SEISMIC ACTIVITY ON DECEPTION ISLAND

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Abstract: Deception Island (62°43’ S; 60°57’ W) is an active volcano located in the southern part of the South Shetland Islands. Under the Spanish National Program for Antarctic Research, surveillance of volcanic activity has been carried out in the zone for the period January–February, since the 1986–87 austral summer. Seismic stations were temporarily established during these surveys in order to study the seismic activity associated with volcanism. The successive surveys showed that the seismicity around the island remains stationary at approximately 1000 events per month, with a released seismic energy of about 3.0 × 10¹³ erg/day. The distribution of located events lies around the system of fractures which crosses the island, and there is a large number of epicenters aligned parallel to the main fault system E-W, which corresponds to the regional tectonic trend defined by the Bransfield Strait Rift.

Key words: Deception Island, Bransfield Strait, volcanology, seismicity, event location

Introduction

Of the active volcanoes currently known in the Antarctic Continent, 25 with histories of activity have been reported (Gonzalez-Ferran, 1991). They are all located in three main areas; the zones surrounding the Ross Sea (Victoria Land with the Erebus volcano, and Marie Bird Land), the eastern part of the Scotia Arc (South Sandwich Islands), and the Bransfield Strait and the South Shetland Islands, where Deception Island is located (see Fig. 1).

The last eruptions on Deception Island in recent times took place in 1967, 1969 and 1970. The 1967 eruption took place from two different vents in the northeastern part of the island. One of the two vents located in the sea, in which a small island appeared. The 1969 eruption was located at the eastern part of the island in a zone covered by a glacier. This eruption destroyed the Chilean station, abandoned a few months earlier. During this eruption several mudflows destroyed the British station located in the southeastern part of Deception Island. Although the Argentinian station suffered no damage, it was qualified as dangerous, and all scientific studies were canceled. The 1970 eruption occurred approximately in the same zone as the 1967 eruption. This eruption was of explosive type and it was not directly observed because of the abandonment of the other stations after the 1967 and 1969 eruptions (Gonzalez-Ferran et al., 1971; Baker et al., 1975; Roobol, 1982). Until these eruptions occurred, Deception Island had played an important role as a Geophysical Observatory at the southern part of the

Fig. 1. Location map of Bransfield Strait and South Shetland Islands. Also shown are the subaerial volcanoes (Deception, Penguin and Bridgeman).

South Shetland Islands. Obviously, the closure of the stations left a substantial area without surveillance, and interrupted the geophysical observations.

The volcanism at the Bransfield Strait Rift is aligned in parallel to the southwestern edge of the South Shetland Islands block and related to the expansion rift processes (Parra et al., 1984). Three islands with external signs of volcanic activity (Deception, Penguin and Bridgeman), (Fisk, 1990) are located in this region (see Fig. 1).

Geophysical data (e.g. Ashcroft, 1972; Barker and Griffiths, 1972; Barker, 1982; Parra et al., 1984) suggest that the South Shetland Islands lie on a continental plate restricted to the east by the Bransfield Strait back-arc marginal basin, to the west by a well-defined trench zone, and to the north and south by transform faults. The South Shetland Trench (Fig. 2) represents the last surviving segment of a subduction zone that originally extended along the entire western margin of the Antarctic Peninsula, while the Bransfield Strait is taken to represent a contemporary episode of extension which has a back-arc geometry with respect to the possible subduction along the South Shetland Islands (see Hawkes, 1961; Barker, 1982; Parra et al., 1984; Pelayo and Wiens, 1989). The Bransfield Strait has opened by more than 100 km over the last million years and is among the world’s fastest opening rifts. Naturally, this process of expansion provides the mechanism for the occurrence of earthquakes with magnitude greater than 6.0, as reported by Pelayo and Wiens (1989).

Deception Island is a young (<0.75 Ma, Smellie, 1988) horseshoe-shaped stratovolcano, 25 km in submerged basal diameter (Smellie, 1988) and about 15 km in diameter for the emerged zone, and has been very active during its entire evolution; at present, it is the most active of the South Shetland Islands-Antarctic Peninsula group. As recognized from the earliest geological studies onwards, the island is an example of a caldera structure. The caldera is open to sea on its southeast side, forming a bay known as Port Foster. Eruptions have occurred all over the island and abundant phreatic and phreatomagmatic explosion craters in the inner bay can be detected (Rey et al., 1990).

Under the Spanish National Program for Antarctic Research, a project has been developed to monitor the presence of volcanic activity on the island through the use of geological and geophysical methods. The studies carried out during the Antarctic Summer Expeditions from 1987 to 1991 are as follows:
- A seismic network of six telemetered stations with digital recording was installed and the characteristics of the seismicity were evaluated (Vila, 1992).
- Samples from fumaroles and thermal springs were collected and processed using standard methods for analytical operations (Martini and Giannini, 1988).
- Thermal anomalies were located, and energetic flow dissipated in anomalous areas were studied, in order to find the global balance of released energy (Ramos et al., 1990).
- Integral studies of the gravimetric and geomagnetic fields were made using terrestrial and marine profiles in the whole island (Vila, 1992).
- Several geological studies, specially directed to the understanding of the geomorphology and petrology, were carried out, in order to identify different kinds of volcanic series and tectonic features (Martí et al., 1990).

Results of surveys show that the current volcanic activity in the island consists of intense seismic activity, fumarolic emissions and thermal anomalies. The study of the chemical composition of low temperature fumaroles and thermal springs which occur at different points of the island, suggests the existence of several shallow and confined water-saturated layers (Martini and Giannini, 1988). The magnetic map of Port Foster shows a zone with unusual negative anomalies (>3000 nT) along a wide area NNW-SSE, where the last eruptions took place (1967, 1969 and 1970) (Vila, 1992). This zone coincides with a surficial low density mass distribution obtained from a gravimetric model (Vila, 1992).

Earthquakes are located through the island and, during the periods of observation, January and February of each year, the number of events is stationary at a rate of about 1000 events per month.

![Fig. 2. Schematic tectonic map of the Scotia Region, after Pelayo and Wiens (1989).](image-url)
All available results suggest the presence of a well-defined linear structure, not a common feature in collapse calderas (Vila, 1992). If this is the case, it would be necessary to revise the previous models which explained the existence of the central depression as a result of an episode of caldera collapse (e.g. Hawkes, 1961; Baker et al., 1975; Smellie, 1988, 1989). These revisions may bring new insight into the real structure of Deception Island.

**Seismic Instrumentation**

During the Antarctic Summer Expeditions 1986–87 and 1987–88, a seismic network with five analog drum recorder stations was operated in order to monitor the seismic activity on Deception. In the 1988–89 survey a digital seismic network was set up, consisting of six FM telemetry stations with the VHF 170 MHz band. The electronic instruments and the software used for the network had been developed for operating under the Antarctic conditions (Ortiz and Vila, 1990). Figure 3 shows the location of the seismic digital network. The analog network in 1987 and 1988 had the same stations except GNS. Three-element directional antennas were used for the transmitters and omnidirectional antennas for the receivers. The digital unit uses a 14 bit analog-digital converter controlled by a dedicated CMOS microprocessor, which operated at 64 or 128 samples per second. Data were digitally recorded on a portable PC, on RAM-DISK, and periodically transferred to a 3.5" floppy disk. The algorithm employed for the detection of the seismic events was the usual one, STA/LTA (Short Term and Long Term Average) (Lee and Stewart, 1981), to which digital high-pass and low-pass filters were added. All geophones were of vertical component, 1 Hz, Mark Products L4C type.

![Location map of seismic digital network. Open triangles show the seismic stations. The solid circle shows the epicenter of the event whose seismograms are given in Fig. 9.](image)

![Number of events versus P-S interval recorded at BAS and RBT during 1987 and 1988 surveys.](image)
General Characteristics of the Seismicity

The several seismic observations during the surveys carried out at Deception Island show the following main trends. The average rate of recorded events is of the order of 1000 per month. To carry out a statistical analysis, a classification of events according to its epicentral distance had been made (for the events not located instrumentally and P and S waveform identified clearly; a tentative epicentral distance was deduced from the difference between P and S arrival time t); 1) local events \( t \leq 2.5 \text{ s} \), 2) regional events \( 2.5 \text{ s} < t < 25 \text{ s} \), and 3) teleseisms \( t \geq 25 \text{ s} \). Figure 4 shows the number of events versus P-S interval in seconds. In all cases a maximum of activity centered at \( 1 - 1.5 \text{ s} \) can clearly be seen. For the 1987 survey a secondary maximum centered at about \( 4 \text{ s} \) can also be observed.

A statistical analysis was carried out based on temporal distribution, Gutenberg-Richter law, evolution of released seismic energy and studies of lapse time between events. The formulae used in this study are those recommended by the Commission on Volcano-Geophysics of the IAVCEI (International Association of Volcanology and Chemistry of the Earth Interior) in the meeting held in Naples in August, 1991, for seismic data analysis in volcanic areas. The magnitude \( M \) is calculated as a function of the epicentral distance \( \delta \) (in km) and the duration of the event \( \tau \) (in seconds) (Lee and Stewart, 1981);

\[
M = 2 \cdot \log \tau + 0.0035 \cdot \delta - 0.87
\]

(1)

The seismic energy released is calculated by the expression (Richter, 1958):

\[
\log E = 9.9 + 1.9M - 0.024M^2
\]

(2)

where \( M \) is the magnitude. It has been found that during the periods under study, the released energy remains constant, with an average value of \( 3.0 \times 10^{13} \text{ erg/day} \) (Vila, 1992).

The distribution of the number of events \( N \) against the magnitude \( M \) provides us with the values of the parameters \( a \) and \( b \) of the Gutenberg-Richter law (Gutenberg and Richter, 1941):

\[
\log N = a + b \cdot M
\]

(3)

Figure 5 displays the Gutenberg-Richter distribution for local events (P-S interval up to \( 4 \text{ s} \)). Table 1 presents the numerical values of coefficients \( a \) and \( b \).

The temporal distribution of events shows the presence of two main episodes (see Fig. 6), characterized by an increment of activity. However, from the point of view of the daily cumulative seismic energy (see Fig. 7), it can be seen

\[\text{Fig. 5.} \quad \text{Gutenberg-Richter distribution for local earthquakes (P-S interval up to \( 4 \text{ s} \)) recorded at BAS from January 14 to February 9, 1987 and from January 14 to February 16, 1988.}\]

\[\text{Fig. 6.} \quad \text{Daily number of events recorded at BAS. Two main episodes can clearly be distinguished (January 21, 1987 and January 16, 1988).}\]
Table 1. Numerical values of the parameters of the Gutenberg-Richter law.

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>Antarctic Summer Expedition (January and February)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year 1987</td>
</tr>
<tr>
<td>Number of Earthquakes</td>
<td>133</td>
</tr>
<tr>
<td>a</td>
<td>2.78</td>
</tr>
<tr>
<td>b</td>
<td>1.37</td>
</tr>
<tr>
<td>r</td>
<td>0.97</td>
</tr>
</tbody>
</table>

![Graph showing cumulative released seismic energy from January to February for 1987 and 1988.](image)

Fig. 7. Cumulative released seismic energy. Both surveys show the same daily average.

that the episodes correspond to a restoration of the daily equilibrium, and present only an oscillation around this mean value.

In subsequent during the Antarctic Summer Expeditions, the statistical study of the seismicity has shown no appreciable variation.

Event Location

In order to carry out the epicentral location, a crustal model was used. The model was obtained from a seismic refraction profile carried out at Port Foster during the Antarctic Summer Expedition of 1987–88 (Ortiz et al., 1990). The distribution of velocities obtained is similar to that of other volcanic areas, consisting of a first layer with a velocity of about 1500 m/s (water saturated) and a thickness of about 0.5 km, followed by the layer with a small increment of velocity as well as thickness, and subsequently, a 4.5 km/s velocity layer of variable thickness over a halfspace with a velocity of 6 km/s. A comparative study of the velocity model in different active volcanoes has been made by Vila (1992). Figure 8 shows the P-wave velocity model used in this study. For S-wave velocity, a relation \( V_p = \sqrt{3 \cdot V_s} \) has been assumed.

Previous studies of the petrology and volcanology of Deception Island (e.g. Hawkes, 1961; Baker et al., 1975; Smellie, 1988, 1989) have suggested the existence of a caldera structure in the central part of the island which is thought to have been formed by the collapse of several pre-existing volcanic edifices (Hawkes, 1961) or by the collapse of a central stratovolcano (Baker et al., 1975). Subsequent to this, the volcanic activity would have continued, associated with the concentric faults around the edge of the caldera (Smellie, 1988), and the distribution of seismic events could be expected to be circular because it would be controlled by ring faults. For this reason, in order to cover the whole inner side of the island the seismic stations were located circularly (see Fig. 3).

Looking at the seismic network, we can see that the distance between stations is no greater than 10 km. This short distance, along with the characteristics of volcanic events with superficial sources (Malone, 1983), accounts for the event with a short S-P time (t). However, because of this small time interval, the S-wave arrival can be masked by the P-wave coda (Kulhanek, 1990). Moreover, we should take into account the large content of background noise (due mainly to microseism and wind). This accounts for the large uncertainties in epicentral locations obtained by using classical HYPO location programs adapted for PC’s (Mendoza and Morgan, 1985; Lienert et al., 1986). For this reason, use of HYPO programs has been complemented by a simple location program that work basically with P-wave arrival times. The computer program calculates the spatial point with the minimum RMS by iteratively solving the direct problem (Vila, 1992). Figure 9 shows an example of seismograms of the event recorded on January 16, 1989. The epicenter location of this event is shown with a solid circle in Fig. 3. Figure 9 displays one example of large differences in amplitude of the four records (note the differences in the vertical scale). The stations with large amplitude, MUR and BAS, are closer to the epicenter (1.0 and 3.6 km respectively) than GNS (5.1 km) and RBH (6.7 km), although the differences in the ray path geometrical spreading do not account for the differences in amplitude. This result is left now as an open question, and will be analyzed further.

From December 28, 1988 to February 25, 1989, more than
Fig. 8. P-wave velocity model adopted for event locations (Ortiz et al., 1990).

EVENT S162113

Fig. 9. Seismic records of event S162113, occurred on January 16, 1989 at 21h 13m UT. Vertical scale is given in units of 14 bit D/A converter (2^14 D/A units correspond to 10^3 cm/s), the instrumental gain is 66 dB. Note that the four stations have different scales. Arrows show the onset of the P-wave.
2000 events were recorded by the seismic network, and more than 1000 of them were also digitally recorded. Only the events recorded by more than three stations were located, resulting in 118 located events, mainly on the island. Locations were carried out in two stages. First, a location in real time was made directed towards the surveillance of the volcano. The allowed maximum RMS error was of 0.3 s and the focal depth was restricted to 2.5, 5 or 7.5 km. As a second step with the aim of improving the accuracy of the location, the allowed RMS error was decreased to 0.1 s for each station, and the focal depth was allowed to vary freely with a step of 100 m. These restrictive conditions reduced the number of located events to 66. Both locations show similar trends. Figure 10 shows the epicentral location corresponding to the second step, separating all events in two groups depending on their focal depth (0 km to 2.5 km and 2.5 km to 7.0 km).

As it has already been said, previous studies on the petrology and volcanology of Deception Island have suggested the existence of a caldera structure in the central part of the island, and subsequently to this, volcanic activity would have continued, associated with the concentric faults around the edge of the caldera. Considering this fact the distribution of epicenters does not respond to the known geology. As a general trend, it follows an East-West distribution that could be interpreted as being due to the activity of a system of fractures which crosses the island in that direction following the main regional trends (Marti et al., 1990). It is emphasized clearly this East-West alignment in Fig. 10 (an evidence of the impossibility of separating, Deception Island from the rest of Bransfield Strait Rift by a seismic point of view).

Conclusions
The successive surveys carried out at Deception Island since the 1987 Antarctic Summer Expedition show that the seismic activity in and around the island during the periods of observation is of approximately 1000 events per month. The distribution of located events is aligned parallel to the main fault system which crosses the island (E-W) following the regional tectonic trend defined by the Bransfield Strait Rift. Seismic results favors the hypothesis that Deception Island does not constitute an isolated point but is well integrated into the regional tectonic features. During the periods studied (January–February), a constant release of energy has been observed.

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