Antarctic Science 10 (4): 455–461 (1998)

Evidence for shallowing and uplift from bathymetric records of Deception Island, Antarctica

A.P.R. COOPER[1], J.L. SMELLIE[1] and J. MAYLIN[1,2]

[1]British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK
[2]Present address: 12 Lilac Close, Chapel Park, Newcastle upon Tyne, NE5 1UU, UK

Abstract: Deception Island is a large volcanic centre in Bransfield Strait, a very young marginal basin between the South Shetland Islands and Antarctic Peninsula. It has a historical record of volcanic activity, with the most recent eruption occurring in 1970. The island is a stratovolcano with a large flooded caldera forming a natural harbour known as Port Foster. It has been a focus of human activity since early last century, as a base for whaling and sealing expeditions and the locus of several scientific stations. During that period, many bathymetric surveys were carried out, the earliest in 1829 and the most recent in 1993. This study concentrates on surveys from 1948 onwards. Because Port Foster can be classified as a restless caldera, the bathymetric records were analysed for evidence of volcano-tectonic deformation, particularly caldera resurgence (uplift) which could have significant consequences for hazard and risk assessments of the volcano. The results show that a distinctive pattern of shallowing and uplift is present, correlating well with known and inferred volcanic and volcano-tectonic processes on the island. In particular, bathymetric records between 1949 and 1993 show uplift rates as high as 0.3–0.5 m a^{-1}, far exceeding normal sedimentation rates in a caldera this size. Rapid uplift in an arcuate offshore area not affected by the sedimentation of recent eruptions suggests that volcano tectonic resurgence or tectono-magmatic effects of an upward migrating magma chamber present a significant risk to the considerable human activity taking place in the region.

Received 25 February 1998, accepted 13 June 1998

Key words: Antarctica, bathymetry, caldera, Deception Island, deformation

Introduction

Deception Island is a large volcano with a submerged basal diameter of *c.* 30 km (Smellie 1990). It is situated at the south-western end of Bransfield Strait, a young (< 1.4 Ma) ensialic marginal basin that separates the South Shetland Islands from the Antarctic Peninsula (Fig. 1). The exposed portion of the volcano probably formed entirely within the present magnetic chron (< 700 ka, Blundell 1962, Valencio *et al.* 1979) and K–Ar dating suggests that it is < 200 ka old (Keller *et al.* 1991). The present edifice represents about 80% of the volume of the volcano (cf. Smellie 1988, 1989). It the result of a period of predominantly submarine activity culminating in an undated, large-scale paroxysmal eruption that generated widespread pyroclastic flows (Smellie *et al.* 1997). The eruption was followed by caldera collapse along a crude annular ring fracture formed by intersecting fractures induced by regional tectonics (Smellie 1988, 1989, Martí & Baraldo 1990, Martí *et al.* 1996). Port Foster probably formed very soon after caldera collapse, by marine inundation of the caldera depression. All post-caldera eruptions have been small in volume. They range from lava effusion to Strombolian, Surtseyan and maar-type eruptions, and are largely confined to a marginal zone in the caldera within 3 km of the ring fracture (Baker *et al.* 1975, Smellie 1988, 1989, Smellie *et al.* 1997). The volcano may have been particularly active during most of the nineteenth and earliest twentieth centuries, when eruptions probably occurred during most decades (Orheim 1972). Well-documented eruptions also took place in 1967, 1969 and 1970 (Baker *et al.* 1975).

The creation of a large natural harbour within the caldera at Deception Island has made it a natural focus of human activity in the South Shetland Islands since early in the nineteenth century. Besides scientific expeditions, the island was visited by a succession of sealing and whaling vessels, culminating in the establishment of a Norwegian whaling station (1912–31) and several scientific stations (1944 to present). The history of human exploration, exploitation and habitation is the longest for any part of Antarctica. Part of the island occupied by the abandoned whaling station has recently been declared by the governments of Chile and Norway as a protected zone, and described as 'the first open museum in the region' (Muñoz 1996).

Because of the prolonged human interest, there have been many bathymetric surveys of Port Foster, the earliest known dating from 1829. These bathymetric surveys are a unique dataset in Antarctica and they were analysed as part of a study into volcano-tectonic deformation processes in a restless caldera. Our study suggests that deformation has occurred throughout the northern sub-basin of Port Foster, where the records can be most clearly interpreted, and the results are described and interpreted below.

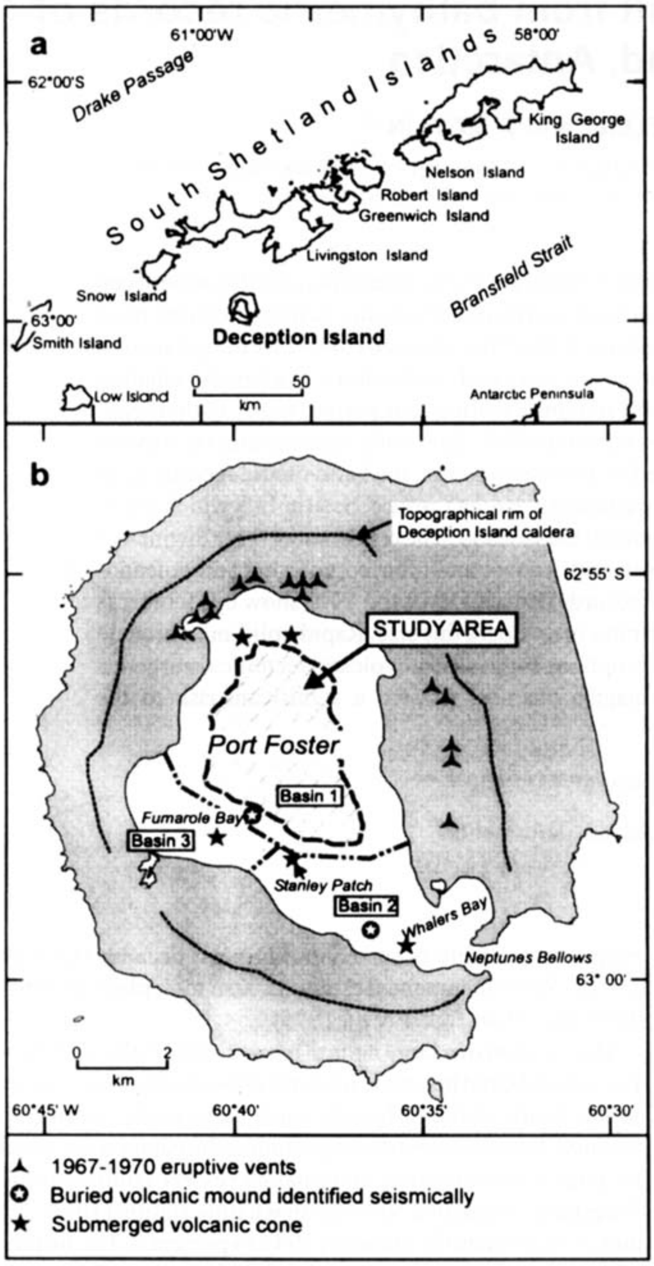

Fig. 1. Sketch maps showing **a.** location of Deception Island in the South Shetland Islands, and **b.** the study area within Port Foster, Deception Island. Basins 1–3 are described in the text.

Bathymetry of Port Foster

The caldera on Deception Island is nearly circular, with maximum diameters of *c.* 9 km E–W and 10.5 km N–S (Fig. 1). Port Foster has smaller dimensions because of numerous post-caldera explosive and effusive eruptions within the caldera, which were focused in a 3 km-wide zone around the circular rim of the caldera wall margins. These eruptions have repeatedly modified the coastline of Port Foster, as was observed following the 1967–70 eruptions (Brecher 1975). Within the flooded part of the caldera, there are also isolated small submerged volcanic cones and buried mound-like edifices identified on seismic records (British Antarctic Survey 1987, p. 28, Kowalewski *et al.* 1990, Rey *et al.* 1990, 1992, Fig 1b). The bay extends in a north-westerly direction from a narrow shallow entrance (< 500 m wide, < 25 m deep) at Neptune's Bellows. It is encircled by a shallow shelf (< 20 m deep) generally < 150 m wide, widening locally to *c.* 450 m, which falls away toward the centre of Port Foster along a steep slope. The slope is scarred by numerous slide scars and furrows, especially north-west and south of Stanley Patch (Rey *et al.* 1990, 1992).

At least three sub-basins can be distinguished by the bathymetry (Fig. 1b). The largest basin occupies the entire northern half of Port Foster north of Stanley Patch and north-east of Fumarole Bay. It has an even bottom surface (*c.* 165 m deep) that rises gently to the north-east, and it is surrounded by steep slopes rising to the narrow littoral shelf or to two other much shallower sub-basins on the south-west and south sides. The larger basin is also generally featureless apart from a N–S orientated area of undulating topography on the east side (Rey *et al.* 1990). The south-west side of the basin, adjoining Fumarole Bay, is strikingly linear. A small basin in the south-east extends from Whalers Bay to Stanley Patch. It is shallow (generally < 110 m) and has an uneven bottom topography. A third smaller basin can be distinguished beneath Fumarole Bay. It is 100–120 m deep with a largely featureless surface that dips gently north-eastwards.

Analysis of bathymetric data

Data sources

The Hydrographic Office, Taunton, United Kingdom, provided photocopies of unpublished hydrographic surveys carried out within Port Foster for the following years: 1829, 1938, 1948, 1968, 1970 and 1993. These data were supplemented by published information from an Argentine chart with data from 1942–53 (Servicio de Hidrografía Naval de Argentina 1968) and a Spanish map with data for 1988–91 (Servicio Geográfico del Ejército 1994). A further survey (unpublished), undertaken by HMS *Endurance* in January 1988 at the request of one of the authors (JLS), was also included in the dataset examined. After examination, coverage was inadequate for the 1829, 1938 and 1968 surveys and these datasets were excluded from the investigation except for broad (non-statistical) comparative purposes.

Data analysis

The surveys were carried out by many different organizations, using a variety of geodetic positioning methods, and recorded in different units. An essential first task was to place each survey in a common geographical framework, and convert the soundings to a common measurement system. To achieve

https://doi.org/10.1017/S0954102098000558 Published online by Cambridge University Press

this, the data were digitized from the source material, and the soundings converted from fathoms to metres. Digitizing took place using a large digitizing table or by scanning and digitizing on a computer screen. Digitized data were re-projected into a common map projection system and coastlines from the various sources were compared. Some earlier surveys showed a consistent shift in position between older and newer maps. The older surveys were translated so that unchanging parts of the coastline coincided with corresponding points on the newer surveys. Only simple translations were required, with no rotation or scaling. This was expected, given that absolute position fixing techniques have advanced considerably over the period concerned, whereas relative fixing techniques have improved mainly in ease of use rather than in accuracy. Unfortunately, in addition to poor data coverage (see above), it proved impossible to obtain a satisfactory fit between the coastline depicted on the 1829 survey and that on more modern charts. The 1948 survey was chosen as the baseline topography because it is the most comprehensive early survey of Port Foster and provided a good fit with later coastlines.

Digital elevation models (DEM) were created using a Delaunay triangulation for each survey, linearly interpolating the data within each triangle and using a horizontal cell size of 50 m. To minimize spurious effects arising from position-fixing errors in the individual survey points and to ensure that the linear interpolation process created a good representation of the topography, only that part of the surface which was deeper than 150 m below sea-level in 1948 was used for further processing. The 150 m isobath was selected because the sea-bottom is almost featureless and flat below this depth, so that horizontal positioning errors between surveys would not affect the depth measured. Restricting the study area to this flat region also avoids the substantial measurement errors which arise from sounding to a sloping surface. Errors introduced by sloping surfaces vary according to the sounding method used. Echo sounders measure the distance to the closest point on the sea-bed, which need not be vertically below the sounding point and which would lead to underestimates of the depths. Conversely, lead-line soundings tend to exaggerate the depth in similar circumstances, as the weight tends to fall down slopes. Currents may also cause a lead line to descend obliquely to the sea-floor.

Finally, depths were corrected to a common vertical datum and were analysed by performing a regression analysis of depth against year for each cell in the DEM. This calculation provided the slope of the regression line, which gave the rate of uplift. Other parameters were also derived, including the correlation coefficient and χ^2 (the sum of the square of the residuals after regression). They are illustrated in Figs 2–4.

Results

The principal conclusion of our analysis of the data is that the seafloor in the northern basin of Port Foster is becoming shallower at a mean rate of 0.07 m a^{-1}. However, the rate of shallowing is not constant over the whole area studied. In some parts, changes in seafloor elevation are apparently negligible (i.e. the surface is static), whereas elsewhere shallowing proceeds at a rate of 0.3 m a^{-1} (Fig. 2). The greatest apparent shallowing is at the northern edge of the study area, where it has occurred at rates exceeding 0.4 m a^{-1}. Elsewhere, significant shallowing is focused along the south-western, north-western and northern edges of the basin, and in an arcuate N-trending zone within the basin on the north-eastern side.

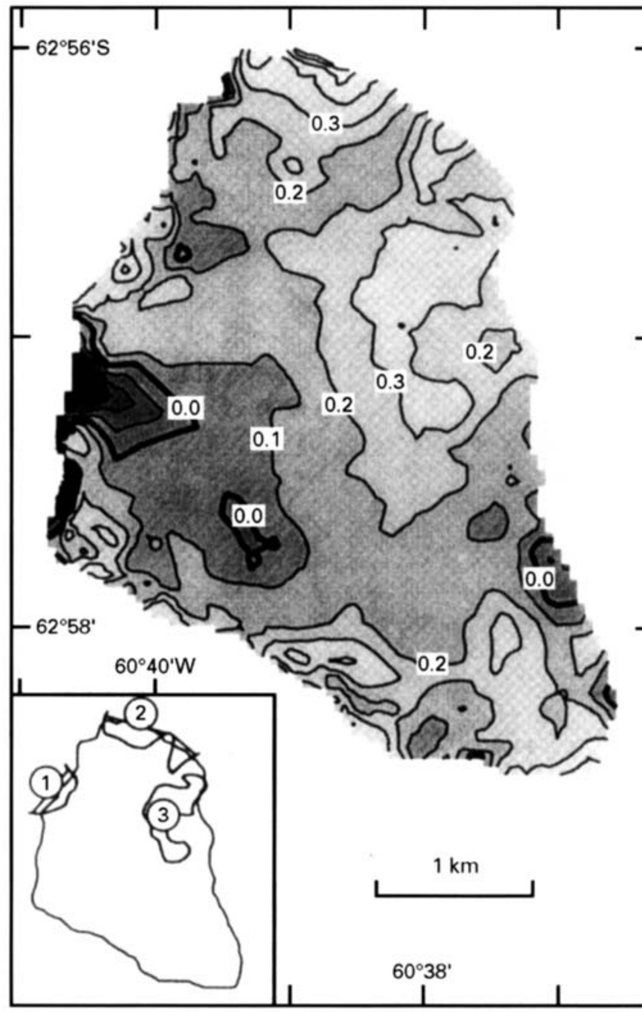

Fig. 2. Contoured map showing rates of shallowing throughout the study area (basin 1, Fig. 1b). The contour interval is 0.1 m a^{-1}. Lighter shades indicate rapid shallowing, and the zero contour is indicated by a heavy line. Inset shows areas of most rapid shallowing (1, 2 and 3) described in the text.

Because the original data were derived in many ways, using a variety of survey techniques, it is possible that results reported here are spurious. However a variogram (Fig. 5) shows a high degree of spatial organization in the results. Points up to 2.5 km apart are highly correlated, providing a strong indication that the pattern of change is real. Correlation

https://doi.org/10.1017/S0954102098000558 Published online by Cambridge University Press

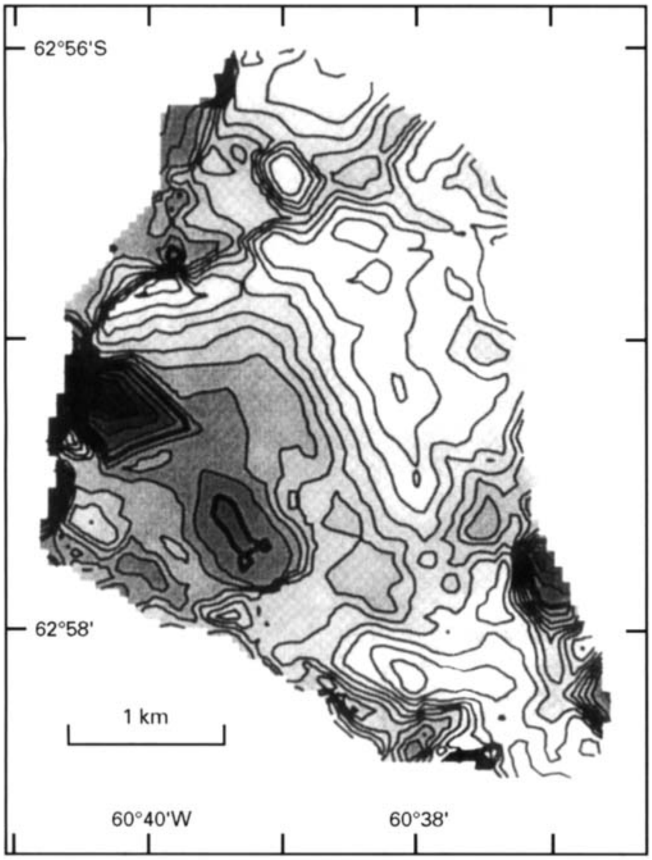

Fig. 3. Contoured map showing variations in correlation coefficient within basin 1. The contour interval is 0.1. Lighter shades indicate greater correlation, and the zero contour is indicated by a heavy line.

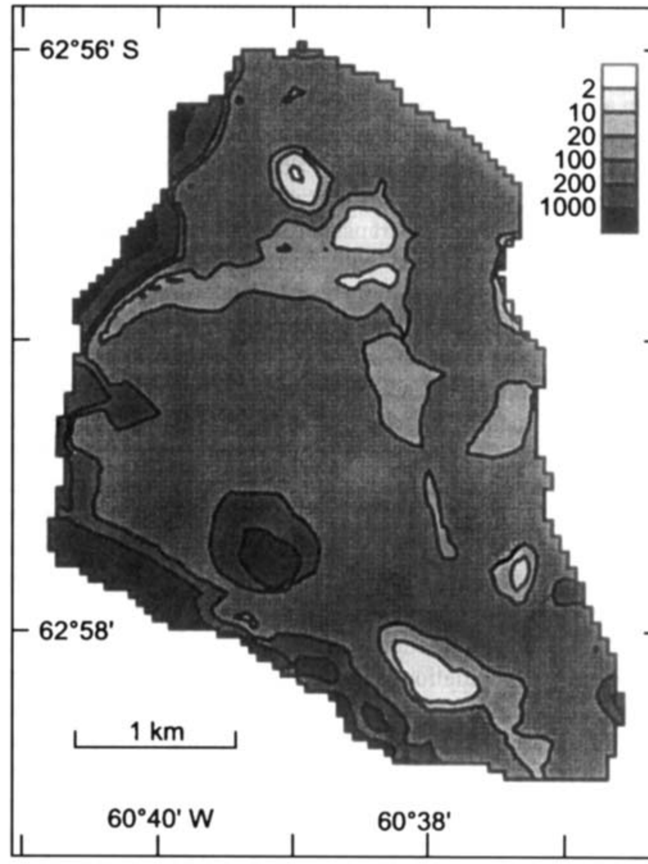

Fig. 4. Contoured diagram showing χ^2 values within basin 1. Lighter shades indicate *lower* values, i.e. greater confidence in the result. Note that the contour interval is non uniform.

coefficients for individual rate determinations are also evidence that the changes are likely to be genuine, being highest where the shallowing is greatest, and least where it is minor or apparently static (i.e. where there is no correlation between time and depth; Fig. 3). χ^2 values are reasonably constant across the study area (Fig. 4), indicating that there is little change in the significance of the result except along the western edge, which has apparently deepened with time. However, the latter corresponds to an area of very high χ^2 values and that result may be artificial. A similar uncertainty is attached to the indication of possible shallowing in a linear zone along the south-western edge of the study area (Fig. 2).

Examination of the 1829 survey strengthens the conclusion that there is a real overall decrease in the depth of water in the northern basin of the caldera. Despite problems in using the 1829 survey (see above), it is possible to locate the surveyed points with sufficient accuracy to allow a broad comparison with the modern depths. Only one 1829 survey point falls within the study area, with a given depth of 97 fathoms (177.4 m). For the same location, extrapolation in time back to 1829 from the modern charts gives an estimated depth of 177 m – a startlingly good correspondence, suggesting the possibility of a remarkably constant rate of uplift averaged over 160 years. Given the difficulty of comparing the 1829 survey with modern surveys, and the conditions under which surveying was carried out in the early nineteenth century (lead line), this result must be viewed with caution. However, it is another indication that the general result is likely to be correct.

A final indication that the result is probably valid is that there is a good correspondence with geological processes and geophysical parameters that are independent of the depth measurements (discussed below).

Discussion

We have shown (see above and Figs 2–5) that the general pattern of shallowing at different rates in different areas is internally consistent and supported by statistical analysis of the data. It remains to demonstrate whether there is a correspondence with geologically reasonable processes or events observed or postulated from independent evidence. Within the context of a restless caldera flooded by the sea, shallowing of the seafloor in the northern sub-basin in Port Foster could be a result of three principal geological processes:

https://doi.org/10.1017/S0954102098000558 Published online by Cambridge University Press

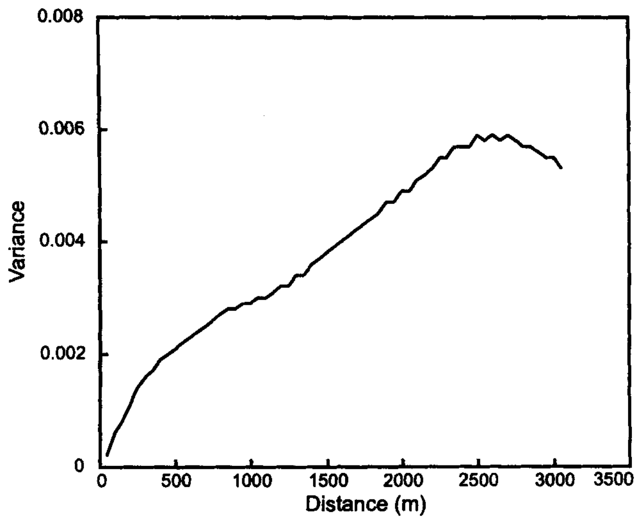

Fig 5. Variogram showing the degree of dissimilarity as a function of distance between points. The diagram shows that points up to 2.5 km apart are well correlated.

1) rapid input of reworked unconsolidated tephra, particularly ejecta from the 1967–70 pyroclastic eruptions,
2) volcano-tectonic effects of caldera development, and
3) local tectono-magmatic effects associated with a high-level magma chamber(s).

Rates of sedimentation in intra-arc sedimentary basins vary widely but may range typically between 0.0001 and > 0.002 m a^{-1} (average 0.0006 m a^{-1}; Smith & Landis 1995, table 7.1), which are much too low to be comparable with Port Foster. Conversely, sedimentation rates within caldera lakes can be significantly higher (e.g. average sedimentation rates of 0.002-0.01 m a^{-1} in Crater Lake (Oregon, USA), which has a similar caldera diameter to Deception Island; Nelson *et al.* 1994), and they are likely to be much higher close to active vents in the years immediately following pyroclastic eruptions. These rates are much closer to those occurring in Port Foster (mean rate 0.07 m a^{-1}). Thus, rapid accumulation of volcanic detritus, by direct pyroclastic input and fluvial redeposition into the basin, may be a viable process to explain the average rate of shallowing in Port Foster. Even parts of the basin which experienced much higher rates of shallowing, reaching > 0.3 and > 0.5 m a^{-1} in places (Fig. 2), might be related to high local input of unconsolidated tephra. This is a likely explanation for sediment accumulation in areas 1 and 2 in Fig. 2. Area 1 corresponds to a sediment fan identified in a multibeam echo sounder survey by Rey *et al.* (1992).

Accumulation in areas 1 and 2 was probably also enhanced by eruptive activity at two small submarine volcanic cones on the north-western periphery of the study area, although the age of the cones is unknown. Area 2 was also almost certainly affected by tephra reworked from the products of the 1967 and 1970 eruptions, vents for which crop out nearby to the north and north-west (Baker *et al.* 1975). By contrast, there is no obvious local source for the arcuate zone of rapid shallowing (3 in Fig. 2). Although eruptions took place from a N–S fissure east of area 3, they were Strombolian and produced a much smaller volume of (coarse) detritus compared to the 1967 and 1970 eruptions (Baker *et al.* 1975). Thus, the 1969 eruption is unlikely to be the sole agent responsible for enhanced deposition in area 3. Moreover, area 3 apparently closes eastwards, thus weakening the suggestion of a direct link with a sediment source in that direction.

Seismic refraction investigations have provided a relatively clear picture of the shallow structure (< 300 m below seafloor) in the Deception Island caldera (Kowalewski *et al.* 1990, Rey *et al.* 1990). They show the tilted and slab-like surface of a seismically isotropic basal unit (A) identified as a pre-caldera (likely pyroclastic) sequence, overlain by two major post-caldera sediment units (B and C). Each of the sediment units B and C can be subdivided further into several sub-units separated by minor unconformities. Bedding within units B and C is also tilted at angles which diminish progressively in the younger beds. They also contain numerous small-displacement normal faults, mainly orientated in NE–SW and NW–SE directions reflecting the regional tectonic influence of the Bransfield Strait marginal basin (Martí *et al.* 1996, cf. Smellie 1988, 1989). The lower of these units (B) forms a large-scale NE-verging monoclinal antiform associated with a WNW–ESE-trending normal fault. The monocline and associated major fault are coincident with the south-west linear margin of the northern sub-basin in Port Foster and with several submarine volcanic cones and hydrothermal mounds (Fig. 1b). Interpretation of the seismic profiles suggests that the major fault, which may be slightly arcuate in plan (concave toward the north-east), is a fundamental structure involved in the development of the caldera. North-eastern parts of older post-caldera units (B and possibly lower parts of C) crop out at higher elevations than younger post-caldera units to the south-west. These spatial relationships suggest either that subsidence of the basin along the monocline exceeded the local sedimentation rates, or that subsidence in the south-western part of the caldera basin may have been accompanied by uplift in the north-east. Thus, the pre-caldera sequence may have acted like a giant 'slab' rotated during progressive caldera development about an ill-defined (?)NW–SE-orientated axis. The apparent geographical coincidence between the zone of rapid shallowing (3 in Fig. 2) and inferred caldera uplift near the north-eastern margin of the study area suggests that a causal relationship is possible. This interpretation is broadly similar to the concept of trap-door caldera deformation described by Mahood & Hildreth (1983). In their model, which was based on the Pantelleria volcano, the trap-door hinge line acted as a locus for post-caldera eruptions. This would provide an explanation for the prominent association between the Deception Island monocline (caldera hinge line?) and several submarine cones and hydrothermal mounds in the southern part of Port Foster.

https://doi.org/10.1017/S0954102098000558 Published online by Cambridge University Press

Finally, area 3 (Fig. 2) is coincident with an elongate zone of low mass density, low magnetic intensity and high seismic (S-wave) attenuation (low Q values) (Ortiz *et al.* 1992, Vila *et al.* 1995). A study of earthquake residuals also suggested the presence of a dyke-like structure with a much lower velocity (25%) than adjacent rocks (Vila, cited in Vila *et al.* 1995). These observations were interpreted as indicating the existence of a hot magmatic intrusion, at least 200 m, wide on the north-eastern side of Port Foster (Vila *et al.* 1995). The presence of bottom water temperatures of 2–3°C in Fumarole Bay and the northern basin in Port Foster (Ortiz *et al.* 1992) also suggests that geothermal heat is being supplied to both of these basins from a high-level magma chamber. Tectono-magmatic effects of the upward migration of this magma chamber may be responsible for some of the rapid shallowing identified in this investigation.

Conclusions

Port Foster is a marine basin within the Deception Island caldera, almost closed except for a narrow, shallow exit at Neptune's Bellows. A mathematical analysis of hydrographical data obtained during multiple surveys of the northern sub-basin of Port Foster since 1829 has identified that the basin floor is rising at a mean rate of 0.07 m a^{-1}. Parts of the basin are becoming shallower much more rapidly, at rates of > 0.3 to > 0.5 m a^{-1}. All of these rates are rapid compared with 'normal' intra-arc volcaniclastic sedimentation, and some exceed sedimentation rates for caldera lakes, although published information on the latter is sparse. It is suggested that much of the shallowing is likely to be a result of volcaniclastic sedimentation in a silled basin and is not a deformational effect related to eruptive episodes. Areas at the north and north-west edges of the study area, with higher rates of shallowing, are probably affected by unusually rapid redeposition of unconsolidated pyroclastic detritus from recently active vents, particularly those which erupted in 1967 and 1970 but including two small undated submarine vents within the northern margin of the basin. By contrast, another offshore area of rapid shallowing, within the north-east part of the basin, cannot be reconciled simply with rapid sedimentation and it is interpreted as being mainly an effect of local caldera uplift, either by volcano-tectonic resurgence or tectono-magmatic effects of an upward migrating high-level magma chamber. If correct, this latter interpretation suggests that the caldera in Deception Island may be deforming (resurging?) at a relatively rapid rate. The volcanic risk is correspondingly higher than has been considered previously (cf. Roobol 1982) and active caldera structures such as that identified by this study should be monitored regularly in order to mitigate the possibly disastrous effects on human lives and activities in the region.

Acknowledgements

The authors are very grateful to the Captains, Officers and crews of HMS *Endurance*, RRS *John Biscoe* and RRS *Bransfield* for their close-ship support of the Antarctic field work of one of us (JLS) during three strenuous field seasons on Deception Island. The Captains, Officers and crews of HMS *Endurance* are also thanked particularly for undertaking the two surveys of Port Foster in 1988 and 1993, which formed an important part of the work on which this paper is based. Dr A. Murray (British Antarctic Survey) provided invaluable advice on the statistical analysis. Reviews by Hans Nelson and Randy Keller were much appreciated.

References

Baker, P.E., McReath, I., Harvey, M.R., Roobol, M.J. & Davies, T.G. 1975. The geology of the South Shetland Islands. V. Volcanic evolution of Deception Island. *British Antarctic Survey Scientific Reports*, No. 78, 81 pp.

Blundell, D.J. 1962. Palaeomagnetic investigations in the Falkland Islands Dependencies. *British Antarctic Survey Scientific Reports*, No. 39, 24 pp.

Brecher, H.H. 1975. Photogrammetric maps of a volcanic eruption area, Deception Island, Antarctica. *Institute of Polar Studies Report, Ohio State University*, No. 52, 10 pp.

British Antarctic Survey. 1987. *British Antarctic Survey Annual Report 1986–87.* Swindon: Natural Environment Research Council, 123 pp.

Keller, R.A., Fisk, M.R., White, W.M. & Birkenmajer, K. 1991. Isotopic and trace element constraints on mixing and melting models of marginal basin volcanism, Bransfield Strait, Antarctica. *Earth and Planetary Science Letters*, **111**, 287-303.

Kowalewski, W., Rudowski, S. & Zalewski, S.M. 1990. Seismoacoustic studies within flooded part of the caldera of the Deception Island, West Antarctica. *Polish Polar Research*, **11**, 259-266.

Mahood, G. & Hildreth, W. 1983. Nested calderas and trapdoor uplift at Pantelleria, Strait of Sicily. *Geology*, **11**, 722-726

Martí, J. & Baraldo, A. 1990. Pre-caldera pyroclastic deposits of Deception Island (South Shetland Islands). *Antarctic Science*, **2**, 345-352.

Martí, J., Vila, J. & Rey, J. 1996. Deception Island (Bransfield Strait, Antarctica): an example of a volcanic caldera developed by extensional tectonics. *In* McGuire, W.J., Jones, A.P. & Neuberg, J., *eds. Volcano instability on the earth and other planets.* Special Publication of the Geological Society, London, No. 110, 253-265.

Muñoz, G. 1996. Museo en la Antártida. *Boletin Antártico Chileno*, **15**, 5-8.

Nelson, C.H., Bacon, C.R., Robinson, S.W., Adam, D.P., Bradbury, J.P., Barber, J.H., Schwartz, D. & Vagenas, G. 1994. The volcanic, sedimentologic, and paleolimnologic history of the Crater Lake caldera floor, Oregon: evidence for small caldera evolution. *Geological Society of America Bulletin*, **106**, 684-704.

Orheim, O. 1972. Volcanic activity on Deception Island, South Shetland Islands. *In* Adie, R.J., *ed. Antarctic geology and geophysics.* Oslo: Universitetsforlaget, 117-120.

Ortiz, R., Vila, J., Garcia, A., Camacho, A.G., Diez, J.L., Aparicio, A., Soto, R., Viramonte, J.G., Risso, C., Menegatti, N. & Petrinovic, I. 1992. Geophysical features of Deception Island. *In* Yoshida, Y., Kaminuma, K. & Shiraishi, K., *eds. Recent progress in Antarctic earth science.* Tokyo: Terra Scientific Publishing Company, 443-448.

REY, J., DE ANDRÉS, J.R. & FERNÁNDEZ LÓPEZ, J.M. 1990. Tectonica reciente en los depósitos submarinos de la Bahía de Decepcion. *In* CASTELLVÍ, J., *ed. III Symposio Español de Estudios Antárticos.* Madrid: Comisíon Interministerial de Ciencia y Tecnología,258-270.

REY, J., SOMOZA, L. & HERNANDEZ-MOLINA, F.J. 1992. Formas de los sedimentos submarinos superficiales en Puerto Foster, Isla Decepción, Islas Shetland del Sur. *In* LÓPEZ-MARTÍNEZ, J., *ed. Geología de la Antártida Occidental.* Salamanca: III Congreso Geología de España & VIII Congreso Latinoamericano de Geología, España, 163-172.

ROOBOL, M.J. 1982. The volcanic hazard at Deception Island, South Shetland Islands. *British Antarctic Survey Bulletin,* No. 51, 237-245.

SERVICIO DE HIDROGRAFÍA NAVAL DE ARGENTINA. 1968. *Isla Decepción.* Chart No. 100, 1:23 150 scale. Buenos Aires: Servicio de Hidrografía Naval de Argentina.

SERVICIO GEOGRÁFICO DEL EJÉRCITO. 1994. *Deception Island.* 1:25 000 Scale. Madrid: Servicio Geográfico del Ejército.

SMELLIE, J.L. 1988. Recent observations on the volcanic history of Deception Island, South Shetland Islands. *British Antarctic Survey Bulletin,* No. 81, 83-85.

SMELLIE, J.L. 1989. Deception Island. *In* DALZIEL, I.W.D., *ed. Tectonics of the Scotia Arc, Antarctica. Punta Arenas, Chile to Ushuaia, Argentina. January 1-February 1, 1989. Field trip guidebook T180. 28th International Geological Congress.* Washington, DC: American Geophysical Union, 146-152.

SMELLIE, J.L. 1990. Graham Land and South Shetland Islands. Summary. *Antarctic Research Series,* **48**, 303-312.

SMELLIE, J.L., LÓPEZ-MARTÍNEZ, J. & SERRANO, E. 1997. Maps of Deception Island, South Shetland Islands. *In* RICCI, C.A., *ed. The Antarctic region: geological evolution and processes* Siena: Museo Nazionale dell'Antartide, 1195-1198.

SMITH, G.A. & LANDIS, C.A. 1995. Intra-arc basins. *In* BUSBY, C.J. & INGERSOLL, R.V., *eds. Tectonics of sedimentary basins.* Cambridge, MA: Blackwell Science, 263-298.

VALENCIO, D.A., MENDÍA, J.E. & VILAS, J.F. 1979. Palaeomagnetism and K-Ar age of Mesozoic and Cenozoic igneous rocks from Antarctica. *Earth and Planetary Science Letters,* **45**, 61-68.

VILA, J., CORREIG, A.M. & MARTÍ, J. 1995. Attenuation and source parameters at Deception Island (South Shetland Islands, Antarctica). *Pure and Applied Geophysics,* **144**, 229-250.