Moment Tensor Waveform Inversion in the Sub-Antarctic Scotia Sea Region: Feasibility Tests and Preliminary Results

A. Vuan\textsuperscript{1*}, M. Russi\textsuperscript{1}, G. Costa\textsuperscript{2} & G.F. Panza\textsuperscript{2,3}

\textsuperscript{1}Dipartimento di Oceanologia e Geofisica Ambientale, Istituto Nazionale di Oceanografia e Geofisica Sperimentale di Trieste, Borgo Grotta Gigante 42c, 34010 Sgonico - Italia
\textsuperscript{2}Dipartimento di Scienze della Terra, Università degli Studi di Trieste, Via E. Weiss 4, 34126, Trieste - Italia
\textsuperscript{3}The Abdus Salam International Center for Theoretical Physics, Trieste - Italia

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Abstract - The availability of average elastic parameters for the lithosphere of the Scotia Sea region, and a suitable database of regional events, allows us to perform a waveform inversion to retrieve focal mechanisms and source time functions. Examples of waveform inversion are presented, for the 30/05/96 event, located in the South Sandwich Trench (Mw = 5.9), and the 15/11/1998 event, close to the South Orkney Is. (Mw = 5.5), together with some feasibility tests. Despite use of only a few seismograms from a limited number of stations, our focal mechanisms are consistent with CMT solutions. The results obtained in synthetic experiments and inverting real data are encouraging for the study of low level seismicity detected by temporary arrays in the Antarctic Peninsula and Tierra del Fuego.

INTRODUCTION

The Scotia Sea is the result of the Tertiary disruption of a continuous Antarctic-Andean margin (Barker & Burrell, 1977) which began between 60 Ma and 34 Ma ago (Lawver et al., 1985). Its tectonic setting and evolution has been considered using the available geological and geophysical data (e.g. Barker & Dalziel, 1983; Barker et al., 1991), the information obtained from major earthquakes (Forsyth, 1975a; Pelayo & Wiens, 1989) and the high-resolution free-air anomaly maps derived from Geosat altimetry (Livermore et al., 1994). Only coarse information is available on crustal and upper mantle seismic velocities in the area. A few local models, based on deep seismic refraction experiments, have been published for the North Scotia Ridge and Falkland Plateau, (Ewing et al., 1971; Ludwig and Rabinowitz, 1982), and for the offshore parts of the western (Trouw & Gamboa, 1992; Grad et al., 1993) and the eastern Antarctic Peninsula (Trouw & Gamboa, 1992).

The data used in this study were recorded by permanent broad-band stations, belonging to the IRIS and ASAIN networks (Russi and Febrer, this volume) and the GSETT-3 IDC (PLCA) network. The location, origin time and magnitude of the events were selected from CMT bulletins (http://www.seismology.harvard.edu).

To help constrain stress conditions at the plate boundaries in the remote Scotia Sea region it is necessary to supplement the information provided by global seismology (e.g. CMT-Harvard solutions, CMT-USGS solutions) with regional and local broad-band studies. For this purpose, taking into account the available velocity models in the Scotia Sea region (Vuan et al., 2000), the waveform inversion method developed by Sileny & Panza (1991) and Sileny et al. (1992), is applied. The method can be applied even if few recordings are available, allowing us to overcome the limits posed by the high level seismic noise present in the Scotia Sea region. The standard analysis based on body wave first arrivals is not useful, because of the small number of operating stations.

The inversion of real data has been preceded by synthetic tests, performed in order to evaluate the capability of the method to give reliable results even when a very small number of records is available and the azimuthal coverage on the focal sphere is far from optimal.

AVAILABILITY OF SHEAR WAVE VELOCITY MODELS

During the last four years data average shear wave velocity models have been defined along selected epicenter-to-station paths (Vuan et al., 1997; 1999), from group velocity tomography (Vuan et al., 2000); and beneath the seismic stations, combining receiver function observations with surface wave dispersion measurements (Vuan, this volume). A new shear wave velocity model at 2x2 degrees in the same region, from the joint inversion of Rayleigh and Love wave local measurements is in preparation.

All the work done to improve the knowledge of the crustal and upper mantle seismic velocities is based on group velocity tomography and on inverting smoothed local dispersion relations. Although the network is too sparse, by using data from seven stations and regional earthquakes with magnitude larger than 4.7, we were able to perform this study with 4 years of data. Group velocity was used to maximize paths for better resolution, and most of the events were too small to have a dependable focal

*Corresponding author (aless@ogs.trieste.it)
mechanism, without which reliable phase velocities could not be obtained with the single station method.

Lateral resolution has been improved by using data not typically employed in larger-scale studies. These include data from our regional network and other temporary arrays, and data from events smaller in magnitude than those used on a continental scale (Ms< 5). We find a good consistency between the main known geological and tectonic features and our group velocity maps (Fig.1), and therefore use the average shear wave velocity models in the moment tensor inversion analysis.

MOMENT TENSOR METHOD

The method we employ to determine the seismic moment tensor has already been applied in volcanic and geothermal areas (Campus et al., 1993; Panza et al., 1993; Kravanja et al., 1999, Sarao’ 2000) and in tectonic environments (Radulian et al., 1996; Campus et al., 1996; Campus and Faeh, 1997; Dufumier & Rivera, 1998, Dufumier & Rouland, 1998; Aoudia et al., 2000).

The inversion scheme (Sileny & Panza, 1991, Sileny et al. 1992) is developed for point-source-like events, to determine the seismic moment tensor and the source time-function from high-frequency waveform data. The possible spatial peculiarities of the rupture process are transformed into complexities of the source time function.

In principle the focal mechanism may contain a non-deviatoric part, so the source is described by the unconstrained moment tensor, which is subsequently decomposed into a volumetric component, a compensated linear vector dipole and a double couple. When dealing with tectonic events we do not lose in generality, but gain in stability, if we constrain to zero the volumetric part of the moment tensor.

The k component of the displacement field at the free surface, excited by a point source may be expressed as the convolution:

\[ u_k(t) = M_\beta(t) * H_{k;j}(t) \]  

(1)

where \( M_\beta(t) \) functions (derivatives of the independent moment tensor components \( M_{ij}(t) \)) are the moment tensor rate functions and \( H_{k;j}(t) \) are the responses of the medium to elementary dipole sources with a time dependence given by a Heaviside function. The summation convention of repeated indices is adopted.

The moment tensor rate functions \( M_\beta(t) \) are

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Fig. 1 - Rayleigh wave group velocity map at 40s (from Vuan et al., 2000). Blues indicate faster than average, and reds slower than average, group velocity. Solid white lines mark the present-day plate boundaries. Low velocity anomalies in the group velocity follow in detail the plate boundaries. The signatures of the North Scotia Ridge (NSR), South Scotia Ridge (SSR) and East Scotia Ridge (ESR), that appears on this map, surround the high velocity anomaly of the Scotia Sea. Focal mechanisms (Mw> 5.5) in the CMT catalog from 1976 to the present are shown. At the South Sandwich trench only intermediate depth earthquakes (70< z <150km) are displayed.
parameterized by means of partly overlapping triangles delayed in time (Nabelek, 1984) with unit area and base length selected according to source characteristics and sampling step. The number and width of the triangles are a priori fixed parameters, while their weights are variable during the inversion.

The source moment tensor inversion does not require the choice of an initial solution and is performed following two sequential steps: (1) determination by linear inversion of the moment tensor rate functions \( M_{ij}(t) \) which describe a general source with varying mechanism, and (2) non-linear factorization of the \( M_{ij}(t) \) obtained in step (1) to retrieve the average source mechanism and the source time function derivative \( f(t) \) that give the best fit to \( M_{ij}(t) \) functions used as data.

If the structural model and the location of the hypocentre are known, the \( M_{ij}(t) \) functions obtained in step 1 are the solutions of the problem. In general this is not the case, and their factorization is necessary. A constant mechanism is deduced from the independent \( M_{ij}(t) \) by factoring them into a product of the average moment tensor and the source time function (STF):

\[
M_{ij}(t) = m_{ij} f(t)
\]

where \( m_{ij} \) are time-independent parameters that give the constant moment tensor describing the source radiation pattern, and \( f(t) \) (STF) describes the slip velocity.

### MOMENT TENSOR INVERSION

The peripheral location of the existing seismic stations with respect to the main seismogenic features, which is constrained by the geographical distribution of islands around the Scotia Arc, and the high level of seismic noise typical of the oceanic environment, can make the waveform inversion for seismic moment retrieval problematic.

To check the ability of the Scotia Sea broad-band seismic stations to retrieve reliably the moment tensor of relevant regional earthquakes, several feasibility tests have been carried out.

### SYNTHETIC EXAMPLES

The synthetic tests we present here examine the case of a seismic event localised at the South Sandwich trench and a poor station distribution. A systematic study of the effect of station distribution is given by Sileny et al., (1996) and Panza & Saraó, (2000), and can be used to assess the applicability of the method to study regional events located in seismogenic zones different from the South Sandwich trench.

To perform the synthetic tests, seismograms have been computed with the mode summation technique (Panza 1985; Florsh et al., 1991) in the frequency range 0.005 Hz to 1 Hz using focal parameters provided by CMT-Harvard (Dziewonski et al., 1981) for the May 30, 1996, Mw 5.9 South Sandwich trench earthquake.

The synthetic velocity seismograms - vertical, radial and tangential components - in the point source approximation have been computed considering a double couple force system and a step time function corresponding to an instantaneous source (The STF is a \( \delta \) function, i.e. in our parametrization it is a triangle of unit area and base equal to two times the data sampling time interval \( D t \)). Due to the epicenter-to-station distances and the frequencies used, the instantaneous point source is an acceptable approximation.

An average oceanic model (Vuan et al., 1999) has been used to parametrize each observation site.

Extensive testing, simulating different station configurations and varying the values of the inversion key parameters, like the damping factor in step 1 and the allowed maximum length of STF in step 2 (Sileny & Panza, 1991), was performed to find appropriate values to be used in real data inversion.

### Table 1 - Summary of results of the synthetic tests. Strike, dip, slip for focal solutions 1 and 2 and depth are tabulated as deviation from the CMT-Harvard solution parameters (Dziewonski et al., 1981). Configurations are shown in figure 1.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Upper Freq. Limit</th>
<th>Focal Solution 1</th>
<th>Focal Solution 2</th>
<th>Focal Solution 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strike</td>
<td>Dip</td>
<td>Slip</td>
<td>Strike</td>
</tr>
<tr>
<td>CMT-Harvard</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.1</td>
<td>+3</td>
<td>0</td>
<td>+3</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>-13</td>
<td>4</td>
<td>-21</td>
</tr>
<tr>
<td>C</td>
<td>0.1</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>8</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>E</td>
<td>0.1</td>
<td>2</td>
<td>-2</td>
<td>3</td>
</tr>
<tr>
<td>F</td>
<td>0.1</td>
<td>5</td>
<td>0</td>
<td>-6</td>
</tr>
<tr>
<td>G</td>
<td>0.1</td>
<td>+9</td>
<td>+1</td>
<td>+10</td>
</tr>
<tr>
<td>H</td>
<td>0.1</td>
<td>0</td>
<td>+3</td>
<td>-1</td>
</tr>
<tr>
<td>I</td>
<td>0.1</td>
<td>+5</td>
<td>0</td>
<td>+6</td>
</tr>
</tbody>
</table>
We discuss here the results obtained in the synthetic tests (summarized in Table 1) using different subsets of stations of a network comprising the existing ASAIN and IRIS Scotia Sea stations. The different configurations we tested are the following: (A) the set of permanent stations deployed before 1997, (B) the set A plus two (hypothetical) OBS, (C) the set A plus one (hypothetical) OBS, (D) a different configuration obtained by using two recently deployed stations (ORCD and HOPE), ESPZ and USHU stations plus two (hypothetical) OBS, (E) the set D with only one (hypothetical) OBS (F) USHU and ORCD stations only, (G) USHU and ORCD stations plus one (hypothetical) OBS, (H) HOPE and ORCD stations operating only, (I) HOPE and ORCD stations operating plus one hypothetical OBS. The hypothetical OBS considered here are located in the Atlantic ocean (18°W and 57.5°S, OBS0; 18°W and 51.7°S, OBS1; 18°W and 63.4°S, OBS2) and some hundred km east from the South Sandwich Trench, and some hundreds km west from the Bouvet triple junction. 

The tests have been performed using synthetic seismograms with high-frequency limits of (1) 0.1 Hz and (2) 1 Hz. With an optimal station configuration (Fig. 2a, conf. B) the tests give satisfactory results as reported in Table 1. The best station distribution is configuration B, but the deployment of only one OBS east of the South Sandwich Is., (Fig. 2a, conf. C), is a great improvement over the present situation (Fig. 2a, conf. A). In fact, using the actual station locations the calculated mechanism slightly differs from the true one, but the deviation is within acceptable limits (see Tab. 1, conf. A). The deviation is due to the peripheral geographical position of the epicenter with respect to the location of the stations. The resolution of the focal parameters does not change when different configurations (D and E) are selected by using
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recently deployed stations.

The relevance of the installation of one OBS at least, located some hundred km east of the South Sandwich trench is confirmed by the results of tests using the configurations F, G, H, and I where only two of the present-day permanent stations are assumed to be operating (this situation can occur very easily in Antarctica due to instrument breakdown and difficult logistics). As it can be easily seen from table 1 especially in the critical situation of configuration F, where the azimuthal coverage ensured by USHU and ORCD stations is poor, the installation of an additional OBS in the Atlantic Ocean would produce significant improvements in the waveform inversion for source moment tensors.

INVERSION OF REAL DATA

Since from the synthetic tests we conclude that the available observed signals can be suitable for our purposes a second set of tests has been performed, applying the source moment tensor retrieval procedure to actual recordings from two relevant Scotia Sea region events.

The observed seismograms for the 30/05/96 South Sandwich Trench (Mw > 5.9) event are very noisy, so a lowpass filter (0.1 Hz cut-off) has been applied both to the observed data and to the computed kernel functions.

The hypocentral coordinates are taken from CMT (Tab. 2) and only the hypocentral depth has been allowed to vary, using a step of 5 km within a depth interval, 40 km wide, centered on the CMT focal depth value.

Three component seismograms of Esperanza (ESPZ), Ushuaia (USHU), Falkland Is. (EFI) and Palmer (PMSA) stations were available for the 30/05/96 earthquake.

The inversion procedure has been applied, varying the subsets of inverted channels. We performed the following attempts using for the inversion mainly the surface wave portion of the records: 1) all the available channels (12), 2) one three component record plus the vertical component from the three remaining stations (total of 6 channels per test). The results obtained for this event using all the available channels are shown in figure 3. Table 2 shows the focal parameters found, compared with CMT solutions. The CMT database contained three events with quite similar locations, focal solutions and depths. The mechanism found (DST) is rotated (~30 degrees) with respect to the CMT one. Both are dip-slip events that could be explained as a downward component of motion of the southern block relative to the northern block.

According to Forsyth (1975), this kind of faulting occurs within the subducted plate and the hypothesis is supported by the observed focal depths. A schematic model of the bending and hinge faulting, within the south American plate (as it underthrusts the Sandwich plate) able to explain both the shallow strike-slip events and this kind of intermediate dip-slip events, can be found in Forsyth, (1975).

Waveforms of PMSA, ESPZ, USHU and HOPE stations were available for the event on 15/11/98. The event is located along the western SSR, few kilometers west of the South Orkney islands (Fig. 4a). The signals

![Fig. 2 - b) Seismographic network configurations used for the synthetic tests.](image)
Tab. 2 - Comparison between CMT-Harvard inversion solutions and the solutions obtained in this work.

<table>
<thead>
<tr>
<th>Event: 96/05/30 03:04:41.2 - Mw=5.9</th>
<th>Event: 98/11/15 13:27:12.8 - Mw=5.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CMT</strong></td>
<td><strong>DST</strong></td>
</tr>
<tr>
<td>Strike 232°</td>
<td>250° / 261°</td>
</tr>
<tr>
<td>123°</td>
<td>110° / 160°</td>
</tr>
<tr>
<td>Dip 30°</td>
<td>51° / 85°</td>
</tr>
<tr>
<td>80°</td>
<td>28° / 44°</td>
</tr>
<tr>
<td>Slip -158°</td>
<td>64° / 67°</td>
</tr>
<tr>
<td>-62°</td>
<td>116° / 168°</td>
</tr>
<tr>
<td>Depth (km) 82</td>
<td>86 - 94</td>
</tr>
<tr>
<td>Scalar moment 10¹⁷ Nm</td>
<td>22 - 40</td>
</tr>
<tr>
<td>Half duration (s) 2.3</td>
<td>1.5 - 2.0</td>
</tr>
</tbody>
</table>

Fig. 3 - a) The focal mechanism solutions obtained, for the May 30, 1996 event (blank star), by the inversion done in this study (DST) and by the CMT-Harvard inversion. The permanent IRIS (EFI, HOPE and PMSA) and IAA-OGS (USHU, ESPZ and ORCD) broad-band stations are shown as well. Black continuous lines indicate the great circle paths for the analyzed signals; b) Fit between real data (continuous line) and synthetic data (dashed line) obtained by inversion of the Vertical and East component data from stations EFI, ESPZ, PMSA and USHU.

Fig. 4 - a) The focal mechanism solutions obtained, for the November 15, 1998 event (blank star), by the inversion done in this study (DST) and by the CMT-Harvard inversion. The permanent IRIS (EFI, HOPE and PMSA) and IAA-OGS (USHU, ESPZ and ORCD) broad-band stations are shown as well. Black continuous lines indicate the great circle paths for the analyzed signals; b) Fit between real data (continuous line) and synthetic data (dashed line) obtained by inversion of the three component data from stations ESPZ, USHU and HOPE.
have been low-pass filtered at 0.2 Hz. The hypocentral coordinates are taken from CMT.

We performed the inversion using: (1) both the shear wave and the surface wave portions of the records; (2) the surface wave portion of the records only. The results are very stable in both cases and the solution found for (1) is shown in figure 4b. Table 2 summarizes the focal parameters found and compares them with CMT solutions. The DST solution is slightly different from CMT. The mechanisms we found (see DST in Fig. 4a) clearly shows components of both strike-slip and normal faulting motion, indicating that some sections of the boundary may consist of transform segments with a large component of extension. The CMT mechanism is a pure normal faulting event. Both DST and CMT solutions for this event resemble similar historical events occurred in the same location (Pelayo & Wiens, 1989).

CONCLUSIONS

Moment tensor inversion techniques are a useful way to investigate the characteristics of the seismic source, and the results of the synthetic tests demonstrate the feasibility to retrieve useful information even using data from only two three component broadband stations. Moreover, knowledge of focal mechanisms on a regional scale is helpful in determination of the apparent initial phase of the seismic source, that becomes essential for reliable phase and group velocity determinations at longer periods.

The inversion of the signals (low pass filtered at 5s or 10s) recorded by the broadband seismographic stations in the Scotia Sea and neighbouring regions reproduces the CMT catalog parameters based on the inversion of many records of teleseismic long period waves (low pass filtered at 45s).

The results of our feasibility tests fully justify an intensive use of the methodology in the Scotia Sea region, and the data recorded during recent experiments in the South Shetland Is. and the Antarctic Peninsula (NSF SEPA Project) will allow our analysis to be extended to relatively low magnitude events.

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REFERENCES


