from north to south), is 65-70 mm/yr [*Livermore et al.*, 1997]. Well-defined marine magnetic lineations show that this ridge system has been active since at least 10 Ma, and probably since 15 Ma, although spreading rates were much slower than the present rate until about 4 Ma [*Barker*, 1995].

Volcanoes of the South Sandwich island arc appear to be built on ocean floor which originally formed at the ESR. Previous rock collections from the South Sandwich Islands suggest a tholeiitic to calc-alkaline primitive island arc series; the oldest radiometric age from the islands is 3.1 Ma [*Baker et al.*, 1981]. Because the crust beneath the central part of the arc has an age of about 10 Ma, crust formed during the earliest phase of East Scotia Sea spreading now probably underlies the upper forearc. Construction of the present island arc on oceanic crust formed at the ESR has three important implications. First, the present crustal thickness and structure determined from SLICE seismic data will allow us to estimate rates of crustal thickening and modification by subduction processes over the past 10 Ma. Second, the arc must have migrated west relative to the Sandwich plate, which in turn implies either a decrease in dip of the subducted slab or removal of part of the lower forearc by subduction erosion. Preliminary displays of the SLICE seismic profiles already provide new evidence about tectonic processes in the forearc, and dating of

South Sandwich (cont. on page 284)

R. D. Larter, E. C. King, P. T. Leat, A. M. Reading, and J. L. Smellie, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, U.K.; D. K. Smythe, Department of Geology and Applied Geology, University of Glasgow, Glasgow G12 8QQ, U.K.

EOS, Transactions, American Geophysical Union, Vol. 79 no. 24, 1998 June 16.

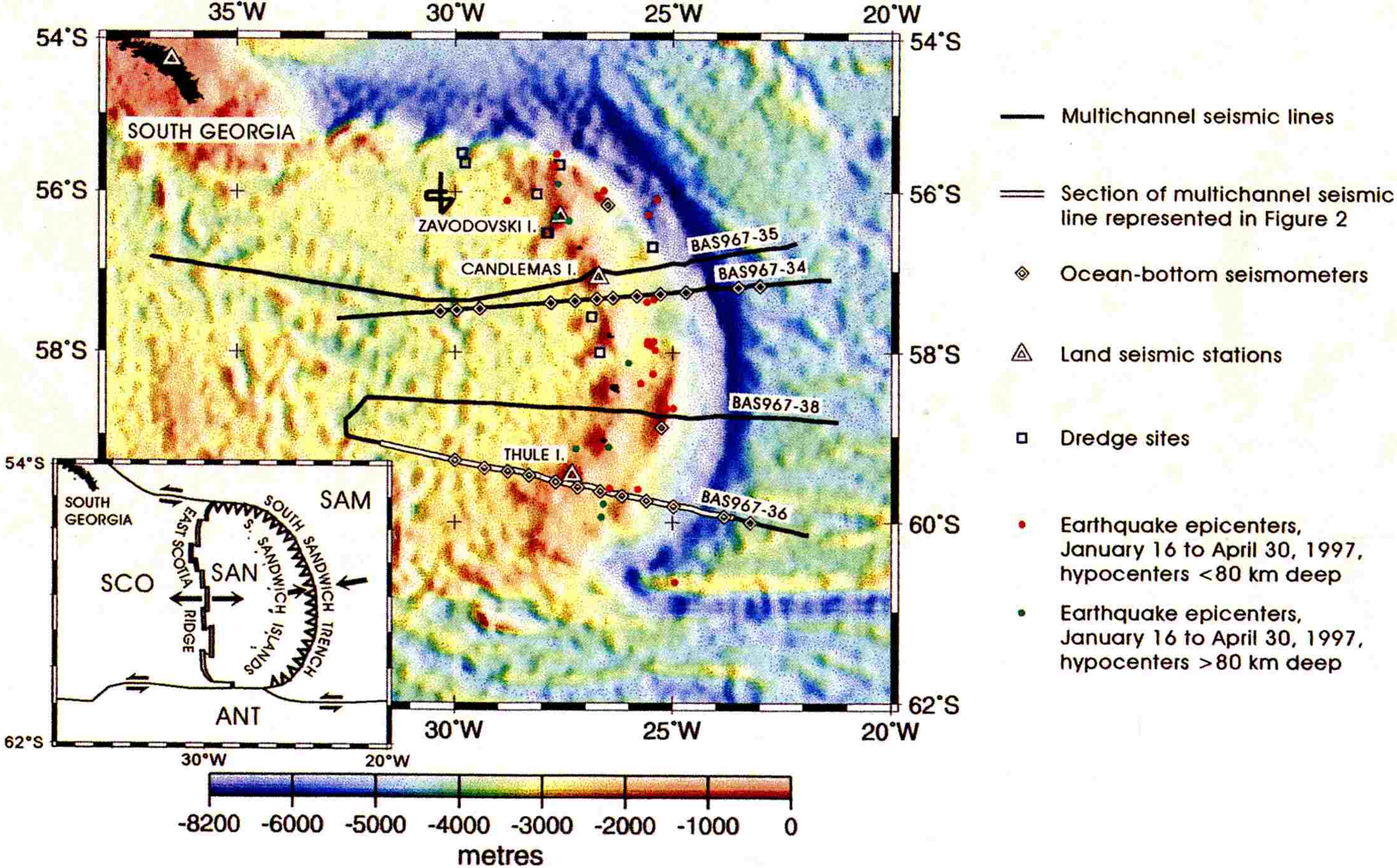

Fig. 1. Locations of SLICE multichannel seismic profiles, ocean-bottom seismometers, land seismic stations, and dredge sites. Preliminary determinations of epicenters for earthquakes shown, which occurred between January 16 and April 30, 1997, are from the USGS National Earthquake Information Center database. Seismic data from these earthquakes were recorded at SLICE land stations and by ocean-bottom seismometers. The color background shows the predicted bathymetry of Smith and Sandwell *[1994], displayed with shaded-relief illumination from the east. Inset shows tectonic setting; SAM, South American plate; SAN, Sandwich plate; SCO, Scotia plate; and ANT, Antarctic plate.*

South Sandwich (cont. from page 281)

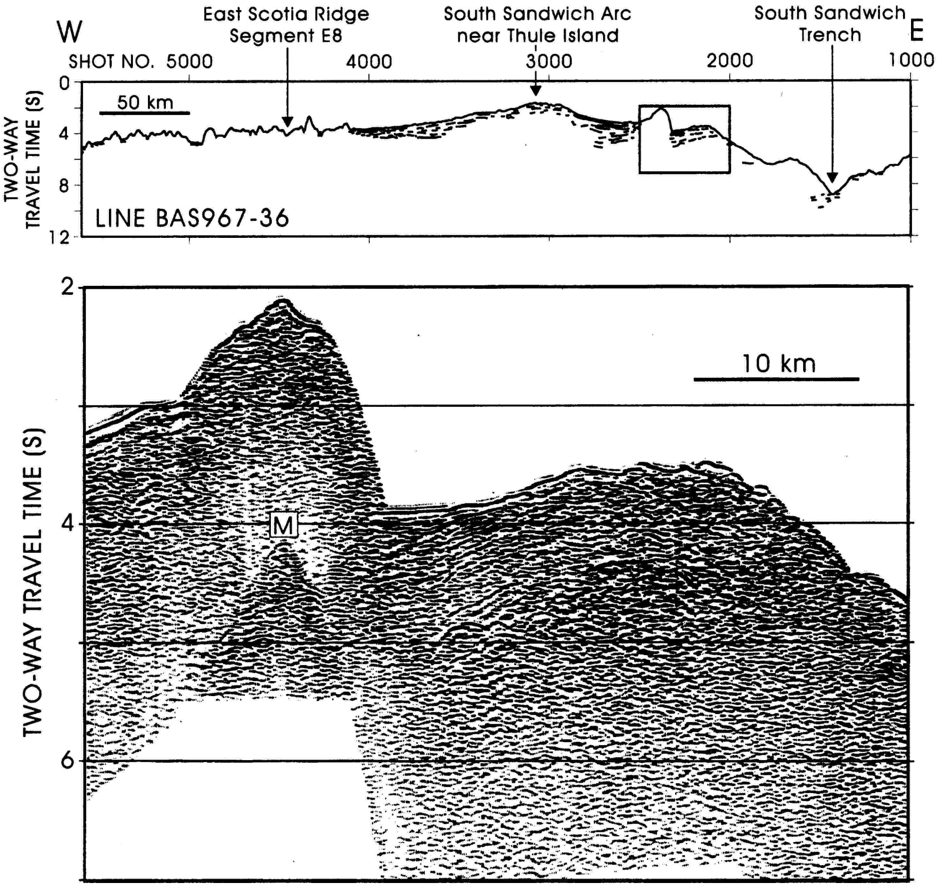

Fig. 2. Line drawing made from near-trace gather of a section of multichannel seismic line BAS967-36 (southernmost profile), and display of near-trace gather data from part of the section showing a large, rotated fault block in the forearc. Location of section shown in the line drawing is marked on Figure 1 and the location of near-trace gather data is boxed on the line drawing. Most of the first seafloor multiple reflection and data below it have been muted out, but one part of the multiple reflection (M) remains beneath the forearc high. Vertical exaggeration at the seafloor is approximately 10:1 on both the line drawing and the data display.

events in the forearc may be confirmed using dredge samples. Third, if the present island arc was built on young back-arc crust, its volcanic rocks cannot have been contaminated by assimilation of older arc or continental crust. The absence of such sources of contamination, which affect magma compositions in many other arcs, means that these volcanic rocks constitute a globally important system for investigation of timing and compositions of fluxes from the subducting slab.

The Antarctic, South American, and Scotia plates are all moving relatively slowly in the hotspot reference frame (< 20 mm/yr), which is widely regarded as approximating an absolute (or average mantle) frame of reference [*Gripp and Gordon*, 1990]. Therefore, the rapid relative motion of the Sandwich plate also implies that it is moving rapidly eastward in an absolute sense. This movement requires eastward retreat of the South Sandwich trench and roll-back of the hinge of subduction at a similar rate. Such rapid trench roll-back is one factor that prompted the hypothesis of eastward-directed mantle flow beneath the Scotia Sea [*Alvarez*, 1982; *Russo and Silver*, 1994]. *Livermore et al.* [1997] sug-

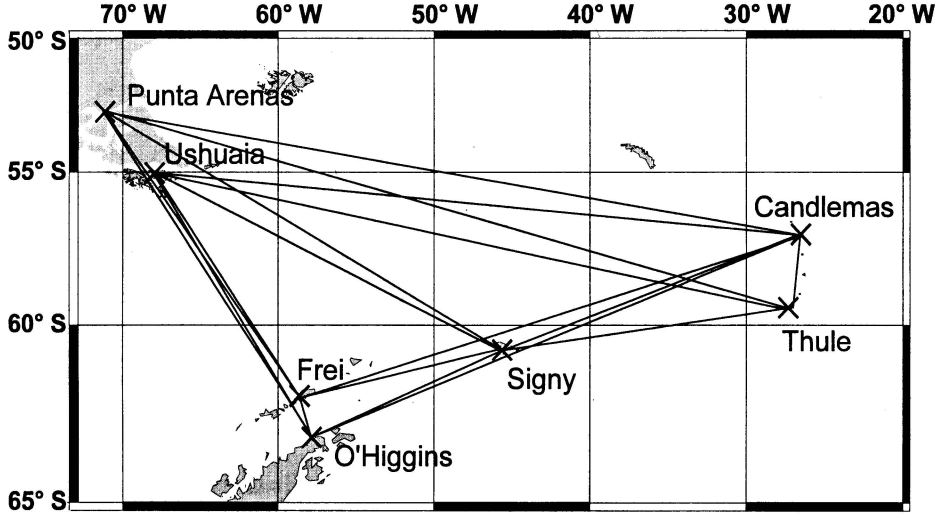

Fig. 3. Map of Scotia Sea region showing locations of SLICE and SCARP GPS stations and the web of baselines measured between them.

gested that roll-back may be generating westward-directed counter flow around the edges of the subducting slab, which can be monitored in the composition of ESR lavas. Observations of shear-wave splitting in teleseismic arrivals will enable seismologists to determine the local orientation of mantle flow beneath the broadband seismic stations (on South Georgia, Candlemas Island, and Thule Island). The modern motion vector of the Sandwich plate is an important parameter in relation to these mantle flow hypotheses because it provides a measure of the rate of slab roll-back. Because the Scotia Sea is completely enclosed by convergent and strike-slip plate boundaries, the only estimates of motion vectors for the Sandwich and Scotia plates relative to other plates are based solely on earthquake slip vectors [*Pelayo and Wiens*, 1989]. Future remeasurement of geodetic GPS monuments established on Candlemas Island and Thule Island during SLICE will directly determine modern Sandwich plate motion.

Arc Structure and Motion

Preliminary displays of SLICE multichannel seismic (MCS) reflection profiles show details of the shallow structure of this trench-arc-back-arc system (Figure 2). The profiles show a relatively steep lower forearc slope with no evidence of significant sediment accretion. Evidence of extensional faulting near the trench-slope break appears on all lines. The presence of tilted fault blocks up to 20 km wide (Figure 2) suggests that this extensional strain regime extends to a depth of many kilometers.

Several local earthquakes occurred during the intervals when a complete line of ocean-bottom seismometers (OBS) had been deployed for recording of wide-angle data from airgun shots. Seismic arrivals from five earthquakes, which occurred while the northern line of OBS was operating, and two earthquakes, which occurred while the southern line of OBS was operating, have been digitized. The body wave magnitudes of these events range between 4.2 and 5.4, and these data will aid in determining the broad distribution of seismic velocities in the upper mantle beneath the arc.

Geodetic GPS measurements were made over a period of several weeks on Candlemas Island and Thule Island. At the same time, teams from the Universities of Hawaii, Texas, and Memphis established long-term GPS stations in Patagonia and on the Antarctic Peninsula to investigate the geodynamics of the Scotia Arc (Project 'SCARP'). Processing of the combined data from the SLICE and SCARP GPS stations will establish the precise position of the South Sandwich Islands relative to South America and the Antarctic Peninsula (Figure 3).

Preliminary analysis of the GPS data and repeat analysis with different data processing software indicates that the precision of the calculated positions is within 20 mm. As existing estimates of Sandwich plate motion relative to the Antarctic and South American plates are about 60 mm/yr and 80 mm/yr respectively, repeated measurements are expected to yield accurate Sandwich-Antarctic and Sandwich-South America motion vectors within a few years. Scientists from the Alfred Wegener Institute for Polar and Marine Science (AWI) have recently carried out a remeasurement as part of their GAP98 GPS campaign.

Helicopter support from HMS *Endurance* enabled British Antarctic Survey (BAS) geologists to visit all of the islands in the archipelago to examine volcanic structures, collect rock samples, and collect fumarolic gas samples. Flights across the ice-covered summits of the islands revealed for the first time that most have small summit calderas. All of the islands were constructed by lava effusion and mildly explosive Strombolian eruptions. Tephra from hydrovolcanic eruptions is minor and there is little evidence for large-scale explosive eruptions connected to caldera collapse. Rock samples for geochemical analysis were collected from submarine parts of the arc, the forearc, and the E1 segment of the ESR by dredging from RRS *James Clark Ross* (Figure 1). HMS *Endurance* also completed the first detailed hydrographic survey of Douglas Strait, the channel separating Cook and Thule islands. The new survey revealed a well-defined circular depression about 5 km in diameter, with a near-flat floor extending to 600 m water depth (Figure 4). The feature is a caldera, and the fresh morphology suggests that it is one of the youngest features of the arc.

SLICE Data Collection

Several related studies were conducted in the 2 years preceding SLICE—swath bathymetry and sidescan sonar surveys covered most of the ESR [*Livermore et al.*, 1997] and part of the South Sandwich forearc, detailed sampling of lavas was carried out along segment E2 of the ESR, and a local seismic survey was conducted over segment E9 (RRS *James Clark Ross* cruises JR09A and JR12). SLICE required close coordination of cruises on the BAS vessel RRS *James Clark Ross* and the Royal Navy ice patrol vessel HMS *Endurance*. On RRS *James Clark Ross* cruise JR18, MCS reflection data were collected on four 600-900 km-long profiles across the trench, arc, and back-arc basin (Figure 1). In addition, three short MCS profiles, totalling 110 line-km, were collected over ESR segment E2, where previously collected 4-channel seismic data revealed a magma chamber reflector [*Livermore et al.*, 1997]. The seismic source for the long east-west MCS profiles was an array of 14 airguns with a total volume of 98 l (5976 cu. ins.). The streamer used had a total active length of 2400 m, consisting of 96 x 25 m hydrophone groups. 30 s of data from each shot were recorded directly to 8 mm magnetic tape cartridges using a modified DFS-V system from the University of Glasgow.

Wide-angle seismic data were collected along two of the profiles using OBS hired from the Geological Survey of Canada (GSC Atlantic) and operated by Geoforce Consultants Ltd. Of the 24 OBS deployed along the controlled-source seismic lines, 23 were successfully recovered and recorded useful data. The OBS data were recorded on analogue magnetic tape and have subsequently been digitized at the Department of Oceanography, Dalhousie University. Additional wide-angle seismic data were recorded at seismic stations established on Candlemas Island and Thule Island by geophysicists deployed from HMS *Endurance*. Data were collected at these land stations using 4.5 Hz geophones and Reftek data recorders. Temporary broadband seismic stations were set up on the same two islands for earthquake studies and operated for 6 weeks. A permanent broadband station on South Georgia (HOPE) became operational in December 1996, having been established through collaboration between BAS and the Incorporated Research

South Sandwich (cont. on next page)

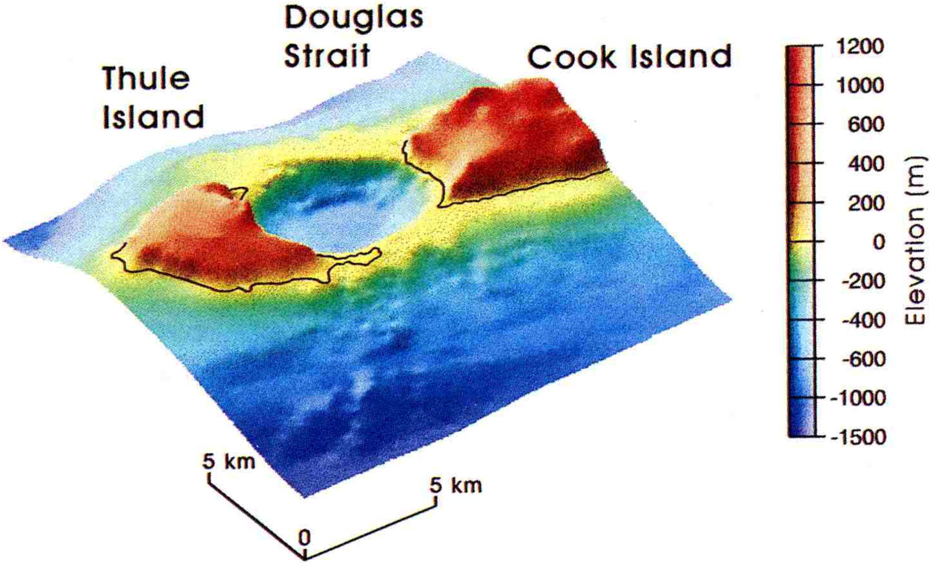

Fig. 4. Perspective view of a digital elevation model of Thule Island, Cook Island, and Douglas Strait, looking from the southwest and shaded-relief illumination from the north. The model incorporates new detailed hydrographic sounding data collected by HMS Endurance *during SLICE and reveals the caldera depression beneath Douglas Strait. Black lines indicate position of coastlines. Digital elevation model constructed by Peter Morris.*

Institutions for Seismology, project International Deployment of Accelerometers (IRIS/IDA). A temporary, automatic station using short-period seismometers set up on Zavodovski Island collected data for 7 weeks. Similar stations were left running on Candlemas and Thule islands when the field parties departed, and continued to collect data for another 8 weeks and 7 weeks, respectively. The Candlemas and Thule stations were recovered in December 1997 by scientists from AWI during cruise ANT XV/2 of R/V *Polarstern*. The local earthquake seismic network was completed by ocean-bottom seismometers deployed from RRS *James Clark Ross* at two locations in the forearc for a total of 4 weeks (two deployments of 2 weeks duration at each location).

SLICE Working Group

The following people participated in fieldwork and RRS *James Clark Ross* Cruise JR18 during the SLICE project: N. J. Bruguier, A. P. Cunningham, E. C. King, R. D. Larter, P. T. Leat, P. Morris, A. M. Reading, J. L. Smellie, L. E. Vanneste, D. C. Abensour, R. J. Iuliucci, R. Shipp, and D. K. Smythe.

Acknowledgements

The members of the SLICE Working Group greatly contributed to this article. We thank the officers, crew, and scientific support staff who participated in the cruises on RRS *James Clark Ross* and HMS *Endurance*. The geologists and geophysicists working on the South Sandwich Islands were assisted in the field by Ash Morton, Brian Newham, and Danuska Rycerz. Peter Bucktrout (photographer) and Peter Convey (biologist) also assisted with fieldwork. We also thank Marty Uyesugi of Geoforce Consultants, Ltd., for preparing the ocean-bottom seismometers, and Lt. Cdr. Derek Turner for coordinating the hydrographic surveys conducted by *HMS Endurance*.

References

Alvarez, W., Geological evidence for the geographical pattern of mantle return flow and the driving mechanism of plate tectonics, *J. Geophys. Res.*, *87*, 6697-6710, 1982.

Baker, P. E., South Sandwich Islands, in *Volcanoes of the Antarctic Plate and Southern Oceans, Antarct. Res. Ser.*, *48*, edited by W. E. LeMasurier and J. W. Thomson, pp. 361-395, American Geophysical Union, Washington, D. C., 1990.

Barker, P. F., Tectonic framework of the East Scotia Sea, in *Backarc Basins: Tectonics and Magmatism*, edited by B. Taylor, pp. 281-314, Plenum, New York, 1995.

Brett, C. P., Seismicity of the South Sandwich Islands region, *Geophys. J. R. Astron. Soc.*, *51*, 453-464, 1977.

Gripp, A. E., and R. G. Gordon, Current plate velocities relative to the hotspots incorporating the NUVEL-1 global plate motion model, *Geophys. Res. Lett.*, *17*, 1109-1112, 1990.

Livermore, R. A., A. P. Cunningham, L. E. Vanneste, and R. D. Larter, Subduction influence on magma supply at the East Scotia Ridge, *Earth Planet. Sci. Lett.*, *150*, 261-275, 1997.

Pelayo, A. R., and D. A. Wiens, Seismotectonics and relative plate motions in the Scotia Sea region, *J. Geophys. Res.*, *94*, 7293-7320, 1989.

Russo, R. M., and P. G. Silver, Trench-parallel flow beneath the Nazca plate from seismic anisotropy, *Science*, *263*, 1105-1111, 1994.