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Moment tensor estimation using regional seismograms from a Tibetan Plateau portable network deployment

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Abstract. We present the results of moment tensor inversions using regional seismograms recorded during the 1991-1992 PASSCAL passive seismic experiment on the Tibetan Plateau. Using data recorded over a one-year period, we estimate the source mechanisms for 38 earthquakes within and near the Tibetan Plateau with moment-magnitudes (M_W) ranging from 3.8 to 5.0. With only one exception, all the events within the Plateau, but away from the Plateau boundary, indicate either strike-slip or extensional faulting, a result consistent with previous studies. Three-fourths of all the events occurred at depths less than 10 km, and all but two depths less than 15 km. Several events, located near the southeastern section of the Plateau, exhibit an unusual m_b-M_W difference of approximately one magnitude unit.

Introduction

In the last decade, the researchers at Harvard [e.g. Dziewonski et al., 1983] have routinely and reliably characterized global seismicity by modeling teleseismic waveforms generated by moderate-to-large events. To accelerate the characterization of seismic activity we must lower the magnitude threshold for reliable source modeling. Smaller sources, although accounting for a small fraction of moment release, are more plentiful and could provide valuable information for regional tectonic analyses in a relatively short time span. To aid in this effort, we should exploit the recent, significant improvements in seismic instrumentation. Notable among these advances is the development of portable, high-quality, broadband, three-component, digital instruments. With careful siting and construction of portable stations, it is possible to achieve data quality comparable to that previously available only from permanent observatory stations. Deployments of instrument arrays or networks can provide both continuous and reliably-triggered recordings of local, regional, and global earthquake activity [e.g. Owens et al., 1993].

In this paper, we illustrate the capabilities of these networks to model regional seismic activity. Our modeling efforts are similar to those illustrated in rapid network deployments for aftershock analyses (Fan et al. [1994]; Protti and Schwartz [1994]) and our work illustrates the utility of regional networks (including those deployed temporarily) to expand available focal-mechanism databases by modeling events in the magnitude 4-to-5 range. We analyzed regional waveforms recorded during a one-year seismometer deployment across the Tibetan Plateau, an ideal region to demonstrate the source modeling capabilities of regional networks. Tibet's sustained seismic activity in the magnitude six and greater range throughout the last 30 years has provided data for previous workers to characterize the tectonic activity in and near the Plateau [e.g. Molnar and Chen, 1983; Molnar and Lyon-Caen, 1989; Holt et al., 1991; Zhao and Helmberger 1991]. These preceding works provide a set of regional stress constraints which we use to demonstrate the reliability and consistency of our results.

The network configuration for the Tibetan Plateau Experiment was designed primarily with earth-structure modeling and logistics in mind, and is not optimized to provide details on Plateau seismic activity (Figure 1). However, the wide aperture of the network permits us to provide meaningful constraints on the seismic processes in the eastern half of the Plateau, with additional information on processes along the Plateau boundary. The instrumentation consisted of 11 Reftek PASSCAL recorders equipped with 16 bit A/D converters and ten Streckheisen STS2 (flat velocity response between 0.0083 Hz and 50 Hz) and one Guralp CMG-3ESP sensors (flat velocity response between 0.033 Hz and 30 Hz). These instruments provided high quality broadband waveforms [Owens et al., 1993]. After examining all the data, we concentrated our efforts on the largest 41 regional-distance events located within or near the Tibetan Plateau.

Moment Tensor Estimation

Ritsema and Lay [1993], Romanowicz et al. [1993], Dreger and Helmberger [1993], Walter [1993], Zhao and Helmberger [1994], and Braunmiller et al. [1995] have discussed many details involved in regional source investigations. We adopted a simple approach which requires minimal pre-processing of the waveforms; we simply deconvolved the instrument response, cut, and bandpass filtered the data prior to inversion. In this aspect, our approach is similar to Ritsema and Lay [1993] except we included periods as short as 20 s, they limited the data to 30 s or longer, depending on the event size.

We only included data with high signal-to-noise ratios which generally limits us to events with at least one station within 500 km of the event. This imposed a lower limit of the size of events suitable for modeling (minimum event size modeled: 3.5×10^{14} Nm). We modeled three-component displacement waveforms starting with the first P-wave arrival and continuing through the surface wavetrain. We inverted the waveforms using a time-domain moment-tensor inversion scheme described by Langston [1981]. Only deviatoric sources were investigated, but non-double couple solutions were permitted. A one-second rise time was assumed and a grid search

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[1]An electronic supplement of this material may be obtained on a diskette or Anonymous FTP from KOSMOS.AGU.ORG. (LOGIN to AGU's FTP account using ANONYMOUS as the username and GUEST as the password. Go to the right directory by typing CD APEND. Type LS to see what files are available. Type GET and the name of the file to get it. Finally, type EXIT to leave the system.) (Paper 95GL00909, Moment tensor estimation using regional seismograms from a Tibetan Plateau portable network deployment, by George E. Randall, Charles J. Ammon, and Thomas J. Owens). Diskette may be ordered from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009; $15.00. Payment must accompany order.

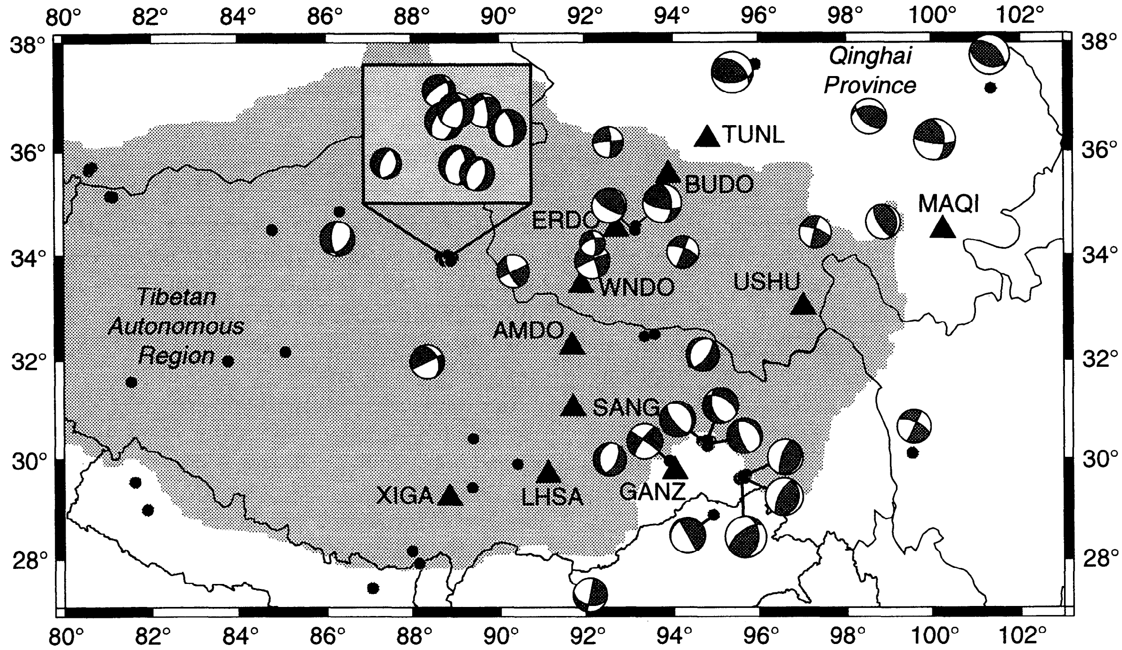

Figure 1. Location of the eleven seismic stations (triangles) and regional events (solid circles) recorded during the one-year deployment in the Tibetan Plateau region. The shaded region represents the area above the 4500 m contour (after topographic smoothing). Political boundaries and Chinese province boundaries are also indicated. Major double couple mechanisms for events analyzed in this study are also shown. The focal mechanism diameter is linearly related to m_b.

was performed to estimate depth, beginning with a coarse five-km sampling from 5 to 15 km and then refined using a search about the best fitting initial estimate. In general, the depth-error curves contain a single minimum. Tests indicated that the estimated mechanisms are robust with respect to expected moderate errors (10-15 km) in the epicenter location.

In the modeled bandwidth, surface waves dominate the observed waveforms, and we used the surface-wave model (M45) from Romanowicz [1982] to compute Green's functions. We tested the sensitivity of our results to the assumed structure by comparing the M45 results with those obtained using the slightly faster Chang Tang model (CT) from Bourjot and Romanowicz [1992] (also derived from surface-wave measurements). We computed complete synthetic seismograms which included all phases using the reflection-matrix method of Kennett (1983). We aligned the data and Green's functions using the first arriving P wave (identified from the broadband data) to reduce the dependence of the source inversion on the selected velocity structure, origin time, and event location. A laterally homogeneous velocity structure is most appropriate when the paths from the source to the station are short (a few hundred km). Unless they are obviously corrupted by noise, we did not weight the data in the inversion, thus allowing the closer stations, which have naturally larger amplitudes, to contribute more to the solution.

The moment-tensor inversion results for 38 events are detailed in Table 1 (available as an electronic supplement). We assigned each event a quality rating based on the available distance and azimuth ranges, waveform fit, stability of the mechanism as a function of depth, and perturbation estimates of uncertainties in the orientations of the Pressure (P), Tension (T), and Null (B) axes. "A" quality events are well constrained, an uncertainty of ±10° in the dislocation parameters strike, dip, rake; "B" quality events are probably good to within about ± 20° in strike, dip, rake; "C" quality events have at least one of the P, T, or B axes relatively unconstrained. Major double couples for all "A", "B", and "C" quality events are shown in Figure 1.

Results from a sample inversion, event 91.222, are presented in Figures 2 and 3. This event occurred within the north-south string of stations, and was close to many of the receivers. The residual-error versus depth curves for the two velocity models are shown in Figure 2 and waveform fits for the two velocity models are shown for the best depth in Figure 3. The error has been normalized by the sum of the squared amplitudes of the data. For both models, the earthquake depth is well-constrained to lie in the range 10 ± 3 km. Averaging over the range of acceptable depths, estimates of the major double-couple strike, dip, and rake are 338±2°, 80±5°, and 180±2° respectively. The ± 2° uncertainties are unusually small, but the strike and rake were very consistent for all depths and both velocity structures; the dip was very consistent for the best-fitting solutions near the optimal depth. These errors are estimated from the results of the trial inversions, but a conservative error estimate for this source may be ±5-10° in the dislocation angles (considering that the true structure is unknown).

For both models, the waveforms are nicely matched by the inversion, and only minor phase problems are observed for a few of the surface waves (Figure 3). Closer stations have relatively larger body waves, and these are also well fit, as is the case for many of the events studied. Although the L_2 norm is most sensitive to large-amplitude surface waves, the body waves are still important in the modeling and make valuable contributions to constraining the source. For this event, M45 produced acceptable fits, but the CT model produced perceptibly better fits. This event is located in the northern Plateau, where the CT model is more appropriate. M45 is more representative of the average Plateau structure and hence we per-

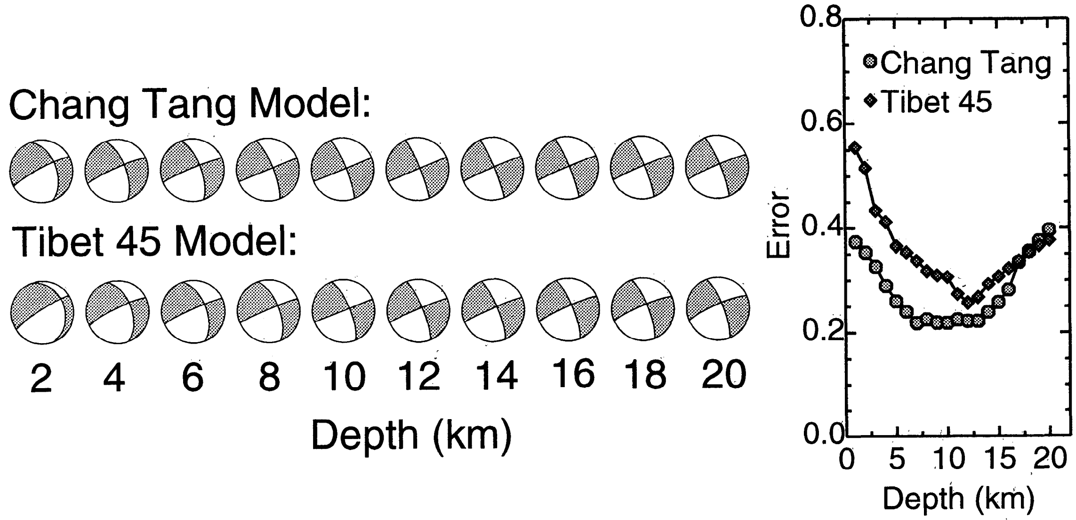

Figure 2. Source-depth analysis of the event 91.222. Two velocity models were used to investigate the sensitivity of the inversion to velocity structure. Both models produce excellent fits to the data and stable mechanisms as a function of depth. The error (sum of squared differences between the observations and the synthetic seismograms) is normalized to the sum of the squared amplitudes of the data, thus the best fitting model explains 80% of the observed seismic signal.

formed our inversions using this model. For "A" and "B" quality events, source models estimated using either velocity model are similar (within errors).

Earthquake Processes near the Tibetan Plateau

Tectonics on the plateau are driven by the compressional forces resulting from the impinging Indian Plate resulting in a translation and rotation of the crust from the Plateau to the east [Molnar and Lyon-Caen, 1989]. With only one exception, all the events within the Plateau, but away from the Plateau boundary, indicate either strike-slip or extensional faulting, a result consistent with previous analyses [e.g. Molnar and Lyon-Caen, 1989]. The exception is a thrust event located near the center of the network. We carefully examined the waveforms for this event and note that all the acceptable mechanisms were thrust events. Although interesting, this one aberration does little to detract from the larger population of events which support the hypothesis that the Plateau is internally deforming and expanding eastward through normal and strike-slip faulting. For events located northeast of the Plateau, our source mechanisms are consistent with the faulting mechanisms of larger events contained in the Harvard CMT catalog [e. g., Dziewonski et al. 1983].

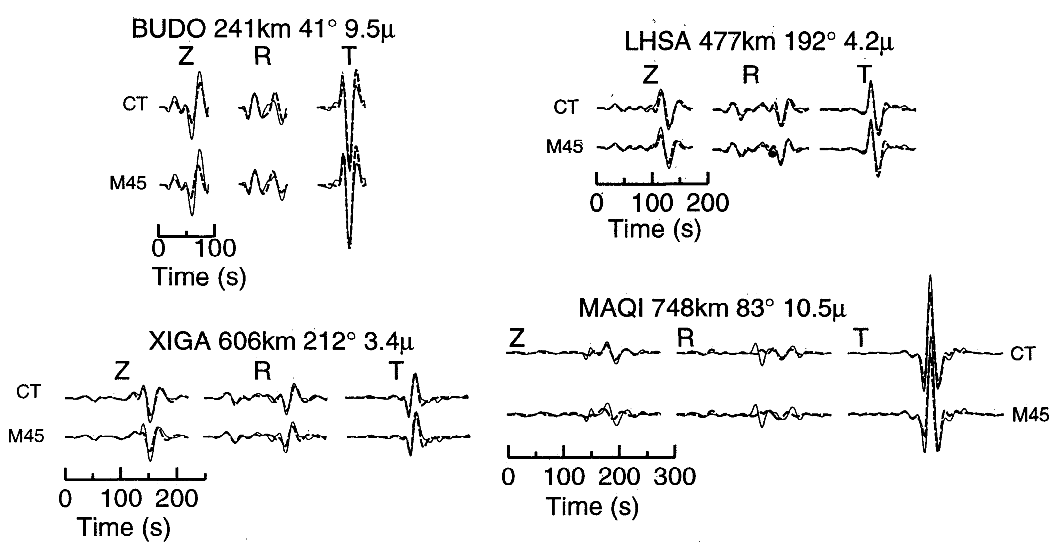

Figure 3. Selected waveform fits for the best fitting mechanisms of Figure 2. The solid line represents the observed waveform, the dashed line the synthetic seismogram. The station code, the distance from the source to the station in kilometers, the azimuth from the source to the station, and the maximum absolute amplitude on the observed transverse component (in microns) are shown above the waveforms for each station. The data are filtered to include signal with periods greater than 20 s; T indicate transverse, R, radial, and Z, vertical components of displacement. The velocity model used in the inversion is identified next to each row of waveforms.

Our results are also consistent with previous studies that have illustrated the shallow nature of Plateau seismic activity [Molnar and Lyon-Caen, 1989, Zhao and Helmberger, 1991]. Three-fourths of all the events occurred at depths less than 10 km, and all but two are consistent with a depth of faulting less than 15 km. The deepest event is located between 20-30 km depth, has a strike-slip mechanism, and is located near the northwest boundary of the Plateau, the other (19 km) is a strike-slip event within the Plateau, near the network. The shallow depth of the events indicates a relative warm lithosphere beneath the Plateau [Zhao and Helmberger, 1991].

Events 91.201, 91.210 and 91.211, located near station GANZ, exhibit intriguing m_b-M_w differences of approximately one magnitude unit. This area has previously been noted for events that have low (explosion-like) M_s:m_b ratios [Blandford, 1977]. The spatial pattern of the faulting in this region is complex. Our results suggest the existence of strike-slip, normal, and thrust faulting in a small geographic region with normal faulting occurring within 100-200 km of thrust faulting. The proximity of this region immediately west of a hypothesized rotation-pole for several crustal blocks comprising the eastern Plateau [Molnar and Lyon-Caen, 1989], may explain the rapid spatial gradient in stress orientations.

Conclusion

Our analysis illustrates the relative ease with which earthquakes can be modeled using temporarily-deployed, regional seismic networks. Naturally, this conclusion applies equally to permanently established regional networks. In fact, permanent networks hold greater promise as velocity models are refined and more details of the earthquake rupture process may be modeled using higher frequency data than employed in our analysis [e.g. Romanowicz et al., 1993; Dreger and Helmberger, 1993; Zhao and Helmberger, 1994]. While seismologists are making substantial progress in characterizing global seismicity using teleseismic investigations of larger events, and from those few regions occupied by permanent seismic networks, supplements from portable regional deployments are critical for an accelerated understanding of regional tectonics in may places throughout the world. Using data recorded during a one-year deployment on the Tibetan Plateau, we illustrated the potential of portable arrays to contribute to seismic source characterizations. Although we primarily modeled events in the magnitude 4 to 5 range, the technique is suitable to modeling shorter period data (and hence smaller events) as more detailed structural models are developed.

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