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Time-Domain Moment Tensors for shallow ($h \leq 40$ km) earthquakes in the broader Aegean Sea for the years 2006 and 2007: The database of the Aristotle University of Thessaloniki

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ABSTRACT

We present a catalog of moment tensor (MT) solutions and moment magnitudes, M_w, for 119 shallow ($h \leq 40$ km) earthquakes in Greece and its surrounding lands (34°N–42°N, 19°E–30°E) for the years 2006 and 2007, computed with the 1D Time-Domain Moment Tensor inversion method (TDMT_INV code of Dreger, 2003). Magnitudes range from $3.2 \leq M_w \leq 5.7$. Green's functions (GF) have been pre-computed to build a library, for a number of velocity profiles applicable to the broader Aegean Sea region, to be used in the inversion of observed broad band waveforms (10–50 s). All MT solutions are the outcome of a long series of tests of different reported source locations and hypocenter depths. Quality factors have been assigned to each MT solution based on the number of stations used in the inversion and the goodness of fit between observed and synthetic waveforms. In general, the focal mechanisms are compatible with previous knowledge on the seismotectonics of the Aegean area. The new data provide evidence for strike-slip faulting along NW–SE trending structures at the lower part of Axios basin, close to the heavily industrialized, and presently subsiding, region of the city of Thessaloniki. Normal faulting along E–W trending planes is observed at the Strimon basin, and in Orfanou Gulf in northern Greece. A sequence of events in the east Aegean Sea close to the coastline with western Anatolia sheds light on an active structure bounding the north coastline of Psara–Chios Islands about 20–25 km in length exhibiting right lateral strike-slip faulting.

1. Introduction

During the last decade, seismology in Greece was marked by the dramatic increase of newly installed broadband stations. The upgrade of the Greek seismological networks started in 1999 when the National Observatory of Athens (NOA; http://bbnet.gein.noa.gr) replaced tens of its permanent short-period stations by LE-3D/20s sensors and continued in recent years by the installations of more modernized seismometers (STS-2, CMG3ESPC/60s). The Aristotle University of Thessaloniki installed its first broadband station (CMG-3ESP sensor) in 2005 and at present it operates a network of 24 broadband instruments (http://seismology.geo.auth.gr). Significantly large permanent broadband networks are also operated by the Seismological Laboratory of the University of Patras (UPSL; http://seismo.geology.upatras.gr; 14 broadband stations mostly distributed in western Greece and Peloponnese), and the University of Athens (UOA; http://dggsl.geol.uoa.gr; 22 broadband stations mostly around the Gulf of Corinth and in central Greece).

Broadband data have been available in Greece since 1999, however, the exchange of waveforms in real-time among the aforementioned Greek seismological institutes, begun in 2007, in the frame of the establishment of the Hellenic Unified Seismological Network (HUSN). The Aristotle University of Thessaloniki (AUTH) started the collection of broadband data in 2005, after its first modern station was installed, and at present it receives waveforms, in real-time, from about 100 stations operated by different institutes (AUTH, NOA, UPSL, UOA, GEOFON; GEOFOrschungszentrum Network, MEDNET; MEDiterranean very broadband NETwork, KOERI; Kandilli Observatory and Earthquake Research Institute). This dramatic increase of available broadband data allowed the computation of moment tensors for even small-to-moderate magnitude events in Greece and its surroundings. This effort started in 2006, when the available broadband stations were rather sparse and is still continuing as part of the routine analysis in the Seismological Station of the Aristotle University of Thessaloniki.

Here, we present a catalog of moment tensor solutions and moment magnitudes for 119 shallow ($h \leq 40$ km) earthquakes in Greece and its surrounding lands (34°N–42°N, 19°E–30°E) for the years 2006 and 2007. Depending on the available waveforms for each earthquake and the quality of the waveforms we were able to

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calculate focal mechanisms for a 119 earthquakes with M_w in the range 3.2–5.7. First we present in brief the method we follow to process the data, and in the following we focus our results in a few regions in Greece for which the new data shed some light on their style of deformation, for the first time.

2. Data, inversion method and application procedure

The waveforms used in the inversions were retrieved from the broadband networks of (a) the Aristotle University of Thessaloniki (AUTH), (b) the National Observatory of Athens (NOA), (c) the University of Patras Seismological Laboratory (UPSL), (d) the Kandilli Observatory and Earthquake Research Institute in Turkey (KOERI), (e) the Institute of Seismology in Tirana (TIR), (f) the Bulgarian Academy of Sciences (SOF), (g) GEOFON and (h) MEDNET.

The number of the available to AUTH broadband recordings varied significantly within the two-year period to which our work refers to. At the beginning we were dealing with a very small number of stations (<4), which progressively grew to ~50 by the end of 2007. Data from these stations are presently being recorded in either real or near-real time at the facilities of the Department of Geophysics of the Aristotle University of Thessaloniki. The locations of the stations, which were progressively incorporated into the moment tensors inversions are shown in Fig. 1a, while further information (exact location, geographical coordinates, operating institute) are summarized in Table 1. Fig. 1b shows the seismicity of the years 2006–2007, for $M \geq 3.2$ extracted from the on-line catalogue of the European Mediterranean Seismological Centre (EMSC) for reasons of comparison with Fig. 5 to be discussed later on. It is obvious that we were able to compute focal mechanisms for all strong ($M > 5.0$) events but also of a small fraction (~10%) of the reported seismicity in EMSC.

The computation procedure followed in AUTH is based on the Time-Domain Moment Tensor INVersion method (TDMT_INV) developed at the Berkeley Seismological Laboratory (Dreger and Helmberger, 1993; Pasyanos et al., 1996; Dreger, 2002, 2003). The TDMT_INV code has been already in use, among others, by the Northern and Southern California Seismic Networks (NCSN and SCSN) in the United States, the Japan National Research Institute for Earth Science and Disaster Prevention (NIED; www.fnet.bosai.go.jp/freesia/index.html) and INGV (http://earthquake.rm.ingv.it/tdmt.php) in Italy for near-real-time computation of moment tensors. In Greece, the method has been applied repeatedly in studies of specific earthquake sequences (e.g. Benetatos et al., 2002, 2005; Roumelioti et al., 2004; Karabulut et al., 2005).

In the TDMT method, synthetic seismograms are represented as the linear combination of fundamental Green's functions where the weights on these Green's functions are the individual moment tensor elements. The full waveforms of the three recorded components of motion are low-pass filtered and inverted to derive the moment tensor. The tensor is then decomposed into a scalar seismic moment, double couple (*DC*) orientation components and a percentage of compensated linear vector dipole (*CLVD*). The isotropic component is constrained to be zero. A library of Green's functions for three one-dimensional (1D) velocity models, proposed for the Aegean area (Novotný et al., 2001) and for the northern and southern Aegean Sea (Karagianni et al., 2005), is build in the form of synthetic displacement seismograms using a frequency–wave number integration method (Saikia, 1994). Both the observed data and the Green's functions are band-pass filtered with a 4-pole acausal Butterworth filter with a low corner of 0.02 Hz and a higher corner at 0.05 Hz for earthquakes of $M_w \geq 5.0$, while for earthquakes of $M_w < 5.0$ are filtered between 0.05 to 0.08 Hz or 0.05 to 0.10 Hz. At these frequencies, where dominant wavelengths are tens of kilometers, we assume a point source for the regional events investigated in this study. The point source assumption allows for linearization in the time domain, which is where we carry out the least squares inversion. We usually invert a time window of 120 s, although this can vary (from 40 to 180 s) depending on the magnitude of the event or the signal/noise ratio, i.e. in cases when a second event follows closely in time we are forced to shorten the inverted time window of the studied event. The quality of the solution is determined by the goodness of the fit between synthetic (*s*) and observed (*d*) waveforms, which is quantified through the variance reduction, *VR*, a measure defined as:

$$VR = \left(1.0 - \frac{\int [d-s]^2 dt}{\int d^2 dt}\right) \times 100 \quad (1)$$

For each event we tested at least two different source locations as initial conditions. Usually we derive the required information (geographical coordinates of the epicenter and focal depth) from the monthly seismicity bulletins of the National Observatory of Athens and of the Seismological Station of the Aristotle University of Thessaloniki, and the on-line catalogue of the European Mediterranean Seismological Centre (EMSC). We observed that the initial conditions, as long as they do not differ significantly (to change the source-stations azimuths), do not change the sense of motion in the computed MT although they result in different *VR* and *CLVD* values. For each event we finally keep the source location that results in the largest *VR* and smallest *CLVD* percentages.

Regarding the optimum depth for each event, the inversion is run with the point source depth at various levels, with an incremental step of 2 km. The optimum solution is identified as the one for which both the variance reduction and percent of double couple are maximized.

A quality factor is assigned to each moment tensor solution based on the *VR*% and the number of stations, *n*, that were successfully inverted. We assign a quality of:

- A to the best solutions, when $VR > 80\%$ and at least three stations are used in the inversion.
- B when $VR = 70–80\%$ or $VR > 80\%$ but with only two stations contributing to the solution.
- C when $VR = 60–70\%$ or only one station has been used in the inversion.

These quality factors have been determined empirically and reflect the stability of the inversion results and the overall reliability of the suggested moment tensor. "A" quality solutions are stable even if the combination or coverage in azimuth of inverted stations changes, while "B" solutions suffer small changes (of the order of $\pm 10^\circ$ in strike and $\pm 5^\circ$ in dip) when the inverted data set is altered. Typical examples of solutions of quality "A" and "B" are shown in Figs. 2 and 3, respectively. Solutions of quality "C" usually show significant instability as they are based on limited amount or poor quality data. In the present work we only present solutions of quality A and B, which we believe are reliable for use in future studies. Fig. 4a and b shows the frequency of analyzed events with respect to the computed M_w, and focal depth. It is observed that most of the events lie in the M_w range from 3.6 to 4.1.

3. Moment tensors for the years 2006 and 2007

3.1. General picture

For the time period 2006–2007, we were able to compute 119 moment tensors of quality A and B. From these, 50 solutions have not been published before; while for the remaining 69 at least one independent solution (a fast solution in most cases) can be found in either the web pages of EMSC and NOA or in Kiratzi et al. (2008). In Table 2 we summarize the source parameters of these events as