5 Submarine morphology and seismic stratigraphy of Port Foster

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Since the early 1980s there have been numerous geophysical investigations of Port Foster, Deception Island (e.g. Kowalewski and others, 1990; Rey and others, 1990, 1992, 1994, 1995, 1996; Grad and others, 1992; Somoza and others, 1994). In this chapter, we focus principally on the results of several mainly Spanish geophysical investigations since 1986. Port Foster was examined by continuous seismic reflection profiling (using Sparker, Geopulse and 3.5 kHz sub-bottom Profiler) and rock dredge hauls during Antarctic cruises Exantarte 87-88, 88-89, 89-90 and 90-91 (Fig. 5.1). Track-line positions were fixed by GPS, with sub-metre resolution. The bathymetry and submarine morphology of Port Foster were determined during several B/O *Hesperides* cruises, mainly by multibeam echo sounder and parametric narrow-beam sub-bottom profile echo sounder TOPAS (Topographic Parametric Sound).

Tectonic setting

Deception Island is the only active volcano known in the Antarctic Peninsula region, with eruptions in 1967, 1969 and 1970. The island is situated at the confluence of two major tectonic structures: the south-western end of Bransfield trough (a marine deep in Bransfield Strait with nascent spreading centre caused by NW–SE extension) and a postulated southerly extrapolation of the Hero Fracture Zone (a former transform fault; Fig. 5.2). Bransfield trough is also crosscut by NW–SE-trending fractures that divide the structure into segments (Grad and others, 1992). The relatively high seismicity and historical eruptive activity on Deception Island probably reflect a continuous release of seismic energy through a regionally extensive NE–SW-trending fracture system associated with the Bransfield Strait rift system (Martí and others, 1990).

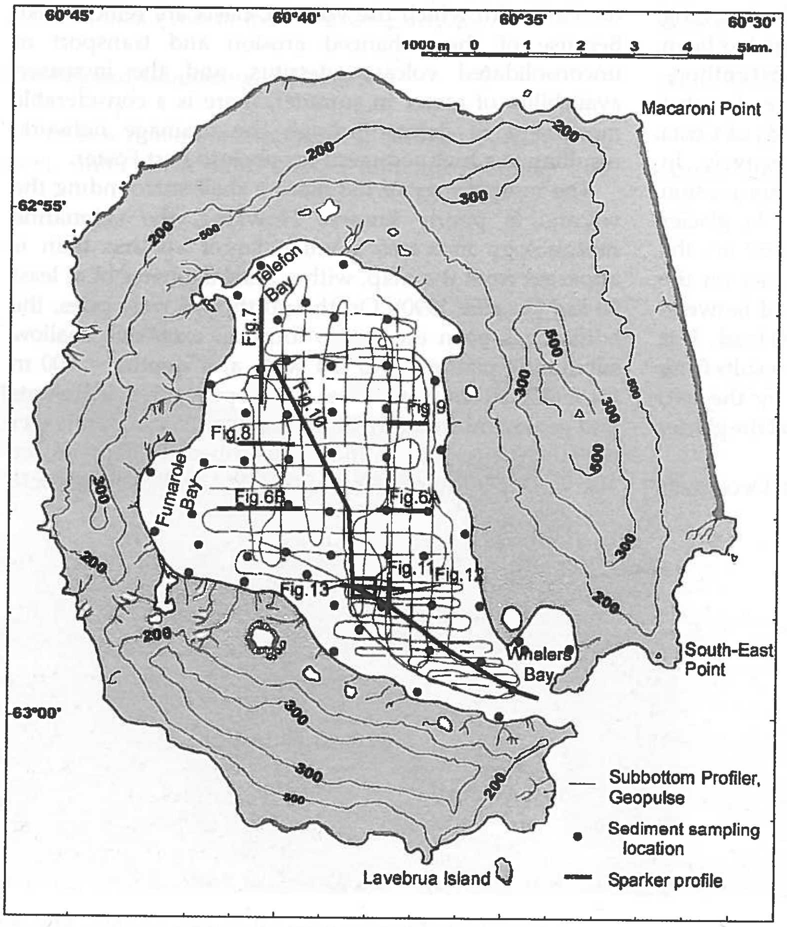

Fig. 5.1. Map showing the positions of seismic track lines (sub-bottom Profiler 3.5 kHz, Geopulse 300 J and Sparker 4 500 J) and sediment sampling grid in Port Foster.

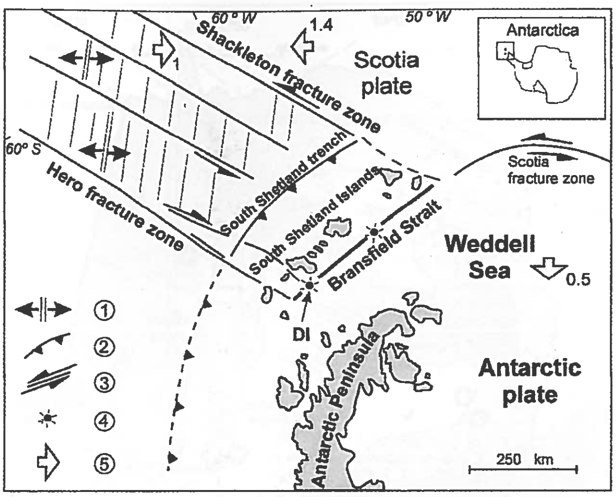

Fig. 5.2. Sketch map showing a simplified regional tectonic framework for Deception Island (after Rey and others, 1995). 1, ocean spreading centre; 2, subduction zone (dashed where inactive); 3, oceanic fracture zone; 4, volcano; 5, plate motion vector (cm/yr; Minster and Jordan, 1978); DI, Deception Island.

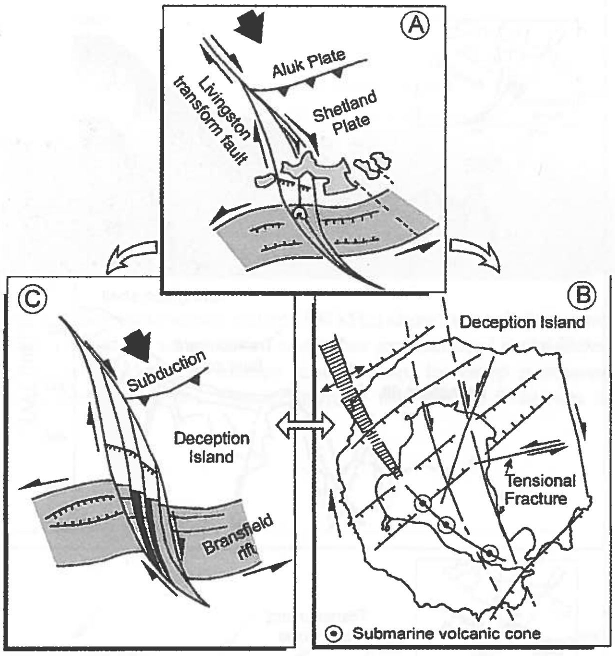

Fig. 5.3. Cartoons illustrating a geodynamic model used to explain recent seismic activity in western Bransfield Strait and fracturing on Deception Island. The 'Livingston transform fault' is a splayed offshoot of the Hero Fracture Zone (Fig. 5.2; after Rey and others, 1996).

Traditionally, the flooded caldera of Deception Island (Port Foster) is thought to be a consequence of a volcano-tectonic catastrophic collapse of the volcanic edifice along arcuate and radial faults (Holtedahl, 1929; Olsacher, 1956; Hawkes, 1961; Casertano, 1963; Baker and others, 1975; Birkenmajer, 1992; Smellie, 2001*b*). However, seismic and other geophysical studies have demonstrated NE–SW linear trends seemingly at odds with a simple volcano-tectonic model of caldera subsidence, in which arcuate patterns should be expected (Ortíz and others, 1992). Since the discovery that the influence of regional fracture systems can also be recognized on the island (Smellie, 1988), an alternative model for caldera formation has arisen involving passive collapse of the volcano superstructure along intersecting orthogonal fault systems induced solely by regional tectonics (Martí and others, 1996). Both models depend on differing interpretations of the geological history of the island: Martí and others (1996) denied the existence of a major caldera-forming eruptive event, whereas Smellie (2001*b*) ascribed such an origin to the Outer Coast Tuff Formation, a thick, island-wide stratigraphical unit formed entirely of pyroclastic current deposits (see Chapter 3).

The fracture systems and distribution of historical eruptions on Deception Island, and recent evidence for fault-related hydrothermal activity in the sedimentary sequences in Port Foster, can probably be related to regional tectonic effects associated with the situation of the volcano at the intersection between the Bransfield Strait rift and the transcurrent Hero Fault Zone (Fig. 5.3). The central part of Bransfield Strait corresponds to a zone of transtension, melt migration and crustal separation with clearly identified extensional faults (Ashcroft, 1972; Baker and McReath, 1971; Grad and others, 1992; Barker and Austin, 1998). Conversely, a zone of transpression with compressional structures exists outboard of the island, on the continental shelf of Livingston Island. Both sets of structures can be reconciled within a model of right-lateral strike-slip movement caused by south-easterly translation of the Aluk plate in Drake Passage relative to a stationary Antarctic plate (e.g. Pelayo and Wiens, 1989; González-Casado and others, 2000). Deception Island is situated within an extensional zone related to the transcurrent movement (right-lateral simple shear). The direction of maximum extension is approximately NNW–SSE, orthogonal to the direction of transcurrent movement. Within this conceptual framework, the distribution of the recent eruptive centres on the island, and hydrothermal centres within Port Foster, can be related to a system of NNW–SSE splay faults that are also hypothesised to cross Livingston Island. Although their positions on Livingston Island are unknown, fractures consistent with the hypothesis have been identified on seismic sections on the shelf area to the south of that island (Fig. 5.4), and secondary tensional structures may also have been responsible for guiding the emplacement of submarine cones and intrusive domes within south-eastern Port Foster (see below).

Fracture systems

Several submarine fracture systems have been identified seismically within Port Foster, although none shows on the present featureless basin floor (Fig. 5.5; Rey and others, 1990). Both these and lineaments postulated from satellite imagery on the island itself (e.g. Martí and others, 1996) form an important orthogonal system with NNW–SSE (160–170N) and NE–SW (045N–060N) trends similar to regional tectonic structures (Ortíz and others, 1990; Rey and others, 1995; Fig. 5.5). These structures are probably responsible for the linear shapes of parts of the outer coast of the island (most obvious between Baily Head and Macaroni Point; see Fig. 3.23) and, probably, for several of

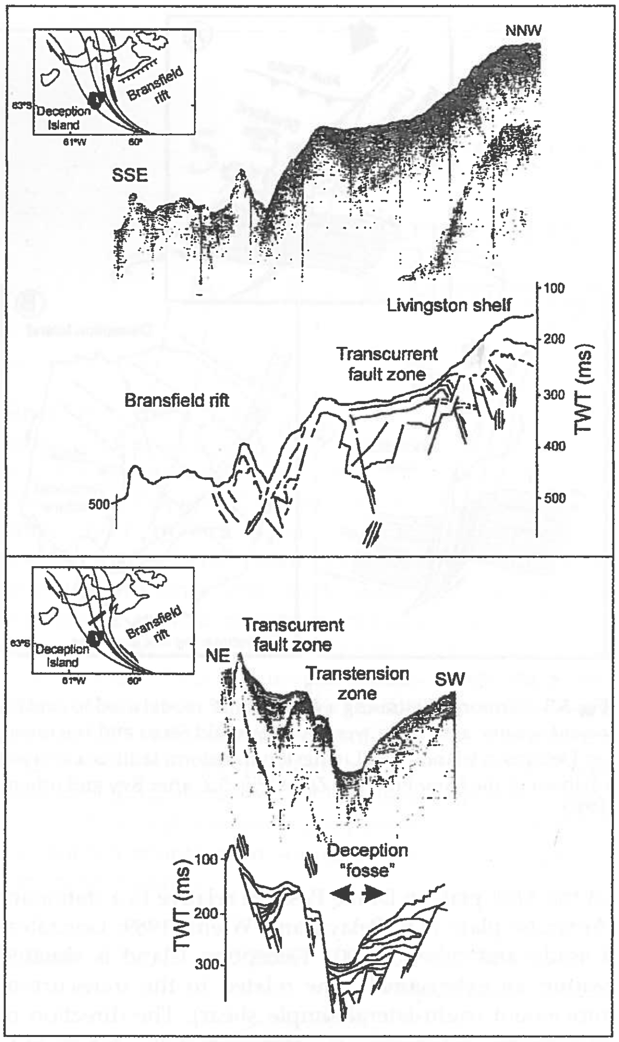

Fig. 5.4. Seismic profiles (Sparker 4 500 J) obtained on the shallow shelf platform north and east of Deception Island, and their schematic interpretation within a conceptual dextral strike-slip zone between Deception and Livingston islands (*cf.* Fig. 5.3; after Rey and others, 1996).

the linear crater chains on the island. Several strong negative magnetic anomalies identified also have NNW-trending orientations and have been related to fractures with those orientations (Ortíz and others, 1992). Finally, a subordinate system of fractures strikes 115–120N in the southern part of the island, around Mount Kirkwood, and was probably responsible for fixing the location of the linear crater chains that erupted there in 1839–1842 (Rey and others, 1995).

Mapping of submarine fault systems from a dense network of seismic profiles (Rey and others, 1990) has verified the existence of a major zone of faults trending 060N across the interior of the bay. Those faults are associated with several graben-like structures. Whilst not extending to the sea floor, they are associated with the deepest parts of Port Foster. Persistent, long-lived fumarolic activity at Pendulum Cove, Fumarole Bay and possibly shoreward of the 1967 land centre appear to be related to this north-easterly-trending system of fractures (Ortíz and others, 1987). The 160–170N-trending fracture system is poorly defined on the marine seismic profiles,

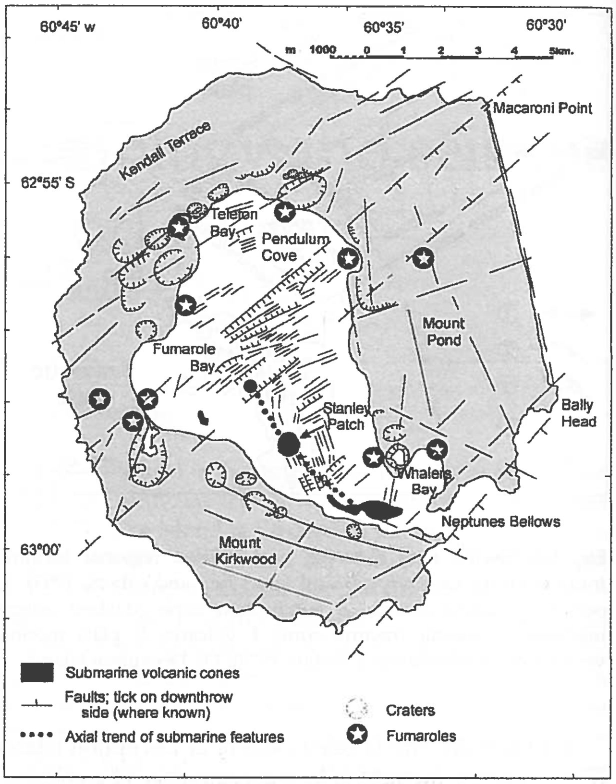

Fig. 5.5. Sketch map showing systems of fractures, volcanic cones and fumarolic areas on Deception Island and in Port Foster (modified after Rey and others, 1997). Most of the subaerial fractures indicated are inferred from morphological evidence and presence of lines of craters.

and has only been identified in the south-easterly sub-basin in Port Foster. Two of the submarine pyroclastic cones in Port Foster (including Stanley Patch) and an elongate, high-level dome-like intrusion between Stanley Patch and Neptunes Bellows have a 150N alignment and may also be structurally controlled.

Submarine morphology of Port Foster

Port Foster has formed in a flooded central caldera depression. It is an elongate lagoon 6 x 10 km in diameter connected to the open sea through a narrow passageway named Neptunes Bellows. It is also a magnificent natural harbour that was used extensively during the early whaling period (see Chapter 1), particularly at Whalers Bay.

Port Foster contains at least two sub-basins (Rey and others, 1992; Cooper and others, 1998): a large and deep northerly sub-basin, and a much shallower southerly sub-basin that extends into Whalers Bay. The northern (largest) sub-basin is almost flat-bottomed, approximately circular and crater-like, with steep rough flanks. It is surrounded by a continuous shelf that is about 500 m wide and extends to 60 m depth, at which point it plunges to about 120 m with gradients of 11 to 22.5%, then gently deepens to 166 m centrally. The eastern and western slopes of the northern sub-basin are steeper and higher than elsewhere. The most extensive shallow flanking shelf of the northern sub-basin is beneath Fumarole Bay, which slopes gently to a break of slope at about 120 m. The flat bottom of the basin is broken

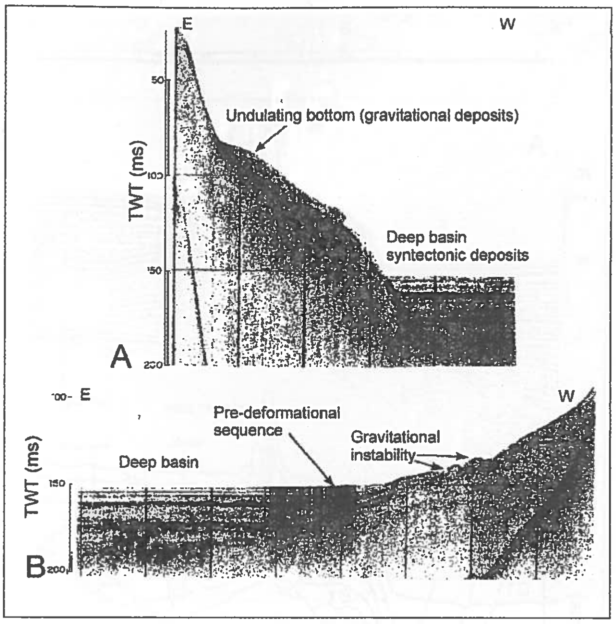

Fig. 5.6. Examples of two sub-bottom Profiler 3.5 kHz seismic profiles obtained within Port Foster, showing undulating slope (A)- and slope bottom (B)- topographies caused by active gravitational slides and slumps. The locations of the seismic sections are indicated in Fig. 5.1 (after Rey and others, 1992).

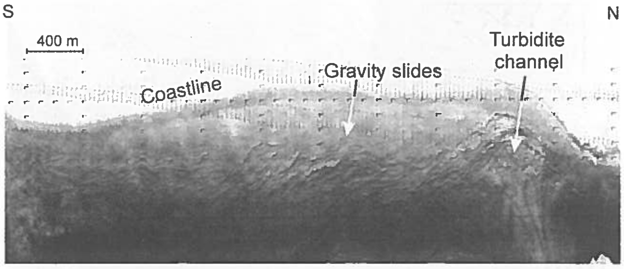

Fig. 5.7. Side-scan sonar record (100 kHz) showing undulating sea floor caused by active slides and other gravitational instabilities. A, gravity slides and slumps scars formed by creep processes; B, turbidite channel. The location of the section is shown in Fig. 5.1.

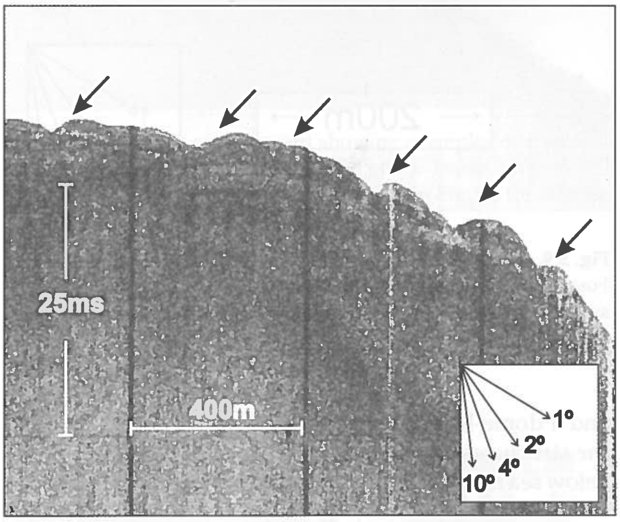

Fig. 5.8. Sub-bottom Profiler 3.5 kHz seismic profile obtained within Port Foster, showing slump scars (arrowed) formed by slow creep movement, probably aided by hydrothermal softening of the underlying volcaniclastic layers. The location of the section is shown in Fig. 5.1.

only by a single small pyroclastic cone or dome at its southern margin; a second small cone structure is also present on the south side of the broad Fumarole Bay shelf (Fig. 5.5). By contrast, the floor of the southern sub-basin has an uneven bottom morphology, with a depth generally < 110 m. It extends from Stanley Patch (a submarine pyroclastic cone) to Whalers Bay.

Submarine morphological features in Port Foster can be grouped genetically, as follows (modified mainly after Rey and others, 1992; see BAS GEOMAP Sheet 6-B, back pocket).

Features associated with tectonic instability: The asymmetrical geometry of Port Foster is probably due to neotectonic processes. Seismic studies have identified an ENE-verging monoclinal structure with a major NNW–SSE-trending axis located on the south-west side, which has lowered the caldera floor on its north-east side (Rey and others, 1990; Cooper and others, 1998; see Fig. 3.24). Thus, Port Foster can be considered as a half graben with an active western margin where the slope is rougher and slump scars and undulating bottom topography are common and formed because of slope instability. The north-western slopes are steeper and higher and show fewer features due to slope instability (Figs 5.6 and 5.7). Characteristic submarine morphologies include the following:

a) Undulations on the sea floor are confined to the marginal slope areas (Figs 5.6 and 5.7). The features appear to line up parallel to the main fracture directions and their abundance suggests that they have probably formed repeatedly because of tectonic instability.

b) Slump scars probably formed by gravitational sliding are mainly located on the south-western slopes of the basin, 2.5 and 3 km south-east and north-west of Stanley Patch (Rey and others, 2000; Fig. 5.8). The slump scar lengths vary between 4 and 300 m, although they can extend up to 500 m parallel to the coast (Figs 5.6 and 5.7). They have a low relief (2–10 m) and were probably formed during multiple slumping phases. It is possible to define three sub-types of slump-related structures formed by mass movement: (1) gravity slides (slumps) that reached the base of slope (Fig. 5.6), (2) slump scars formed by slow creep movements (Figs 5.7 and 5.8), and (3) rotational slides that show a slump-scar back-wall similar to subaerial analogues (Fig. 5.9).

c) Depositional lobes are sedimentary deposits generated by turbiditic progradational processes (Fig. 5.6). They occur on the basin floor and are rooted at the topographical break where the basin slopes give way to the flat basin floor.

Features associated with volcanism: Each of the submarine volcanic cones is characterized by relatively steep slopes

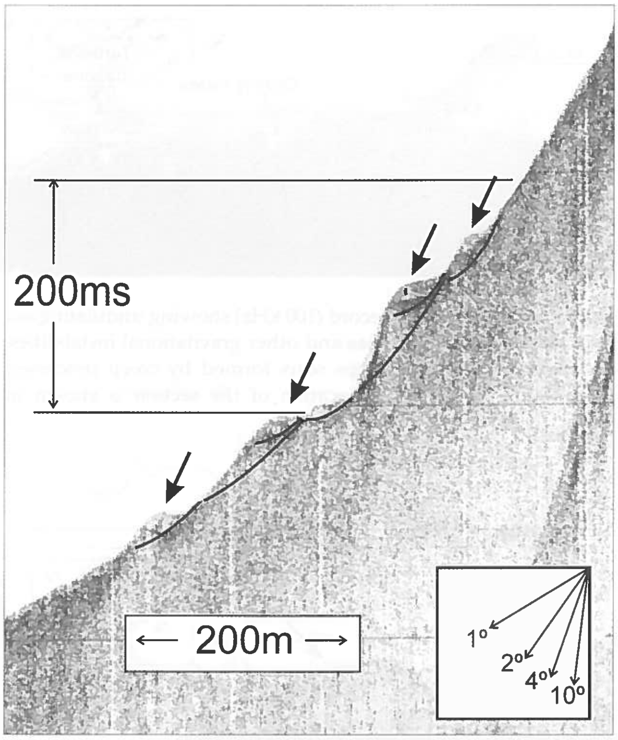

Fig. 5.9. Sub-bottom Profiler 3.5 kHz profile obtained within Port Foster, showing rotational slides with slump-scar back-walls similar to analogous subaerial structures. The location of the section is shown in Fig. 5.1.

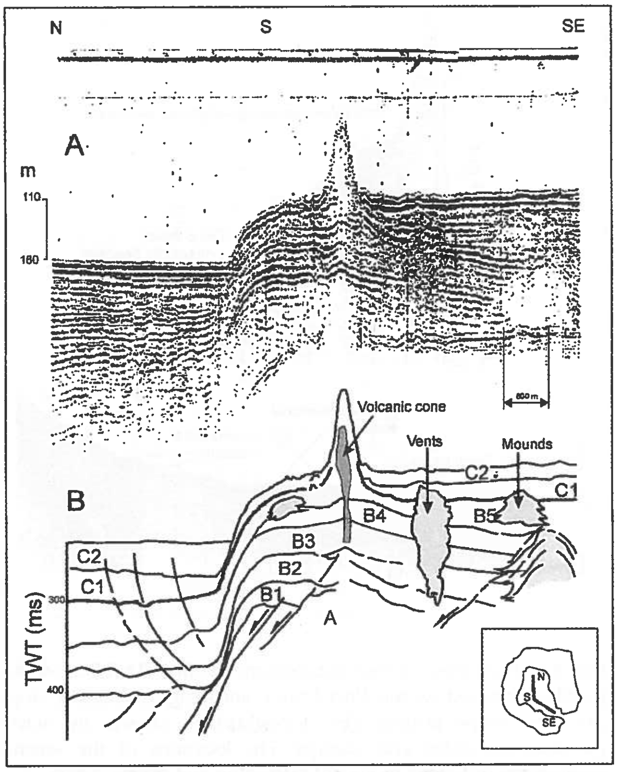

Fig. 5.10. Composite seismic reflection profile (Sparker) (A) and its interpretation (B) obtained across Port Foster, showing the seismo-acoustic depositional units described in the text (A, B and C) and associated volcanic and hydrothermal structures (after Rey and others, 1995). Inset shows the location of the profile (see Fig. 5.1).

and a dome-like or cone morphology. In vertical section, the structures extend continuously to at least 50 m depth below sea floor, and they cut across and deform the deeper sedimentary sequences (Fig. 5.10). They are situated mainly in the southern part of Port Foster and together they have an arcuate NNW–SSE alignment. The largest cone (Stanley Patch) rises more than 50 m from the sea floor and it has a small summit depression about 100 m across (likely crater; Figs 5.11 and 5.12).

Features associated with changes in eustasy:

a) Progradation wedges are particularly prominent on the eastern and south-western sides of the basin margin, usually at depths of about 120 m. They are sedimentary units and seismic imaging shows the broad outcrops to have an internal prograding sigmoid geometry strongly resembling till deltas (Fig. 5.13; *cf.* Alley and others, 1989). The till deltas on Deception Island are related to episodes of glacier growth and stagnation during low sea level stages (e.g. King and Fader, 1986).

b) Linear runnels, grooves and channels have U-shaped sections and are incised into the basin slopes, particularly the lower slopes on the eastern side of the basin (Fig. 5.12). They are typically orientated roughly perpendicular to the coastline and they resemble glacial marks made by moving ice (Belderson and others, 1972). They are associated with the progradation wedges, and are frequently located in the topset areas of till deltas.

Features associated with deep-water hydrodynamic processes: These are current-generated structures, including sand waves (ripples) and small sandbars, that occur along channel margins close to Neptunes Bellows.

Sediment distribution in Port Foster

Using dredge samples and sidescan sonar imagery of the basin floor, the distribution of sediment types within Port Foster has been mapped by Rey and others (1990, 1992; see BAS GEOMAP Sheet 6-B, back pocket). Sediment mean grain size variations are related to the proximity of the coastline and water depth. Proximal sediments (water depths < 50–70 m) consist of volcaniclastic (mainly pyroclastic?) gravels and morainic deposits, whereas deeper-water regions are dominated by sands and muds. The sediment grains were probably formed by a variety of processes: pyroclastic, glacial, periglacial, nival, aeolian and marine (Rey and others, 1990, 1992). The pattern of water circulation in Port Foster is not well-known, but there are signs that bottom currents locally influenced the distribution of sand and mud and sediment bedforms in shallow-water areas. For example, at Neptune Bellows current velocities associated with tides are enhanced because of confinement by the narrow channel, and ripple marks are developed along the channel margins (Rey and others, 1990).

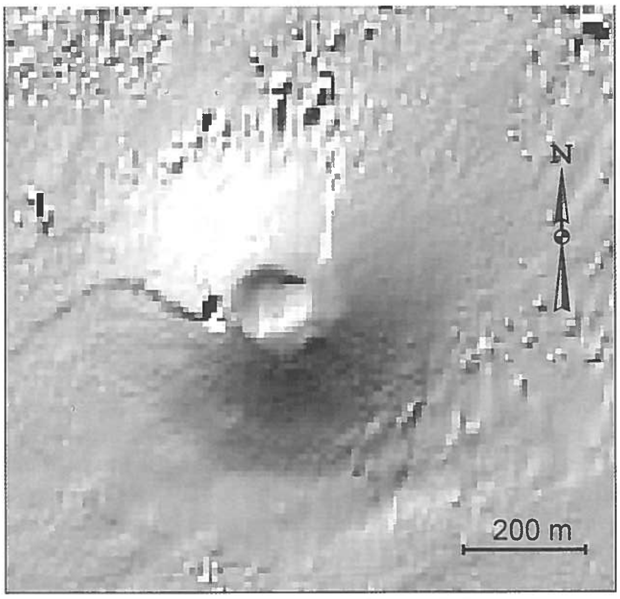

Fig. 5.11. Multibeam sea-floor relief image of Stanley Patch, first identified as a volcanic edifice in 1987 (British Antarctic Survey, 1987); see Fig. 5.1 for location.

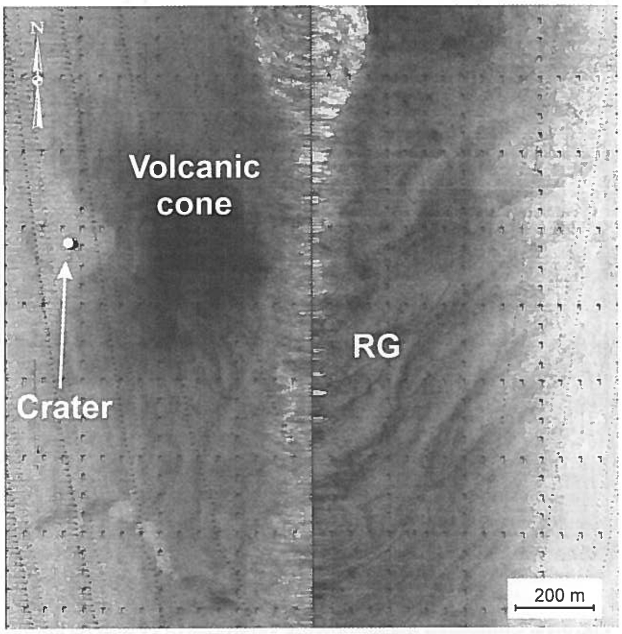

Fig. 5.12. Side-scan sonar record showing examples of a volcanic cone with summit crater (Stanley Patch), linear runnels and grooves (RG) (after Rey and others, 1992); see Fig. 5.1 for location.

Sediment thicknesses reach at least 80 m on the western side of Port Foster. If they are << 10 000 years in age (Smellie, 2001*b*; and see Chapter 7), a high sediment accumulation rate is implied (*c.* 1 cm a^{-1}). The high rates can be explained by the enclosed nature of the sedimentary basin, a provenance dominated by easily eroded unconsolidated pyroclastic material, enhanced sediment transport during annual spring thaw periods and episodes of glacier melting associated with eruptions, and glacial activity.

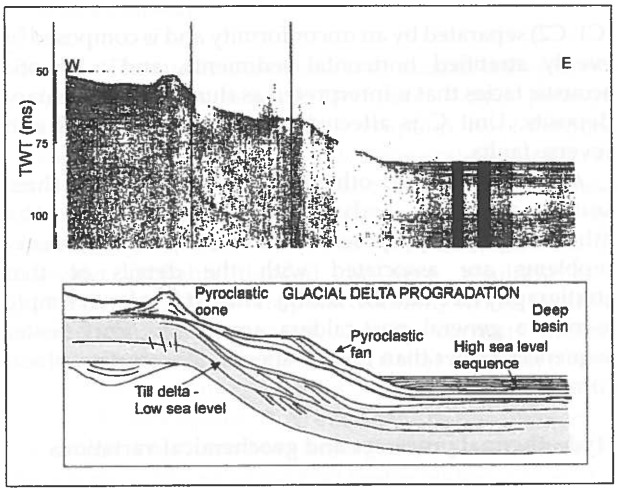

Fig. 5.13. Geopulse seismic profile obtained in southern Port Foster, showing possible till delta sequence formed at lower sea level than present, and later deeper-water deposits associated with higher sea level (after Rey and others, 1992); see Fig. 5.1 for location.

Seismo-acoustic stratigraphy of Port Foster

Seismic reflection profiles obtained in Port Foster show several well-defined seismo-acoustic sequences, high-level magmatic intrusions, stratigraphically confined hydrothermal mounds and fault offsets. The positions of the magmatic intrusions are apparently related to extensional fractures that affect the sedimentary deposits. Three seismo-acoustic sedimentary units are identified, each separated by tectonically enhanced unconformities. Each unconformity is interpreted in terms of deformation events that disturbed the geometry of the sedimentary materials (Fig. 5.10).

The basal unit (A) is acoustically transparent and is correlated with the precaldera lithofacies mapped on the island, including the extensive and thick Outer Coast Tuff Formation (syn-caldera; Smellie, 2001*b*). The intermediate unit (B) consists of several sub-units (B1-B5), each separated by unconformities and apparently formed synchronously with several significant volcanic and tectonic events (see Chapter 3). The sub-units contain three types of distinctive structures: mounds, cones and irregular, sub-vertical, acoustically diffuse structures (Fig. 5.10). The mound-like structures are situated at the bases of unconformities between sub-units B3 and B5; they are intercalated with the adjacent successions of evenly stratified sediments. The cones crop out on the present sea-floor and form prominent symmetrical edifices that rise up to 50 m, the largest being Stanley Patch. The third type of structure has irregular steep margins and is acoustically diffuse, in which internal sediment stratification can be faintly discerned and is locally deformed. These structures are interpreted to have been superimposed on the sediment succession by upward fluid transport. They locally extend up into the base of the uppermost acoustically defined unit (C). Unit C occupies a broad trough-like structure formed by deformation of the underlying units A and B by the large-scale monoclinal structure described above. It is divided into two sub-units

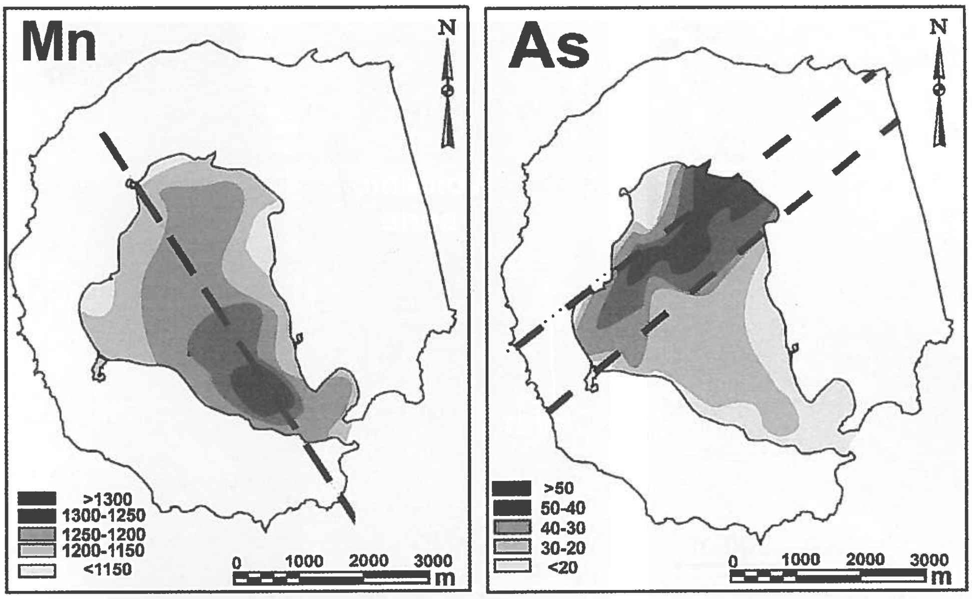

Fig. 5.14. Contoured maps showing variations of Fe and As abundances (in ppm) in dredge samples from Port Foster; the dredge sites are shown in Fig. 5.1. Note that the highest contents in Mn also coincide with the positions and NW–SE alignment of submarine volcanic cones and domes shown in Fig. 5.10; the highest contents in As reflect a NE–SW alignment comparable with the fracture system thought to be responsible for many of the long-lived fumaroles and hot springs on the island (after Rey and others, 1997).

(C1, C2) separated by an unconformity and is composed of evenly stratified horizontal sediments, and a chaotic acoustic facies that is interpreted as slumped sedimentary deposits. Unit C is affected by numerous normal and reverse faults.

Although Rey and others (1997) correlated the three seismo-acoustic sedimentary units with the lithostratigraphy proposed by Birkenmajer (1992), many problems are associated with the details of that stratigraphy (see Smellie, 2001*b*). Thus, it is safer to simply ascribe a general post-caldera age to the Port Foster sequences rather than pursue specific lithostratigraphical correlations.

Hydrothermal processes and geochemical variations

Hydrothermal activity, such as fumaroles and hot springs, is apparently associated mainly with a system of NE–SW fractures in several areas (e.g. Fumarole Bay, Pendulum Cove, former Telefon Bay and possibly Whalers Bay; Ortíz and others, 1987, 1992; Ramos and others, 1989). Those authors proposed that hydrothermal fluids are produced by venting of shallow aquifers heated convectively (to *c.* 200°C) by gases released from an underlying magma chamber.

On the basis of geochemical studies of dredge samples obtained in Port Foster, a recent mineralization system has been described, which shows significant geographical variations in element distribution patterns (Rey and others, 1995, 1997). Although the contents of these elements in the sediment samples analysed are apparently high (e.g. Fe_2O_3: 10.75%, Mn: 1361 ppm), the abundances are within the range shown by unaltered Deception Island magmas (Appendix 4). However, there are distinct NNW–SSE and NE–SW asymmetrical element-specific distribution patterns of enrichment 'anomalies', which may reflect a structural control on the positions of the fluid emissions:

1) Fe, Mn, Na and K abundances progressively decrease from Neptunes Bellows north-west into Port Foster (essentially coincident with the positions of several submarine cones and domes; Fig. 5.5), and
2) abundances of As, Al, Ca, Mg and K are greatest in a well defined SW–NE-trending zone above the northern sub-basin (Fig. 5.14).

Rey and others (1997) suggested that the formation of the two zones of contrasting element enrichments may be time controlled, but there is currently no way of dating reliably the mineralization of Port Foster sediments.