Determination of volumetric variations and coastal changes due to historical volcanic eruptions using historical maps and remote-sensing at Deception Island (West-Antarctica)

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Abstract

Deception Island is an active volcano in the South Shetland Islands (Antarctic). Its eruptions have been recorded since 1842, the last episode occurring between 1967 and 1970. This study quantifies the geomorphological changes which have taken place as a result of historical volcanic activity on the island. The linear and volumetric results obtained for the Telefon Bay and Craters of 1970s where the Surtseyan eruption took place in 1967 are presented in detail.

Key words: *volcanic eruption, volumetric estimation, coastal changes, Geographical Information System*

Introduction

Deception Island (West Antarctica) is a horseshoe-like Quaternary volcanic island that shows well-recorded geomorphic events related to recent eruptions. Historical eruptions at Deception Island took place in 1842, 1912, 1917, 1967, 1969 and 1970 (Orheim, 1971). During this period of time, the island's geomorphic evolution was controlled by different volcanic eruptions, by modifying both the inner and the outer shoreline and the appearance of new volcanic edifices like cinder cones and crater-lakes from maar and phreatomagmatic -type eruptions (Roobol, 1973; Ortiz et al., 1992).

Deception Island has been occupied by whaling bases and several Antarctic Stations since the 19th century. Accordingly, different maps and cartographic representations were produced which reflected the eruptions that were taking place. Specifically, we have used historical maps of Deception Island of 1829, 1956, 1957, 1968, 1970 and the latest cartography of 2003 with aid of high resolution QuickBird satellite imagery.

The development of new mathematical methods and algorithms for map projection and geo referencing allows comparisons to be drawn between historical maps and modern satellite images. The geomorphic evolution of landforms with rapid geomorphic processes (i.e. volcanic landforms) could be determined by comparing these two types of information in digital format. The objective of this work is therefore to determine the geomorphic variation undergone by Deception Island, the volume difference caused during the course of several eruptions in the 19th and 20th centuries and the coeval variation of the shoreline associated with these eruptions. With this aim, this study addresses the difficulties involved in homogenising all the cartographic and geographic information (namely cartographic projections and associated errors) obtained over the years in the same area from different sources and using different projections and geodetic systems.

Regional setting

Deception Island (South Shetlands, West Antarctica), is a horseshoe-shaped volcanic island with a well-developed collapsed caldera (Port Foster) and it represents an active volcanic complex (Fig. 1). The island evolved within a back-arc basin (Rey et al. 1995; Galindo-Zaldívar et al., 1996; Gonzalez-Casado et al., 2000; Muñoz et al. 2005) called the Bransfield Strait. This strait is elongated trending NE-SW and is bounded to the southeast by a ridge and to the northwest by a former trench. The island lies in a strike-slip stress regime (Gonzalez-Casado et al., 2000) with the maximum horizontal stress (S_{HMAX}) trending NE-SW. The volcanic sequence that built up the island evolved from submarine pillow lavas to subaerial eruptions, mainly Strombolian and phreatomagmatic (Maestro et al. 2007; Pérez-López et al., 2007), indicating that Deception Island evolved through the collapse of a huge volcanic edifice under a regional stress regime with S_{HMAX} oriented NE-SW. This regional stress produced movement on oblique-normal and normal faults, trending NNE-SSW to ENE-WSW, due to the interaction between the regional tectonic regime of the Bransfield Strait (NE-SW) and the dynamics of the magma chamber emplacement within the island.

Fig. 1

The present landscape shows a flooded caldera (Fig. 2), where the last volcanic eruptions occurred along the inner rim of the caldera. The inner shoreline is irregular and elongated NW-SE. The caldera boundary and the collapse scarp affect pre-caldera deposits and the location of post-caldera eruptive centres and cinder cones (Smellie, 2001; Smellie, 2002; Pérez-López et al. 2007). Postcaldera eruptions have covered and extensively modified the inner shoreline. Holohan et al. (2005) described fracture sets associated with caldera collapse, pointing out that ring and radial faults control the brittle deformation, and probably determine the location of later eruptions associated with the caldera rim. The outer shoreline of the island exhibits a complex evolution, with high lava cliffs on the northern and western shorelines, and a linear coastline due to the action of submarine faulting to the east of the island (Fernández-Ibáñez et al., 2005).

Fig. 2

Historical eruptions of Deception Island

The first historical eruption was noted in 1842 (Fig. 2) and it was controlled by a N-trending fracture, producing cinder cones and associated lava flows over a distance of 4 km (Marti and Baraldo, 1990; Marti et al., 1996). This eruption was Strombolian-type, beginning at Mt Kirkwood with a volcanic explosivity index (VEI scale) of 2. Between 1912 and 1917 a phreatomagmatic eruption took place close to Whalers Bay and Kroner Lake, producing pyroclastic deposits embedded into glacial deposits.

The last eruptive processes took place between 1967 and 1970 with a total volume of material erupted between 0.12 km^3 (Roobol, 1982) and 0,20 km^3 (Baker et al., 1975). The 1967 eruption began northwards the inner bay, close to Telefon Bay, and it was controlled by an NNE-trending fracture. The eruptive column reached 2500 m, affecting the Chilean Antarctic Station "Pedro Aguirre Cerdá", which was partially destroyed. This 1967 eruption generated an ephemeral NE-SW trending island (known as Yelcho or Marinero Suárez), which was annexed to the main body of the island in the followings eruptions with a coastal change (Clapperton, 1969) (Fig. 3). The eruption caused a basal surge of volcano-sedimentary lapilli with 0.05 km^3 of pyroclastic material (Roobol, 1982).

Similar to 1967, the eruption of 1969 was also Strombolian, with a total emitted volume of 0.03 km^3 (Roobol, 1982). The eruptive centres were located along three fissures. The first one is NNW-trending, the second appeared north of the first and the third, with the same orientation (NNW-SSE), was located at Pendulum Cove (Fig. 1). Furthermore, during the 1969 eruption, a lahar destroyed the British Antarctic Station "John Biscoe" located in Whalers Bay and changing the geomorphology and shoreline of the surrounding area.

Finally, the 1970 eruption was recorded by the seismographs of the British Antarctic Survey, because the island lacked of human presence. However, there are several photographs of the eruption due to its relatively long duration (almost a month). The eruptive centres were located in the northern part of the island, in Craters of the 1970s, and are aligned with the eruptive centres generated in 1967. This eruption generated NNW-trending craters with depths ranging between 40 and 300 m. The eruption began in the bay and later extended to the land surface, with a total emitted volume of 0.04 km^3 of pyroclastic material (Roobol, 1982). The eruptive column reached a height of 11 km and fall materials were located at a distance of 100 km from the main focus of the eruption. During this eruption, Yelcho Island was annexed to the inner shoreline of Telefon Bay, and the Chilean Antarctic Station was totally destroyed by volcanic bombs. Therefore the volcanism on Deception Island during the 19th and 20th centuries principally affected the inner rim of the volcanic caldera and was associated with fractures with regional orientation (NNW-SSE). These eruptions began with a Strombolian nature, with small magma volume and durations ranging from hours to days. Subsequently, the eruption emitted small lava flows covering the inner rim. Finally, when the magma reached water bodies, phreatomagmatic and maar-type eruptions occurred, with the presence of small cinder cones aligned with fractures.

Cartography and rationale

The changing morphology at Deception Island is well-recorded throughout different historical maps, cartographies and satellite imaginary. However, each map and satellite image were projected in different geodetic systems. Accordingly, we have performed a cartographic comparative analysis of different maps of Deception Island, covering different time periods. To determinate the volumetric variations inland and coastal changes between the historical eruptive process, we have compared maps digitally. With this aim, we projected the historical cartographies in the same cartographic system and with the same geodetic constraints of the new cartography of the island (WGS84 projection UTM 20S). Then we have identified those invariant points on the maps in order to obtain the error associated with the re-projection and zones of variation. Where possible, we obtained digital elevation models DEM from the topographic maps. Finally, we compared the numerical models obtained to determine changes in both volume and shoreline, in some cases with a line generalization process, overlapping all of the historical cartographies and the new cartography.

The following historical topographic information, aerial photo, new cartography and satellite imagery sets were collected and loaded into a multidisciplinary GIS called SIMAC (Torrecillas et al., 2006):

1- Topographic map made by E. N. Kendall of 1829 and published by the Journal of Royal Geographical Society of the United Kindom (Roobol, 1973).
2- Topographic maps at 1:10000 scale by H. Brecher of 1956, 1968 and 1970 (Brecher, 1975). The 1956 map was plotted from aerial photography at 1:29000 scale (6 inch focal length, 9x9 inch format), taken in 1956 by Hunting Aerosurveys; the 1968 map was from stereographic cover of the whole of the island from aerial photographs taken in 1968 by the *Servicio de Hidrografía Naval Argentino*, at 1:28000 scale (K-17 camera, focal length 6 inches, format 9x9 inches) and the 1970 map was from a topographic map at 1:23150 scale from aerial photography at 1:28000 scale by the same agency and using the same camera and parameters as for the 1968 map, with the aim of photographing the eruption which occurred on the island in the same year.
3- Topographic map of Deception Island 1:25000 by D.O.S. using a Lambert geographic projection, plotted in 1956 (D.O.S., 1957).

4- New topographic map of Deception Island 1:5000 of 2006 by Spanish *Servicio Geográfico del Ejercito* (S.G.E., 2006) plotted using Quickbird high resolution satellite imagery of 2003.

We have also used sketches (Hawkes, 1961; Baker et al., 1975; Roobol, 1982; Birkenmajer, 1991, 1992) and other historical maps, like 1:200000 scale one printed for D.O.S. by the British Ordnance Survey sheet W 62 60 of 1968, although were discarded due to lack of precision and detail.

Fig.3

Results and Discussion

The studies made possible by the availability of these data encompass the following comparisons: study of land volume and shoreline in the Telefon Bay and Craters of 1970s area between 1956-1968, 1968-1970 and 1970-2003, study of land volume and shoreline for the whole of Deception Island between 1956-2003 and study of inner shoreline (Port Foster) between 1829-2003.

Land volume and shoreline in the Telefon Bay and Craters of 1970s: 1956-1968, 1968-1970 and 1970-2003

Research into these periods was based on the three maps of H. Brecher plotted in 1956, 1968 and 1970 and the new map of S.G.E. of 2003. The Brecher´s maps do not have areas in common, and it is therefore necessary first to demarcate the zones to be compared. This study area was chosen as a graphic mask for each of two the digital elevation models (DEM), to calculate first their volume and then the volumetric difference between the periods of 1956-1968 and 1968-1970, see Fig. 4, for 1970-2003 the study area matches up with the map of 1970 (see Fig. 5).

Fig. 4

Fig. 5

Also, the Brecher´s maps display local coordinates with no information about the cartographical projection, the datum or ellipsoid used. However, there is a point given in geographical coordinates accurate down to the level of minutes and located at the centre of a crater. H. Brecher mentioned that the sea level recorded for 1970 may have an error of 3 metres in height, and that the maps took into account a margin of error of 5 metres with regard to the absolute values.

The Brecher´s maps were initially geo-referenced to their system of local coordinates with RMS between ±1.78m and ±1.95m, the RMS error being less than ±2 m. They were then digitalized with a semi-automatic digitizing algorithm of contours so we discard this error, estimated at ±7 m the planimetric error and at ±3 m the altimetric error. Brecher's three maps all received the same digital treatment, with the same photogrammetric scanner, geo-referencing and automatic vectoring process. The data comparison therefore eliminates system errors and reduces both random errors and errors produced by the actual map plotting itself to a minimum. Similarly, error is also kept to a minimum in the shoreline study. Now, Brecher´s maps are prepared to be compared between 1956-1968 and 1968-1970.

The main problem in this study was to find a way to adapt H. Brecher's data, plotted using local coordinates and an unknown projection or datum, to the WGS84 system UTM projection (Bugayevskiy, 2000) of the SGE map of 2003, with which it was going to be compared.

We partially solved the datum incognita by resorting to datums used by Argentina, U.S.A., U.K. or Chile at the time the photographs were taken, such as “South American 1969 mean for Argentina, Bolivia”, “Deception Island Datum”, “Antarctica Provisional South American 1956 Chile (Southern, Near 43ºS)”,”Provisional South Chilean 1963 Chile (Near 53ºS) (Hito XVIII)”, South American 1969 Argentina” or “South American 1969 Chile”. Although the maps were plotted from local coordinates, global geographic coordinates are offered for one single point (60º39’W, 62º55’ S). Assuming the existence of different datums for these coordinates is possible via geodesic transformations, principally of 3 parameters (Helmert 3D) considering the age of some datums, to obtain the coordinates of this point in UTM projection and WGS84. Also, the spot can be located on the SGE map in UTM projection and WGS84, the closest approximation to this location could verify the datum used to record Brecher’s information. The direct SGE map identification for that point gives the UTM coordinates (619552m, 3021872m) with ±5m of cartographic planimetric error and about ±25m the planimetric location error, which are very close to those provided by the *Deception Island* Datum of (619597m, 3021828m) -the data reveal no changes exceeding ± 300m for the rest of the datums-.

The studied area is 5x3 km in size, so any local projections have minimal planimetric deformation. Hypothetically assuming that the UTM projection was employed, a couple of translations were carried out on the data. The first was for a global approximation (ΔX = 616000, ΔY= 3012000) and the second was for a local approximation (ΔX = 3500, ΔY= -6300). Furthermore, was necessary to resort to affine transformation to make the data correspond first of all to the planimetry with RMS of ±22m.

With regard to elevation measurement, the SGE map and H. Brecher’s data each have their own 0 elevation data. The possible relationship with the present values must therefore be determined, and to that end variations in spot heights and shoreline had to be studied. This eliminated the uncertainty about 0 elevation on Brecher's map, evaluated by himself at 3m. The chosen method involved visual adjustment and then the subtraction of surfaces to balance out the differences in elevation. The preliminary study of both DEMs showed that the mean error estimated was 2 m high and we therefore increased the Brecher map by the same value. Moreover, the numerical extraction between both models displays evidence for relevant morphological changes, although large errors in invariant points were noted (see Fig. 6). We therefore evaluated each DEM independently for the reference value of 0, also eliminating the error due to the map displacement from the overlapping image.

Fig. 6

Hence, the difference in volume and shoreline can then be calculated for the periods 1956-1968, 1968-1970 and 1970-2003, see TABLE 1.

These data revealed an increase in volume of 0.057 km^3 in the period 1956-1968, probably associated with the 1967 eruption. During this eruption an ephemeral island emerged 987m long, 390 m wide and with a total volume of 0.004 km3. The thickness of the black lapilli ranged between 3- 5 m (Roobol, 1979). Furthermore, an increase of 0.01 km^3, related to the 1969 eruption, appeared for the interval between 1968 and 1970. The aforementioned island was annexed, with craters appearing close to Craters of 1970s in the north-eastward zone. Several topographic points display a reduction in topographic elevation of 100m and the ice cover was partially melted. Finally, the volumetric values show a negative difference of 0.053 km^3 during the period 1970-2003. We suggest that this figure can be put down to a combination of high erosion rates

(1000mm/kyr, Rapprich et al, 2007), thawing due to climate variability and the appearance of craterss in Telefon Bay and Craters 1970 zones.

With regard to the shoreline, in 1956-1968 this study included the small area of land lying adjacent to the island and omitted in the volumetric study owing to the lack of common data to the two dates, producing a continuous shoreline linking the two maps (see Fig. 4). The coastal area on the 1968 map was also completed to make the whole shoreline continuous. The results show between 1956-1968 an increase in the shoreline of 2 km, mainly because of the small central islet that had now appeared (2,7 km) and a sharp indentation in the coastline due to a new craters within the 1970s craters. In 1968-1970, there was a reduction of 1.4 km essentially because of the disappearance of the central islet due to the mainland annexing it during the 1969 eruption. In 1970-2003, the values obtained for differences in shoreline reveal a loss of shoreline of approximately 5% related to the accumulation of material during the beach destruction process in the inner bay shoreline.

TABLE 1

1 *Land volume and shoreline in Deception Island: 1956 – 2003*

In this comparative study, the D.O.S. map of 1956 was taken and compared with the SGE map of 2003 in WGS84 system with UTM projection. The D.O.S. map was plotted to Lambert Conformal Conic -termed Lambert Conic Orthomorphic on the map but it does not supply all the data that is needed to project, such as the parallels employed in the secant cone -, using the Clarke 1880 ellipsoid with a local datum from astrological fixes -but Laplace points possibly used in the plotting are not shown and are needed to compare the two maps; only a geodetic base in Whalers Bay is marked-.

Tests were carried out to ascertain the correct transformation. We first tried the datum known as Deception, which gave such good initial results with Brecher's map. Using this datum, different parallels were tried and the Lambert Conic Projection map was geo-referenced and rectified. It was then projected and transformed geocentrically into a WGS84 UTM projection. The best result obtained offered positional errors of around 160m in the northern zone, although in other areas the level of error was maintained at around 20-40m. In these circumstances it was decided to subject both maps to affine transformation (with 90 links and RMS of 75m), since this would at least unify their shapes positionally as much as possible. The affine transformation used here gives a high quality match for 80% of the transformed area, with more questionable results appearing for external cliff areas (i.e. Lavebrua Island, Stonethrow Crest and Telefon Ridge). Once the D.O.S. map had been transformed, a DEM was generated to be compared with the 2003 map.

The extraction process for both the DOS and the 2003 DEM also revealed high sensitivity due to associated errors. Analyzing the areas differing by more that ±30m in greater detail, and discarding data from Stonethrow Crest, Telefon Ridge, the outer cliffs and Lavebrua Island, it was in these areas that the last eruptions occurred. This extraction shows the mainland annexing of Yelcho Island, increasing terrain in Telefon Bay, Craters of 1970s, Pendulum Cove and Whalers Bay, and decreasing areas in the southern part of Mount Kirkwood and Mt Pond, although in Mt Pond this could be related to landslides. We therefore demonstrated a land increase of 0.101 km^3, in accordance with the values estimated by others studies during the last eruptive process (1969-1970) (Roobol, 1982; Baker et al., 1975). Orheim (1972) studied the open fissure during the 1969 eruption. An extrapolated mean present-day elevation value would show an increase of 26m. This value could explain the remaining topographic elevation obtained from our analysis.

TABLE 2

With regard to the inner shoreline, the line to be compared first had to be adapted to give it the same level of detail (the 2003 shoreline is at a scale of 1:5000 as opposed to the 1:25000 of the D.O.S. map). To do this, linear generalization techniques were adopted, with vertex elimination values of around 20 m and curve smoothing values of 2 m (both values having been established following tests and taking into account past experience in this type of processing), the aim being to make both curves equal in the number of their vertexes and in their appearance. In the curve comparison for the whole shoreline, the number of vertexes in the two curves was 1195 in 1956 as opposed to 1043 in 2003, while for the inner bay were 204 in 1956 and 209 in 2003. The linear generalization led to the loss of 200m of the existing shoreline, a fact which indicates the difficulty of carrying out a comparative study of this type to an acceptable degree of accuracy. The differences reveal a loss of shoreline of 2.5 km. The values obtained by focussing only on the values of the inner shoreline, in order to be able to relate these to the most recent study, are practically negligible (50m), as can be seen in TABLE 2, the growth in shoreline along most of the coast between Pendulum Cove and Whalers Bay having been offset by the intrusion of the sea into the maars. The shrinkage of the glacial front from Mount Pond should also be taken into consideration.

2 *Shoreline in Port Foster: 1829 - 2003*

The map plotted by the cartographer Lieutenant E.N. Kendall during the scientific expedition led by Captain Henry Foster in 1829 was the first ever made of Deception Island. Its cartographic quality leaves much to be desired, but it is nevertheless useful when analysing historical landforms. Comparison between the map and the new cartography revealed evidence of rapid morphological evolution around the shores of Port Foster (see Fig. 7).

Its digitalization involved several transformations based on 77 control points along the perimeter of the island at points with no volcanic deformation and on the dividing lines for Kendall´s map. Five methods were used to adapt it to the SGE map: affine transformation, second- and third-degree polynomial transformation, adjustment transformation and spline transformation. The method which gave the best result was adjustment transformation, which deforms the map considerably around the control point. Most of the methods widened out the southern part of the map, and this shows that Kendall's map was plotted with some type of conic projection.

The shoreline shown on Kendall’s deformed map was compared with the existing shoreline as it appears on the SGE map of 2003. To do so, and considering that Kendall’s map is very inaccurate in comparison with the current map, the shoreline on both maps was digitalized to a visual reference scale of 1:50000, thus equating the number of vertexes which make up the inner shoreline on each map and unifying their spatial and geometric accuracy. The values obtained are shown in Table 2 where a discrease of shoreline is valued at 3 km.

The changes which took place in 1956 and 2003, when no significant decrease in the size of the inner shoreline was appreciable, were mentioned earlier. However, the changes which occurred in the period 1829-1956 need to be described in order to explain the 3 km reduction in shoreline.

Orheim (1971) pointed to six pyroclastic eruptions during the period 1907-1920, also Roobol (1973) suggested two groups of altered features in 1829-1956: youthfull flooded craters were infilled and new craters probably formed before 1912 when the whaling station was constructed in Whalers Bay. The main difference in the shoreline not mentioned in the other sections concerns the alterations which took place at the north shore of Whaler Bay where a flooded crater open to sea has been largely infilled (Roobol, 1973), Kroner Lake peninsula, formed after 1856 with two vents, was occupied by a small pond in 1968, the coastline aggraded southward by 50-100m and the shallow bay was further silted by laharic debris up to 4 m from the Pond Glacier moraines (Roobol, 1973). Furthermore, the shore north of Mount Kirkwood is smoother today.

3 *Conclusions*

Dramatic morphological changes due to volcanic activity can be studied with modern 3D GIS methodologies applied to historical maps. Numerical modelling of landforms makes it possible to estimate volumetric and linear changes related to external (erosion rates and coastal dynamics) and internal (volcanic eruptions) processes.

The study initially focussed on Telefon Bay and the Craters of 1970s area and its scope was then extended to the whole island. The maps used were those of E.N. Kendall, H. Brecher, the British D.O.S. map and the current Spanish SGE map from Quick Bird satellite image.

The studies made using maps by the same author had no problems with errors due to DEM or shoreline differences, but those made using maps from different sources with different projections or geodetic systems had to resort to affine transformations, because converting the map into geographic coordinates and then using the Helmert 3D geodetic transformation did not produce the desired results. When comparing cartographic sources, planimetric error (relief displacement) is usually compensated for, because in an elevation where the highest point is displaced the difference will be positive on one side and negative on the other, so the error is not so significant in the overall data. In such cases the volumes were calculated separately and, although a cut/fill was obtained for both, we studied only those significant differences exceeding 20m or 30m.

To analyze the shoreline on maps by different authors and in different scales, a generalization process was applied for a specific scale and the number of peaks was made equal to ensure the same level of detail and thereby minimize error.

For data obtained for Telefon Bay and the Craters of 1970s area, the measurement study zone is approximately the same. It can be seen that the area underwent an initial increase in its surface volume in 1968 and that this was then followed by a reduction of the same magnitude, leaving it now almost at the same levels it had displayed previously. Values obtained here for volumetric changes from GIS analysis are in agreement with those values estimated by Roobol (1982) and Baker et al. (1975) from field work at Deception Island. Furthermore, our analysis revealed other landform modifying processes related to melting of the ice and erosion rates. We estimated a total erupted volume between 1956 and 1967 of more than 0.005 km3 (Roobol, 1982). The inner coastal shoreline was reduced during the most recent eruptive processes 1967-1970.

Studies carried out on the island indicate that the island has increased in volume by 0.101 km3 since 1956. They also once again returned the same levels of magnitude as the value of 0.2 km3 given by Roobol (1982) for the amount of material erupted in the period 1967-1970. It should be remembered that, as we mentioned earlier, not all the material was deposited on the island above sea level, and the surface is also subject to thawing and erosion. Nevertheless, the tendency is positive Also, the inner shoreline has gradually contracted since 1829, this trend becoming more widespread over the last 30 years.

Linear anamorphosis (UTM) has not been taken into consideration because its contribution for the purposes of these rough calculations is negligible.

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TABLE and TABLE CAPTIONS

Zone	Year	Source	Volume (km3)	Difference Vol (km3)	Shore perimeter (km)	Diff. Perimeter (km)
Telefon-CR70	1956	Brecher	0.627		7.191	
Telefon-CR70	1968	Brecher	0.683	0.056	9.913	2.722
Telefon-CR70	1968	Brecher	0.693		10.164	
Telefon-CR70	1970	Brecher	0.704	0.010	8.727	-1.436
Telefon-CR70	1970	Brecher	1.134		9.278	
Telefon-CR70	2003	Spanish SGE	1.081	-0.053	8.857	-0.420

Table 1: Volume and perimeter results for Telefon Bay and Craters of 1970s

Zone	Year	Source	Volume (km3)	Difference Vol (km3)	Shore perimeter (km)	Diff. Perimeter (km)
Island	1956	D.O.S	14.364			
Island	2003	Spanish SGE	14.466	0.101		
Inner shoreline	1829	Kendall			38.852	
Inner shoreline	2003	Spanish SGE			35.508	-3.344
Island	1956	D.O.S.			90.693	
Island	2003	Spanish SGE			93.162	-2.468
Inner shoreline	1956	D.O.S.			35.203	
Inner shoreline	2003	Spanish SGE			35.255	-0.052

Table 2: Volume and perimeter results for the whole island.

FIG. CAPTIONS

Fig. 1: Regional setting and location of Deception Island (South Shetland Islands, Antarctica)

Fig. 2: Toponyms of research and historical eruption sites on Deception Island. . Solid lines represent regional morphological lineations.

Fig. 3: Morphological changes in Telefon Bay and Craters of the 1970s since: a) 1829 (Kendall's map), b) 1956 (D.O.S. map), c) 1956 (Brecher´s map), d) 1968 (Brecher´s map), e) 1970 (Brecher´s map) and f) 2003 (QuickBird image).

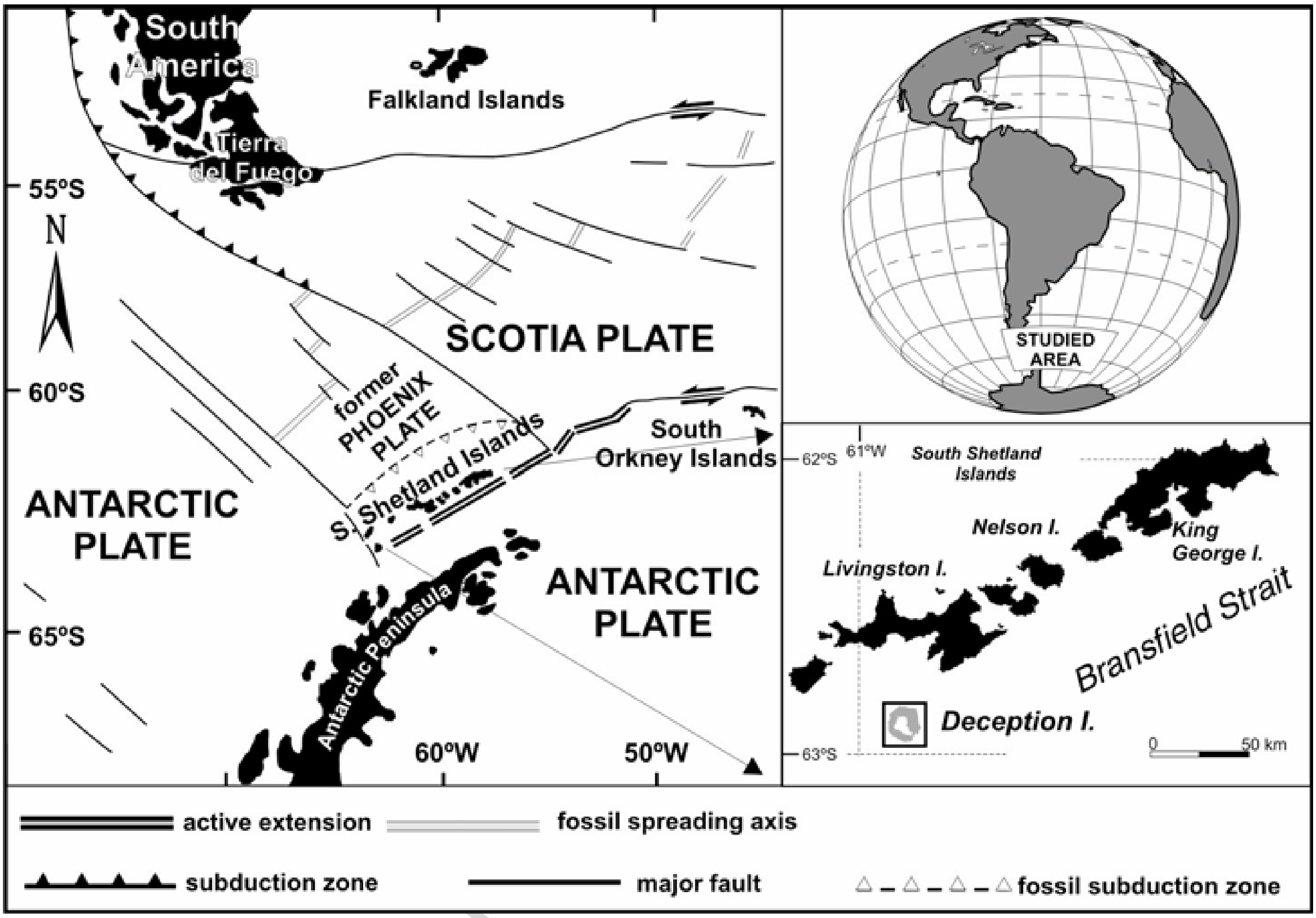
Fig. 4: Demarcation of the area common and determination of coastal area growth: a) Area common to the maps of 1956 and 1968, b) Coastal area growth between 1956 and 1968, c) Area common to the maps of 1968 and 1970 and d) Coastal area growth between 1968 and 1970.

Fig. 5: DEM of 1970 and 2003 for Craters of 1970s study area.

Fig. 6: Difference in elevation values between Brecher's 1970 map and the current 2003 SGE map showing new features in Craters of 1970´s and a slope error

Fig. 7: Difference in topographic elevation values between the DOS map of 1956 and the current 2003 SGE map, and the 1829 shoreline from Kendall´s map over the current limit of Deception Island.

Fig. 1.



South America
Falkland Islands
Tierra del Fuego
55ºS
N
60ºS
65ºS
SCOTIA PLATE
former PHOENIX PLATE
S. Shetland Islands
South Orkney Islands
ANTARCTIC PLATE
ANTARCTIC PLATE
Antarctic Peninsula
60ºW
50ºW
STUDIED AREA
62ºS
61ºW
South Shetland Islands
Nelson I.
King George I.
Livingston I.
Bransfield Strait
Deception I.
63ºS
0
50 km
active extension
fossil spreading axis
subduction zone
major fault
fossil subduction zone

Fig. 2.

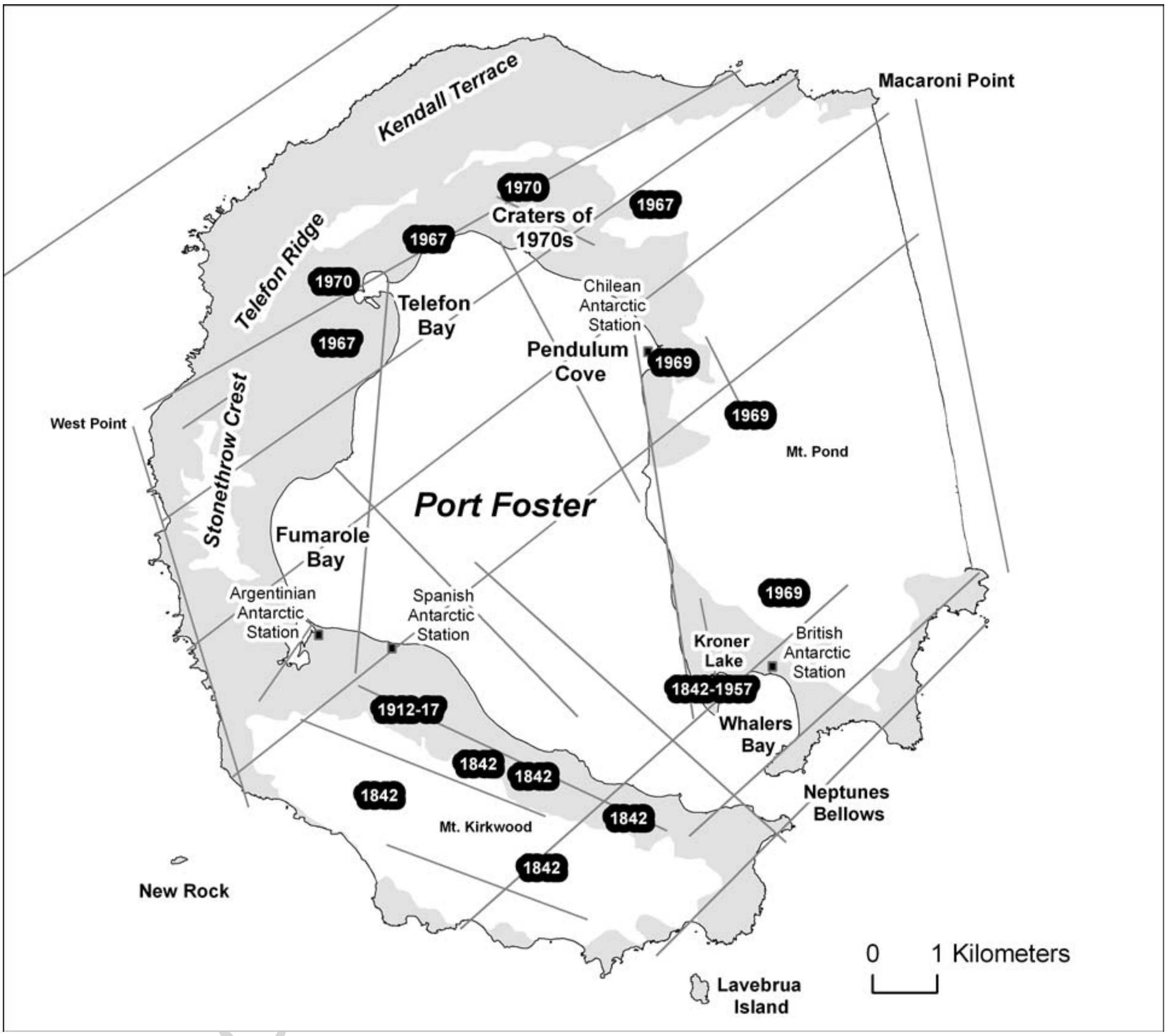

Kendall Terrace
Macaroni Point
1970
Craters of 1970s
1967
1967
Telefon Ridge
1970
Telefon Bay
Chilean Antarctic Station
1967
Pendulum Cove
1969
West Point
Stonethrow Crest
1969
Mt. Pond
Port Foster
Fumarole Bay
1969
Argentinian Antarctic Station
Spanish Antarctic Station
British Antarctic Station
Kroner Lake
1842-1957
1912-17
Whalers Bay
1842
1842
1842
Neptunes Bellows
1842
Mt. Kirkwood
1842
New Rock
0 1 Kilometers
Lavebrua Island

Fig. 3.

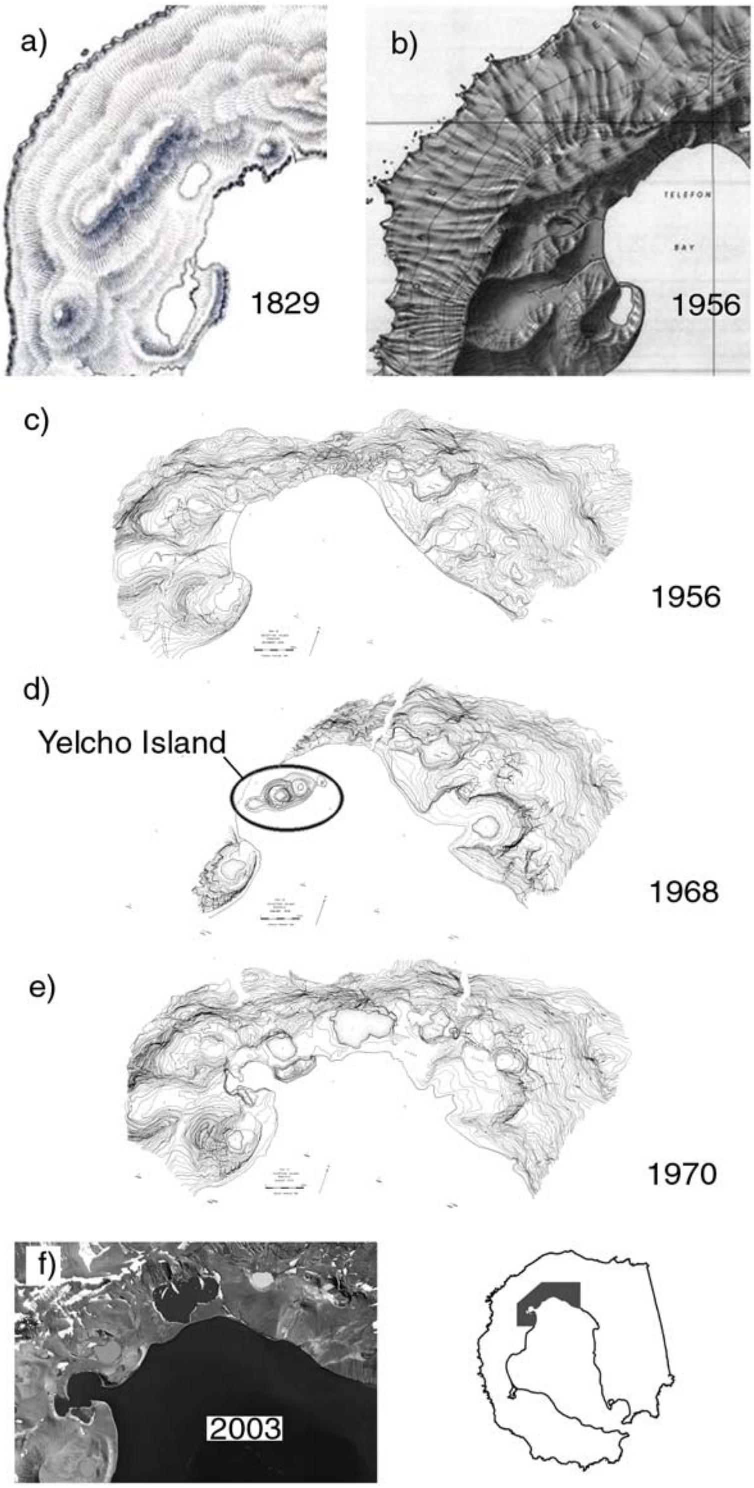

a)
1829
b)
TELEFON
BAY
1956
c)
1956
d)
Yelcho Island
1968
e)
1970
f)
2003

Fig. 4.

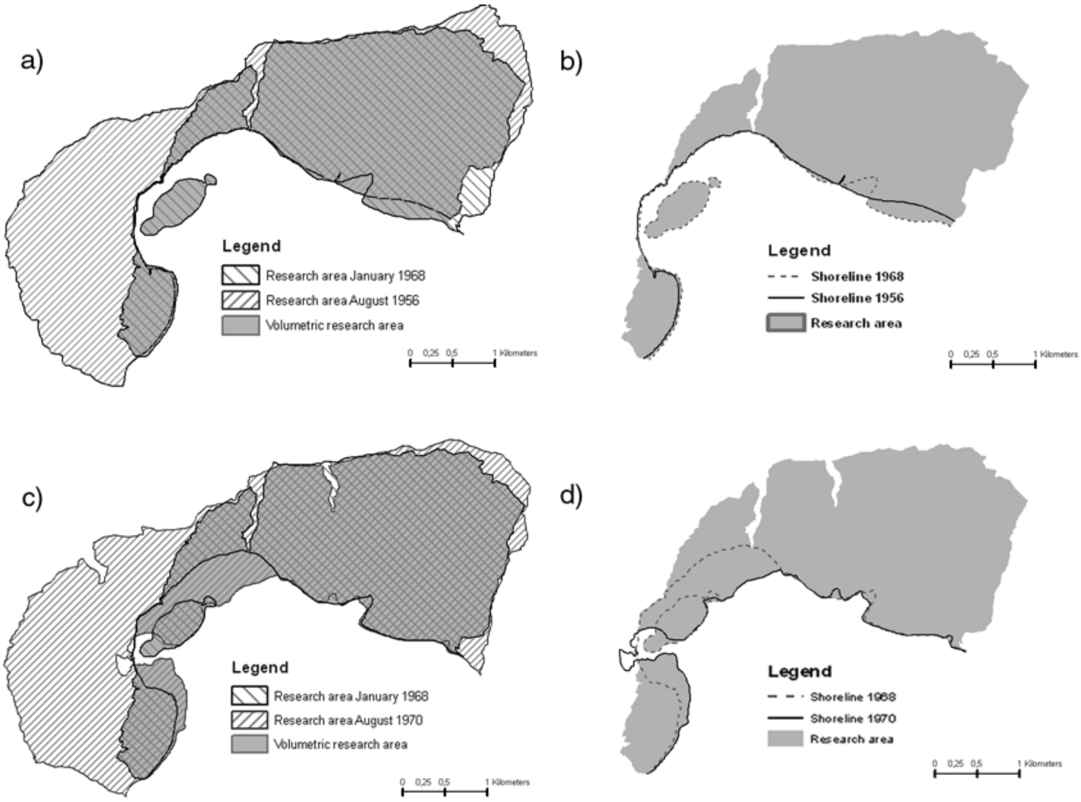
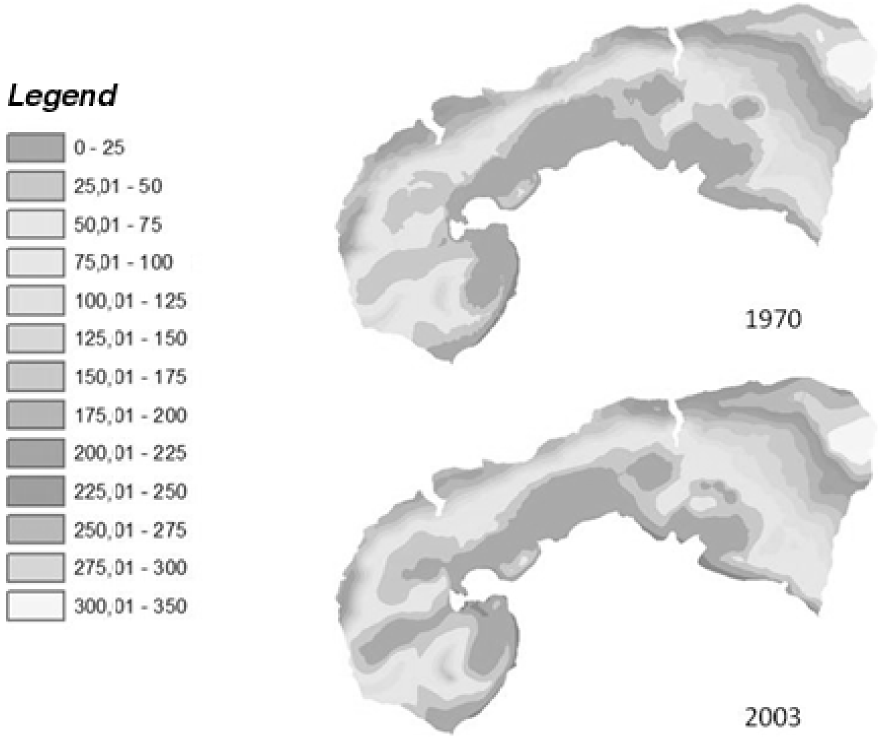

a)
Legend
Research area January 1968
Research area August 1956
Volumetric research area
0 0,25 0,5 1 Kilometers
b)
Legend
Shoreline 1968
Shoreline 1956
Research area
0 0,25 0,5 1 Kilometers
c)
Legend
Research area January 1968
Research area August 1970
Volumetric research area
0 0,25 0,5 1 Kilometers
d)
Legend
Shoreline 1968
Shoreline 1970
Research area
0 0,25 0,5 1 Kilometers

Fig. 5.


Legend
0 - 25
25,01 - 50
50,01 - 75
75,01 - 100
100,01 - 125
125,01 - 150
150,01 - 175
175,01 - 200
200,01 - 225
225,01 - 250
250,01 - 275
275,01 - 300
300,01 - 350
1970
2003

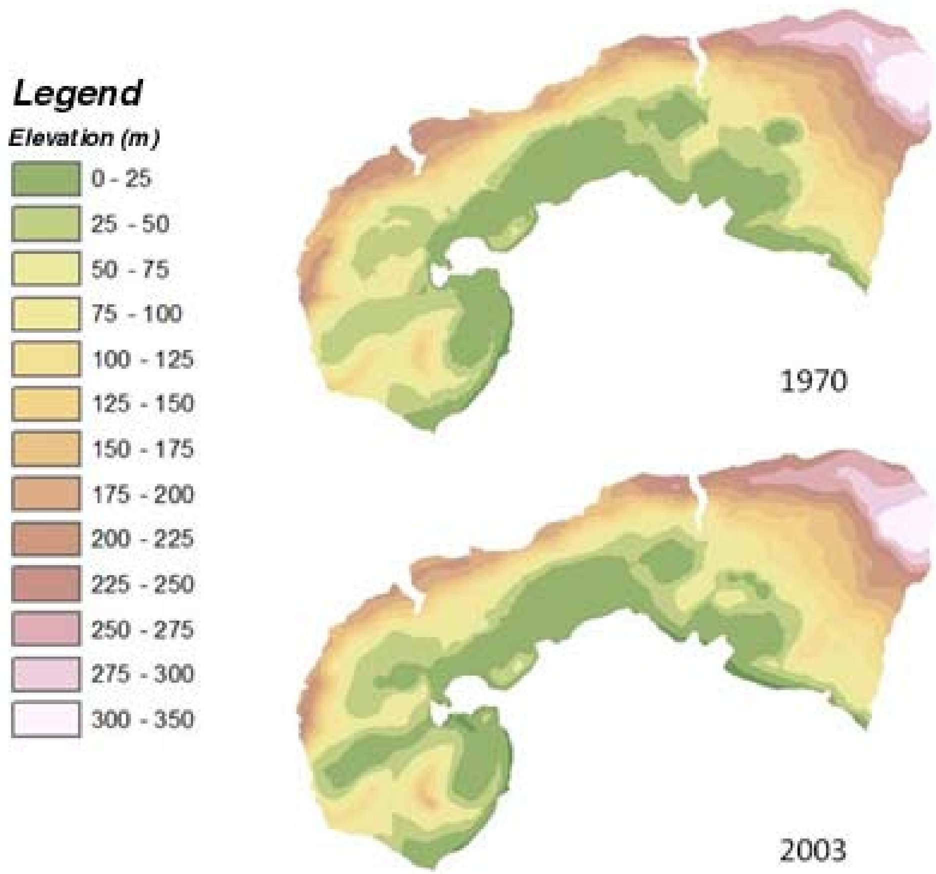
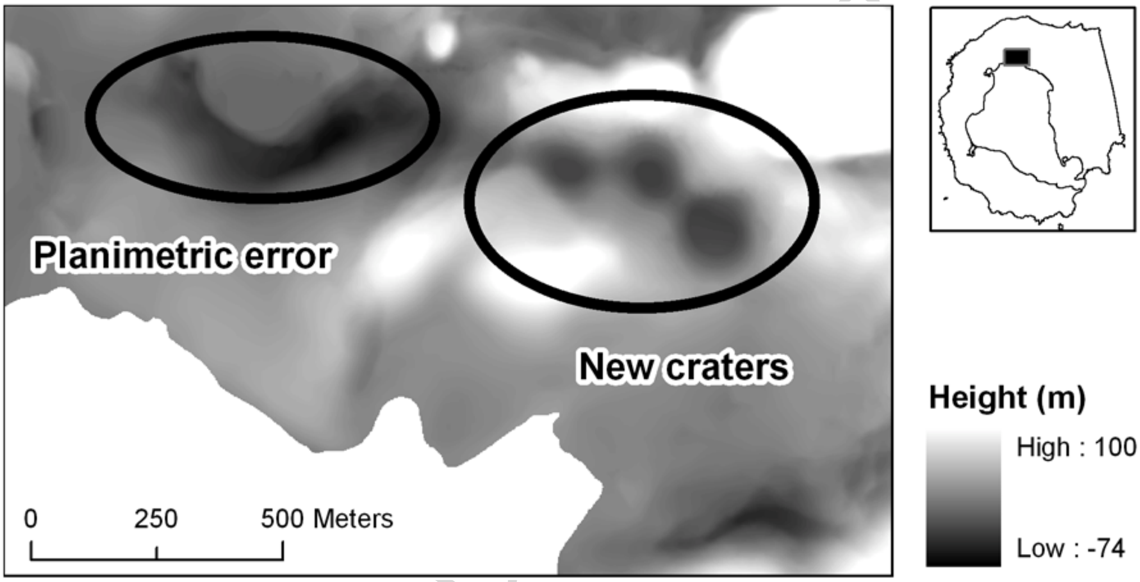

Legend
Elevation (m)
0 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
150 - 175
175 - 200
200 - 225
225 - 250
250 - 275
275 - 300
300 - 350
1970
2003

Fig. 6.



Planimetric error
New craters
0
250
500 Meters
Height (m)
High : 100
Low : -74

Fig. 7.

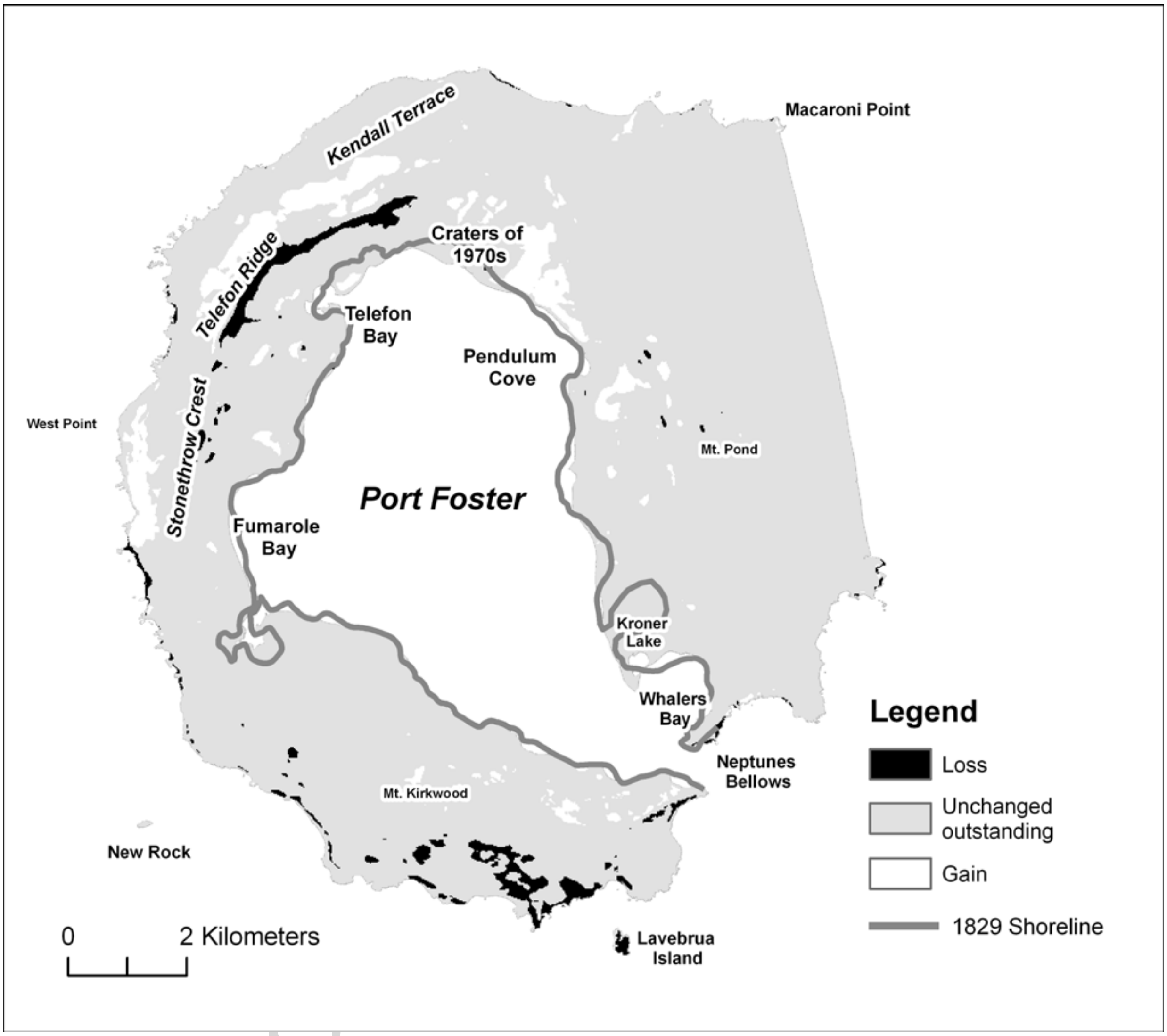
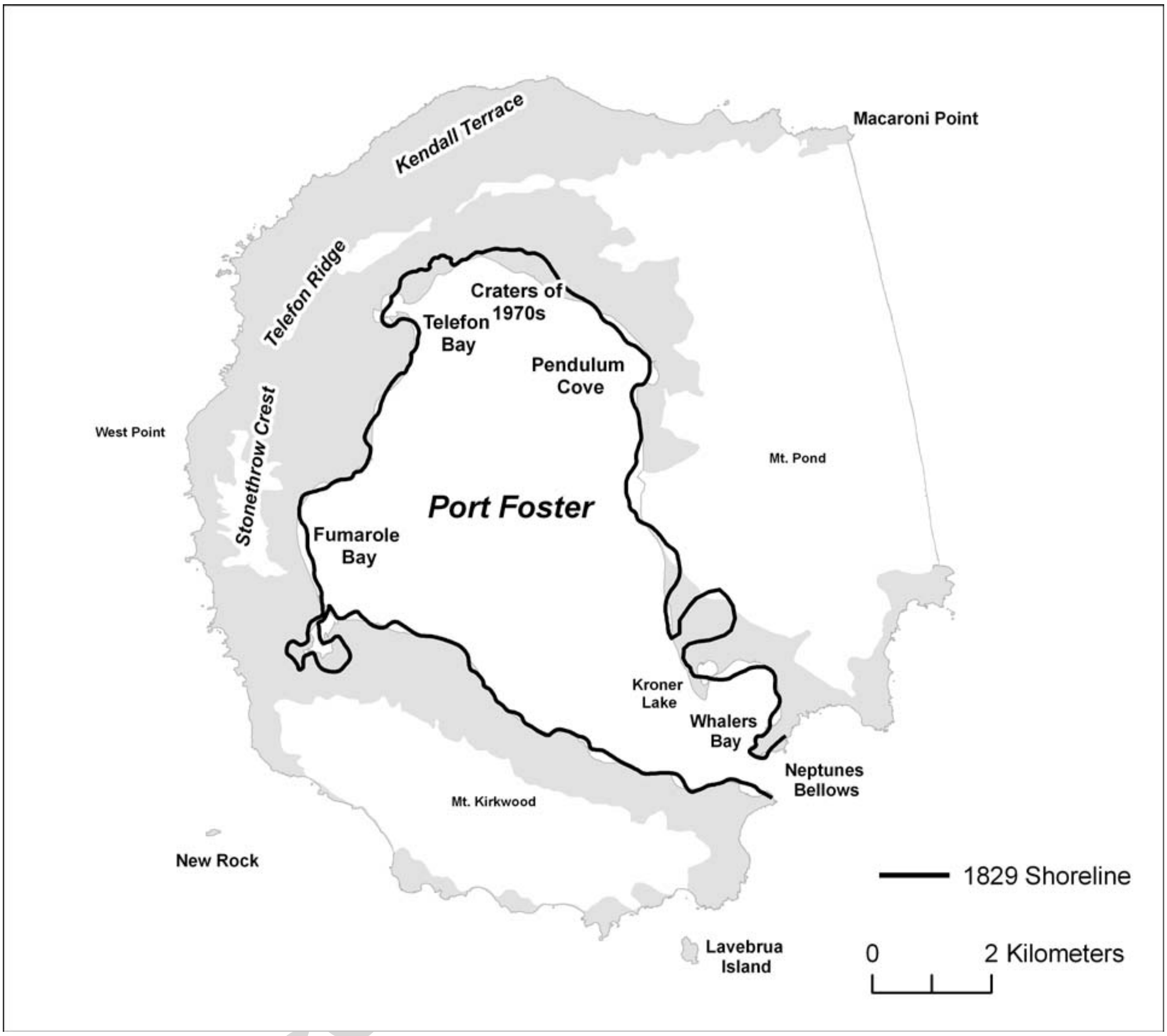

Macaroni Point
Kendall Terrace
Telefon Ridge
Craters of 1970s
Telefon Bay
Pendulum Cove
Stonethrow Crest
West Point
Mt. Pond
Port Foster
Fumarole Bay
Kroner Lake
Whalers Bay
Legend
Neptunes Bellows
Loss
Mt. Kirkwood
Unchanged outstanding
New Rock
Gain
0
2 Kilometers
1829 Shoreline
Lavebrua Island

Fig. 8.


Kendall Terrace
Macaroni Point
Telefon Ridge
Craters of 1970s
Telefon Bay
Pendulum Cove
West Point
Stonethrow Crest
Mt. Pond
Port Foster
Fumarole Bay
Kroner Lake
Whalers Bay
Neptunes Bellows
Mt. Kirkwood
New Rock
1829 Shoreline
Lavebrua Island
0
2 Kilometers