The eruptive history of Deception Island can be described in four major phases:

**Phase 1.** The earliest phase, comprising subaqueous eruptions, constructed at least 80% of the volcanic edifice and was responsible for its overall form as a volcanic shield with gentle surface gradients. Because it is entirely submerged, it has not been examined. By comparison with uplifted and exposed oceanic volcanoes elsewhere, it is inferred to be formed of pillow lava and hyaloclastite breccia, which would have formed non-explosively mainly during subaqueous effusion.

**Phase 2.** The shoaling and early subaerial emergence of the volcano is represented by rocks of the Fumarole Bay and Basaltic Shield formations, respectively. Those were formed by lava fountaining from several, possibly co-eruptive centres in shallow water, and a small subaerial edifice constructed during low-energy explosive eruptions and lava effusion.

**Phase 3.** The sudden connection of magma between two magma chambers beneath Deception Island probably triggered the caldera-forming eruption on Deception Island. That eruption is the only large-scale event known to have affected the volcano, and the eruption characteristics (dynamics, dominant lithofacies, etc) are significantly different from other eruptions on the island. Seawater probably flooded the vent, resulting in a relatively low, dense eruption column, whose collapse formed multiple pyroclastic density currents (mainly pyroclastic flows). The products of that eruption (Outer Coast Tuff Formation) draped the entire island with a minimum thickness of 70-80 m, and the present margins of the island may have been enlarged by 6 or 7 km in all directions. Collapse of the Port Foster caldera occurred at the end of the eruption. Seismo-acoustic studies have also identified large slumped sections of the submerged outer flanks of the island (and east side of Mount Pond?), which may have formed during or immediately following caldera collapse.

**Phase 4.** In early post-caldera time, eruptions occurred from centres widely scattered across the island, along fissures imposed on the island by regional tectonics. All later post-caldera eruptions, including all those in historical times, were confined to centres in a 1.5 km-wide annular zone within the caldera. All of the post-caldera eruptions were of small volume (e.g., < 0.05 km³ for each of the eruptions in 1967 to 1970). Eruptions were of two types. At low elevations around the shores of Port Foster, they were highly explosive and hydrovolcanic, because of the impact of seawater and groundwater on the erupting magma. In addition to tephra fall, fast-moving pyroclastic currents (mainly surges, rarely pyroclastic flows) are characteristic of these eruptions. At higher elevations, principally around the crest of the caldera rim, eruptions were much less explosive and commonly involved lava effusion. However, eruptions from centres situated beneath glaciers at any elevation released substantial volumes of meltwater, often highly charged with debris (lahars or volcanic mudflows).
Hazard maps

Monitoring system

Spanish seismologists at their station on Deception Island monitor seismographs for about 2 months annually (generally between late December and late February), but the network is not in place throughout the year. As that period also corresponds to the major period of tourist activity on the island, it is probably acceptable as a minimum level of volcano monitoring, and it is certainly much better than no monitoring at all. Argentine scientists previously monitored gases sampled sporadically at several low-temperature fumaroles, but that work has apparently been discontinued.

Risk assessment

Only the volcanic hazard has been assessed so far, but, as a first step toward judging the volcanic risk, the future eruptive behaviour has also been estimated. Both are described below:
Types of volcanic hazards identified

*Note: the volcanic activity described below is that which is most likely to pose a significant hazard to persons and vessels on and around Deception Island. It is not a catalogue of all volcanic phenomena that may occur.*

*Ash fall.* During an explosive eruption, the magma is torn apart by the expansion of dissolved gases. Particles of the magma are thrown into the air as ash, pumice and lapilli, where they freeze and fall to the ground. Larger particles follow ballistic trajectories close to the vent (normally within a few hundred metres), but finer particles (mainly ash, smaller lapilli and pumice) are entrained in the eruption column above the vent. The column (or plume) typically reaches elevations of several km very rapidly, and may exceed 10 km. It is driven mainly by expanding heated air and it drifts downwind. Because prevailing winds on Deception Island are mainly from the west (> 50 % of winds), the eastern side of the island is at greatest risk from the effects of ash fall. However, in the three best-documented eruptions, between 1967 and 1970, very little of the island escaped at least some ash fall (Fig. 1). In documented eruptions of Deception Island, the columns probably rose < 10 kilometres, unlike much higher columns at other volcanoes. The ash and other particles fall out of the cooling drifting cloud, with larger particles and thickest deposits closest to the vent. Such fall deposits can extend many tens to hundreds of km. For example, ash from the 1970 eruption fell on King George Island, > 150 km away, and numerous layers of Deception Island ash are preserved in marine sediments in the Scotia Sea, > 800 km distant. Close to the erupting vent, a thick accumulation of ash can be very hot and heavy, causing severe damage to wooden buildings. For example, the abandoned Chilean station at Pendulum Cove was buried and burned down as a result of falling ash from the 1969 fissure eruption, the closest vents being situated 400-500 m away. Otherwise, ash fall and ballistic projectiles endanger people by impact, burial, causing ingestion of fine particles in air and water, and carrying noxious gases, acids and salts.
Figure 1. Sketch maps showing the distribution and average thicknesses (in cm) of ash falls during eruptions on Deception Island in 1967, 1969 and 1970. Small open circles in each diagram indicate the location of the erupting centres.

Pyroclastic currents. These are amongst the most hazardous of volcanic events. They vary widely but share many characteristics. All are gravity-driven, rapidly moving, ground-hugging or inflated mixtures of hot rock fragments and gases. Two main types are often distinguished, flows and surges. Pyroclastic flows have a relatively high concentration of solids, whereas pyroclastic surges have lower solid concentrations. Laterally-directed blasts (as occurred in the 1980 Mount St Helens eruption) are a third possible category of pyroclastic current, formed where depressurisation of a magma chamber is precipitated catastrophically by a mountain landslide, but it is probably an unlikely occurrence on Deception Island. A continuum probably exists between these three types of pyroclastic currents. Pyroclastic currents are often very hot (300–>800°C) and move at high speeds (10 to several hundred metres per second). Pyroclastic flows consist of a dense basal flow that hugs the ground, together with a preceding or overriding turbulent ash-cloud surge. Convection of ash particles from the moving current can also distribute falling ash. Investigations on the island indicate that pyroclastic flows occurred but have been uncommon during most of the history of the volcano; they were abundant only during the caldera-forming eruption (Outer Coast Tuff Formation). Conversely, pyroclastic surges are the most characteristic feature of many Deception Island eruptions. Surges typically travel faster than pyroclastic flows. Unlike pyroclastic flows,
which will be restricted by topography and flow in valleys, the more-expanded hot gas and ash mixtures in surges can flow across topography. On Deception Island, mapped surge deposits only extend about 1.5 km from known vents. They can travel much farther, but on Deception Island are unlikely to form a serious threat > 2 km from vents, in most cases. Although some surges may be hot, similar to pyroclastic flows, most of those on Deception Island were probably relatively cold and contained water and/or steam at temperatures mainly below the boiling point of water. Any eruptions within or at low elevations around the margins of Port Foster are likely to be characterised by abundant pyroclastic surges. It should be noted that pyroclastic currents can travel across water. Death is likely for people caught up in a pyroclastic current.

**Lava flows, lava domes and lava fountains.** Erupting magma that has lost most of its gases forms lava flows, domes and/or lava fountains. Eruptions of this type on Deception Island probably occurred at low effusion rates, and the lava tended to produce many small flows that piled up near their vents and did not extend long distances. Conversely, larger-volume eruptions of lava created lava flows that mantled the south and west coasts and parts of Kendall Terrace. Lava fountaining is common throughout the eruptive history of the island. The first eruption observed, in 1842 by the sealer Smiley, was probably of that type. Conversely, lava domes are unknown on Deception Island, but they may occur in future. Domes usually form from relatively viscous magma, and their sudden collapse can generate hot rock-falls or even small pyroclastic flows and/or surges. The major hazard from lava flows is damage or destruction by burying, crushing or burning everything in their paths. They are confined in valleys and can be easily outrun. Lavas can also cause floods by melting snow and ice, but the interaction is usually not explosive. Where lavas enter lakes or the sea, they commonly form low platforms known as lava-fed deltas (e.g. Punta de la Descubierta, headland south of Entrance Point, South East Point). Lava-fed deltas are very common in oceanic volcanoes and are being constructed currently in an eruption on Hawaii. Apart from a tendency for large slabs (hundreds of metres in extent) of the upper surface of a platform to collapse into the sea, and for small explosions between hot lava and seawater, they are generally not very dangerous.

**Structural collapse and rock falls.** Volcanoes are susceptible to large-scale structural collapse due to steep volcanic slopes containing weak materials, and presence of faults. Slope failures, including rock falls, slides, avalanches and sector collapse, can be triggered suddenly and move very rapidly. They can cause secondary hazards such as tsunamis and even unleash eruptions (cf. Mount St Helens, 1980). On a smaller scale, rock falls in strategically important places can cause major problems. For example, the collapse of Cathedral Crags could easily block Neptunes Bellows and prevent ship egress to/from Port Foster.

**Hydrothermal eruptions.** Because Deception Island is an island, with lakes and a large area covered by glaciers, water is important. It is heated by magma at depth, and returns to the surface in steamfields, fumaroles and hot pools (see below). The process is illustrated in the pattern of seismic activity, which shows peak activity in days following heavy snowfall or rain. However, in hydrothermal systems, the hot water can flash to steam, perhaps triggered by earthquakes fracturing the volcano, and cause small but powerful explosions. Damage from hydrothermal eruptions is unlikely to extend more than a few hundred metres from the vent. Such explosions may occur without warning, but they are probably rare on Deception Island.

**Volcanic gases.** Volcanic eruptions are driven by expanding gases, mainly water and carbon dioxide, but including poisonous minor gases such as sulphur dioxide, hydrogen sulphide, chlorine and fluorine. These gases are also emitted from fractures in the ground between eruptions. They can also be very hot. For example, gases with measured temperatures exceeding 250°C were recorded in fumaroles 10 months after the 1967 eruptions. They are usually only present in toxic amounts very close to vents, particularly the heavy gases (e.g. carbon dioxide and hydrogen sulphide) in poorly-ventilated craters. Deception Island is a windy place and its craters are
comparatively shallow and well ventilated. Noxious volcanic gases are therefore likely to be a minor hazard.

**Steamfields, fumaroles, heated ground.** Deception Island contains several areas of heated ground, etc, which are a conspicuous and normal surface expression of heat escape on the island. All but one are confined to the caldera, and they are long lived. They are mainly situated around the shores of Port Foster, but examples occur on the summit of a hill 500 m NW of the Argentine station, at the north end of the Mount Pond ridge, and on the outer slopes west of Stonethrow Ridge. Temperatures of most are < 40-60°C, but a beach pool at Pendulum Cove commonly reaches 70°C and fumaroles at Fumarole Bay are generally 100-107°C. Temperatures fluctuate daily, typically in response to tides. Sudden subsidence of the sea floor beneath Whalers Bay in 1920-21 also caused the sea to boil and blistered the paint on ships’ hulls. In addition to the possible presence of noxious gases and hydrothermal explosions, people may be scalded by unprotected exposure to steam or very hot water (e.g. Pendulum Cove).

**Lahars and floods.** A lahar is a moving mixture of volcanic debris and water. It may be hot (few hundred °C) or cold. Lahars on Deception Island are likely to be cold. The physical properties of lahars are controlled by grain size and water content, but they typically have relatively high yield strength, bulk density and apparent viscosity. With variable sediment bulking, flow transformations between lahars and watery floods occur. Flow velocities vary greatly according to channel dimensions, volume and grain size distribution; published examples vary from 1.3 to 40 metres per second, with mean values about 20—30 metres/second. Lahars moving at high velocities can surmount topographical barriers. They are generated in several ways, including expulsion of sediment from crater lakes, and avalanching of water-saturated debris during slope failure or bursting of dams. Pyroclastic currents can transform into (hot) lahars by incorporation of meltwater from snow and ice. Because of their high bulk density and velocity, lahars destroy and/or bury structures in their path, as happened to the British scientific station at Whalers Bay in the 1969 eruption on Deception Island. Lahars have sharply defined topographical limits (i.e. valley-confined) and people can usually climb quickly to safety away from areas threatened by lahars. They are a characteristic feature of meltwater floods associated with subglacial eruptions and are likely to have affected Deception Island frequently in the past. For example, the prominent deep and broad flat-bottomed valley situated about 0.5 km west of Crater Lake is carved through thick ash deposits. The valley contains a misfit stream (i.e. a stream too small to have eroded the surrounding valley), which is sourced in the steep backing caldera cliff. It is likely that the valley was eroded mainly during a flood of meltwater released by an eruption beneath the Mount Kirkwood glacier.

**Earthquakes.** Volcanic earthquakes on Deception Island are generated by explosions, movement of lava, heated water and gases at depth and associated crack formation, and large-scale mass movements. Tectonic forces may also affect Deception Island and are caused by plate movements associated with deep consumption of Pacific Ocean floor at the South Shetland trench and plate separation in Bransfield Strait. It can often be difficult to distinguish between the different earthquake mechanisms. Volcanic earthquakes are typically small and shallow, seldom exceeding magnitude 5 on the Richter scale. During January 1992, unusually high seismicity on Deception Island included several magnitude-3 events. These are the largest recorded so far and can be detected by persons in favourable locations on the island without the use of instruments. Conversely, tectonic earthquakes or large mass movements can exceed magnitude 7. Damage caused by earthquakes is typically restricted to proximal areas, as a result of ground shaking and cracking. The earthquakes can also trigger mass movements that may lead to avalanches, rock falls and lahars. Many eruptions are preceded by increased seismicity (i.e. number, magnitude and duration of earthquakes) and it is a useful, if crude, indication of impending eruption (e.g. 1969 eruption on Deception Island).
**Tsunamis and standing waves.** Tsunamis are unusually high sea waves or wave trains that are generated by the sudden displacement of water caused by fault displacements of the sea floor, large mass movements of the land, or some submarine eruptions. They travel at high speeds through deep water and increase in height when approaching shores. Tsunami triggered by eruptions and slope failures have occurred at Deception Island in the past, with consequences for ships both outside the island and in Port Foster. Because Port Foster is virtually landlocked, volcanic explosions and sea floor movements within the basin can set up oscillatory standing waves. Waves oscillating at least 1.5 m were recorded during the 1967 eruption and made small boat operations hazardous; this is especially true in the narrow shallow channel at Neptunes Bellows.

**Future eruptive behaviour of the volcano**

Examination of the historical record shows that the eruptive pattern appears to be one of several eruptions closely spaced in time followed by several decades of dormancy. However, even the most detailed record, that of tephra layers in the Mount Pond glacier, may record only half the eruptions that occurred on the island during the period represented. Conversely, eruptions during the 20th Century suggest that the frequency inferred from ice tephra has probably slowed slightly from that in the late 18th and 19th Centuries (i.e. from one eruptive period every 17 years to one every 33 years). If this style of historical eruptions is continued, any new eruptions will probably be of small volume and from centres within the caldera. Both lava effusion and explosive eruptions are likely. Fallout of tephra will probably only affect those parts of the island down-wind of the centres, as occurred during the 1967—1970 eruptions. However, the presence of Deception tephras dispersed > 800 km (in the Scotia Sea) suggests that some post-caldera eruptions may have been much more violent than experienced in recent centuries.

The discovery of significant present-day inflation of the sea floor in part of Port Foster suggests the possibility that the caldera may be resurfing, raising the possibility of another caldera collapse and associated large-scale eruption. Seismo-acoustic studies of Port Foster also suggest that there has been step-like deformation of the caldera floor in the past related to resurgence, although there is no known link to coincident eruptions. The eruptive style and probability of occurrence of eruptions related to a further caldera collapse are hard to assess. The first (and only known) caldera-forming eruption was apparently triggered by the interaction of two magmas, and the probability of a similar event recurring is probably very low. In addition, explosivity during an eruption within Port Foster will probably be reduced by hydraulic pressure and water flooding the vent, until the vent is built to very shallow levels. Finally, so long as small eruptions take place around the caldera margins, it seems likely that pressures in the magma chamber will be relieved and prevent a climactic caldera collapse eruption.

**Risk mitigation measures**

Because Antarctica is treated as international territory, no nation has yet come forward to accept responsibility for mitigating the volcanic risk on Deception Island. However, the volcano has been intensively studied geologically by the British Antarctic Survey and two methods have been proposed to mitigate the volcanic risk: a suggested alert scheme, and an escape strategy in case of an eruption. These are described below.

**Suggested alert scheme for eruptions on Deception Island**

Until now, no alert scheme has been published for Deception Island despite the comparatively high levels of human activity on the island (by Antarctic standards, at least). The simple scheme presented in Table 1 is adapted from that used by the Alaska Volcano Observatory (United States Geological Survey; http://www.avo.alaska.edu/avo4/updates/color_code.html). It is well suited to
Deception Island and is recommended. Captains of vessels proposing to enter Deception Island, or pilots of aircraft flying near to the island should pay attention to any bulletins on the current state of activity of the volcano that are issued from either the senior seismologist at the Spanish station on the island, or by an appropriate spokesperson representing a recognised scientific authority operating in the Antarctic (e.g. British Antarctic Survey, Spanish Antarctic Programme or National Science Foundation (USA)).

Table 6.1: Alert scheme for eruptions on Deception Island (modified after system used by USGS Alaska Volcano Observatory).

<table>
<thead>
<tr>
<th>Colour code</th>
<th>Alert state</th>
<th>Description</th>
<th>Action</th>
</tr>
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<tbody>
<tr>
<td>GREEN</td>
<td>No eruption is anticipated.</td>
<td>Volume is quiet, uninflationary - Normal activity expected. This is the normal alert state for Deception Island.</td>
<td>No reported - Normal activity expected.</td>
</tr>
<tr>
<td>YELLOW</td>
<td>An eruption is possible in the next few weeks and may occur with little or no additional warning.</td>
<td>Volume is normal, an eruption may occur. Human activity detected locally.</td>
<td>No reported - Normal activities expected.</td>
</tr>
<tr>
<td>ORANGE</td>
<td>Explosive eruption occurring or is possible within a few days and may occur with little to no warming.</td>
<td>Ash plumes not expected to reach 10 000 m above sea level.</td>
<td>All persons to depart the island immediately. No vessels to enter Port Foster. All vessels to give the island a wide safety margin. Vessels and or any other vessel must remain within a few miles of the island until otherwise advised. Anyone ashore in Port Foster should be advised that the caldera has returned to a code orange alert.</td>
</tr>
<tr>
<td>RED</td>
<td>Major explosive eruption is in progress or expected within 24 hours. Large ash plumes are expected to exceed 10 000 m above sea level.</td>
<td>Significant to extremely major explosive activity expected at any time. Strong volcanic activity detected over a defined monitoring network.</td>
<td>All persons to immediately depart the island. Major explosive activity likely to destroy all life on the island rapidly. Vessels and or any other vessel must remain within a few miles of the island until otherwise advised. These restrictions terminate when and andare advised that the island has returned to a code green alert.</td>
</tr>
</tbody>
</table>


Escape strategy in case of a volcanic eruption on Deception Island

This escape strategy is based on the premise that eruptions will be similar to those documented in 1967—1970, i.e. with a limited geographical impact on the island (code orange alert state; Table 1). A sudden collapse of the caldera could result in a much more serious eruption, with potentially devastating effects on anyone on the island at the time. Escape from the island during a caldera collapse eruption is unlikely. However, its probability is probably very low and it will probably be preceded by significant precursory activity, particularly widespread ground inflation and associated earthquakes, during several days or weeks prior to the eruption. However, any eruptions can take place with relatively little immediate warning.

1. Inner coast areas are likely to be hazardous because of ash fall, possible pyroclastic surges (within c. 2 km of an eruption centre), tsunami and irregular rapid tidal oscillations. Tidal effects are likely to be pronounced by water ramping onto beaches, and they may prevent the use of inner coast beaches for boat uplift. People may therefore have to be uplifted from the outer coast.

2. If ships are present within Port Foster when an eruption occurs, they should depart the island immediately, ideally after uplifting all people ashore. Masters of vessels should observe extreme caution whilst departing Neptunes Bellows because of tidal rips and surges, which are enhanced at the narrow shallow entrance channel. They should also avoid routes that skirt close under Cathedral Crags, because of the possibility of rock falls from the unstable cliffs.
3. All rescuing vessels and helicopters should avoid passing through or under the eruption clouds because of the damaging effects of gritty ash particles on machinery.

4. Escape routes to the outer coast of the island are shown in Figure 2. All escape routes from the inner bay to the outer coast are strenuous, both climbing up onto the caldera rim and (in most cases) descending again on the outside. The caldera wall is steep (impassable cliff in places) and draped in highly mobile scree. It is impossible to use ground vehicles (e.g. ATVs) to transport people out of the caldera. Although exit routes are passable for ATV’s at two places, much skill and local knowledge of the routes are required and the routes are impassable to ATVs carrying a passenger.

5. All routes to the outer coast will take hours to complete, ranging from about 2 hours for the easiest route (Whalers Bay to Baily Head) to 3 or 4 hours (or more) if the unnamed bay on the north coast or at Macaroni Point are the only options. These are minima and based on times likely to be taken by young relatively fit persons. The routes are physically arduous as most surfaces are yielding (mainly composed of coarse ash and lapilli). Exhaustion is likely and should be anticipated, even in fit persons. Descending to beaches on the outer coast is also generally difficult because of steep slopes. Apart from routes shown from Goddard Hill to Macaroni Point and the unnamed bay on the north coast (Fig. 2), there are no recommended safe routes over snow and ice. Because of important difficulties peculiar to glaciers (e.g. crevasses, whiteout, slippery surfaces), other glacier travel should be avoided unless with trained guides using suitable equipment (e.g. ice axes, ropes, harnesses). Such equipment is unlikely to be readily available in an emergency.

6. Helicopter uplifts are usually the best option as most of the outer coast beaches are narrow, bouldery and shelf steeply into deeper water, causing beach surf even on calm days. Some beaches (e.g. north of Punta de la Descubierta) also have a submerged offshore bar hazardous to small boats. If wind conditions are suitable, it may be possible to uplift people by helicopter from the inner coast. The most appropriate action can be judged at the time. The best sites for uplift by helicopter are shown in Figure 2.

Figure 2. Sketch map showing suggested escape routes on Deception Island during a volcanic crisis corresponding to no more than a code orange alert state. Although helicopter uplifts can probably be effected, with variable difficulty, almost anywhere, the best areas are indicated on the diagram by hatching. Note that all routes are physically exhausting for most persons.