GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO. 5, PAGES 531-534, MARCH 1, 1997

Intermediate-focus earthquakes under South Shetland Islands (Antarctica)

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Abstract. This study is based on data from five field surveys (1992-1996) of seismic monitoring on Deception Island (South Shetland Islands, Antarctica). In the 1994-95 and 1995-96 surveys earthquakes were recorded by a seismic array. In previous surveys data were collected by a high-dynamic range, short-period station. The analysis of the events shows evidence of intermediate-focus seismicity [50<H<100 km] related to the underplating zone of the South Shetland plate. Because of poor station coverage we had to use unconventional techniques to locate the events, such as zero lag cross-correlation method that provide information about apparent velocity and back-azimuth, ray-tracing procedure and particle motion patterns. These criteria allowed us to identify 15 earthquakes that could be considered as intermediate-focus events, for which some focal parameters were estimated. We conclude that the subduction zone between the Drake plate and South Shetland microplate has a moderate level of intermediate-depth microseismicity.

Introduction

The region located around the South Shetland Islands and Trinity Peninsula, Antarctica (Figure 1a), is a place of complex tectonic phenomena. In particular, the transition zone between the Drake plate, the Antarctic plate and the South Shetland microplate shows that the tectonic underplating has played a major role in the process of the formation of the crust (Acosta et al., 1992; Grad et al., 1993). The presence of active volcanoes (Smillie, 1988) and shallow- and intermediate-depth seismicity (Pelayo and Wiens, 1989) makes the study of this zone very interesting. The opening of the Bransfield rift (2 My ago) generated a new microplate, the South Shetland plate, bounded by the Shackleton and Hero fractures, by the South Shetland trench to the north and by the Brandsfield rift to the south (Henriet et al., 1992). Several authors have interpreted the state of the subduction: Barker (1982) reported no observed earthquake activity connected with the subducted slab; Barker and Burrell (1977) interpreted this slab as probably formed by the surviving segment of a subduction zone that originally extended along the western margin of Antarctic Peninsula, pointing out that probably at the present it is inactive; Kaminuma (1995) reports a description of the seismicity around Antarctic Peninsula updated to 1990 using the ISC catalog. His conclusions are that neither subduction of the South Shetland plate nor rifting of the Bransfield rift are active; Pelayo and Wiens (1989), in their study of the seismotectonic characteristics of the Scotia Sea region, mapped the seismic activity of the 1963-85 period showing 8 earthquakes with magnitude greater than 5 in the South Shetland region. At least two of these earthquakes were located at 35 and 55 km depth below the crust. These authors concluded that the earthquakes, associated with the Drake passage, South Shetland, and Bransfield Strait are difficult to interpret. In particular, due to the lack of moderate and strong deep earthquakes, these authors concluded that there is a little evidence of a downgoing slab. Grad et al. (1993) obtained a velocity model of the crust in the region by using deep seismic sounding. These authors assumed an interface contact, dipping 25° toward S-E, between the Drake and the South Shetland microplates (Figure 1b).

The extreme weather conditions, the non-uniform distribution of permanent bases in the region and the lack of permanent local seismic stations do not allow a systematic study of the seismicity. The large gap of seismic stations (Kaminuma, 1992) does not allow to detect and to locate earthquakes with magnitude smaller than 5.

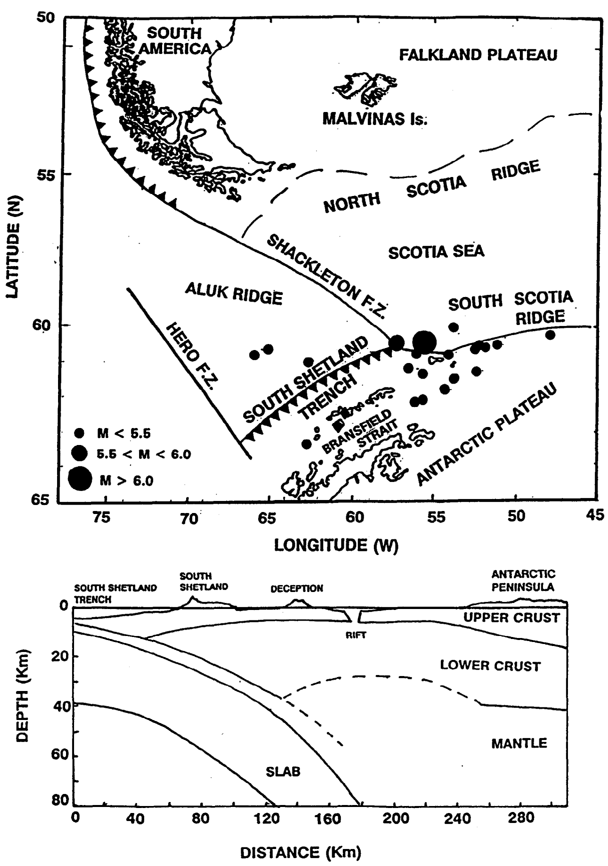

Figure 1. (*Top*) Schematic tectonic map of the South Shetland Islands between Antarctic Peninsula and Bransfield rift and the South Shetland Trench, including the seismicity of the region in the 1985-95 period from the PDE catalog (dots). (*Bottom*) Model of the region obtained from deep seismic sounding by Grad et al. (1993).

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Paper number 97GL00314.
0094-8534/97/97GL-00314$05.00

Table 1. Velocity Model.

Depth (m)	Vp (km/s)	Vp/Vs
20	0.5	1.43
574	1.5	1.60
1412	1.76	1.65
6000	4.54	1.73
12000	6.0	1.73
25000	7.6	1.73
∞	8.2	1.73

In Figure 1a we show the earthquakes which occurred inside the area under study, reported in the PDE catalog for the 1985-95 period. No magnitude smaller than 4.8 is present in the list, while all the focal depths, except one, are fixed at 10 km. The unique source depth different from 10 km is fixed at 33 km, and occurred on March 16, 1989 (63.328° S and 62.446° W, m_b=5.3). Due to the presumed uncertainties related to the locations of the PDE catalog, we can not exclude that this earthquake has a possible intermediate-depth focus. The present data cannot be compared directly with those of the PDE catalog because all of their magnitudes are smaller than 4.9, and we exclude that they were detected at teleseismic distances. However, they add information about the local seismicity of the South Shetland Islands, opening a number of new questions, as, for example, whether or not the South Shetland microplate is a site of active subduction.

In this study we present results from the analysis of seismic data which show some evidence of intermediate-focus seismicity [50<H<100 km] correlated to the underplating zone of the South Shetland plate. Although the number of earthquakes analyzed here (15 events) is modest, there is evidence of active tectonic under the South Shetland microplate.

Seismic instrumentation

A three-component seismic station was setup near the Argentinean base (62° 59' S, 60° 42' W) of Deception Island in December 1992 - March 1993 and December 1993 - March 1994. It was composed by Mark L4C seismometers with a 14 bits A/D converted controlled by a PC. The signal time was synchronized by a GPS time receiver and the sampling rate used was 100 sps.

A seismic array was deployed in a zone of 500 x 600 m near the Spanish Station 'Gabriel de Castilla' (1 km far from the Argentinean base) in December 1994 - March 1995 and December 1995 - March 1996. The seismic array was composed by: 15 vertical Mark L15B seismometers with response electronically enlarged to be flat for ground velocity between 1 and 48 Hz; three three-component seismometers Mark L4C with response enlarged between 0.1 and 48 Hz; and a broad-band Guralp CMG-3ESP with flat response between 0.033 and 48 Hz in 1994-95. A 16 bits A/D converter PC controlled was used. The time signal was synchronized by GPS and the sampling rate was 200 sps.

Data analysis

We used the zero-lag cross-correlation method (Frankel et al., 1991) to locate the earthquakes registered by the seismic array. This method provides us information about the back-azimuth of the epicenter and the apparent velocity of the seismic waves. The selected seismograms were band-pass filtered between 3 and 8 Hz to reduce the contamination of low-frequency noise of oceanic and volcanic origin, and the high-frequency noise due to wind. We divided the recorded earthquakes into two groups according with their waveform: group A could be considered as intermediate-focus events, and group B which could be interpreted as shallow-focus earthquakes. Group A presents higher apparent velocities (10-63 km/s) than group B (5-11 km/s). A strong refraction in the shallowest layers may produce similar apparent velocities whatever focal depth. However, we observed significant differences between both groups, showing that the low velocity layers in the surface do not affect significantly to the evaluation of the apparent velocity. Other possible source of strong refraction could be located in a deeper layer. This effect also was not observed because we obtained, for the intermediate-focus events, velocities greater than 10 km/s, and there are no evidences of a fast layer in the area. Therefore, the observed apparent velocity seems to be controlled by the depth of the seismic source. Once the back-azimuth and the apparent velocity were obtained, we read visually the S-P time for the seismograms of the three-component stations. To calculate the focal depth and epicentral distance we used a simple ray-tracing procedure, based on a flat layered model. Grad et al. (1993) have shown that the velocity structure of this region is complex and far from a flat velocity model. In our study we used the model listed in Table 1 that is an 'average' model based on a field experiment (hammer experiment) for the first layer, on a refraction seismic profile for the second and third layers (Ortiz et al., 1989), and on the model of Grad et al. (1993) for the remaining layers. In Table 2 we list the locations of the intermediate-focus earthquakes and in Table 3 the shallow-depth events.

Errors in the estimation of the back-azimuth and apparent velocity are related to noise, which produces a lack of correlation among the signals recorded at the array stations, and to very local site effects which could distort the waveforms. These errors can be studied and we obtained a maximum error in the back-azimuth estimations of 15 degrees. The error related with the ray-tracing procedure is more difficult to estimate. We checked the effect of the model in this procedure with other 'standard models'. From this test it results that the estimation of the depth depends on the velocity

Table 2. Intermediate-focus Earthquakes Located by the Seismic Array.

N	Date	GMT	S-P (s)	Dist. (km)	Depth (km)	BAZ (deg)	V_{ap} (km/s)	M_w
1	12/XII/94	01:17:06	9.86	39	60	315	13.0	3.8
2	25/I/95	08:22:57	8.18	22	54	277	18.5	3.8
3	28/I/95	20:23:16	10.79	21	76	254	27.5	3.0
4	11/II/95	21:54:19	9.60	23	66	250	21.7	4.0
5	15/II/95	19:43:54	9.53	21	66	250	24.0	3.5
6	27/XII/95	19:26:26	13.36	71	67	297	10.0	3.9
7	18/I/96	08:44:38	12.96	30	90	297	22.4	3.0
8	6/II/96	06:05:07	11.09	9	80	162	63.3	3.2

Table 3. Shallow Earthquakes Located by the Seismic Array.

N	Date	GMT	S-P (s)	Dist. (km)	Depth (km)	BAZ (deg)	V_{ap} km/s	M_w
1	1/I/95	20:32:22	10.40	69	22	28	7.7	3.5
2	5/II/95	16:20:06	4.18	16	23	357	11.1	2.7
3	5/II/96	13:59:29	5.31	21	7	353	4.7	1.7
4	5/II/96	19:52:37	5.33	21	7	349	4.7	2.0
5	9/II/96	05:17:22	7.61	47	24	344	8.0	2.1
6	11/II/96	17:50:24	6.85	24	17	213	5.4	2.1

Table 4. Intermediate-focus Earthquakes Located by the Three-Component Station.

N	Date	GMT	S-P (s)	Dist. (km)	Depth (km)	M_w
1	28/XII/92	09:09:36	7.74	17	53	3.5
2	8/I/93	14:54:01	11.21	26	78	4.2
3	16/I/93	13:26:30	10.12	23	70	3.8
4	20/I/93	01:56:35	10.94	25	76	3.8
5	19/I/94	19:19:47	12.51	29	87	4.6
6	24/I/94	10:58:10	7.30	16	49	2.4
7	16/II/94	04:43:03	19.36	56	130	3.3

model used, but this kind of bias is not so strong to move an event from group A to B or vice-versa.

We performed an additional test to confirm the intermediate-depth origin of the earthquakes of group A studying the particle first motion of P waves. We observed an almost vertical incidence, as expected, for the group A events, while a complex particle motion pattern was observed for the group B events (Figure 2). This test is important because this information can be used to classify the earthquakes in intermediate- and shallow-focus events, even when the earthquake data were available at the three component station only. In Figure 2 (b, c) we show two examples of the particle motion pattern for two earthquakes that have been classified as intermediate-focus events and registered by the three-components station only. By using this procedure we identify seven more earthquakes as intermediate-focus events. Their back-azimuth was estimated from the two horizontal components using the first 0.25 seconds of the P-wave onset. This estimation was obtained by fitting the particle motion with a line whose direction was considered as the back-azimuth. A check of this method was performed by using the co-variance matrix of the signal, evaluating the angle that its largest eigenvector forms with the north direction. Because we do not have apparent velocities for these earthquakes we cannot obtain their focal depths. However, to obtain a rough estimation, we assumed an apparent velocity of 23 km/s (the averaged apparent velocity for events of group A) and calculated their focal parameters. In Table 4 we report this information from this data set. There are two earthquakes whose locations are considered doubtful by us: one of them because its focal depth is smaller than 50 km and the other one because its S-P time made its focal depth deeper than 130 km. Perhaps, for this earthquake, a slower apparent velocity has to be considered. In Figure 3 we plot the epicentral position and the focal depth of the earthquakes listed in Tables 2, 3 and 4. The magnitudes (Mw) reported in Tables 2, 3 and 4 are Moment Magnitudes. Seismic moment estimation was obtained applying the Brune's ω^2 model to the S-wave spectrum corrected for instruments and attenuation. We wanted to observe if the activity of the slab is more or less stable along time. As can be observed, the slab shows a moderate continuous activity, at least in the analyzed time period.

Conclusions

We have identified 15 earthquakes recorded in the South Shetland Islands (Antarctica) that could be considered as intermediate-focus events (focal depth greater than 50 km). The data were recorded during several field surveys carried out in Deception Island since 1992. In two of these surveys a dense small-aperture seismic array was deployed. The epicentral distribution map plotted in Figure 3 shows that the analyzed earthquakes are located around Deception Island, within a distance of about 80 km

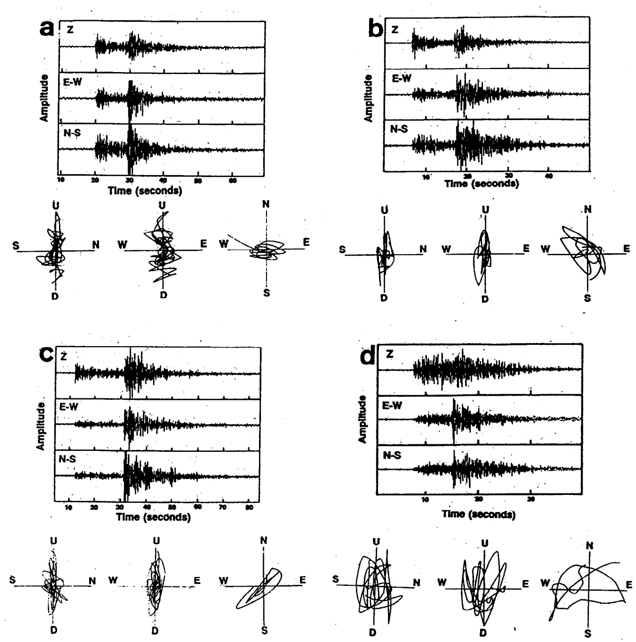

Figure 2. Four examples of seismograms and particle motion of three intermediate earthquakes (a, b, c) and one shallow event (d). The time scale of the seismograms is 10 seconds. (a) is number 5 in Table 2, (b) is 7 and (c) is 2 in Table 4, and (d) is 5 in Table 3. See text for explanations.

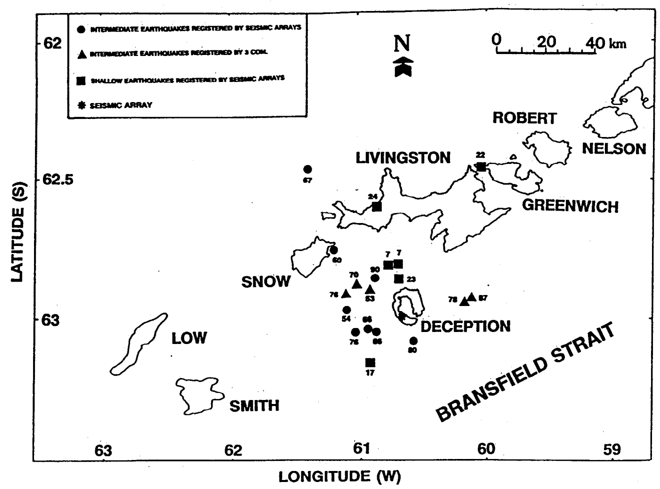

Figure 3. A possible epicentral position of the studied earthquakes. Dots: intermediate-focus earthquakes located by using the seismic array. Triangles: earthquakes recorded by the three-component station only and located by using an apparent velocity of 23 km/s. Squares: shallow-focus events located by the seismic array. Numbers near the locations represent the estimated focal depth.

from the island. The focal depth ranges between 53 and 90 km. Although the estimation of these focal depth could be biased by the velocity model used, there are little doubts about their intermediate origin. The apparent grouping of the seismic activity around Deception Island is probably due to the low magnitude of the recorded earthquakes rather than a real spatial clustering of the activity. This low magnitude explains why the seismic stations located on King George Island or on the Antarctic Peninsula did not record these earthquakes. The estimated focal depths could be consistent with an active subduction generated by the contact between the Drake plate and the South Shetland microplate, as speculated by Grad et al. (1993). We suppose that the subduction zone between the Drake plate and South Shetland microplate has a moderate level of intermediate-focus microseismicity. This activity was detected by Pelayo and Wiens (1989) who reported two earthquakes with focal depth around 55 km, but it is quite difficult to observe with the existing seismic instrumentation due to the low level of magnitude. The extreme weather conditions in the area during the autumn and winter and the low density of seismic stations in the region do not permit studies for intervals longer than some months. This lack of seismic stations does not allow a precise location of the recorded earthquakes. The deployment of permanent seismic stations in some of the permanent antarctic bases of the South Shetland region may not improve the analysis, since the position of these bases is very concentrate basically on King George Island and Trinity Peninsula and the observed magnitudes of the events are low. Several spring and summer surveys with large aperture arrays could be more useful for this kind of studies.

Acknowledgments. This paper has been partially supported by the projects ANT91-1265, ANT93-1217-E, ANT94-0854-C02 and ANT95-0994-C03 and by the Grupo de Investigación en Geofísica J.A. 4057. We gratefully acknowledge Prof. S. K. Singh, Dr. G. Esktröm, Dr. L. Astiz, Dr. D. Giardini and Dr. K. Kaminuma and an anonymous reviewer for their useful comments, and to Spanish Army and Spanish Navy for providing us with logistic help during the Antarctic surveys in the 'Gabriel de Castilla' station.

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(Received: August 5, 1996; revised: October 25, 1996; accepted: November 20, 1996)