DEVELOPMENT OF AUTOMATED MOMENT TENSOR SOFTWARE AT THE PROTOTYPE INTERNATIONAL DATA CENTER

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ABSTRACT

We are porting to the Prototype International Data Center (PIDC) seismic moment tensor software used at the Berkeley Seismological Laboratory for the routine monitoring of earthquake strain release (Romanowicz et al., 1993; Pasyanos et al., 1996). The moment tensor software also forms an integral core in our efforts to automatically and rapidly characterize strong shaking from large earthquakes using information derived from sparse regional distance network (e.g. Dreger and Kaverina, 2000). Two separate moment tensor methodologies are employed: a surface wave spectral amplitude and phase method and a three component inverse method. For the purpose of screening seismic events for nuclear treaty monitoring the automatic determination of seismic moment tensors can contribute on several levels. First, seismic moment tensors provide robust estimates of the scalar seismic moment, which is a component of some regional distance discrimination techniques, or is a necessary source parameter for their calibration (e.g. Woods et al., 1993; Patton and Walter, 1993, Mayeda et al., 1993; Mayeda and Walter, 1996). Second, the seismic moment tensor inversions provide estimates of source depth. Finally, the seismic moment tensor may be used to examine the degree that seismic radiation deviates from a pure double-couple model of a tectonic event (e.g. Dreger et al., 2000), thereby providing an additional screening capability. Automated procedures are needed to be able to handle the annual numbers of low magnitude events on a global scale. The objective of our project is to port an automatic system for the analysis of seismic events of $Mw \geq 5.5$ on a global scale with the goal of refining capabilities to estimate seismic moment tensors for seismic events down to $Mw=4.5$. We will present the results of a performance test of the methods using $M_W>4.5$ data recorded by the IMS primary network for a three-month period. The derived source parameters will be compared against Harvard CMT and regional network solutions.

KEY WORDS: seismic, moment tensor software, PIDC

OBJECTIVE

Introduction

Seismic moment tensor analysis as described in what follows offers improved screening of seismic events. On a global scale approximately 100,000 M4 events occur annually and therefore an automated system is needed to quickly review the seismicity to monitor the CTBT.

The purpose of this project is to adapt and port to the Prototype International Data Center (PIDC) a set of codes developed and routinely used at UC Berkeley (Romanowicz et al., 1993; Dreger and Romanowicz, 1994; Pasyanos et al., 1996) to determine seismic moment tensors and source depth of seismic events automatically and close to real-time. While these codes are being used at UC Berkeley to monitor the strain release in natural earthquakes in northern California, the moment tensor inversion approach provides a potentially powerful event screening procedure in several ways (Pechmann et al., 1995; Dreger and Woods, 1999): (1) by providing estimates of M_w (moment magnitude), a more accurate measure of event size; (2) by providing estimates of source depth, which will help distinguish natural events (depths typically >> 1km) from nuclear explosions and (3) by providing estimates of radiation characteristics (i.e. deviations from the typical double-couple radiation of earthquakes). Indeed, nuclear explosions may display large non double-couple components (>50%) whereas earthquakes typically exhibit over 70-80% double couple (Dreger and Woods, 1999). Of perhaps greater importance is the ability of moment tensor studies to identify tectonic earthquakes or seismic events at significant source depth, thereby reducing the number of events that must be more closely examined in the monitoring of the CTBT. The initial performance goal of the ported software is the automated determination of moment tensors on a global scale for larger events (M>5.5-6.0) with a reduced threshold in a specifically targeted region. Later releases of the software will incorporate calibration information for several regions of interest, allowing moment tensor determinations at a lower magnitude threshold of approximately M~4-4.5.

The primary issues that are to be addressed during the course of this project are: (1) meeting the real time operational requirements at the PIDC in terms of the degree of automation including the assessment of solution quality; (2) revising the software to perform under the very different operational situation of the PIDC (eliminating the dependence on always available station data at near regional distances in calibrated regions as is the case in northern California, and to develop the capability to analyze data with the very sparse and uncalibrated IMS network configuration). This implies that the seismic moment tensor inversions cannot be expected to run as efficiently and to as low a magnitude as desired without additional effort; (3) and to utilize path calibration information already obtained for regions of interest to improve on capabilities of analyzing low magnitude events in specific target regions.

Moment Tensor Background Information

The use of broadband waveforms, as provided by modern broadband digital seismic stations, through moment-tensor inversion, provides robust estimates of source magnitude (M_w), information about the source mechanism, as well as depth of the source. Thus seismic moment tensors offer a potentially powerful method for screening observed seismicity to potentially identify suspect events, events which deviate from typical source depths and double-couple radiation. Events with anomalous non-double couple radiation patterns (e.g. Patton 1988; Dreger and Woods, 1999) may be flagged to receive more in depth analysis. Previous work has demonstrated that seismic moment tensors of nuclear explosions are anomalous compared to tectonic earthquakes (Patton, 1988; Stump and Johnson, 1984; Vasco and Johnson, 1989), however there is difficulty in resolving a pure isotropic source with regionally recorded long-period data (Patton, 1988). Recent experience with the methods we have developed indicates that anomalous radiation of nuclear explosions and non-tectonic seismic events may be identified with a relatively sparse network of stations (e.g. Dreger and Woods, 1999; Dreger et al., 2000).

The moment tensor formalism was first developed 20 years ago (e.g. Mendiguren, 1977, and has been since applied successfully in various settings, for the study and/or routine cataloguing of moderate to large earthquakes on the global scale, using either a time-domain waveform approach (e.g. Dziewonski et al., 1981) or a frequency domain, surface-wave spectral approach (e.g. Romanowicz, 1982; Romanowicz and Guillemant, 1984). When a good signal/noise ratio is available, it has been demonstrated that data from a single three-component station are sufficient to obtain an accurate moment tensor solution for large earthquakes at teleseismic distances (Ekstrom et al., 1986). At regional distances it has been shown that it is possible to obtain robust estimates of the seismic moment tensor for moderate sized earthquakes with as few as a single station (e.g. Dreger and Helmberger, 1991; Fan and Wallace, 1991; Walter, 1993). For large earthquakes and in global applications, relatively low frequency data can be used, and propagation corrections need not be known with great accuracy, so that standard 1D reference models of the earth, and, more recently, 3D models obtained from global tomography are generally sufficient to obtain acceptable solutions. More recently, with the proliferation of sparse regional broadband networks, moment tensor inversions have been adapted to the case of smaller events observed at regional distances. In this case, propagation corrections for shorter period waves (typically 15-40 sec) that are more sensitive to complex crustal structure, need to be accurately estimated using appropriate regional models. At U.C. Berkeley, we have developed two independent approaches for moment tensor estimation of earthquakes of moderate magnitude at regional distances (Romanowicz et al., 1993). These procedures have been automated and implemented to routinely provide reliable estimates of earthquake size, mechanism and depth in quasi-real time (within 10 minutes of the occurrence of an event, Pasyanos et al., 1996), in the framework of our real-time program (REDI, Gee et al., 1996). The solutions are broadcast over a paging-system to subscribers, as well as over the Internet, to interested scientists and governmental agencies. In our particular application, in addition to providing accurate moment-magnitude (M_w) estimation down to about Mw 3.5-4 within our monitoring region (central and northern California), for larger earthquakes the mechanism and depth information is critical for the estimation of finite-source parameters, and consequently of distribution of shaking as estimated from a sparse seismic network (Dreger, 1997; Dreger and Kaverina, 2000).

The resulting moment-tensor catalog of 389 moment tensor solutions over the last 8 years includes events to a lower limit of Mw 3.5. The catalog may be accessed from the WWW at:

http://www.seismo.berkeley.edu/~dreger/mtindex.html

The first moment tensor methodology we employ is a time domain waveform fitting procedure that utilizes the entire long-period wavefield (Dreger and Romanowicz, 1994; Pasyanos et al., 1996; Fukuyama et al., 1998; Fukuyama and Dreger, 2000). For the majority of events in northern and central California, three 1D crustal/upper-mantle velocity models are adequate. One model describes the relatively faster wave propagation of the thicker Sierra block, another describes the relatively slower wave propagation in the thinner California Coast Ranges (Pasyanos et al., 1996), and the third has been developed for the offshore Mendocino region. It is clear from our work in California that the complete waveform method operates quite well with only a few calibrated velocity models even in a region as complex as California, and is capable of monitoring seismicity in the 30 to 700 km distance range. The code operates in Japan with a single calibrated velocity model for the entire region (Fukuyama et al., 1998; Fukuyama and Dreger, 2000). With this method data from a single station is often sufficient, however in practice we use three-component data from several stations to improve the azimuthal coverage of the focal sphere (Pasyanos et al., 1996).

The second moment tensor methodology we use is a frequency domain, surface wave approach, adapted from the two-step method of Romanowicz (1982), for which calibrated fundamental mode surface wave phase velocities, in the period range 10-60 sec, are used for propagation corrections (Pasyanos et al., 1996). This method utilizes surface waves, which are the largest of the regional phases allowing for the analysis of smaller seismic events. We are able to analyze events to a magnitude of 3.5 using Berkeley Digital Seismic Network stations in the 100 to 500 km distance range. With sufficient azimuthal coverage this method is found to perform quite well.

In Figure 1 the data fits and solutions that were obtained for a small California earthquake are compared. The very good comparison between the complete waveform approach and the surface wave methods illustrate how two parallel methods can be used to gain confidence in the results. By running two independent seismic moment tensor approaches it is possible to compare the automatic results and to use similarity in the solutions as an indicator of robustness.

RESEARCH ACCOMPLISHED

During the first year of this project we have reached the following milestones.

Both the complete waveform and surface inversion routines have been installed on the Center for Monitoring Research computer system, and are presently undergoing testing and tuning.

The installed software has been modified to obtain parametric event and seismic station information directly from the pIDC database. Additionally, the raw waveform data from primary IMS stations are automatically retrieved. Data from the auxiliary IMS network may be requested and employed during analyst review of the solutions.

We have compiled an IMS data set, which spans the 90 day period from July 19 (day 200) to October 16 (day 290), 1999. The locations of events during this period and IMS Primary stations from which waveform data was collected is shown in Figure 2A. Figure 2B shows the available Harvard CMT solutions, which will be used for calibration purposes. In some regions it will be possible to use other catalogs of moment tensor and first motion solutions for calibration. For this period two data sets have been compiled. One with 30 M>= 5.4 events, and the second with 330 M>=4.4 events. These event lists are used to test the bulk processing capabilities of the two moment tensor methodologies, and to identify and correct software bugs and other problems.

We have begun detailed investigations of the seismic moment tensor inversion results in order to learn how to improve the bulk processing performance and the quality of the inversion results. These investigations have included inversions in three different frequency passbands (0.005-0.02Hz, 0.00714-0.03Hz, and 0.02-0.05Hz), and also the study of body wave, complete waveform and differentially weighted combined inversions. Figure 3 compares waveform inversion results for a Mw5.9 Kamchatka event, which occurred on September 16, 1999. The solution shown in Figure 3b compares very well with the Harvard solution in terms of the relatively deep source depth (50 km vs. 68 km), the non-double-couple nature of the radiation pattern, and in terms of the scalar seismic moment (8.7e24 vs. 1.2e25 dyne cm). This particular solution is derived from the complete three-component displacement waveforms in the 0.02 to 0.05 Hz passband from three stations located at distances between 28^{o} to 35^{o}. The Green's functions were computed from the IASPEI91 velocity model. The P and S body wave portions of the seismograms were weighted higher to increase their contribution in the inversion. Figure 3a and 3c compares the complete waveform inversion without differential weighting, and a body wave only result, respectively. In all three cases there is reasonably good agreement with solutions obtained by other researchers. Complete waveforms in the 0.00714-0.03 Hz passband yielded results comparable to that in Figure 3a. These results indicate that complete three-component waveforms from a few distant stations are sufficient for the recovery of the seismic moment tensor and also source depth. At these long-periods however it is expected that shallow source depth resolution will be poor due to the vanishing tractions at the free-surface. In these cases regional distance stations, and shorter periods may be used. These results also show that it will be beneficial to utilize both body and surface waves in the inversions.

At the end of July 2001 we visited the Center for Monitoring Research to coordinate the integration of our software package into the pIDC R&D test bed.

CONCLUSIONS AND RECOMMENDATIONS

The preliminary results we have obtained indicate that it is possible to recover reasonable estimates of the seismic moment tensor using only a few stations and a globally averaged 1D seismic velocity model. Future work will include the bulk processing of the 330 M>4.4 test events, investigating the results for different global 1D-velocity models, the development of an automated method of assessing solution, and the focused monitoring of a region. This later task will involve the use of ground truth and calibration information available at the Center for Monitoring Research. Possible regions for this focused analysis include the Lop Nor and Novaya Zemlia test sites, former Soviet Union, and the Middle East.

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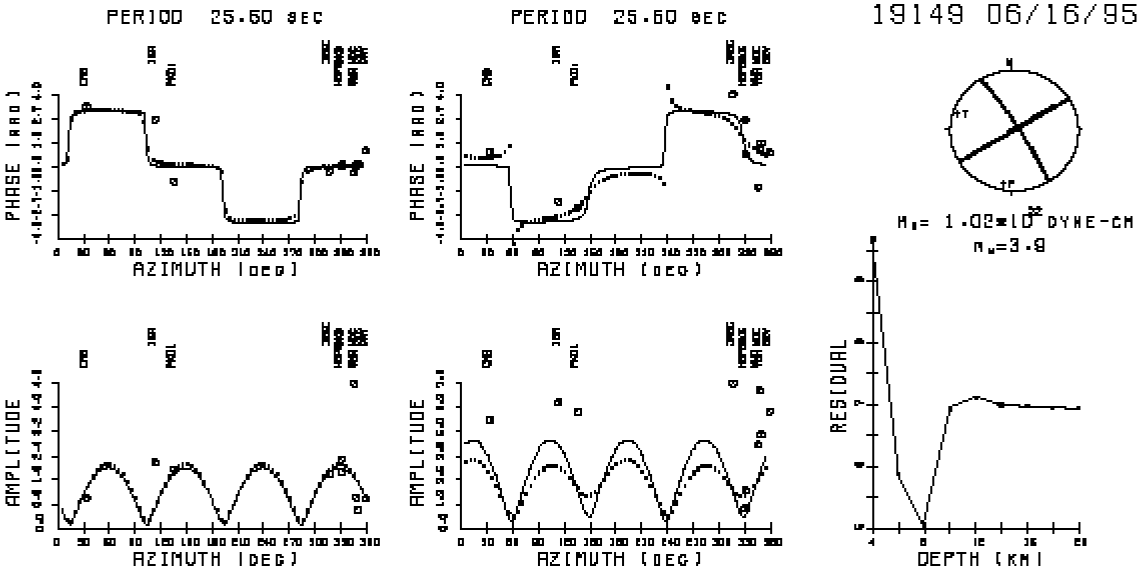

INITIAL	FINAL	21:20:36 Event origin time
Mo = 1.5e22 dyne-cm	Mo = 1.0e22 dyne-cm	21:27 REDI Page
Mw = 4.08	Mw = 3.97	21:29 Data Extracted
NP1 238/88/-6	NP1 58/89/6	21:31 Inversion Completed
NP2 328/84/-178	NP2 328/84/179	21:32:14 MT Page is sent
z = 20 km	z = 8 km	
tau = 1.0 sec	tau = 1.0 sec	

Figure 1A. Example of the regional surface-wave method for an event located near Hollister, California on July 16, 1995. The automatic solution is shown as small circles, the revised as solid lines, and the measured amplitude and phase as large circles. Love wave amplitude and phase are compared on the left, and Rayleigh wave amplitude and phase are compared on the right. The automatic and revised focal mechanism, and source depth as a function of residual are shown to the far right. The text gives the parametric details, and a chronology for the automatic processing and reporting for this event.

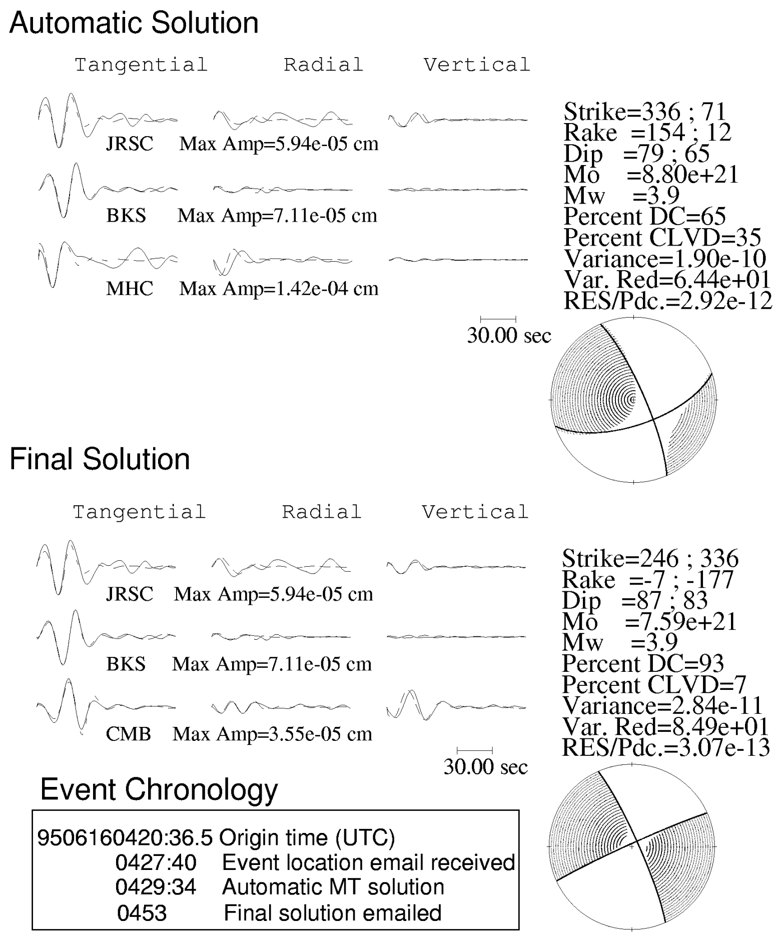

Figure 1B. The automatic and revised solutions for the same event discussed in Figure 1A are compared for the complete waveform method. The analyst review resulted in the removal of the noisy MHC station, and the inclusion of CMB, which provided much better azimuthal coverage. The data is shown as solid lines and the synthetic seismograms as dashed lines. The complete waveforms include phases such as P_{nl}, S_n body waves, and Love and Rayleigh surface waves.

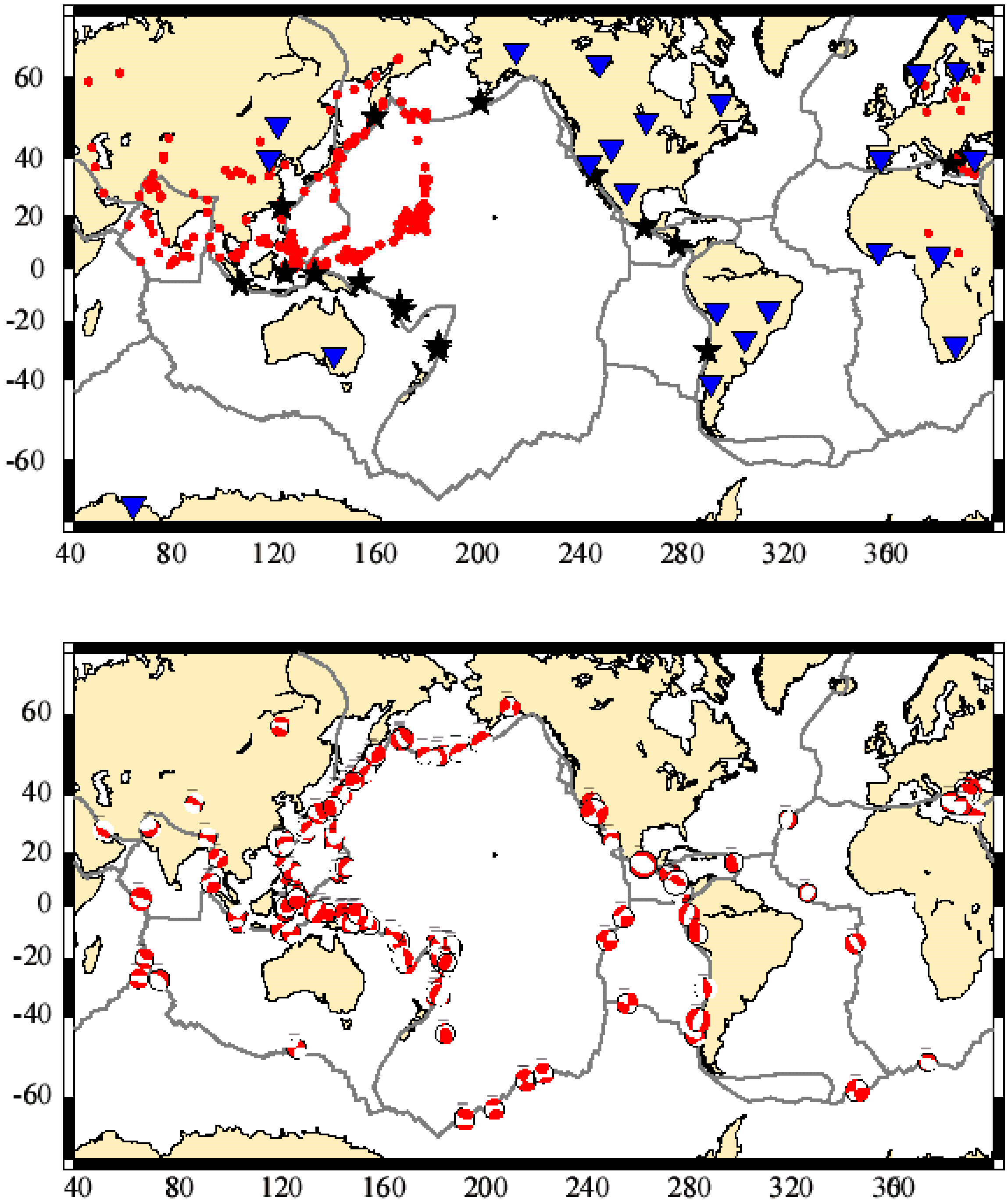

Figure 2. A) Map showing the locations of Mb>4.4 (red circles) and Mb>5.4 (black stars) events from the REB during the 90 day period from July 19, 1999 to October 17, 1999. IMS primary stations from which data was obtained are shown as inverted blue triangles. There are 330 Mb>4.4 events and 28 Mb>5.4 events during this time period. B) Harvard CMT solutions for the same time period.

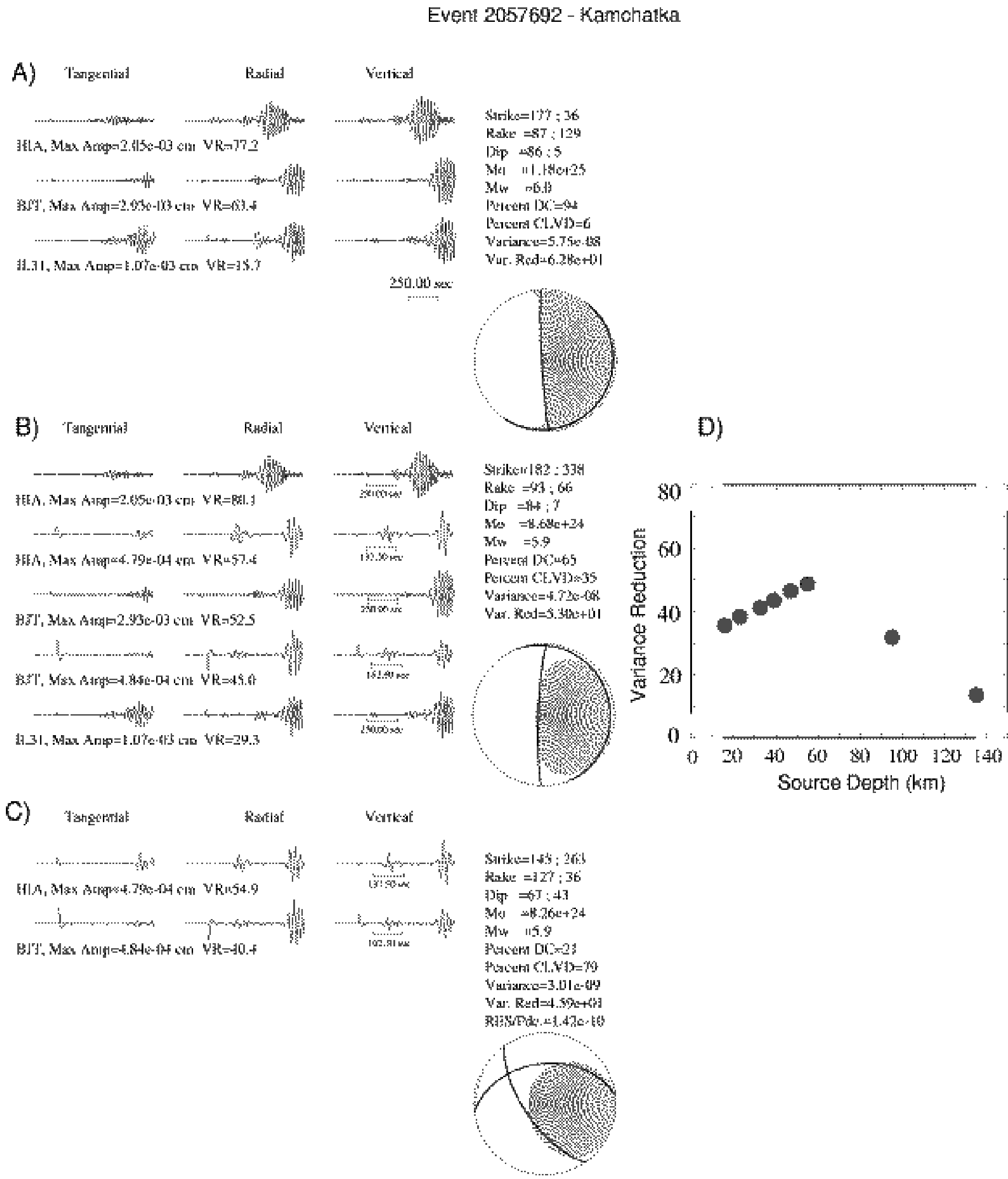

Figure 3. A) Inversion results for the September 18, 1999 Kamchatka event obtained by fitting complete three-component waveforms in the 50 to 20 second period passband from three IMS primary stations located between 28-35 degrees from the event. B) Inversion results for the case when P and S body waves have increased weight. This solution compares very closely with the Harvard CMT. The Harvard CMT resulted in a depth of 67 km, and the variance reduction vs. depth plot shows that a maximum occurs at a depth of 50 km. Only the depths shown were tested and it is possible that a better fit would be obtained if depths between 50 and 100 km were tried. C) Inversion results for the case when only P and S body waves are used.