Investigating the Focal Mechanisms of the August 4th, 2003, M_w 7.6, South Orkney Islands Earthquake and its Aftershocks Sequence

M. P. Plasencia Linares, M. Guidarelli, M. Russi and G. F. Panza

Abstract The $M_w = 7.6$ earthquake, known as *Centenary Earthquake*, occurred in the Scotia Sea region near the South Orkney Islands, Laurie Island, where is located the permanent Argentinean Antarctic Base Orcadas, here from 1997 operates a seismographic station ORCD, which has recorded several thousands of aftershocks, the most energetic ones recorded by all the instruments of the Antarctic Seismographic Argentinean-Italian Network (ASAIN). The aftershocks data available at ORCD station, till 60 days following the main shock were compiled. The plot of aftershocks rate with time was found to be oscillatory decay. Then, we inverted regional waveforms from ASAIN and International Federation of Digital Seismograph Networks (FSDN) stations to determine source parameters and source time functions for a set of aftershocks with magnitudes in the range 4.3–5.6 m_b. For the regional inversion we applied a methodology for the determination of the seismic moment tensor by means of full waveform inversion. The results obtained reflect the normal character of the main system fault, characterizing the study area.

1 Introduction

The South Orkney Microcontinent (SOM), is the largest (250 × 350 Km) continental element of the South Scotia Ridge which located between the Antarctic and the Scotia plates, and represents a remnant of the original continuous ridge linking the tip of South America with the Antarctic Peninsula (Dalziel and Elliot 1973; De Wit 1977; Dalziel 1984).

The South Scotia Ridge is located along the Antarctic—Scotia Plate boundary, and is characterized by a geodynamic setting reflecting the complicated evolution of the Scotia Sea area which included several spreading episodes (Barker et al. 1991).

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S. D'Amico (ed.), *Moment Tensor Solutions*, Springer Natural Hazards,
https://doi.org/10.1007/978-3-319-77359-9_17

The main tectonic feature is the left-lateral transcurrent fault running all along the plate boundary located at the northern shelf edge of the SOM (Forsyth 1975). A broad area of complex deformation accomplishes the strike-slip movements, with both extension and compression tectonics along it.

The western part of the Antarctica Plate-Scotia Plate boundary, north of Powell Basin, has been interpreted by Acosta and Uchupi (1996) as characterised by transtensional tectonic; while evidences of accretionary prism at the northern side were considered as indication of compression, due to plate convergence, in the westernmost part of the plate boundary (Lodolo et al. 1997) and along the northern side of the SOM (Kavoun and Vinnikovskaya 1994; Maldonado et al. 1998). Busetti et al. (2000) suggested that the northern edge of the SOM is characterised by strain partitioning with strike-slip zone accommodating the transcurrent motion and oceanward a trust zone accommodating the convergent component, that according to Braun and Beaumont (1995) model, correspond to an obliquely convergent plate boundary dominated by transcurrent condition. Eastward, at the plate boundary between the SOM and Discovery Bank, Pelayo and Wiens (1989), from seismological studies, suggested a transtensional tectonic, characterised by a combination of extension and transcurrent motion, by zones of oblique extension as well as discrete transform faults and extensional segments. The southeast and southwest borders of the SOM are passive margins connecting the SOM to the proto-oceanic Powell Basin on the west and to the oceanic Jane Basin on the east sides, relative to the rifting that separated the SOM from the Antarctic Peninsula.

2 Data

Even if the SOM is a small continental fragment of the Scotia Sea region, the study of its tectonic characteristics benefited from the integration between seismological data and other geophysical data. A large amount of seismological data have been made available after the deployment of broadband instruments in the Scotia Sea region since the early 90 as an extension of the global seismological network.

In the last 15 years several at least seven permanent seismographic stations were deployed in the Scotia Sea regions and Antarctica. Esperanza, Hope Bay (ESPZ), Jubany—King George Islands (JUBA), Despedida—Tierra del Fuego (DSPA), Orcadas—South Orkney Islands (ORCD), San Martín—Marguerite Bay (SMAI), Belgrano II—Nunatak Bertrab (BELA) and Marambio—Seymour Island (MBIO) stations constitute the Antarctic Seismographic Argentinean Italian Network (ASAIN), a cooperation between the Italian Programma Nazionale di Ricerche in Antartide (PNRA) and the Argentinean Dirección Nacional del Antártico (DNA); while East Falkland Islands (EFI), Palmer, Anvers Islands (PMSA) and South Georgia Island (HOPE) are also distributed by the Incorporated Research Institutions for seismology (IRIS) consortium. In spite of the development of a permanent seismographic network in the area, the application of seismological methodologies to the study of the South Orkney region was not possible until the end of 2003, because the low level

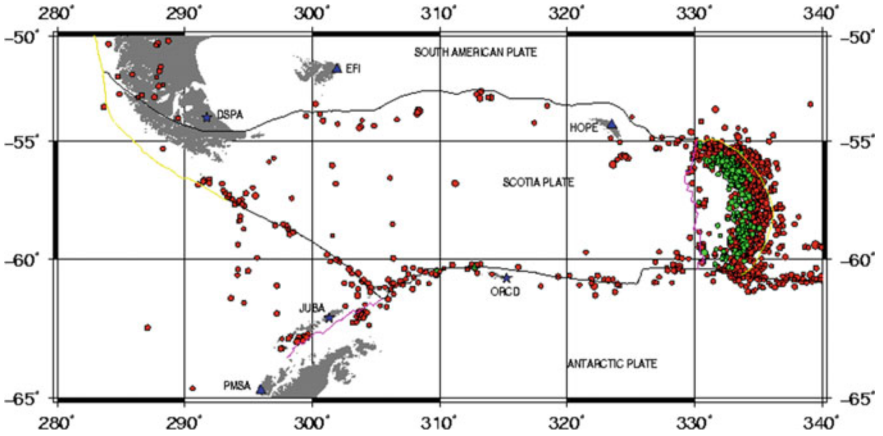

Fig. 1 Seismicity of the Scotia Sea region, 1973–2007. NEIC catalogue. Stars represents ASAIN stations and triangles global network stations

of seismicity. Figure 1 shows the distribution of earthquakes in the Scotia Sea region until 2007. This gap in the seismicity of the South Orkney area was filled after the Centenary Earthquake sequence which started on August 4, 2003 with a $M_w = 7.6$ earthquake, located offshore of the South Orkney Island and 2 years later a low level seismicity had yet remained.

This study provides an analysis of the *Centenary Earthquake* sequence centered on the determination of the source parameters for seven aftershocks. The determination of source mechanisms for the earthquakes in the South Orkney region can provide information about the stress conditions and the tectonic setting in the area and help to remove the limitations posed by the scarcity of events recorded in the past.

3 The Centenary Earthquake and Its Aftershock Sequence

On August 4, 2003 a major earthquake occurred in the south-eastern Scotia Sea, along the South Scotia Ridge and about 70 Km East from the Argentinean Base Orcadas (Laurie Island, South Orkney Islands), where the ASAIN station ORCD has been operating since 1997 (Russi and Febrer 2001). The moment magnitude was estimated as $M_w = 7.6$ according to CMT-Harvard. The August 4, 2003 earthquake was nicknamed Orcadas *Centenary Earthquake* because the Orcadas Base was opened exactly 100 years before and has been continuously operating since then. The *Centenary Earthquake* is the strongest event recorded in the SOM region. Recordings of the main shock from the ASAIN broadband digital stations ORCD and JUBA are shown in Fig. 2. The top trace corresponds to the clipped ORCD station records at a distance of about 100 Km from the epicenter, the bottom trace shows records at JUBA station at a distance of about 700 Km from the epicenter. All ASAIN stations

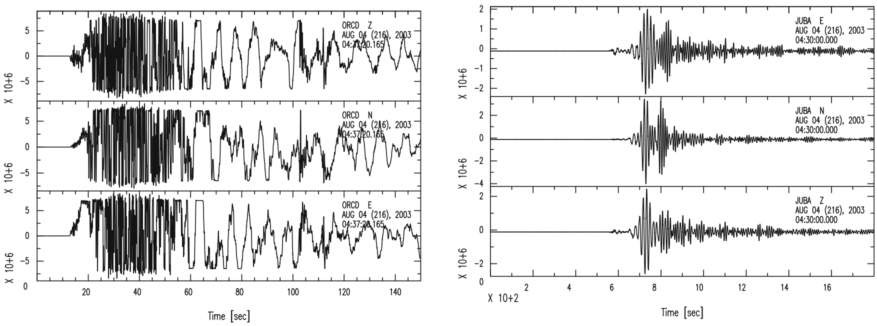

Fig. 2 Centenary Earthquake seismograms recorded by ORCD and JUBA, ASAIN stations

are equipped with Güralp broad-band seismographs: CMG-3T seismometer 0.01 s–50 Hz, CMG-DM24 24-bit Datalogger, GPS timing, great capacity storage media, allowing continuous recording of more than 2 years of the three component seismic channels at 100, 20 and 2 samples/s and connected to Internet.

Immediately after the *Centenary Earthquake* a noticeable aftershock sequence started. Within three hours from the main shock about twenty events, with magnitude larger than 4.0 occurred. In the following 24 hours, more than 50 events with magnitude within the range 3.6–5.6 m_b were recorded. The stress energy following a main shock is slowly released as a sequence of aftershocks. According to Omori law, the rate of aftershocks decays with time as $1/t$, where t is the time from the main shock. A generalization of Omori's Law was proposed by (Utsu 1961): the rate of aftershocks decays with time as $1/(t + t_0)^n$, where t_0 is a constant and n is the exponent. From this generalized Omori's relation, the number of aftershocks, N, occurring per unit time is proportional to $1/t^n$, when $t \gg t_0$. The aftershocks activity of the California earthquakes gave the value of n lying between 0.5 and 1.5 (Reasenberg and Jones 1989), which is also observed in most of the aftershock activity in the rest of the world. The plot of the rate of aftershocks against time for 60 days, following the main shock, is shown in Fig. 3.

In the Fig. 4 dash and dash-dotted lines indicate the hyperbolic fit, $77.58\,t^{-1.1}$, and the exponential fit, $41.41\,e^{-0.17\,t}$, respectively.

The superimposed oscillations present in the rate of decay of aftershocks are analytically extracted by subtracting the exponential and hyperbolic fits from the observed decay curve. Then we calculated the amplitude and phase spectra of the resulting curves. In order to find the nature of aftershocks it is necessary to examine the phase spectra, whether these oscillations correspond to random time series or deterministic series.

The result of this test is called z score or test statistic value. If $|z|$ score is greater than 1.96, then the data under consideration are not random at a confidence level of 95%. Using the test, the z score of the phase spectra of hyperbolic and exponential cases are found to be -7.52 and -6.97 respectively. Hence the oscillations present in the aftershocks activity are not random.

The ORCD station recorded several hundreds of aftershocks. The geographical distribution of aftershocks with magnitude larger than 3.6 m_b, occurred in the period August-December 2003, covers an ellipsoidal area, with the major axis extending for more than 150 Km in the E-W direction, along the main trend of the border between the Antarctica and the Scotia plates.

4 Determination of Source Mechanisms

To study the source mechanism we considered events occurred between August 4, 2003 and December 3, 2003. To investigate the source characteristic of the main shock we applied an amplitude spectra inversion methodology (Bukchin 1995) to teleseismic records from FSDN stations. We were able to determine source characteristics for the larger aftershocks using a regional waveform inversion methodology (Šilený et al. 1992; Šilený 1998). We selected 7 events, among those with magnitude greater than 4.3 m_b, which have sufficient signal to noise ratio and were recorded of FDSN stations that operates in the Antarctic area.

The moment tensor inversion is performed through the following processing steps. After data acquisition and pre-processing (we need data that have a good coverage of the focal sphere), linear trends are identified and removed. High frequency noise in

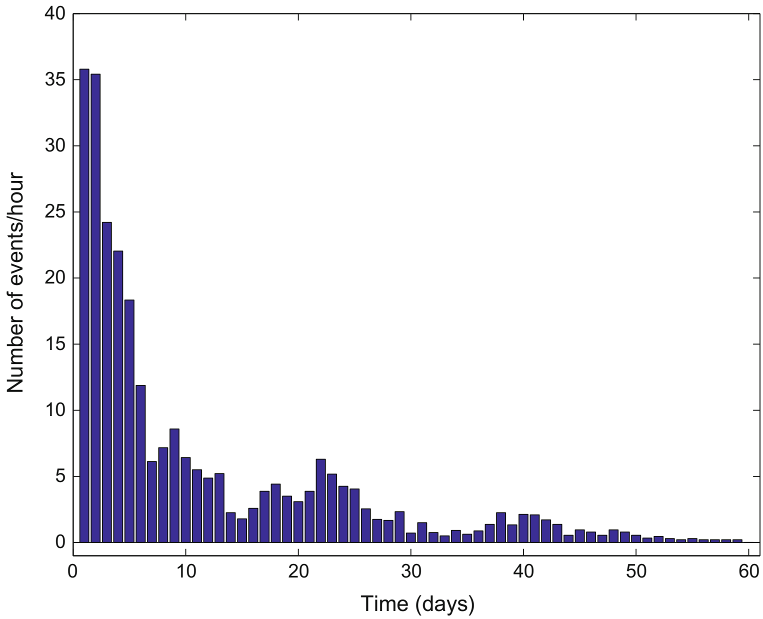

Fig. 3 Number of aftershocks per hour after the Centenary Earthquake, observed at ORCD station, for sixty days following the main shock

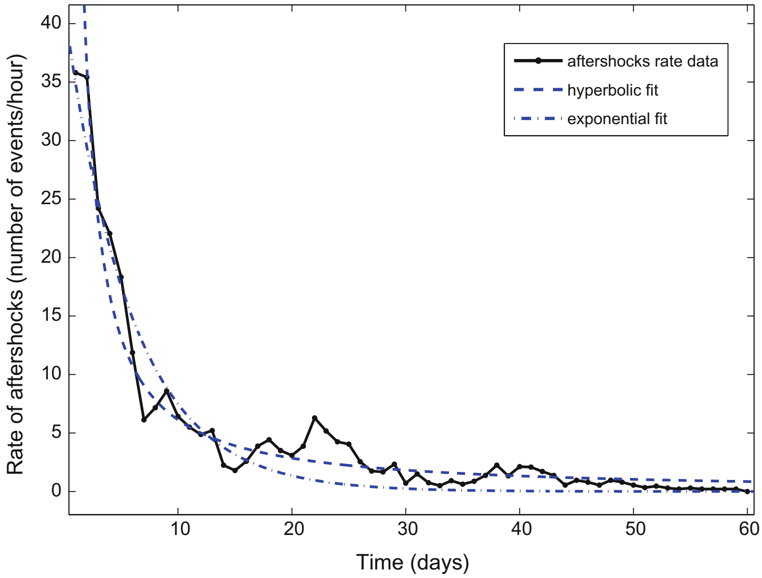

Fig. 4 Continuous trace shows the plot of rate of aftershocks of Centenary Earthquake, 2003, against time, dash trace shows the hyperbolic fit and dash-dotted shows the exponential fit

the data is removed by low-pass filtering. We low-pass filter the data at the frequency of 0.07 Hz for all the events. This filtering frequency was chosen because it enables us to make use of the point source approximation when studying the source in that frequency range. To consider the instrument effect we apply the instrument response to the synthetic Green's functions and compare them with the observed data. We do not deconvolve the instrument response from the data. After mean removing, tapering and filtering, we select the temporal window of the seismograms to be inverted for the retrieval of the moment tensor components. The synthetic Green's functions are calculated using the structural models obtained by Vuan et al. (2000) from group velocity tomography.

To study the lower magnitude events of the aftershock sequence we used the regional waveforms recorded by the broadband instruments of the ASAIN network and the IRIS consortium located in the Scotia Sea region. For the source characteristics determination we decided to use a methodology that had already been applied for earthquakes in the Scotia Sea region (Vuan et al. 2001; Guidarelli et al. 2003; Guidarelli and Panza 2006) and produced reliable results.

The INPAR (INdirect PARameterization) method, developed by Šilený (1992, 1998), proved to give reliable results even when only a few seismograms from a limited number of stations are available (Kravanja et al. 1999); such possibility is particularly important in regions where logistics is a major problem like in the Scotia Sea region. Kravanja et al. (1999) demonstrated that the INPAR method can absorb part of the inconsistency caused by poor forward modeling, which makes the availability of average models sufficient for our purposes. Limits and possibilities of this approach have been discussed in several papers (e.g., Panza 2000; Sarao et al. 2001; Šilený et al. 1996).

The method works in the point source approximation and consists of two main steps. In the first step (linear) the six Moment Tensor Rate functions (MTRF), obtained deconvolving from the data the Green's functions computed by the modal summation (e.g., Panza 1985; Panza et al. 2000) are inverted, without any constraints, with a damped least squares algorithm. In the second step (non-linear) 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 the Šilený's method since, when taking only the coherent part at different stations, the influences on the solutions of strong non-modelled structural heterogeneities and of scattering can be reduced. The problem is non-linear and 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 genetic algorithm is employed in the search of the solutions and in the estimate of the error areas (Šilený 1998).

5 Aftershocks Source Mechanisms

Here we will describe in detail the solution obtained for each event analysed. The map with the fault plane solution of events is reported in Figs. 5, 6.

The resulting mechanisms for events 1 and 2 are normal faulting mechanisms, and our solution agrees with the results given by Harvard Centroid Moment Tensor (CMT). Both of the events are shallow. Event 3 present a normal source mechanism with a small strike slip component, and also agrees with the results of the Harvard-CMT. Event 4 show a normal fault solution while the Harvard-CMT present a dominantly strike slip mechanism. Event 5 is characterized by a normal source mechanism with strike slip component. For events 2–5 a Harvard-CMT solution is available, the main differences exist for the event number 4. The possibility of relocation of hypocentral coordinates even for shallow events is one of the main features of the INPAR method, since it permits a refinement of focal depth mainly when depth values are fixed (15.0 Km) a priori in Harvard-CMT inversion scheme.

6 Conclusions

The source characteristics of the most relevant aftershocks have been investigated by means of the INPAR method, which is a suitable tool to study medium energy sources in areas where a small number of stations is available to record the regional seismicity and the standard procedures employing first arrival data are not effective to analyze situations where a relevant noise level is present (Kravanja et al. 1999).

DATE	Depth (km)	Half duration	Scalar moment (dyn cm)	Mw	Fault Plane Solution	
04/08/2003 12:53:51.0	4	1.2	4.35E+25	6.3	19 58 -145 / 268 61 -38	
04/08/2003 18:18:29.6	5	1.2	8.31E+24	5.8	160 11 -76 / 326 80 -93	
	15	1.1	1.12E+24	5.3	6 23 -81 / 176 68 -94 CMT	
06/08/2003 17:01:54.4	49	1.1	1.36E+24	5.4	119 18 -155 / 5 83 -74	
	15	1.0	6.88E+23	5.2	268 18 -128 / 128 76 -78 CMT	
14/08/2003 08:41:31.6	2	1.0	1.11E+24	5.3	61 12 -179 / 330 90 -78	
	15	1.0	7.45E+23	5.2	30 47 -171 / 295 84 -43 CMT	
29/08/2003 14:50:34.8	24	1.1	4.44E+24	5.7	253 24 98 / 65 66 86	
	15	0.8	3.29E+23	5.0	138 36 -92 / 320 54 -89 CMT	
09/10/2003 18:49:33.6	9	1.1	8.06E+23	5.2	226 19 95 / 41 71 88	
03/12/2003 03:17:24.8	2	1.1	3.90E+24	5.7	17 54 24 / 272 71 141	

Fig. 5 Aftershocks focal mechanisms determined with constrained epicenter location

DATE	Hypoc. Coord.	Half duration	Scalar moment (dyn cm)	Mw	Fault Plane Solution	
04/08/2003 12:53:51.0	7 -60.54 -42.46	1.2	5.28E+25	6.4	84 27 -99 / 275 63 -85	
04/08/2003 18:18:29.6	2 -61.12 -43.49	1.2	2.93E+24	5.5	42 20 -65 / 196 72 -99	
	15 -61.23 -43.59	1.1	1.12E+24	5.3	6 23 -81 / 176 68 -94 CMT	
06/08/2003 17:01:54.4	18 -60.23 -44.73	1.1	1.46E+24	5.3	292 22 -152 / 176 80 -70	
	15 -60.34 -45.03	1.0	6.88E+23	5.2	268 18 -128 / 128 76 -78 CMT	
14/08/2003 08:41:31.6	22 -60.84 -43.59	1.2	2.90E+24	5.5	310 25 -93 / 134 65 -88	
	15 -60.61 -42.37	1.0	7.45E+23	5.2	30 47 -171 / 295 84 -43 CMT	
29/08/2003 14:50:34.8	17 -60.52 -43.29	0.9	2.98E+24	5.5	129 32 -103 / 324 59 -82	
	15 -60.56 -43.21	0.8	3.29E+23	5.0	138 36 -92 / 320 54 -89 CMT	
09/10/2003 18:49:33.6	6 -59.94 -44.55	1.1	5.87E+23	5.1	62 19 -161 / 315 84 -72	
03/12/2003 03:17:24.8	6 -61.05 -42.27	1.2	9.28E+23	5.2	190 40 -143 / 70 67 -56	

Fig. 6 Aftershocks focal mechanisms determined with not constrained epicenter location

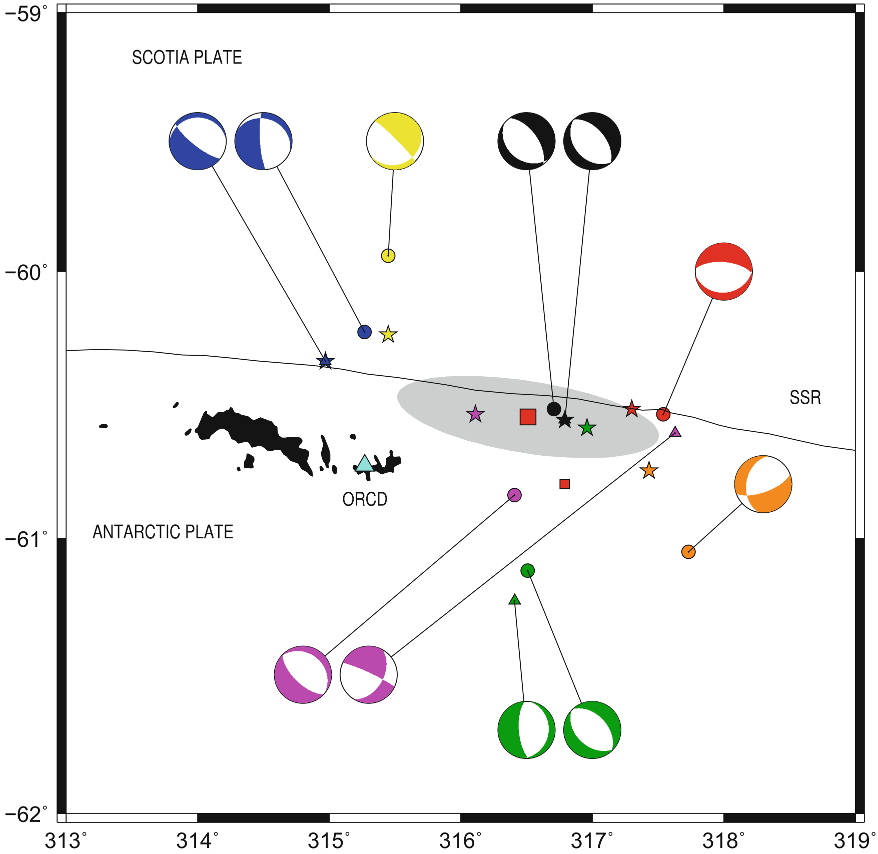

Fig. 7 Map with the location of events analysed in this study, stars: USGS locations, circles: INPAR locations and triangles: Harvard-CMT locations, in grey the rupture area

Still few information is available on the structural of the South Orkneys microcontinent and its tectonical setting. Most of the existing information on the structural and geodynamics setting comes from some seismic profiles performed by Italian, Spanish and Russian vessels during the late decade of the twentieth century, and the of average structural parameters for the lithosphere of the Scotia Sea region by surface waves tomography (Vuan et al. 2001).

According to the interpretation of this information plus gravity and bathymetry data a structural map for the SOM area has been constructed, this map is displayed in Fig. 7 together with the focal mechanisms of the events analised. The strike slips kinematics of the fault system on the northern border, which is also part of the Scotia Plate–Antarctic Plate margin along the South Scotia Ridge, and the existence of a convergent component responsible for the subduction of the Scotia Plate below the Antarctic Plate are put into in evidence.

Besides allowing us to fill a relevant gap in the seismicity map of the South Scotia Ridge the analysis of *Centenary Earthquake* and its aftershock sequence waveform data resulted in an increased seismological information about the characteristics of the seismic sources acting in the area which confirm the structural evidences collected by seismic experiments and gravimetry and the hypotheses of the existence both of transpresive and transtensive areas along the northern border of the SOM found in the literature.

Acknowledgements The project "Broad Band seismology in the Scotia Sea Region" is financially supported by the Italian Programma Nazionale di Ricerche in Antartide in the framework of the PNRA research area "Geodesia e Osservatori". Thanks are due to the Argentinean institutions cooperating to the ASAIN: Dirección Nacional del Antártico–Instituto Antártico Argentino. We are also extremely grateful to the military and civilian personnel operating in the Argentinean Bases Esperanza, Jubany (Now Carlini), Orcadas, San Martín, Belgrano II and Marambio for their help in maintaining the field installations and in the seismographic stations operation. We also thank the Abdus Salam International Centre for Theoretical Physics (ICTP) and the OGS for financing Milton P. Plasencia Linares's TRIL fellowship. Thanks are due to M. Busetti for her help in the geological interpretation of the results.

References

Acosta J, Uchupi E (1996) Transtensional Tectonics along the South Scotia Ridge; Antarctica. Tectonophysics 267:31–56

Barker PF, Dalziel IWD, Storey BC (1991) Tectonic development of the Scotia Arc region. In: Tingey RJ (eds) The geology of Antarctica. Oxford University Press, Oxford, pp 215–248

Braun J, Beaumont C (1995) Three-dimensional numerical experiments of strain partitioning at oblique boundaries: Implications for contrasting tectonic styles in the southern Coast Ranges, California, and central South Island. New Zealand. J Geophys Res 100(B9):18059–18074

Bukchin BG (1995) Determination of stress glut moments of total degree 2 from teleseismic surface wave amplitude spectra. Tectonophysics 248(3–4):185–191

Busetti M, Zanolla C, Marchetti A (2000) Geological structure of the South Orkney Microcontinent. Terra Antarct 8(2):71–78

Dalziel IWD (1984) Tectonic evolution of a forearc terrane, southern Scotia Ridge. Antarctica. Geol Soc Am Spec pap 200:32

Dalziel IWD, Elliot DH (1973) The Scotia Arc and Antarctic margin. In: Stehli FG, Nairm AEM (eds) The ocean basins and continental margins, vol I. The South Atlantic Plenum Press, New York, pp 171–246

De Wit MJ (1977) The evolution of the Scotia Arc as a key to the reconstruction of the southwestern Gondwanaland. Tectonophysics 37:53–81

Forsyth DW (1975) Fault plane solutions and tectonics of the South Atlantic and Scotia Sea. J Geophys Res 80:1429–1443

Guidarelli M, Russi M, Plasencia Linares MP, Panza GF (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 Rep 9:25–34

Guidarelli M, Panza GF (2006) Determination of the seismic moment tensor for local events in the South Shetland Islands and Bransfield Strait. Geophys J Int 167:684–692

Kavoun M, Vinnikovskaya O (1994) Seismic stratigraphy and tectonic of the Northwestern Weddel Sea (Antarctica) inferred from marine geophysical surveys. Tectonophysics 240:299–341

Kravanja S, Panza GF, Šilený J, (1999) Robust retrieval of seismic point source time function. Geophys J Int 136:385–394

Lodolo E, Coren F, Schreider AA, Ceccone G (1997) Geophysical evidence of a Relict Oceanic Crust in the Southwestern Scotia Sea. Mar Geophys Res 19:439–450

Maldonado A, Zitellini N, Leitchenkov G, Balanya JC, Coren F, Galindo Zaldívar J, Lodolo E, Jabaloy A, Zanolla C, Rodrigues Fernandez L, Vinnikovskaya O (1998) Small ocean basin development along the Scotia-Antarctica plate boundary and in the northern Weddell Sea. Tectonophysics 236:371–402

Panza GF (1985) Synthetic Seismograms: the rayleigh waves modal summation. J Geophys 58:125–145

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

Panza GF, Saraó A (2000) Monitoring volcanic and geothermal areas by full seismic moment tensor inversion: are non-double couple components always artifacts of modelling? Geophys J Int 143:353–364

Pelayo AM, Wiens DA (1989) Seismotectonics and relative plate motions in the Scotia Sea Region. J Geophys Res 94(B6):7293–7320

Reasenberg PA, Jones LM (1989) Earthquake hazard after a mainshock in California. Science 243:1173–1176

Russi M and Febrer JM (2001) Broad-band seismology in the Scotia Sea region, Antarctica. Italian and Argentinean contributions to the Scotia Sea Broad-band Network. In: Brancolini G, Panza GF, Russi M, Wu F (eds) Results from the workshop broadband seismic observations and the geodynamics of the Scotia Sea Region, Trieste, Italy, 25-26 ottobre 1999. Terra Antartica 82:29–34

Saraò A, Panza GF, Privitera E, Cocina O (2001) Non double couple mechanisms in the seismicity preceding 1991–1993 Etna volcano eruption. Geophys J Int 145:1657–1667

Šilený J, Panza GF, Campus P, (1992) Waveform inversion for point source moment tensor retrieval with optimization of hypocentral depth and structural model. Geophys J Int 108:259–274

Šilený J, Campus P, Panza GF, (1996) Seismic moment tensor resolution by waveform inversion of a few local noisy records-I. Synthetic test. Geophys J Int 126:605–619

Šilený J, (1998) Earthquake source parameters and their confidence regions by a genetic algorithm with a "memory". Geophys J Int 134:228–242

Utsu T (1961) A statistical study on the occurrence of aftershocks. Geophys Mag 3(3):710–724

Vuan A, Russi M, Panza GF (2000) Group velocity tomography in the subantarctic Scotia Sea region. Pure Appl Geophys 157:1337–1357

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

Wessel P, Smith WHF (1998) New, improved version of generic mapping tools released. EOS Trans Amer Geophys U 79(47):579