Geophys. J. Int. (2006) **167,** 684–692 doi: 10.1111/j.1365-246X.2006.02953.x

Determination of the seismic moment tensor for local events in the South Shetland Islands and Bransfield Strait

M. Guidarelli[1] and G. F. Panza[1,2]

[1] *Dipartimento di Scienze della Terra, Università di Trieste, via E. Weiss* 4, 34127 *Trieste, Italy. E-mail: mguidar@dst.units.it*
[2] *The Abdus Salam International Centre for Theoretical Physics, SAND Group, Trieste, Italy*

Accepted 2006 February 2. Received 2005 December 2; in original form 2005 June 28

SUMMARY

Six events with magnitude between 3 and 5.6 have been analysed based on regional waveforms recorded by the temporal Seismic Experiment in Patagonia and Antarctica seismic broad-band network in the Bransfield Strait and the South Shetland Islands in the period 1997–1998. The source parameters have been retrieved using a robust methodology (INDirect PARametrization) to stabilize the inversion of a limited number of noisy records. This methodology is particularly important in oceanic environments, where the presence of seismic noise and the small number of stations makes it difficult to analyse small magnitude events. The source mechanisms obtained are quite variable but consistent with the active tectonic processes and the complicated structure of the South Shetland Island region.

Key words: Bransfield Strait, earthquake-source mechanism, moment tensor.

INTRODUCTION

The determination of the seismic source mechanism in oceanic environments with the presence of seismic noise and a small number of stations can hardly be performed using standard techniques. A typical example of this situation can be found in the oceans surrounding the southern tip of South America and the Antarctic Peninsula, where the remote location has posed severe logistic problems to the deployment of seismological instruments. The INDirect PARametrization (INPAR) method (Šílený & Panza 1991; Šílený *et al.* 1992) has recently been used to determine source mechanisms in the Scotia Sea region. The studies of Vuan *et al.* (2001) and Guidarelli *et al.* (2003) justify an intensive use of this methodology in the Scotia Sea region to retrieve the source parameters using a limited number of noisy recordings. The main reason for using the INPAR method is that it can give reliable results even when only a few seismograms from a limited number of stations are available (Kravanja *et al.* 1999). Kravanja *et al.* (1999) also demonstrated that the method has the capacity to absorb spurious effects of inexact modelling of the structure, which makes the availability of average models sufficient for our purposes.

The INPAR method has been applied in different tectonic settings, and several synthetic tests have been performed in order to verify the reliability and the applicability of the method. The method has successfully been applied within tectonic (Campus *et al.* 1996; Radulian *et al.* 1996; Vuan *et al.* 2001; Chimera *et al.* 2003), volcanic, and geothermal environments (Campus *et al.* 1993; Cespuglio *et al.* 1996; Guidarelli *et al.* 2000; Kravanja *et al.* 2000; Saraò *et al.* 2001; Guidarelli *et al.* 2002). Campus & Fäh (1997) have confirmed the capability of the method to retrieve reliable isotropic components and to distinguish between tectonic earthquakes and man-made explosions.

The application of the INPAR method to data recorded during recent experiments in the South Shetland Islands and Bransfield Strait allow us the analysis of relatively low-magnitude events, which can hardly be studied with traditional methods.

MOMENT TENSOR FROM WAVEFORM INVERSION: THE METHOD

We study the earthquakes recorded in the Bransfield Strait and the South Shetland Islands using the INPAR method. The method works in the point-source approximation and consists of two main steps. The first step is a linear inversion and the six moment tensor rate functions (MTRF), $\dot{M}_{ij}(t)(i, j = 1, 2, 3)$, are retrieved. They are obtained extracting, with a damped least-squares algorithm, from the data the base functions (which are the responses of the medium to sources represented by elementary single forces with the time dependence given by a Heaviside function), computed by the modal summation method (e.g. Panza 1985; Florsch *et al.* 1991; Panza *et al.* 2000). Therefore the procedure does not require the *a priori* assumption of an initial source model. Differences in source depth influence the relative excitation of normal modes, causing systematic errors in the inversion if the depth is kept fixed at a value too far from the true one. Similarly, systematic errors in the inversion arise from relevant deviations of the earth model from the actual properties of the Earth. The base functions are thus computed (e.g. using the modal summation method) for a set of values of the source depth lying between two extremes, defined on the basis of hypocentral estimates, and two structural models A and B, assumed to represent the range of variability of the possible models of the study area. Indicating the different values of the source depth with the variable X, and representing the different structural models with the parameter

Table 1. List of the events recorded in the Bransfield Strait and analysed in this study; the hypocentral locations were computed by Robertson Maurice *et al.* (2003). For each event, the number of records used in the inversion is reported in the last column.

No. of event	Date	Origin time	Latitude	Longitude	Depth (km)	No. of records
1	19/2/1997 (a)	20:3:50.10	−61.7260	−54.8650	28.7	10
2	27/1/1999	6:55:21.45	−62.0809	−60.8650	34.0	14
3	19/2/1997 (b)	20:34:0.66	−61.7530	−54.5920	29.7	9
4	5/8/1997	20:11:26.13	−62.3577	−61.8456	0.0	7
5	9/9/1997	8:49:22.91	−63.9621	−64.0340	80.0	7
6	23/12/1998	6:10:28.96	−64.4059	−56.4426	26.7	8

Y ($0 \leq Y \leq 1$), then structure A, used to compute the base functions, corresponds to $Y = 0$, while structure B corresponds to $Y = 1$. The structural models corresponding to the values of the variable Y in the range [0, 1] are more similar to A if $Y < 0.5$, and more similar to B if $Y > 0.5$. In the course of the inversion intermediate values of the parameters X and Y are computed, incrementing the initial values with steps chosen *a priori*. The base functions corresponding to intermediate values of depth and structure are computed with a linear interpolation of the base functions evaluated at the grid defined by the assumed set of depths and structures (Šílený *et al.* 1992; Campus *et al.* 1996). For that reason, it is not straightforward to relate the inverted Y value to a physical earth model but Y suggests qualitative information about which of the two models (A or B) gives the best fitting with the real data. The difference between the observed records and the synthetic seismograms, corresponding to a given source depth and structural model, is computed using a L_2-norm. The norm can be considered as a function of the parameters X and Y, and its minimum is searched.

The MTRF, obtained after the first step of the inversion, are six linearly independent functions of time, but if we assume that the time dependence is the same for all six components, i.e. the mechanism of the source does not change during the focal process, we can then write

$$\dot{M}_{ij}(t) = \dot{m}_{ij} f(t),$$

where $f(t)$ is a function called the source time function, which contains information about the energy release at the source and $\dot{m}_{ij}$ describe an average source mechanism. The second step of the inversion is then a non-linear one, and the retrieved MTRFs, describing a source mechanism varying in time, are reduced to a constant moment tensor and the corresponding source time function, taking only the correlated part from each MTRF. This is a basic point of

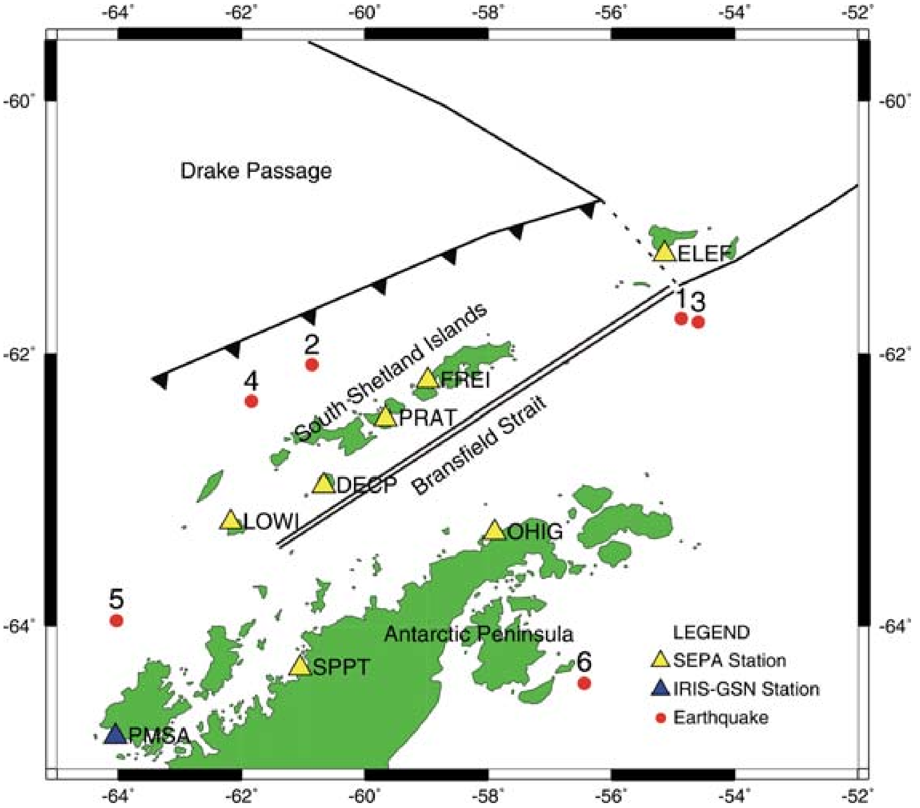

Figure 1. Locations of the events analysed in this study as determined by Robertson Maurice *et al.* (2003) (circles). Triangles correspond to the stations recording the data used in this study. The tectonic elements of the study area are taken from Pelayo & Wiens (1989) and Galindo-Zaldívar *et al.* (1996).

Table 2. Source parameters used for the synthetic tests.

Parameters for synthetic tests	
Depth	25 km
Strike	136
Dip	82
Rake	128

the INPAR method since, when taking only the coherent part at different stations, the influences on the solution of non-modelled structural heterogeneities and of scattering are reduced. The problem is non-linear and it is solved iteratively by imposing constraints such as positivity of the source time function and, when clear readings of first arrivals are available, consistency with polarities. The full moment tensor can be decomposed into a volumetric part (V) representing volume changes, a CLVD related to lenticular crack activation accompanied by possible fluid motion, and a double couple (DC) part due to dislocation movements. A genetic algorithm is used in the search of solutions and in the estimate of error areas (Šílený 1998). The genetic algorithm is used to find the point where the misfit function is a minimum and at the same time to map the model space in its vicinity with the aim of estimating the confidence regions of the model parameters.

To retrieve information about the error of the solution we use the posterior probability density function to mark confidence zones of the model parameters. From the size and shape of the confidence areas we can decide about the reliability of the solution. The MTRFs retrieved from the waveform inversion, and then the average mechanism and source time function, are considered to be affected by three types of errors, generated, respectively, by: (1) the noise present in the data; (2) the horizontal mislocation of the hypocentre adopted to compute the base functions in the depth grid used in the inversion and (3) the improper structural models used to compute the base functions (Šílený *et al.* 1996).

DATA ANALYSIS

We analyse, in this study, the data recorded during the Seismic Experiment in Patagonia and Antarctica (SEPA), a two-year deployment of broad-band seismic instrumentation in the South Shetland Islands and the Bransfield Strait. The events selected for this study are reported in Table 1, with the hypocentral locations computed by Robertson Maurice *et al.* (2003). Two of the events are located in the northeast end of the Bransfield Basin, just south of Elephant Island; two in the forearc; one in the southwestern part of the Bransfield Strait and one southeast of the Antarctic Peninsula (Fig. 1).

Synthetic tests

Synthetic tests have preceded the analysis of real data to investigate possible artefacts in the solutions due to numerical noise or to the station configuration. We computed synthetic seismograms corresponding to station receiver paths, for which we have waveforms, simulating the 1997 February 19 earthquake with the source parameters reported in Table 2, and a source time function represented by a triangle 0.2 s wide. Then, we made the inversion filtering the seismograms at 0.07 Hz and using one structural model only.

The synthetic test gives good results, with a correlation 1.0 between 'real' data and synthetic seismogram (see Fig. 2). The fault plane solution reproduces quite well the source parameters in Table 2, and the depth retrieved is 27 km. According to these

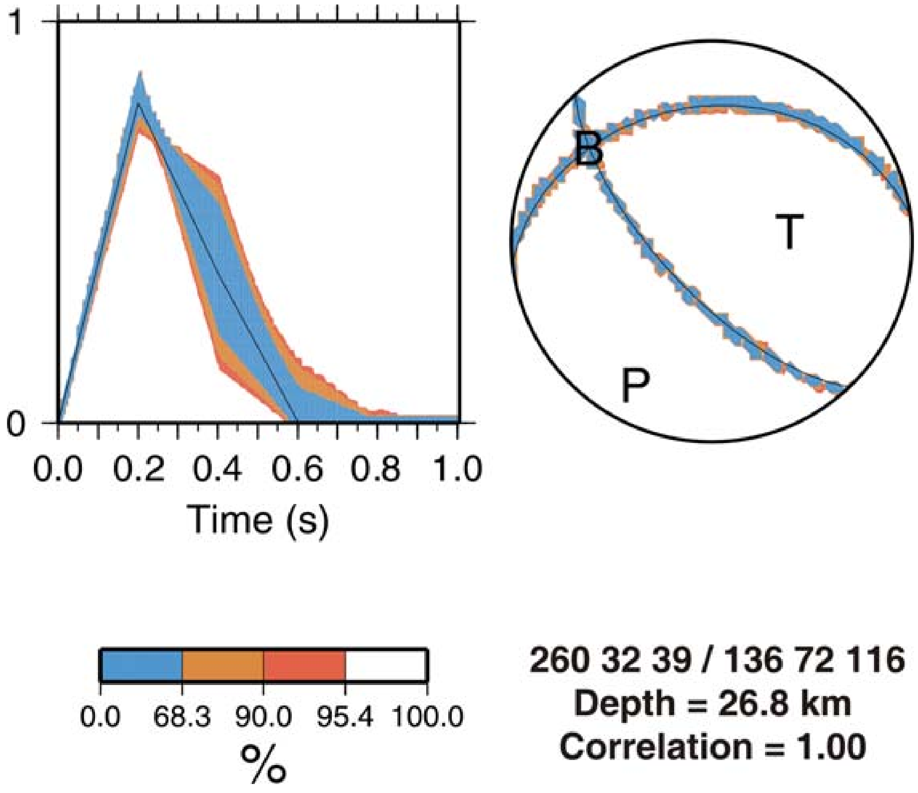

Figure 2. Results from the waveform inversion in the synthetic test plotted with confidence areas. Left-hand panel: source time function. Right-hand panel: fault plane solution.

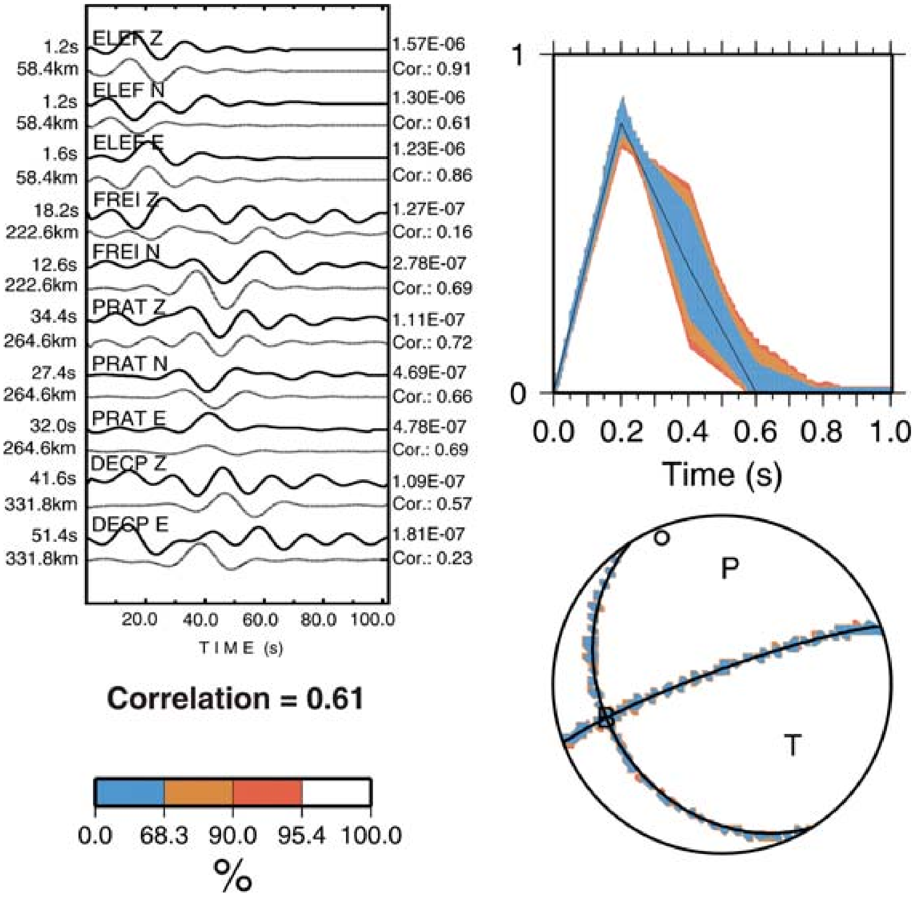

Figure 3. Results from the waveform inversion for the event of 19/2/1997(a) (1). Top left-hand panel: waveform fit. We report on the left-hand panel the epicentral distance and the starting time of the temporal window containing the inverted signal, whereas we report the peak values of the amplitude and the correlation value on the right-hand panel. Top right-hand panel: source time function and bottom right-hand panel: focal mechanism with confidence areas.

synthetic tests, the quality of the focal-sphere coverage by the available seismic stations is quite good and we can expect reasonable retrieval of the source mechanism. The reliability of the solutions is checked through the error analysis that takes into account the variance due to the noise in the available records, the mislocation of the hypocentre, and the improper structural models used to construct the base functions. The variance is turned into confidence regions of the eigenvalues and eigenvectors of the moment tensor and into error bars of the source time function. As seen in Fig. 2, the source mechanism and the source time function are well resolved; therefore with the actual station configuration for this event the INPAR method is able to retrieve reliable solutions.

We have also carried out synthetic tests that simulate the station configurations for the other events in Table 1 and we have obtained similar results.

Real data analysis

We start the analysis with the event number 1, recorded on 1997 February 19, which is located in the northeast end of the Bransfield Basin, just south of Elephant Island. For the inversion of real data, we use 10 waveforms at four stations (vertical, N–S, and E–W components) that have been low-pass filtered at 0.07 Hz using a Gaussian filter. Since with the INPAR method we can consider two structural models that acceptably represent the average properties of the region in which the events occurred, we calculate the base functions using the structural models used by Robertson Maurice *et al.* (2003) and those obtained by Vuan *et al.* (2000, 2005); we choose the appropriate model according to the region where the source receiver path propagates. After mean removing, tapering and filtering using a cosine box, we select the temporal window of the seismograms to be inverted for the retrieval of the moment tensor components; we perform the inversion with the volumetric component constrained to zero, as it is natural in tectonic environments. Nevertheless, experiments made including the volumetric part in the inversion give a negligible size for this component.

The mechanism shows dominantly thrust faulting with a small strike slip component. The value of the variable Y, corresponding to the structural model, is 0.5, suggesting that a model intermediate between the two used seems to be the most appropriate to represent the area under study. The focal mechanism and the source time function are reported with their confidence areas in Fig. 3.

The second event analysed, recorded on 1999 January 27, is located in the forearc, 50 km from the coast of Livingston Island. We use 14 waveforms at seven stations (vertical, N–S, and E–W components), with the volumetric component constrained to zero: the resulting mechanism is a thrust fault (see Fig. 4). Events number 1 and 2 were also analysed by Robertson Maurice *et al.* (2003). The fault plane solution of event 2 is in quite good agreement with that obtained by Robertson Maurice *et al.* (2003), but the mechanisms for event 1 are sensibly different in the two studies. In order to investigate

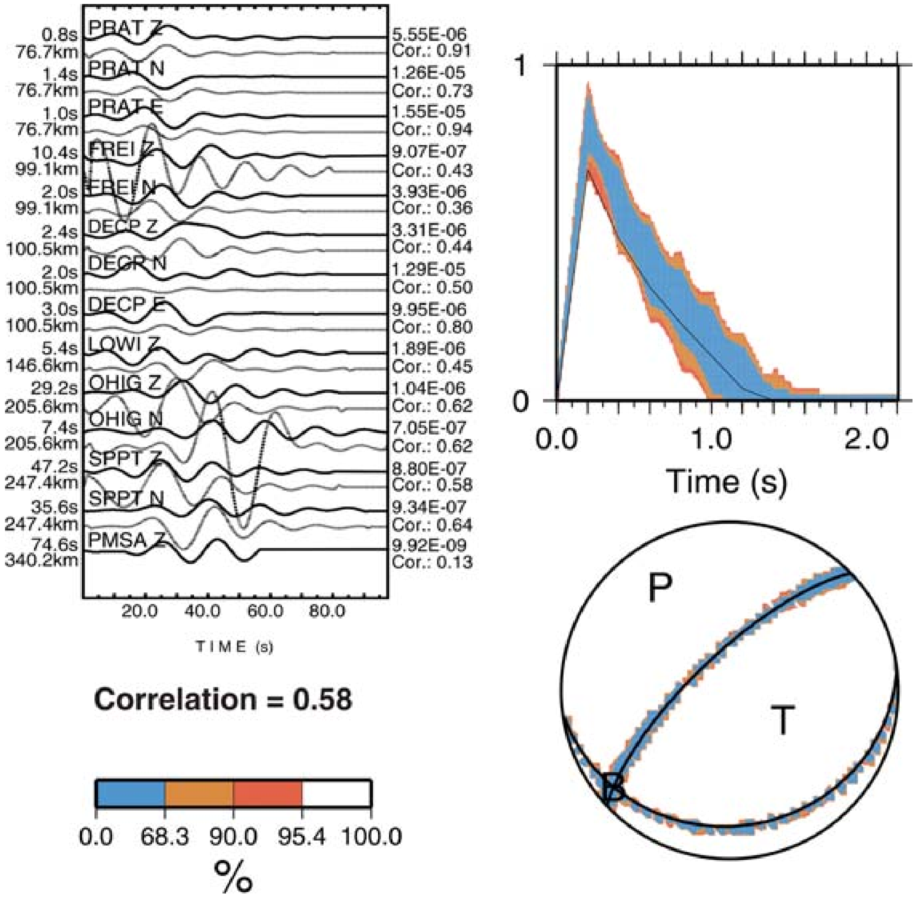

Figure 4. Results from the waveform inversion for the event of 27/1/1999 (2). For details see description of Fig. 3.

the reason of such discrepancy, we perform a new inversion fixing, as done by Robertson Maurice *et al.* (2003), the hypocentral depth at 10 km and we obtain a dominantly normal faulting mechanism, very similar to that retrieved by Robertson Maurice *et al.* (2003), but the correlation in this case is significantly lower (0.37). Thus, the constraining of the source depth strongly hampers the validity of the retrieved mechanism. We have also analysed event 1 using the inversion methodology proposed by Mao *et al.* (1994), which uses a gradient scheme to obtain the solution of the problem. The method assumes *a priori* a double couple and the depth of the hypocentre is optimized simultaneously with strike, dip and rake angles. The solution we have obtained is in agreement with the dominantly thrust faulting mechanism obtained with the INPAR method.

We have analysed four other events recorded by the SEPA instruments deployed in the region (numbers 3–6 in Table 1). The results of the inversions are reported in Fig. 5. A part from event 4, all the fault mechanisms are well resolved. The resolution for the source time functions (STF) is worse than the resolution for the fault plane solutions for most of the events. The low resolution for the STF of events 3, 4 and 6 is a consequence of their low magnitude (with respect to the other events) that makes them remarkably affected by the local noise.

The fault plane solutions for all six events are shown in Fig. 6 and Table 3. As mentioned in the methodology description paragraph, it is possible to constrain the inversions with first arrival polarities when clear readings are available. We were able to use such constraints for inversions of events 1 and 3 (reported in Figs 3 and 5). The resulting mechanism of event number 3, located close to event number 1 towards the northeast end of the Bransfield Basin south of Elephant Island, is a thrust faulting mechanism. The fault plane solution for event 4 shows a dominant strike slip component, but it is not well resolved. Event 5 is located south west of the Bransfield Strait and it is characterized by a normal fault mechanism, while event number 6, east of the Antarctic Peninsula has a dominant thrust component. The source depths retrieved with the inversions are reported as a depth range in Table 3. The resolution for hypocentral depth is worse for events 3 and 4, the events with the lowest magnitude within the analysed set.

DISCUSSION

The South Shetland Island region is an area of active tectonic processes with complicated structure. To help constrain stress conditions at the plate boundaries, it is necessary to supplement the information provided by global seismology (e.g. CMT-Harvard solutions) with regional and local broad-band studies. Although global seismic catalogues present low levels of seismicity in the South Shetland Island-Antarctic Peninsula region, Robertson Maurice *et al.* (2003) evidenced a high level of local seismicity (m_b 2–5) in the area through the analysis of data recorded by a temporal deployment of a local network (SEPA Project).

The first systematic study of earthquake focal mechanisms determined for shallow and intermediate seismicity (Pelayo & Wiens 1989) indicates NW–SE extensional stresses in the area, compatible with the backarc extension in the Bransfield Basin. Pelayo &

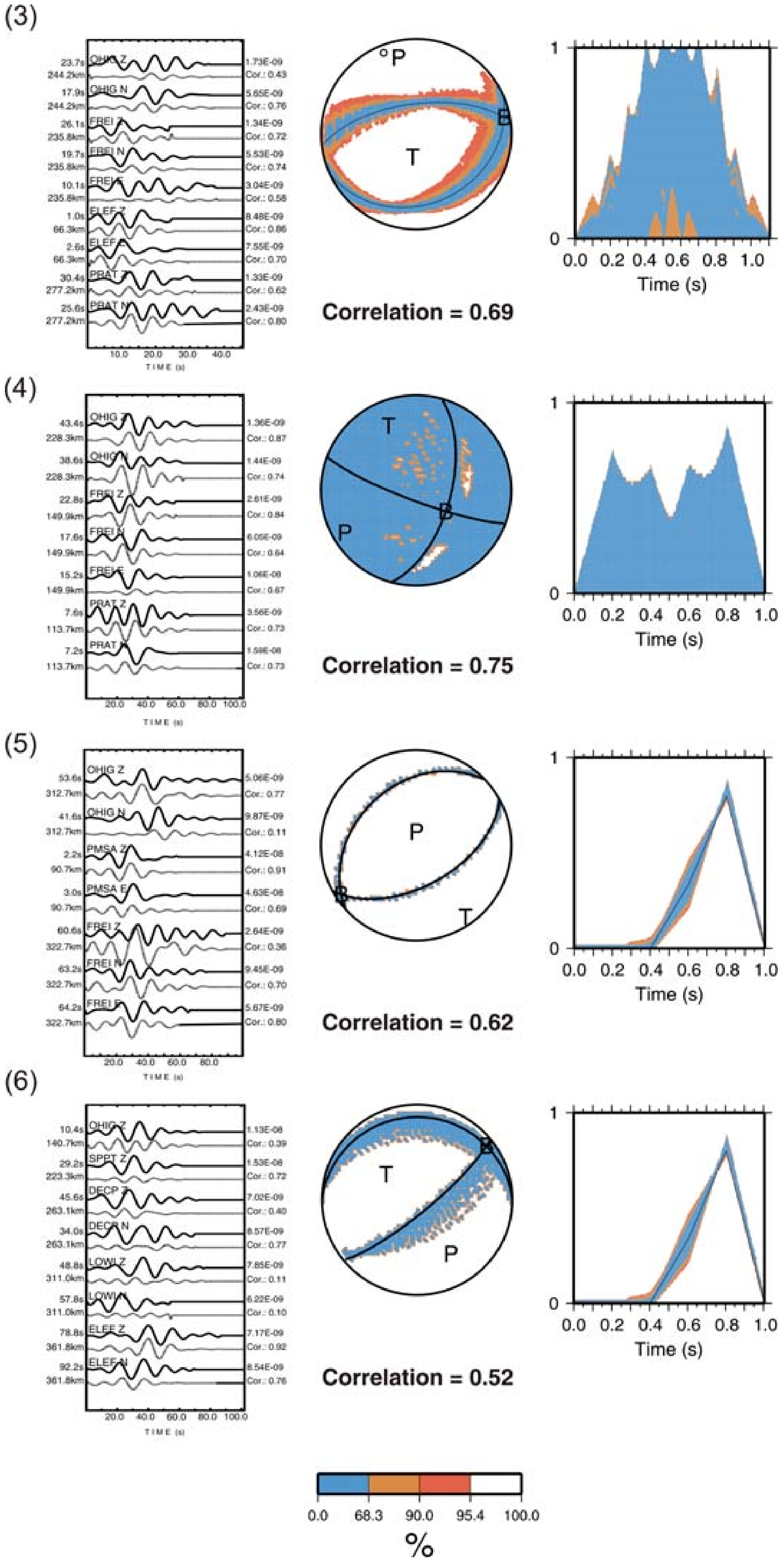

Figure 5. Results from the waveform inversion for events of 19/2/1997(b) (3), 5/8/1997 (4), 9/9/1997 (5) and 23/12/1998 (6). Left-hand panel: waveform fit, for details see description of Fig. 3. Middle panel: focal mechanism and right-hand panel: source time function with confidence areas.

Table 3. The results of the inversions for the six events analysed in this study. Events are numbered according to Table 1. M_w is the magnitude from scalar seismic moment according to Kanamori (1977).

No. of event	Date	Depth (km)	Half duration (s)	Scalar moment (N m)	M_w	Nodal planes
1	19/2/1997	43–53	0.3	6.24e+16	5.1	148 30 166/250 83 60
2	27/1/1999	39–53	0.6	2.92e+17	5.6	227 73 78/83 20 124
3	19/2/1997	0–14	0.5	1.20e+14	3.3	65 27 74/263 64 98
4	5/8/1997	9–35	0.5	1.42e+14	3.4	110 81 30/15 60 170
5	9/9/1997	38–44	0.5	1.56e+15	4.1	227 36 −101/61 55 −82
6	23/12/1998	43–45	0.5	7.64e+14	3.9	270 14 129/50 79 81

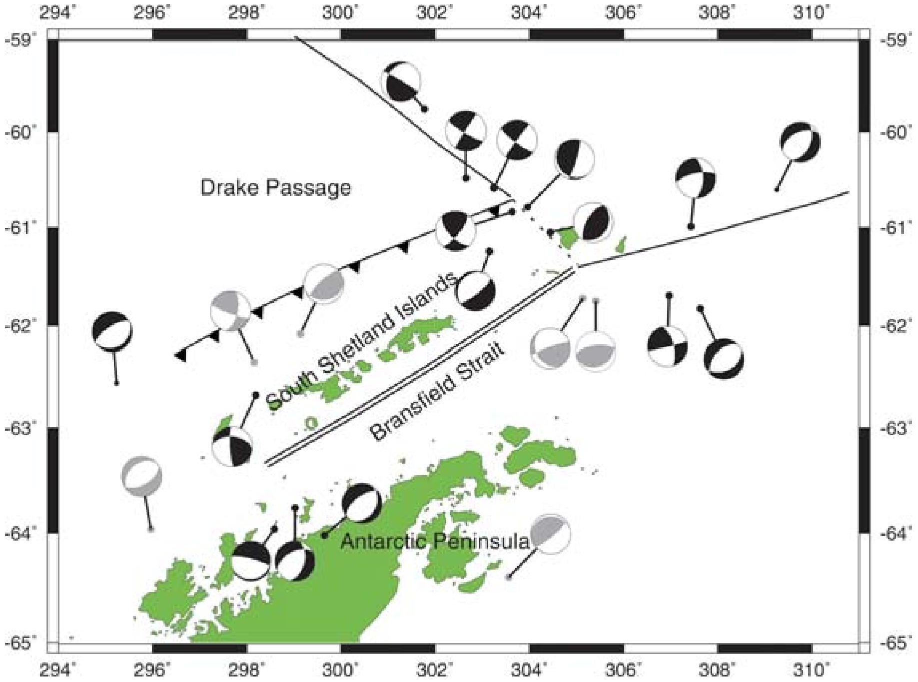

Figure 6. CMT focal mechanisms for events between 1976 and 2004 (black) and the six focal mechanisms determined in this study (grey). The focal sphere sizes are not scaled by magnitude. The tectonic elements of the study area are taken from Pelayo & Wiens (1989) and Galindo-Zaldívar *et al.* (1996).

Wiens (1989) also found seismological evidences of subduction at the South Shetland Trench, with the location of a couple of events at depths that would suggest the presence of a subduction environment. Ibáñez *et al.* (1997) also found an intermediate-focus seismicity (focal depth between 50 and 100 km), in addition to the shallow seismicity, that could be consistent with an active subduction along the South Shetland Trench.

In this study, we have determined the focal mechanisms for six earthquakes in the South Shetland Island and Antarctic Peninsula region. Two events (1, 3) are located south of Elephant Island (Fig. 6) and show dominant thrust faulting mechanisms. They are located at different depths, about 48 km for event 1 and about 4 km for event 3, but the resolution for event 3 is lower. The dominant thrust faulting mechanisms can indicate the presence of compressional or transpressional activity. Near Elephant Island is located the NE end of the Bransfield Basin. According to Galindo-Zaldívar *et al.* (2004) in the northeastern extremity of the Bransfield Basin it is possible to find compressional or transpressional episodes in a generally extensional setting. These episodes may be related to the subduction of the Shackleton Fracture Zone below the South Shetland Block. In fact, the area around Elephant Island is a complex environment, characterized by the presence to the north of the Elephant triple junction. The Elephant triple junction corresponds to the intersection of the Shackleton Fracture Zone, with a left-lateral motion, the active subduction of the South Shetland Trench, and the sinistral transpressional fault zone of the South Scotia Ridge. A thrust faulting event near Elephant Island was found by Pelayo & Wiens (1989); they explained the mechanism with the presence of active underthrusting of the lithosphere along the subduction zone.

Event number 2 is located in the forearc, 50 km from the coast of Livingston Island. The depth (about 45 km) and the thrust faulting mechanism are consistent with the presence of subduction at the South Shetland Trench, as underlined by other studies (Pelayo & Wiens 1989; Maldonado *et al.* 1994; Ibáñez *et al.* 1997; Robertson Maurice *et al.* 2003).

The fault plane solution for event 4 has a dominant strike-slip component, but it is not well resolved (Fig. 5). A similar mechanism is reported by the CMT databases (Fig. 6) along the north western boundary of the South Shetland Block, north of Livingston Island. Event 5 is located in the western part of the Bransfield Basin and it is characterized by a normal fault mechanism. According to the CMT catalogue, there are other normal faulting events in the southern part of the Bransfield Basin (see Fig. 6). The mechanisms could indicate the presence of an extensive regime but it is difficult to state whether the event is related to the back arc extension in the Bransfield Strait. In fact, the southwestern boundary of the South

Shetland Block is poorly defined and is located in a broad region of crustal deformations related to the transition from active to inactive subduction at the soutwestern end of the South Shetland Trench (Maldonado *et al.* 1994; Galindo-Zaldívar *et al.* 2004).

Event number 6, east of the Antarctic Peninsula and with a dominant thrust component, is in the inner part of the Antarctic Plate and does not seem to be related to the Antarctic Plate boundaries. The mechanism we found suggests a compressive regime in the area.

CONCLUSIONS

We have analysed six events recorded between 1997 and 1998 in the South Shetland Islands and the Bransfield Strait by the instruments of the SEPA experiment. We have applied a methodology (INPAR) for the full waveform inversion to retrieve the moment tensor. The results of our study confirm the applicability of the INPAR method to determine the source mechanisms using a limited number of noisy records. The source mechanisms obtained are quite variable but consistent with the active tectonic processes and the complicated structure of the South Shetland Island region. The mechanisms around Elephant Island reflect the influence of the Elephant triple junction, with the intersection of the Shackleton Fracture Zone, the South Shetland Trench and the South Scotia Ridge. Our results in the forearc, north to the South Shetland Islands, seem to confirm the presence of active convergence along the South Shetland subduction zone.

ACKNOWLEDGMENTS

We acknowledge two anonymous referees whose criticism helped in improving the manuscript. This study was funded by the Italian Programma Nazionale di Ricerche in Antartide (PNRA), project 2002–2003 ('Struttura della litosfera e geodinamica del Mare di Scotia'). We would like to acknowledge the IRIS consortium, D. Wiens, and S. Robertson-Maurice for providing data from the SEPA. All maps were generated with the Generic Mapping Tools (GMT) data processing and display package (Wessel & Smith 1991, 1998).

REFERENCES

Campus, P. & Fäh, D., 1997. Seismic monitoring of explosions: a method to extract information on the isotropic component of the seismic source, *J. Seism,* **1,** 205–218.

Campus, P., Cespuglio, G. & Panza, G.F., 1993. Full moment tensor retrieval and fluid dynamics in volcanic areas: the case of Phlegraean Fields (south Italy), in *Atti dell'Accademia dei Lincei of the International Conference Large Explosive Eruptions (The problem of eruptions, forecasting and warning; limits and possibilities)*, pp. 81–101, Accademia dei Lincei, Rome.

Campus, P., Suhadolc, P., Panza, G.F. & Šílený, J., 1996. Complete moment tensor retrieval for weak events: application to orogenic and volcanic areas. In Seismic source parameters; from microearthquakes to large events, *Tectonophysics,* **261,** 147–163.

Cespuglio, G., Campus, P. & Šílený, J., 1996. Seismic moment tensor resolution by waveform inversion of a few local noisy records. II. Application to Phlegraean Fields (southern Italy) volcanic tremors, *Geophys. J. Int.,* **126,** 620–634.

Chimera, G., Aoudia, A., Saraò, A. & Panza, G.F., 2003. Active tectonics in Central Italy: constraints from surface wave tomography and source moment tensor inversion, *Phys. Earth planet. Int.,* **138,** 241–262.

Florsch, N., Fäh, D., Suhadolc, P. & Panza, G.F., 1991. Complete synthetic seismograms for high-frequency multimode SH-waves, *Pageoph,* **136,** 529–560.

Galindo-Zaldívar, J., Jabaloy, A., Maldonado, A. & Sanz de Galdeano, C., 1996. Continental fragmentation along the South Scotia Ridge transcurrent plate boundary (NE Antarctic Peninsula), *Tectonophysics,* **258,** 275–301.

Galindo-Zaldívar, J., Gamboa, L., Maldonado, A., Nakao, S. & Bochu, Y., 2004. Tectonic development of the Bransfield Basin and its prolongation to the South Scotia Ridge, northern Antarctic Peninsula, *Mar. Geol.,* **206,** 267–282.

Guidarelli, M., Saraò, A. & Panza, G.F., 2000. Analysis of seismicity by seismic moment tensor: the Phlegraean Fields (Southern Italy) case. *Internal Report IC/IR/2000/5,* p. 69, The Abdus Salam International Centre for Theoretical Physics.

Guidarelli, M., Saraò, A. & Panza, G.F., 2002. Surface wave tomography and seismic source studies at Campi Flegrei (Italy), *Phys. Earth planet. Int.,* **134,** 157–173.

Guidarelli, M., Russi, M., Plasencia Linares, M.P. & Panza, G.F., 2003. The Antarctic Seismographic Argentinean-Italian Network and the progress in the study of structural properties and stress conditions in the Scotia Sea region, *Terra Antartica Reports,* **9,** 25–34.

Ibáñez, J.M., Morales, J., Alguacil, G., Almendros, J., Ortiz, R. & Del Pezzo, E., 1997. Intermediate-focus earthquakes under South Shetland Islands (Antarctica), *Geophys. Res. Lett.,* **24,** 531–534.

Kanamori, H., 1977. The energy release in great earthquakes, *J. geophys. Res.,* **82,** 2981–2987.

Kravanja, S., Panza, G.F. & Šílený, J., 1999. Robust retrieval of seismic point source time function, *Geophys. J. Int.,* **136,** 385–394.

Kravanja, S., Batini, F., Fiordelisi, A. & Panza, G.F., 2000. Full moment tensor retrieval from waveform inversion in the Larderello geothermal area, *Pure appl. Geophys.,* **157,** 1379–1392.

Maldonado, A., Larter, R.D. & Aldaya, F., 1994. Forearc tectonic evolution of the South Shetland margin, Antarctic Peninsula, *Tectonics,* **13,** 1345–1370.

Mao, W.J., Panza, G.F. & Suhadolc, P., 1994. Linearized waveform inversion of local and near-regional events for source mechanism and rupturing processes, *Geophys. J. Int.,* **116,** 784–798.

Panza, G.F., 1985. Synthetic Seismograms: the Rayleigh Waves Modal Summation, *J. Geophys.,* **58,** 125–145.

Panza, G.F., Romanelli, F. & Vaccari, F., 2000, Seismic wave propagation in laterally heterogeneous anelastic media: theory and applications to seismic zonation, *Adv. Geophys.,* **43,** 1–95.

Pelayo, A.M. & Wiens, D.A., 1989. Seismotectonics and relative plate motions in the Scotia Sea Region, *J. geophys. Res.,* **94**(B6), 7293–7320.

Radulian, M., Ardeleanu, L., Campus, P., Šílený, J. & Panza, G.F., 1996. Waveform inversion of weak Vrancea (Romania) earthquakes, *Stud. Geoph. Geod.,* **40,** 367–380.

Robertson Maurice, S.D., Wiens, D.A., Shore, P.J., Vera, E. & Dorman, L.M., 2003. Seismicity and tectonics of the South Shetland Islands and Bransfield Strait from a regional broadband seismograph deployment, *J. geophys. Res.,* **108**(B10), 2461 doi: 10.1029/2003JB002416.

Saraò, A., Panza, G.F., Privitera, E. & Cocina, O., 2001. Non double couple mechanisms in the seismicity preceding 1991–1993 Etna volcano eruption, *Geophys. J. Int.,* **145,** 319–335.

Šílený, J., 1998. Earthquake source parameters and their confidence regions by a genetic algorithm with a 'memory', *Geophys. J. Int.,* **134,** 228–242.

Šílený, J. & Panza, G.F., 1991. Inversion of seismograms to determine simultaneously the moment tensor components and source time function for a point source buried in a horizontally layered medium, *Stud. Geophys. Geod.,* **35,** 166–183.

Šílený, J., Panza, G.F. & Campus, P., 1992. Waveform inversion for point source moment tensor retrieval with optimization of hypocentral depth and structural model, *Geophys. J. Int.,* **109,** 259–274.

Šílený, J., Campus, P. & Panza, G.F., 1996. Seismic moment tensor resolution by waveform inversion of a few local noisy records-I. Synthetic tests, *Geophys. J. Int.,* **126,** 605–619.

Vuan, A., Russi, M. & Panza, G.F., 2000. Group velocity tomography in the subantarctic Scotia Sea region, *Pure appl. Geophys.,* **157,** 1337–1357.

Vuan, A., Russi, M., Costa, G. & Panza, G.F., 2001. Moment tensor waveform inversion in the sub-Antarctic Scotia Sea region: feasibility tests and preliminary results, *Terra Antartica,* **8**(2), 55–62.

Vuan, A., Robertson Maurice, S.D., Wiens, D.A. & Panza, G.F., 2005. Crustal and upper mantle S-wave velocity structure beneath the Bransfield Strait (West Antarctica) from regional surface wave tomography, *Tectonophysics,* **397,** 241–259.

Wessel, P. & Smith, W.H.F., 1991. Free software helps map and display data, *EOS, Trans. Am. geophys. Un.,* **72,** 445–446.

Wessel, P. & Smith, W.H.F., 1998. New, improved version of Generic Mapping Tools released, *EOS, Trans. Am. geophys. Un.,* **79,** 579.