PERGAMON

Deep-Sea Research II 50 (2003) 1595–1609

DEEP-SEA RESEARCH
Part II

www.elsevier.com/locate/dsr2

Editorial

Ecosystem studies at Deception Island, Antarctica: an overview

1. Introduction

The Southern Ocean represents one of the most extreme marine environments on Earth, characterized by low temperature throughout the water column and extensive seasonal ice cover resulting in high temporal variability in primary production (Smith and Nelson, 1986; Arrigo et al., 1997). This fluctuating production of organic matter heavily impacts the marine ecosystem. Ship-based measurements and observations during all seasons of the year have provided a description of ecosystems encompassing surface to benthic communities (Ainley et al., 1991; Lancraft et al., 1991; Siegel et al., 1992; Hopkins et al., 1993; Grebmeier and Barry, 1991; Knox, 1994). However, seasonal ice cover has impeded year-round studies of how these ecosystems function, especially under such extreme conditions.

Long time-series studies are critical in understanding processes affecting marine ecosystems on seasonal and annual time scales (Austen et al., 1991; Brodeur and Ware, 1992; Deuser et al., 1995). Such studies are especially important in geographic regions, such as the Southern Ocean, that experience high annual variability in physically and/or chemically mediated processes (e.g., Franklin, 1989). *In situ* long-term monitoring has been employed successfully in the Southern Ocean to document extreme temporal variability in the sinking of particulate matter (e.g., Collier et al., 2000). Much of this variability appears related to seasonal ice cover and the production of organic matter in the surface waters of both open-ocean (Wefer et al., 1988; Fischer et al., 1988; Wefer and Fischer, 1991) and shelf (Fukuchi et al., 1988; Dunbar et al., 1989, 1998; DeMaster et al., 1992) environments.

A study of the marine ecosystem associated with Port Foster, Deception Island, in the South Shetland Islands, Antarctica (Fig. 1), was undertaken with the intent of utilizing a long time-series approach to monitoring the unique marine communities in this polar environment throughout an annual cycle. Such long time-series studies are essential to understanding the impact of global warming in these highly temperature-sensitive environments. Evidence is now accumulating that the Antarctic Peninsula area has warmed over the past half century by as much as 2.5°C along the western coastline (Vaughan and Doake, 1996; Vaughan et al., 2001). Warming in the Antarctic Peninsula region, including the South Shetland and South Orkney Islands, has been related to changes in marine populations ranging from predators such as penguins (Fraser et al., 1992) seals and albatross to prey such as krill (Reid and Croxall, 2001).

Port Foster, the sunken, seawater flooded caldera of Deception Island, was chosen for our studies because of its proximity to Antarctic stations located within the South Shetland Islands and along the northwestern side of the Antarctic Peninsula (Fig. 1) where long time-series climate and marine community data have been collected for decades. Deception Island is also the site of several scientific stations occupied by British, Chilean, Argentine and Spanish contingents since the mid-1930s. This island also afforded a unique opportunity to work in a semi-enclosed environment that could be monitored effectively with long-term instrumentation while being free from

doi:10.1016/S0967-0645(03)00081-X

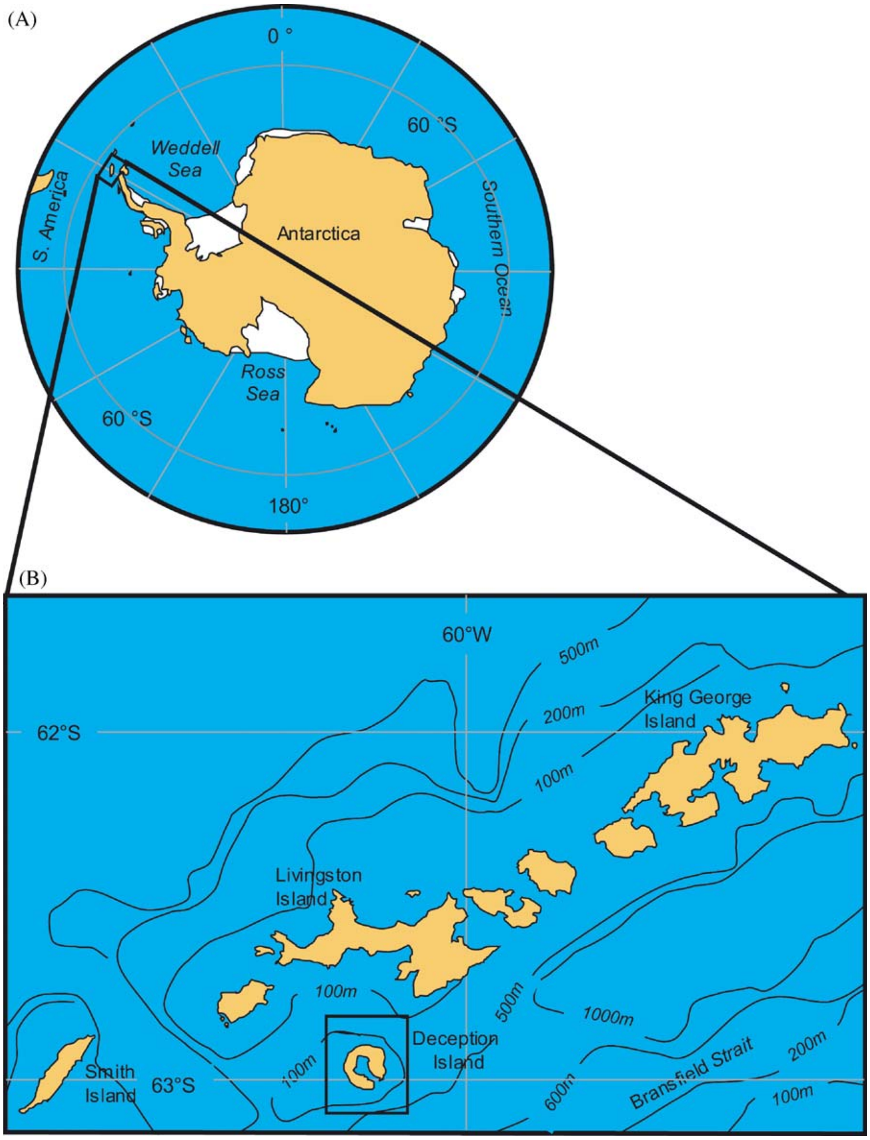

Fig. 1. Regional map: (A) southern tip of South America and the Antarctic continent, (B) South Shetland Island Chain with Deception Island highlighted.

the damaging effects of the increasing prevalence of icebergs due to warming in the peninsular region.

2. Area of investigation

2.1. Geological setting

Deception Island is an active volcano on the southwestern end of the South Shetland Island chain. This island chain parallels the northeastern curvature of the Antarctic Peninsula but is separated from the Antarctic continent by the narrow Bransfield Strait (Fig. 1B). The volcanic activity of Deception Island is attributed to its location in the confluence of two tectonically active features, the southwestern section of Bransfield Trough and the intersecting southern extension of the Hero Fracture zone (Rey et al., 1995).

The South Shetland Island volcanic arc formed in association with subduction of the Drake plate into the South Shetland trench (Barker and Austin, 1998). Barker and Austin (1998) suggest that tectonic crustal extension in the back-arc region behind the South Shetland Islands formed the Bransfield Strait. Seismic-wave field analyses of events centered at Deception Island (Ibáñez et al., 2000) and ^{3}He values (Schlosser et al., 1988) measured in the Bransfield Strait waters further support the interpretation that volcanism at Deception Island is associated with eruption of mid-ocean-ridge-like basalt in a back-arc environment. There is regular seismic activity attributed to both tectonic and volcanic processes at Deception Island. Volcanic activity at Deception Island, has been prevalent over the last century, with eruptions in 1967, 1969 and 1970 (Baker et al., 1975).

The volcanic cone of Deception Island extends to 542 m above sea level (Mount Pond), with an emergent diameter of 15 km (Marti et al., 1996). A large flooded caldera located in the center of the island communicates with the surrounding Bransfield Strait through a narrow channel (Neptune's Bellows) (Fig. 2) is approximately 550 m wide at the narrowest point with a sill depth of 11 m. The large protected embayment formed within the caldera, Port Foster, is 9.8 km long by 5.7 km wide situated along a northwest to southeast axis with the opening to Bransfield Strait through the collapsed southeast wall of the volcanic cone. The sharp topography of the surrounding walls of the volcano is overlain by pyroclastic ash and lapilli-tuff that is snow-covered from June through November. Glaciated portions of the prominent peaks, Mount Pond and Mount Kirkwood, extend to the periphery of the island on the eastern and southern shore line (Marti et al., 1996) covering approximately 57% of the island (Smellie et al., 1997). This permanent ice also extends down to the beaches as ice-cored moraines in several locations along the eastern shoreline of Port Foster. The outer perimeter of Deception Island is characterized by precipitous cliffs and exposed outcrops of basalt and permanent ice that are frequently buffeted by wind-driven seas. Transport of sediment (lapilli-tuff) by wind and melt water into Port Foster has been documented (Gallardo et al., 1977; Drago, 1987). This transported material settles to the sea floor (Fratt and Dearborn, 1984) resulting in a relatively flat expanse of sand and silt across the caldera that ranges in water depths from 130 to 160 m. Bathymetric records between 1949 and 1993 indicate shoaling rates of up to 0.5 m per annum that have been attributed to fluvial re-deposition and pyroclastic input (Cooper et al., 1998). Small volcanic cones are located around the southern end of Port Foster (Fig. 2) where the highest rates of uplifting occur (Cooper et al., 1998).

The surrounding slopes of Port Foster are generally precipitous at higher elevations tapering gradually to a series of cliffs, runoff canyons and narrow beaches. Small embayments exist including Whalers Bay and Pendulum Cove on the eastern shoreline and Fumarole Bay on the western shoreline (Fig. 2). Telefon Bay at the northern extent of Port Foster is the site of the volcanic eruption in 1967 which formed a new island (Orheim, 1972). The most recent eruptions in 1969 and 1970 were centered on Mount Pond, creating several large fissures in the permanent ice cover.

Fumarolic emissions, thermal springs, and sediments generally occur along a principal fracture that transects the island in a NE–SW direction encompassing the areas of Fumarole Bay, Telefon Bay, and Pendulum Cove (Ortiz et al., 1992). Temperatures of fumarolic discharges as high as 110°C have been recorded in the area of Fumarole Bay depending on the tidal cycle. Bottom-water temperatures of 2–3°C have been reported in the central and northern sector of Port Foster, suggesting geothermal heating (Ortiz et al., 1992). At low tide, steam rises from the overlying waters and beach sediments primarily in the vicinity of Fumarole and Whalers Bay, and Pendulum Cove. Emissions of H_2S and H_2 have been reported in the vicinity of Fumarole Bay (Ortiz et al., 1992). Methane concentrations in Port Foster indicate some venting of hydrothermal fluids (Tilbrook and Karl, 1993). High concentrations of Fe, Mn and Si in water collected nearshore and in freshwater lakes on Deception Island indicate volcanic enrichment (Elderfield, 1972).

There are 11 freshwater ponds and lakes surrounding the caldera ranging from <1 to 36 m in depth and from 2.6×10^3 to

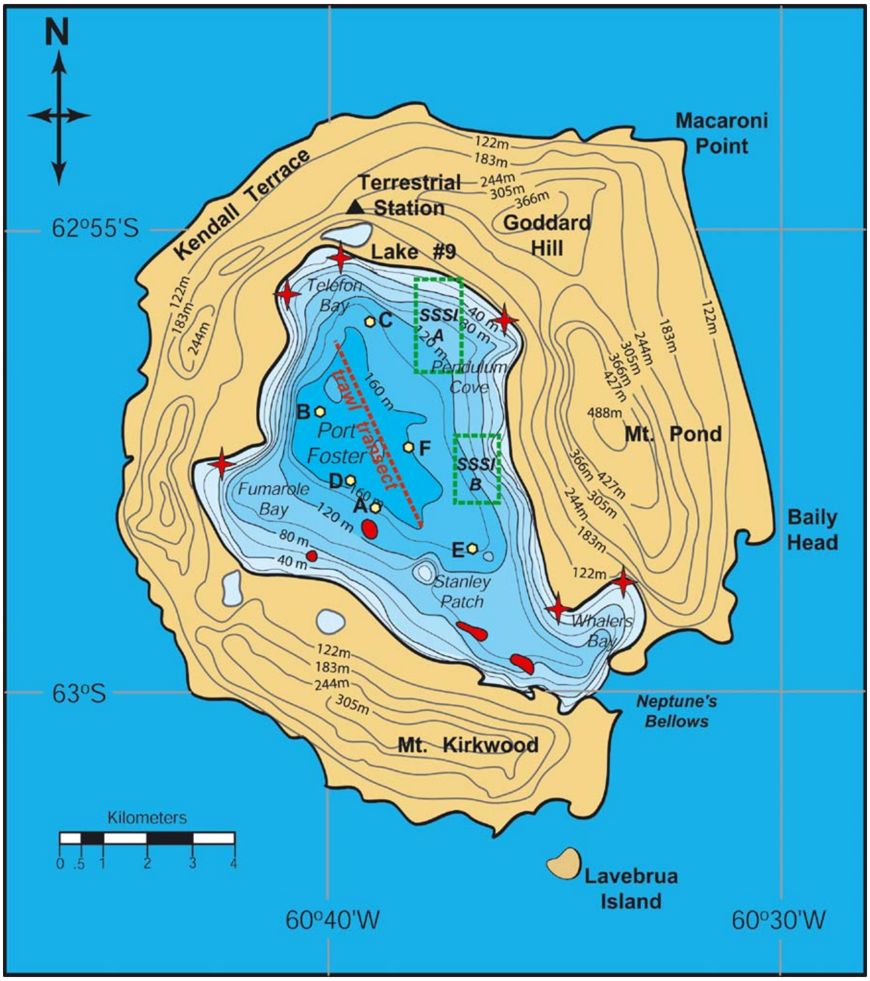

Fig. 2. Chart of Deception Island with corrected bathymetry of Port Foster and showing, fumaroles = ✦ (Cooper et al., 1998), submarine volcanic domes = ● (Rey et al., 1995) SSSI sites (A and B), long-term mooring locations (A—thermistor array, B—thermistor array with acoustic Doppler current profiler, C—thermistor array, D—sediment traps and time-lapse camera, E—vertically profiling acoustic array, F—vertically profiling pump sampler), pelagic and benthic trawling transect, and the Terrestrial station (▲).

$298.3 \times 10^3\,m^2$ in area (Drago, 1989). The largest lake (Lake #9) lies in close proximity to the northern shore of Port Foster (Fig. 2). The only visible terrestrial vegetation on the island are patches of lichens and bryophytes located primarily in areas of moisture and substrate stability (Smith, 1988).

2.2. Historical perspective

The South Shetland Islands, including Deception Island, were first explored and claimed by Great Britain in 1819, with its subsequent charting in 1820. The principal interest in these islands was the southern fur seal populations, which were exploited to near extinction by 1830. The commercial enterprise of whaling reached the Antarctic in the late 1800s, and a Norwegian Whaling station was built and operated from 1910 until 1931 in Whalers Bay, the protected embayment just inside Neptune's Bellows (Fig. 2). Depletion of whale stocks in the Antarctic brought the demise of the whaling station at Deception Island. However, the British Antarctic Survey developed the old Norwegian whaling station at Whalers Bay into a scientific station in 1944. In subsequent years Argentine and Chilean stations were established in Port Foster at Fumarole Bay and Pendulum Cove, respectively. A major eruption in the vicinity of Telefon Bay caused the temporary evacuation of these stations in 1967. A subsequent eruption on Mount Pond in 1969 produced a heavy deluge of pyroclastic material in the area of Pendulum Cove and Whalers Bay, burying portions of the Chilean and British stations, leading to their final evacuations at that time. These two stations have never been rebuilt, and only two seasonal bases currently exist on Deception Island, the Argentine station and a Spanish seismic station, both located on the shore of Fumarole Bay. The remains of the whaling station and the British station at Whalers Bay were designated a historic site under the Antarctic treaty of 1995. Tour ships frequent Port Foster in austral summer, disembarking their passengers to explore this historic site and the fumarole areas in Pendulum Cove. There is considerable concern about increasing tourism and its impact on this "fragile ecosystem" (Smith, 1988). Sites of special scientific interest (SSSI; Fig. 2) were established in both marine and terrestrial sites at Deception Island by the Antarctic Conservation Act of 1978 to protect areas from anthropogenic intervention and permit long-term studies on the impact of volcanic activity on the associated communities of organisms.

2.3. Biological perspective

No definitive studies of the pelagic and benthic communities within Port Foster were conducted prior to our studies that were initiated in 1999. The pelagic fauna, particularly krill populations of *Euphausia crystallorophias*, *E. superba* and *Thysanoessa* sp. were identified in Port Foster (Everson, 1987; Brinton and Townsend, 1991). *E. crystallorophias* and *E. superba* have been found incapacitated along the beach in Pendulum Cove as a result of elevated hydrothermal temperatures (Brierley, 1999). Brinton and Townsend (1991) compared *E. crystallorophias* in Port Foster with populations in the Bransfield Strait and found similar frequency distributions of size and developmental stage in the two locations at the same time. These findings suggested that *E. crystallorophias* from Port Foster and Bransfield Strait belonged to the same population. Other pelagic species identified included the notothenioid fishes *Notothenia newnesi* and *Champsocephalus gunnari* (Everson, 1987).

Benthic communities reported from Port Foster include species found at comparable depths elsewhere in the Antarctic (Arntz et al., 1994). Littoral and sub-littoral macroalgae within Port Foster include species of Chlorophyta, Phaeophyta and Rhodophyta belonging primarily to widely distributed Antarctic, polar and cold-water species (Clayton et al., 1997; Gallardo et al., 1999). Macrobenthic fauna in Port Foster is characterized by low taxonomic richness and high biomass compared to other sampling areas within the South Shetland Islands (Arnaud et al., 1998). Arnaud et al. (1998) describe a depth zonation of dominant benthic taxa in Port Foster with Ascidiacea between 40 and 50 m, Echinoidea Regularia from 100 to 150 m and Ophiuroidea dominating below 150 m. These faunistic zonations are coincident with changes in sediment type from gravel at the shallow stations to sandy and ultimately muddy sediments at the deepest depths. The dominance of benthic suspension feeders at shallower depths has been related to a close coupling with food in the overlying water (Saiz-Salinas and Ramos, 1999). The dominant macrobenthic fauna were the echinoid, *Sterechinus neumayeri* and the ophiuroid, *Ophionotus victoriae* (Gallardo et al., 1977; Retamal et al., 1982; Fratt and Dearborn, 1984; Gallardo, 1987; Arnaud et al., 1998). Gallardo et al. (1977) found that the structure and composition of the benthic community in Port Foster were altered after the 1967 eruption and attributed these changes to volcanic perturbation.

Top predators on Deception Island and in the immediate vicinity of Port Foster during our study included gentoo (*Pygoscelis papua*) and chinstrap (*P. antarctica*) penguins, frequently seen gliding through the water in search of krill or resting on the beaches (Kendall et al., 2003). The cape petrel (*Daption capense*) nested in the high cliffs near Neptune's Bellows and sought pelagic prey both inside and outside of Port Foster. Other avian inhabitants were the Antarctic skua (*Catharacta antarctica*) and kelp gulls (*Larus dominicanus*). The dominant mammal on the island is the southern fur seal (*Arctocephalus gazella*), which frequently forms large aggregations on southwestern beaches of Port Foster near Neptune's Bellows.

3. Climatic conditions of area

Day length ranges from a winter minimum of 5–6 h to a summer maximum of 19–20 h at this latitude (cf. Smith and Sakshaug, 1990), with seasonal ice covering up to 80% of Port Foster in July and August (Igarzabal, 1974). Increasing air temperature in the western Antarctic Peninsula region over the past half century has been correlated with high inter-annual variability of sea ice coverage (Smith et al., 1996), suggesting that ice cover within Port Foster is changing as well. There is also a statistical coherence between air temperature and ice cover with the Southern Oscillation Index, a major indicator of El Nino Southern Oscillation events (Smith et al., 1996).

Because of the changing climatic conditions reported for the region surrounding Deception Island, we developed a long time-series Terrestrial station to continuously monitor air temperature and wind velocity as well as take a daily picture of Port Foster to record weather and sea-ice conditions from a promontory on the northern ridge at 200 m altitude (Fig. 2). Over the period of deployment from 12 March 1999 until 21 November 2000, the temperature at the Terrestrial station ranged from -12.6° in August 2000 to 2.7°C in March 1999. Daily average wind speeds were highest in June ($47.4\,\mathrm{m\,s^{-1}}$) but highly variable throughout the year. Ice became visible in the daily photographs of Port Foster in July and disappeared in November 2000 (Smith et al., 2003). Representative photographs of ice-free and ice-covered conditions in Port Foster are shown in Fig. 3.

4. Erupt program

The primary goal of our study was to monitor the seasonal changes in the marine ecosystem within Port Foster utilizing remote sensing instrumentation for continuous sampling combined with seasonal sampling on cruises. Our field program at Deception Island, ERUPT, began in March 1999 and continued through November 2000 (Table 1). Measurements and sampling ranged from local weather to the physical, chemical, biological and geological oceanography of Port Foster. Ice cover, air temperature and wind velocity (Table 1) were monitored by the Terrestrial station located on the northern ridge of Deception Island (see Fig. 3).

To characterize the water column, three thermistor arrays were positioned in the central area of Port Foster to measure water temperature at 10-m intervals from the bottom to within 20 m of the surface (Fig. 4). An acoustic Doppler current profiler was placed at the base of one of these thermistor moorings to provide an integrated measure of current velocity throughout the water column. An acoustically activated pop-up buoy was secured to the top of each array at 20 m depth to avoid contact with ice and surface ships while permitting instrument recovery and data retrieval. Vertical profiles of salinity, temperature, dissolved oxygen, fluorescence, transmissivity and irradiance data, and water samples for nutrient analyses were collected using a CTD/rosette at seven stations in Port Foster during each cruise (Table 1). Sampling stations included the north, center and southern end of Port Foster, Stanley Patch and the peripheral coves (Whaler's Bay, Pendulum Cove, Telefon Bay and Fumarole Bay: Fig. 2). Salinity and temperature data along with water samples were collected from shallow near-shore and beach interstitial water sites, especially targeting areas with water temperatures higher than ambient indicating hydrothermal activity.

An upward-looking acoustic array was developed and moored on the sea floor to monitor the vertical distribution, movements and size of acoustically reflective targets (macrozoplankton and micronekton) through the water column (Fig. 4). To provide identification of the faunal targets recorded with the acoustic array, a vertically profiling pump sampler was developed. This pump sampler was designed to make timed excursions to the surface while collecting and preserving the

(A) Ice Free

(B) Ice Cover

Fig. 3. Terrestrial station photographs of Deception Island and Port Foster viewed from the northern ridge looking south with Lake #9 in the foreground and Neptune's Bellows in the distance to the southeast and Mount Kirkwood to the southwest. (A) Port Foster under ice-free conditions on 16 April 1999. (B) Port Foster with ice cover on 12 September 2000.

pelagic fauna by depth with each profile. Phytoplankton were collected with towed, open surface nets and enumerated seasonally. Macrozooplankton and micronekton were sampled at discrete 50-m depth intervals from the surface to the bottom on a diel schedule using 1 and 10 m^2 multiple opening/closing net systems on each cruise (Table 1). A portable weighing station was established ashore at the northern end of Port Foster to measure fresh biomass of dominant pelagic species avoiding problems with shipboard motion.

Sediment traps equipped with timed sequencers were moored at 50 and 20 m above bottom in central Port Foster (160 m total water depth; Fig. 4) to collect the sinking particulate matter at 10–18-day intervals for organic and inorganic chemical analyses (Table 1). At the bottom of this mooring was a time-lapse camera system to take hourly photographs of the sea floor and record sedimentation events as well as the distribution, size and movements of the epibenthic megafauna.

Benthic surveys were conducted on the first two cruises with an ROV equipped with a video camera (Table 1). A small piston operated grab respirometer (POGR) was deployed on cruises to measure in situ sediment community oxygen consumption and recover sediment for chemical and biological analyses and infaunal abundance

Table 1
Summary of time-series measurements and sampling conducted at Deception Island from March 1999 through November 2000

Sampling month	1999										2000										
Erupt cruises	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N
	I								II			III			IV						V
Measurements/sampling																					
Weather																					
Wind speed/direction	M	—	—	—	J										M	—	—	—	—	—	N
Air temperature	M	—	—	—	J										M	—	—	—	—	—	N
Photographic monitoring	M	—	—	—	J										M	—	—	—	—	—	N
Oceanography																					
Water column																					
Ice cover monitoring	M	—	—	—	J										M	—	—	—	—	—	N
Current speed/direction												F	—	—	—	—	—	—	—	—	N
Temperature																					
Long term (thermistor array)	M	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	N
Short term (CTD)	M								N			F			M/J						N
Salinity	M								N			F			M/J						N
Nutrients (NO_3, SiO_4, PO_4)	M								N			F			M/J						N
Dissolved oxygen	M								N			F			M/J						N
Chlorophyll/phaeopigments (in vivo—surface)	M								N			F			M/J						N
Sinking particulate matter (50 mab, 20 mab)																					
Total mass	M	—	—	—	—	—	—	—	—	D					M/J	—	—	—	—	—	N
Total carbon	M	—	—	—	—	—	—	—	—	D					M/J	—	—	—	—	—	N
Inorganic carbon	M	—	—	—	—	—	—	—	—	D					M/J	—	—	—	—	—	N
Organic carbon	M	—	—	—	—	—	—	—	—	D					M/J	—	—	—	—	—	N
Total nitrogen	M	—	—	—	—	—	—	—	—	D					M/J	—	—	—	—	—	N
Chlorophyll-*a*	M	—	—	—	—	—	—	—	—	D					M/J	—	—	—	—	—	N
Phaeopigments	M	—	—	—	—	—	—	—	—	D					M/J	—	—	—	—	—	N
Phytoplankton																					
Species composition	M								N			F			M/J						N
Abundance	M								N			F			M/J						N
Macrozooplankton																					
Species composition	M								N			F			M/J						N
Vertical distribution	M								N			F			M/J						N
Abundance	M								N			F			M/J						N
Biomass	M								N			F			M/J						N
Micronekton																					
Species composition	M								N			F			M/J						N
Vertical distribution	M								N			F			M/J						N
Abundance	M								N			F			M/J						N
Biomass	M								N			F			M/J						N
Sediments																					
Bathymetry	M								N												
Chemical composition																					
Total carbon									N			F			M/J						N
Inorganic carbon									N			F			M/J						N
Organic carbon									N			F			M/J						N
Total nitrogen									N			F			M/J						N
Chlorophyll-*a*/phaeopigments									N			F			M/J						N
Macrofauna/meiofauna																					
Species composition									N			F			M/J						N
Abundance									N			F			M/J						N

Table 1 (*continued*)

Sampling month	1999										2000										
Erupt cruises	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N
	I								II			III			IV						V
Biomass									N			F			M/J						N
Sediment community oxygen consumption									N			F			M/J						N
Epibenthic megafauna																					
Species composition	M								N			F			M/J						N
Distribution	M								N			F			M/J						N
Abundance	M								N			F			M/J						N
Movement (activity)[b]	M	—	—	—	—	—	—	—	—	—	—	F			M/J	—	—	—	—	—	N
Fishes																					
Species composition	M								N			F			M/J						N
Abundance	M								N						M/J						N
Reproduction	M								N			F			M/J						N
Diet	M								N			F			M/J						N
Parasites	M								N			F			M/J						N
Marine birds and mammals																					
Species composition	M								N			F									N
Abundance	M								N			F									N
Distribution	M								N			F									N
Instrumentation																					
Weather																					
Terrestrial station	M	—	—	—	J										M/J	—	—	—	—	—	N
Oceanography																					
Thermistor array	M	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	N
ADP												F	—	—	—	—	—	—	—	—	N
Sediment traps	M	—	—	—	—	—	—	—	—	D					M/J	—	—	—	—	—	N
Upward-looking acoustic array															M/J	—	—	—	—	—	N
Pump sampler[a]												F	—	—	—	—	—	—	—	—	N
Time-lapse camera	M	—	—	—	—	—	—	—	—	—	—	F			M/J	—	—	—	—	—	N
Piston operated grab respirometer									N			F			M/J						N
ROV survey	M								N												

The five ERUPT cruises are denoted by roman numerals and represent those periods of point measurements and sampling (capitol letter for month of sampling). Time series measurements are denoted by solid lines joining the periods of continous monitoring.

[a] Pump sampler deployed did not function.

[b] Data not presented in this volume.

and biomass. Sediment samples were also obtained with grab samplers and gravity corers. Epibenthic megafauna including demersal fishes were photographed along a transect line (Fig. 2) with a camera sled; an otter trawl was used to sample these conspicuous animals for identification, biomass and chemical analyses. Small boat surveys allowed sampling of intertidal and subtidal sediments with their associated biota. The avian and mammal populations within Port Foster were surveyed on all but one cruise (Table 1).

A common trawling transect was chosen for all the pelagic and benthic trawling, which extended over the length of Port Foster from northwest to southeast, avoiding any obstructions in bottom topography and our long-term moorings while still leaving the ship ample freedom to adjust course for changing weather conditions (Fig. 2).

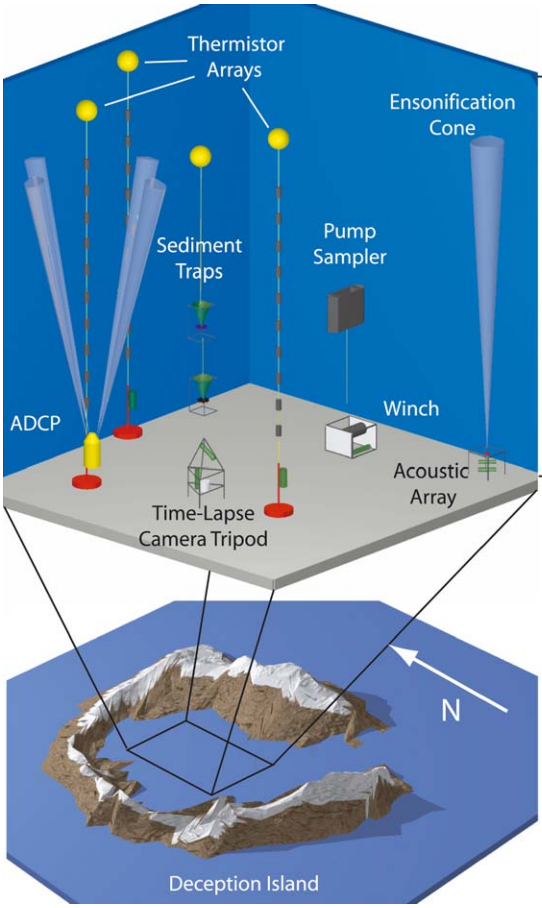

Fig. 4. Graphic presentation of Deception Island showing the long-term moorings.

During the first cruise of the ERUPT program in March 1999, the long time-series instrumentation, including the Terrestrial station, thermistor arrays, sediment traps and time-lapse camera, was deployed to record and collect samples throughout the field program with servicing on each subsequent cruise (Table 1). The upward-looking acoustic array, POGR and pump sampler were deployed later in the program. High wind speeds ($>65\,\mathrm{m\,s^{-1}}$) and wind-blown volcanic ash and ice caused unexpected damage to our Terrestrial station, requiring major repair and downtime amounting to almost 1 year. The low temperature and corrosive nature of the waters in Port Foster created problems with the acoustic Doppler profiler (ADP) and sediment trap arrays, while large chunks of aeolian ash jammed the collection mechanism on the pump sampler. These problems were overcome through the program and the resulting data sets, although interrupted during the time-series, still provide an unprecedented long-term examination of an Antarctic ecosystem. The thermistor arrays proved to be the most reliable instrumentation, recording water temperature throughout the study (Table 1).

Deception Island is a very unique ecosystem that is restricted in size and has several terrestrial and marine areas designated as sensitive sites (SSSI) to be avoided. Because of this situation we chose a sampling program of the pelagic and benthic biota to minimize our impact on this ecosystem so that our collections would not create an anthropogenic disturbance. All trash was held on board each cruise, the wastewater was only expelled from holding tanks when the ship was well clear of Deception Island, and all mooring anchors were removed at the end of the study.

4.1. Significant findings

This section includes the principal findings presented in the following 15 contributions in the volume.

- Deception Island is a very active volcano although there have been no eruptions reported since 1970. Seismic networks consisting of a variety of instruments, including radio-telemetered stations, autonomous digital seismic stations, broadband seismometers, and seismic arrays, have identified two main types of seismic signals generated by the volcano, namely volcanic tremor and long-period events and volcano-tectonic earthquakes. Volcanic tremors and long-period events occur in seismic swarms lasting from hours to days (Ibáñez et al., 2003).
- A description of the equipment developed to provide long time-series monitoring of the Deception Island ecosystem is presented, including: (1) an autonomous weather station (Terrestrial station) to record daily conditions and ice cover, (2) an underwater time-lapse camera/sediment trap array to photograph the seafloor and sequentially collect sinking

particulate matter, (3) an acoustic array to monitor movements of macrozooplankton and nekton, (4) an autonomous, vertically profiling pump sampler to collect macrozooplankton, (5) thermistor arrays to record water temperatures within the water column, (6) an ADP to record current velocities, and (7) a POGR to measure sediment community oxygen consumption and recover surface sediments (Glatts et al., 2003).

- A Terrestrial station installed on a ridge 200 m above Port Foster measured weather, ice and snow conditions. Daily averaged wind speeds ranged from 0.2 $m\,s^{-1}$ in October to 47.4 $m\,s^{-1}$ in June with wind prevailing from the southwest and less frequently from the northeast. Daily averaged air temperatures ranged from $-12.6°C$ in August to 2.7°C in March. Ice cover on Port Foster began in late July 2000 and was intermittently visible through early November (Smith et al., 2003).
- Water temperature in Port Foster is stratified in the austral summer, but is overcome by shear instability as the water cools in the fall/winter, probably due to wind stress. Tides and solar radiation forcing dominate diurnal and semi-diurnal variability, and the presence of baroclinic tides and internal waves indicate that the currents interact with the complex topography inside Port Foster. Water parcels have a mean residence time of 2.4 years in Port Foster with a 1% volume exchange over each tidal cycle (Lenn et al., 2003).
- During the seasons of light limitation and low primary productivity, local currents were effective at redistributing dissolved biochemical components throughout Port Foster. In austral summer the dissolved nutrient and oxygen distributions reflected consumption of nutrients by primary producers. The mid-depth maximum observed in ammonia profiles implies excretion of metabolites by resident pelagic fauna (Sturz et al., 2003).
- Particulate matter fluxes measured at 20 and 50 mab increased in mid-winter and were positively correlated with local wind speed. Fluxes were higher at 20 mab and there was an inverse relationship between mass flux and % organic carbon and particulate total nitrogen at both sampling depths in Port Foster. SCOC, an estimate of carbon demand by the sediment community, exceeded the organic carbon flux to the seafloor (supply) and alternative sources of organic carbon input to the benthos are discussed (Baldwin and Smith, 2003).
- The caldera floor of Port Foster is covered with a layer of yellowish-brown volcaniclastic sandy mud composed primarily of basaltic-andesitic lithic fragments and volcanic glass. Minimum sediment accumulation rate was estimated to be at least 5 $mm\,yr^{-1}$. There has been little change in foraminiferal abundance since the mid-1970s but changes were observed in the species dominance (Gray et al., 2003).
- The copepod *Metridia gerlachi* in Port Foster had three generations per year with a population maximum of $>200\,m^{-3}$ in June 2000. *M. gerlachei* were estimated to remove 68–205% of phytoplankton standing stock per day when this species was most prevalent (King and LaCasella, 2003).
- From March 1999 through February 2000 the pelagic community in Port Foster was dominated by krill, primarily *E. crystallorophias* and *E. superba*. The pelagic community composition shifted during early 2000, and samples from May and November 2000 contained a more diverse assemblage and large numbers of non-migrating cydippid ctenophores. This change in composition was accompanied by displacement of the biomass mode to greater depths (Kaufmann et al., 2003).
- *RNA:DNA* in the krill, *E. superba,* mirrored the chlorophyll-*a* concentration in the water column of Port Foster, being highest during spring peaks in phytoplankton abundance. Activities of lactate dehydrogenase and citrate synthase were higher in male *E. superba,* suggesting their higher burst and swim performance. Enzyme activity and RNA:DNA suggest *E. superba* exhibit reduced metabolism during the winter when phytoplankton production is reduced (Cullen et al., 2003).
- The epibenthic community at Port Foster was primarily composed of deposit-feeding taxa, with the ophiuroid, *O. victoriae*, the dominant organism. Comparative trawls off Livingston

and King George Islands yielded a more diverse epibenthic assemblage, with a dominant suspension-feeding community of sponges and tunicates. Sediment infauna had a high abundance of foraminifera, nematodes, and polychaetes. The major contributors to infaunal biomass were bivalve mollusks and polychaetes (Lovell and Trego, 2003).

- *O. victoriae*, an ophiuroid, *S. neumayeri*, a regular echinoid, and Porifera were the most abundant taxa of epibenthic megafauna in Port Foster. Abundances of *O. victoriae* and *S. neumayeri* peaked in June 2000, coinciding with a large number of small individuals (Cranmer et al., 2003)
- Eleven species of fishes were recorded in the study region, all in the suborder Notothenioidei. Some benthic feeding fishes from Port Foster had heavy worm parasite infestation, possibly due in part to the embayment's sheltered nature (Ruhl et al., 2003).
- A temperature-tolerant interstitial worm with associated epibiotic bacteria was the most abundant faunal species found in shallow water fumaroles. In contrast to other metazoan meiofauna, the distribution of this species is positively correlated with the water temperature. The outer surface of these animals was colonized by apparently symbiotic, rod-like bacteria (Bright et al., 2003).
- The Antarctic fur seal was the dominant pinniped and its abundance has increased since the 1986/1987 austral summer season. Chinstrap penguins were the most dominant seabirds. The most dominant flying seabirds were the kelp gulls and cape petrels (Kendall et al., 2003).

Acknowledgements

The ERUPT program was successful only through the efforts of many participants and support personnel including the Captain and crew of R.V.L.M. Gould and the technical support crews of ASA and later Raytheon. We thank our NSF sponsors, Polly Penhale, Edward Carpenter, and Al Sutherland for support and generous understanding during all phases of our study. Al Sutherland participated on our first cruise to Deception Island, providing enthusiastic support on deck and ashore. His skills with hand-held GPS helped in positioning the Terrestrial station while avoiding SSSI sites. Bob Wilson participated on two cruises to carefully chart the bathymetry of Port Foster. Wayne Pawelek served as an invaluable associate, preparing many of our free vehicle instruments for deployments, especially the pump sampler system on two cruises. REU support from NSF allowed the participation of 16 undergraduate students who were invaluable in our pelagic and benthic trawling operations. Sarah Gray and Henry Ruhl painstakingly prepared the chart of Deception Island incorporating the latest bathymetric measurements made on each cruise.

References

Ainley, D.G., Fraser, W.R., Smith, W.O., Hopkins, T.L., Torres, J.J., 1991. The structure of upper level pelagic food webs in the Antarctic: effect of phytoplankton distribution. Journal Marine Systems 2, 111–122.

Arnaud, P.M., Lopez, C.M., Olaso, I., Ramil, F., Ramos-Espla, A.A., Ramos, A., 1998. Semi-quantitative study of macrobenthic fauna in the region of the South Shetland Islands and the Antarctic Peninsula. Polar Biology 19, 160–166.

Arntz, W.E., Brey, T., Gallardo, V.A., 1994. Antarctic zoobenthos. Oceanography Marine Biology Annual Review 32, 241–304.

Arrigo, K.R., Wothen, D.L., Lizotte, M.P., Dixon, P., Dieckmann, G., 1997. Primary production in Antarctic sea ice. Science 276, 394–397.

Austen, M.C., Buchanan, J.B., Hunt, H.G., Josefson, A.B., Kendall, M.A., 1991. Comparison of long-term trends in benthic and pelagic communities of the North Sea. Journal Marine Biological Association United Kingdom 71, 179–190.

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 10, 81.

Baldwin, R.J., Smith Jr., K.L., 2003. Temporal dynamics of particulate matter fluxes and sediment community response in Port Foster, Deception Island, Antarctica. Deep-Sea Research II, this issue (doi: 10.1016/S0967-0645(03)00089-4).

Barker, D.H., Austin Jr., J.A., 1998. Rift propagation, detachment faulting and associated magmatism in Bransfield Strait, Antarctic Peninsula. American Geophysical Union 91, 24017–24043.

Brierley, A.S., 1999. A comparison of Antarctic euphausiids sampled by net and from geothermally heated waters: insights into sampling bias. Polar Biology 22, 109–114.

Bright, M., Arndt, C., Keckeis, H., Felbeck, H., 2003. A temperature-tolerant interstitial worm with associated epibiotic bacteria from the shallow water fumaroles of Deception Island, Antarctica. Deep-Sea Research II, this issue (doi: 10.1016/S0967-0645(03)00095-X).

Brinton, E., Townsend, A.W., 1991. Development rates and habitat shifts in the Antarctic neritic euphausiid *Euphausia crystallorophias*, 1986–87. Deep-Sea Research 38A, 1195–1211.

Brodeur, R.D., Ware, D.M., 1992. Long-term variability in zooplankton biomass in the subarctic Pacific Ocean. Fisheries Oceanography 1, 32–38.

Clayton, M.N., Wiencke, C., Kloser, H., 1997. New records of temperate and sub-Antarctic marine benthic macroalgae from Antarctica. Polar Biology 17, 141–149.

Collier, R., Dymond, J., Honjo, S., Manganini, S., Francois, R., Dunbar, R., 2000. The vertical flux of biogenic and lithogenic material in the Ross Sea: moored sediment trap observations 1996–1998. Deep-Sea Research II 47, 3491–3520.

Cooper, A.P.R., Smellie, J.L., Maylin, J., 1998. Evidence for shallowing and uplift from bathymetric records of Deception Island, Antarctica. Antarctic Science 10, 455–461.

Cranmer, T.L., Ruhl, H.A., Baldwin, R.J., Kaufmann, R.S., 2003. Spatial and temporal variation in the abundance, distribution and population structure of epibenthic megafauna in Port Foster, Deception Island. Deep-Sea Research, this issue (doi: 10.1016/S0967-0645(03)00093-6).

Cullen, M., Kaufmann, R.S., Lowery, M.S., 2003. Seasonal variation in biochemical indicators of physiological status in *Euphausia superba* from Port Foster, Deception Island, Antarctica. Deep-Sea Research, this issue (doi: 10.1016/S0967-0645(03)00088-2).

DeMaster, D.J., Dunbar, R.B., Gordon, L.I., Leventer, A.R., Morrison, J.M., Nelson, D.M., Nittrouer, C.A., Smith Jr., W.O., 1992. Cycling and accumulation of biogenic silica and organic matter in high-latitude environments: Ross Sea. Oceanography 5, 146–153.

Deuser, W.G., Jickells, T.D., King, P., Commeau, J.A., 1995. Decadal and annual changes in biogenic opal and carbonate fluxes to the deep Sargasso Sea. Deep-Sea Research I 42, 1923–1932.

Drago, E.C., 1987. Limnological studies on Deception Island, South Shetland Islands: morphology and origin of lentic environments. Antarctic Aquatic Biology 7, 193–205.

Drago, E.C., 1989. Thermal summer characteristics of lakes and ponds on Deception Island, Antarctica. Hydrobiologia 184, 51–60.

Dunbar, R.B., Leventer, A.R., Mucciarone, D.A., 1998. Water column sediment fluxes in the Ross Sea, Antarctica: atmospheric and sea ice forcing. Journal of Geophysical Research 103, 30741–30759.

Dunbar, R.B., Leventer, A.R., Stockton, W.L., 1989. Biogenic sedimentation in McMurdo Sound, Antarctica. Marine Geology 85, 155–179.

Elderfield, H., 1972. Iron, manganese and silicon in waters of Deception Island. British Antarctic Survey Bulletin 30, 103–108.

Everson, I., 1987. Some aspects of the small scale distribution of *Euphausia crystallorophias*. Polar Biology 8, 9–15.

Fischer, G., Futterer, D., Gersonde, R., Honjo, S., Ostermann, D., Wefer, G., 1988. Seasonal variability of particle flux in the Weddell Sea and its relation to ice cover. Nature 335, 426–428.

Franklin, J.F., 1989. Importance and justification of long-term studies in ecology. In: Likens, G.E. (Ed.), Long-term Studies in Ecology: Approaches and Alternatives, pp. 3–19. Springer Verlag, New York.

Fraser, W.R., Trivelpiece, W.Z., Ainley, D.G., Trivelpiece, S.G., 1992. Increases in Antarctic penguin populations: reduced competition with whales or a loss of sea ice due to environmental warming? Polar Biology 11, 525–531.

Fratt, D.B., Dearborn, J.H., 1984. Feeding biology of the Antarctic brittle star *Ophionotus victoriae* (Echinodermata: Ophiuroidea). Polar Biology 3, 127–139.

Fukuchi, M., Hattori, H., Sasaki, H., Hoshiai, T., 1988. A phytoplankton bloom and associated processes observed with a long-term moored system in Antarctic waters. Marine Ecology Progress Series 45, 279–288.

Gallardo, T., Perez-Ruzafa, I.M., Flores-Moya, A., Conde, F., 1999. New collections of benthic marine algae from Livingston and Deception Islands (South Shetland Islands) and Trinity Island (Bransfield Strait) Antarctica. Botanica Marina 42, 61–69.

Gallardo, V.A., 1987. The sublittoral macrofaunal benthos of the Antarctic shelf. Environment International 13, 71–81.

Gallardo, V.A., Castillo, J.G., Retamal, M.A., Yanez, A., Moyano, H.I., Hermosilla, J.G., 1977. In: Llano, G. (Ed.), Adaptations Within Antarctic Ecosystems, pp. 361–387. Smithsonian Institute, Washington DC.

Glatts, R.C., Uhlman, A.H., Smith Jr., K.L., Baldwin, R.J., 2003. Long time-series monitoring of the ecosystem at Deception Island, Antarctica: description of instrumentation. Deep-Sea Research II, this issue (doi: 10.1016/S0967-0645(03)00083-3).

Gray, S.C., Sturz, A., Bruns, M.D., Marzan, R.L., Dougherty, D., Law, H.B., Brackett, J.E., Marcou, M., 2003. Composition and distribution of sediments and benthic foraminifera in a submerged caldera after 30 years of volcanic quiescence. Deep-Sea Research II, this issue (doi: 10.1016/S0967-0645(03)00090-0).

Grebmeier, J.M., Barry, J.P., 1991. The influence of oceanographic processes on pelagic–benthic coupling in polar regions: a benthic perspective. Journal Marine Systems 2, 495–518.

Hopkins, T.L., Lancraft, T.M., Torres, J.J., Donnelly, J., 1993. Community structure and trophic ecology of zooplankton in the Scotia Sea marginal ice zone in winter (1988). Deep-Sea Research 40, 81–105.

Ibáñez, J.M., Almendros, J., Carmona, E., Martinez-Arevalo, C., Abril, M., 2003. The recent seismo-volcanic activity at Deception Island volcano. Deep-Sea Research II, this issue (doi: 10.1016/S0967-0645(03)00082-1).

Ibáñez, J.M., Del Pezzo, E., Almendros, J., La Rocca, M., Alguacil, G., Ortiz, R., Garcia, A., 2000. Seismovolcanic signals at Deception Island volcano, Antarctica: wave field analysis and source modeling. Journal Geophysical Research I 105, 13905–13931.

Igarzabal, A.P., 1974. Rasgos morfologicos de Isla Decepcion Islas Shetland del sur Antartida Argentina. Direccion Nacionale Antartida 172, 31.

Kaufmann, R.S., Fisher, E.C., Gill, W.H., King, A.L., Laubacher, M., Sullivan, B., 2003. Temporal patterns in the distribution, biomass and community structure of macrozooplankton and micronekton within Port Foster, Deception Island, Antarctica. Deep-Sea Research II, this issue (doi: 10.1016/S0967-0645(03)00092-4).

Kendall, K.A., Ruhl, H.A., Wilson, R.C., 2003. Distribution and abundance of marine bird and pinniped populations within Port Foster, Deception Island, Antarctica. Deep-Sea Research II, this issue (doi: 10.1016/S0967-0645(03)00096-1).

King, A.L., LaCasella, E.L., 2003. Seasonal variations in abundance, diel vertical migration, and population structure of *Metridia gerlachei* at Port Foster, Deception Island, Antarctica. Deep-Sea Research II, this issue (doi: 10.1016/S0967-0645(03)00091-2).

Knox, G.A., 1994. The biology of the Southern Ocean. Cambridge University Press, London, 444pp.

Lancraft, T.M., Hopkins, T.L., Torres, J.J., Donnelly, J., 1991. Oceanic micronektonic/macrozooplanktonic community structure and feeding in ice covered Antarctic waters during the winter (AMERIEZ 1988). Polar Biology 11, 157–167.

Lenn, Y.-D., Chereskin, T.K., Glatts, R.C., 2003. Seasonal to tidal variability in currents, stratification and acoustic backscatter in an Antarctic ecosystem at Deception Island. Deep-Sea Research II, this issue (doi: 10.1016/S0967-0645(03)00085-7).

Lovell, L.L., Trego, K.D., 2003. The epibenthic megafaunal and benthic infaunal invertebrates of Port Foster, Deception Island (South Shetland Islands, Antarctica). Deep-Sea Research II, this issue (doi: 10.1016/S0967-0645(03)00087-0).

Marti, 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.), Volcanic Instability on the Earth and Other Planets, Vols. 110, Geological Society of America Special Publication, pp. 253–265. Boulder, CO.

Orheim, O., 1972. Volcanic activity on Deception Island, South Shetland Islands. In: Adie, R.J. (Ed.), Antarctic Geology and Geophysics, pp. 117–120. International Union Geological Sciences, Oslo, Norway.

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. (Ed.), Recent Progress in Antarctic Earth Science, pp. 443–448. Terrapub, Tokyo.

Reid, K., Croxall, J.P., 2001. Environmental response of upper trophic-level predators reveals a system change in an Antarctic marine ecosystem. Proceedings Royal Society London 268, 377–384.

Retamal, M.A., Quintana, R., Neira, Y.F., 1982. Analisis cuali y cuantitativo de las communidades benthonicas en Bahia Foster (Isla Decepcion) (XXXV Expedicion Antarctica Chilena, enero 1981). INACH-Ser. Cientifica 29, 5–15.

Rey, J., Somoza, L., Martinez-Frias, J., 1995. Tectonic, volcanic, and hydrothermal event sequence on Deception Island (Antarctica). Geo-Marine Letters 15, 1–8.

Ruhl, H.A., Hastings, P.A., Zarubick, L.A., Jensen, R.M., Zdzitowiecki, K., 2003. Fish Populations of Port Foster, Deception Island, Antarctica and vicinity. Deep-Sea Research II, this issue (doi: 10.1016/S0967-0645(03)00094-8).

Saiz-Salinas, J.I., Ramos, A., 1999. Biomass size-spectra of macrobenthic assemblages along water depth in Antarctica. Marine Ecology Progress Series 178, 221–227.

Schlosser, P., Suess, E., Bayer, R., Rhein, M., 1988. ^{3}He in the Bransfield Strait waters: indication for local injection from back-arc rifting. Deep-Sea Research 35A, 1919–1935.

Siegel, V., Skibowski, A., Harm, U., 1992. Community structure of the epipelagic zooplankton community under the sea-ice of the northern Weddell Sea. Polar Biology 12, 15–24.

Smellie, J.L., Lopez-Martinez, J., Serrano, E., 1997. Maps of Deception Island, South Shetland Islands. In: Ricci, C.A. (Ed.), The Antarctic Region: Geological Evolution and Processes. Museo Nazionale dell Antartide, Siena, pp. 1195–1198.

Smith Jr., K.L., Baldwin, R.J., Glatts, R.C., Chereskin, T.K., Ruhl, H., Lagun, V., 2003. Weather, ice, and snow conditions at Deception Island, Antarctica: long time-series photographic monitoring. Deep-Sea Research II, this issue (doi: 10.1016/S0967-0645(03)00084-5).

Smith, R.C., Stammerjohn, S.E., Baker, K.S., 1996. Surface air temperature variations in the western Antarctic Peninsula region. in: Ross, R.M., Hofmann, E.E., Quetin, L.B. (Eds.), Foundations for Ecological Research West of the Antarctic Peninsula, Antarctic Research Series, Vol. 70, pp.105–121.

Smith, R.I.L., 1988. Botanical survey of Deception Island. British Antarctic Survey Bulletin 80, 129–136.

Smith Jr., W.O., Nelson, D.M., 1986. Importance of ice edge phytoplankton production in the Southern Ocean. Bioscience 36, 251–257.

Smith Jr., W.O., Sakshaug, E., 1990. Polar phytoplankton. In: Smith Jr., W.O. (Ed.), Polar Oceanography, Part B, Chemistry, Biology and Geology, pp.477–525. Academic Press, San Diego, CA.

Sturz, A., Gray, S.C., Dykes, K., King, A.L., Radtke, J., 2003. Seasonal changes of dissolved nutrients within and around Port Foster, Deception Island, Antarctica. Deep-Sea Research II, this issue (doi: 10.1016/S0967-0645(03)00086-9).

Tilbrook, B.D., Karl, D.M., 1993. RACER: methane enrichments in Port Foster, Deception Island. Antarctic Journal United States 27, 165–166.

Vaughan, D.G., Doake, C.S.M., 1996. Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula. Nature 379, 328–331.

Vaughan, D.G., Marshall, G.J., Connolley, W.M., King, J.C., Mulvaney, R., 2001. Devil in the detail. Science 293, 1777–1779.

Wefer, G., Fischer, G., 1991. Annual primary production and export flux in the Southern Ocean from sediment trap data. Marine Chemistry 35A, 597–613.

Wefer, G., Fischer, G., Fuetterer, D., Gersonde, R., 1988. Seasonal particle flux in the Bransfield Strait, Antarctica. Deep-Sea Research 35A, 891–898.

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