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Short Note

Source Parameters for Moderate Earthquakes in the Zagros Mountains with Implications for the Depth Extent of Seismicity

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Abstract Six earthquakes within the Zagros Mountains with magnitudes between 4.9 and 5.7 have been studied to determine their source parameters. These events were selected for study because they were reported in open catalogs to have lower crustal or upper mantle source depths and because they occurred within an area of the Zagros Mountains where crustal velocity structure has been constrained by previous studies. Moment tensor inversion of regional broadband waveforms has been combined with forward modeling of depth phases on short-period teleseismic waveforms to constrain source depths and moment tensors. Our results show that all six events nucleated within the upper crust (< 11 km depth) and have thrust mechanisms. This finding supports other studies that call into question the existence of lower crustal or mantle events beneath the Zagros Mountains.

Online Material: Results for moment tensor inversion and depth phase modeling are shown for five additional events.

Introduction

The depth distribution of earthquakes in convergent plate boundaries and the implications it has for rheologic strength distribution in the lithosphere have been highly debated for many years (Nowroozi, 1971; Bird *et al.*, 1975; Baker *et al.*, 1993; Maggi *et al.*, 2000; Jackson, 2002; Tatar *et al.*, 2004). Much of the debate has centered on the seismically active Zagros Mountains where plate subduction is believed to have ceased ca 5 Ma (Berberian and King, 1981). Early seismic studies of the region using the event location information in the International Seismic Catalog (ISC) and U.S. Geological Survey (USGS) catalog reported earthquakes in the upper crust and upper mantle but not in the lower crust (Nowroozi, 1971; Bird *et al.*, 1975). More recent studies, however, have reexamined earthquake depths and suggest that earthquakes occur only within the upper crust (Baker *et al.*, 1993; Maggi *et al.*, 2000; Jackson, 2002; Tatar *et al.*, 2004). For example, Maggi *et al.* (2000) modeled teleseismic *P* and *SH* waveforms to determine earthquake source depths in several regions, including the Zagros Mountains, for events reported to have nucleated within the lower crust or upper mantle. All 13 events investigated in the study for the Zagros Mountains were found to have nucleated within the upper 20 km of the crust.

For several decades, the preferred model of lithospheric strength and earthquake depth distribution has been the so-called "jelly-sandwich" model (Jackson, 2002). In this model, the lithosphere consists of a strong upper crust, a weak, ductile lower crust, and a strong upper mantle. This three-layered lithospheric model was based on the assumption that rock strength is primarily a function of composition (Brace and Byerlee, 1970; Brace and Kohlstedt, 1980; Chen and Molnar, 1983) and the thermal structure of the lithosphere (Brace and Kohlstedt, 1980; Afonso and Ranalli, 2004). Other studies, however, have argued that the depth of the brittle-ductile transition may also depend on fluid content (Hirth and Kohlstedt, 1996; Mackwell *et al.*, 1998). Lithospheric models that account for these factors show considerable variability in the depth distribution of lithospheric strength (Brace and Kohlstedt, 1980; Hirth and Kohlstedt, 1996; Mackwell, *et al.*, 1998; Jackson, 2002).

In this article, we contribute to the debate about the depth extent of continental seismicity and the strength of the lithosphere by studying six moderate earthquakes that occurred between 1997 and 2003 in the central Zagros Mountains for which lower crustal or upper mantle focal depths have been reported in a number of catalogs (e.g., Global Centroid Moment Tensor [CMT] Project, National Earthquake Information Center, ISC, Tables 1, 2). We focus on these events in the 1997–2003 time interval because they occurred where crustal structure is best constrained within the Zagros Mountains and because broadband seismic data at regional distances were provided from the Saudi Arabian National Di-

Table 1
Depths and Magnitudes from Public Catalogs

			EHB*	ISC		CMT	
Event Number	Date	Time	Depth (km)	Depth (km)	m_b	Depth (km)†	M_w
1	13 Nov 1998	13:01:10	9	15	5.3	f33	5.4
2	31 Oct 1999	15:09:40	15	38	4.9	f33	5.2
3	1 Mar 2000	20:06:29	20	47	5.0	f15	5.0
4	13 April 2001	1:04:27	20	29	4.9	26	5.1
5	17 Feb 2002	13:03:53	15	f15	5.5	f33	5.3
6	10 July 2003	17:06:38	11	19	5.8	f15	5.7

*EHB is Engdahl, van der Hilst, and Buland (Engdahl *et al.*, 1998, 2006).
†f indicates a fixed depth.

gital Seismic Network (SANDSN). We have combined these data with other data from open stations to constrain source depth and focal mechanism for each event by inverting for moment tensors and performing a grid search over source depth. Source depths have been further constrained by forward modeling teleseismic depth phases using short-period data from GSN and NORSAR stations.

Geologic Setting

The Zagros Mountains of southern Iran, Turkey, and Iraq are part of a large tectonic region that marks the convergent boundary between the Arabian and Eurasian plates following the closure of the Neo-Tethys Sea. The Zagros Mountains are primarily located along the southwestern border of Iran where Global Positioning System measurements indicate that oblique convergence occurs at a rate of 2.2 cm per yr (Vernant *et al.*, 2004). The Zagros Mountains parallel the coast of the Persian Gulf for approximately 1200 km from Turkey in the north, to the Strait of Hormoz in the south, and range in width from 200 to 300 km (Tatar *et al.*, 2004; Fig. 1). Seismicity rates in this region are among the highest in the world for a fold and thrust belt (Talebian and Jackson, 2004; Tatar *et al.*, 2004).

Previous geophysical studies provide constraints on crustal structure for parts of the Zagros region. In the central Ghir region of the Zagros Mountains (see Fig. 1), a combined study of local *P*- and *S*-wave traveltimes and teleseismic receiver functions indicates that the crustal thickness averages 47 km (Hatzfeld *et al.*, 2003). This estimate of crustal thickness is consistent with thicknesses of 45 ± 2 km determined by receiver functions (Paul *et al.*, 2006). The crust is divided into an upper, 11 km thick, sedimentary layer and a lower, 35 km thick, crystalline basement layer (Hatzfeld *et al.*, 2003). A Bouguer gravity anomaly study by Snyder and Barazangi (1986) found that Moho depth increased smoothly from 40 km in the south beneath the Persian Gulf to 65 km just north of the Zagros Mountains (Fig. 1).

The Zagros Mountains are bordered to the northeast by the Iranian plateau. This plateau has an average elevation of 1500 m (Zamani and Hashemi, 2000). A low mountain range separates the Iranian plateau into two distinct regions with the eastern region extending into Afghanistan (Zamani and Hashemi, 2000). Surface wave tomography indicates the presence of a low velocity zone beneath the Iranian plateau (Maggi and Priestley, 2005). The unusual presence of a low velocity zone in a convergent margin and the existence of Neogene volcanism within the plateau (Berberian and King, 1981) indicate a warm, buoyant upper mantle beneath the plateau (Maggi and Priestley, 2005).

To the southeast, the Zagros Mountains are bordered by the Makran. The Oman Line, or the Minab fault, separates these two regions. Although both regions were created by the convergence along the Eurasian plate, they differ in convergence mechanisms. The Zagros Mountains have undergone continent-continent convergence with the Arabian plate for the past 5 m.y. without evidence for continuing subduction (Berberian and King, 1981) while subduction of the Indian plate continues beneath the Makran (Quittmeyer and Jacob, 1979). Thus, seismicity extends to much greater depths in the Makran relative to the Zagros Mountains.

Table 2
Event Information

				Moment Tensor Inversion		Depth Phases
Event Number	Date	Time	Latitude, Longitude	M_w	Depths (km)	Depths (km)
1	13 Nov 1998	13:01:10	27.793° N, 53.640° E	5.5	6–10	4–7
2	31 Oct 1999	15:09:40	29.413° N, 51.807° E	5.4	5–11	4–5
3	1 Mar. 2000	20:06:29	28.395° N, 52.848° E	5	7–11	7–10
4	13 April 2001	1:04:27	28.281° N, 54.872° E	4.9	5–10	8–11
5	17 Feb 2002	13:03:53	28.093° N, 51.755° E	5.2	2–10	2–6
6	10 July 2003	17:06:38	28.355° N, 54.169° E	5.7	7–11	4–7

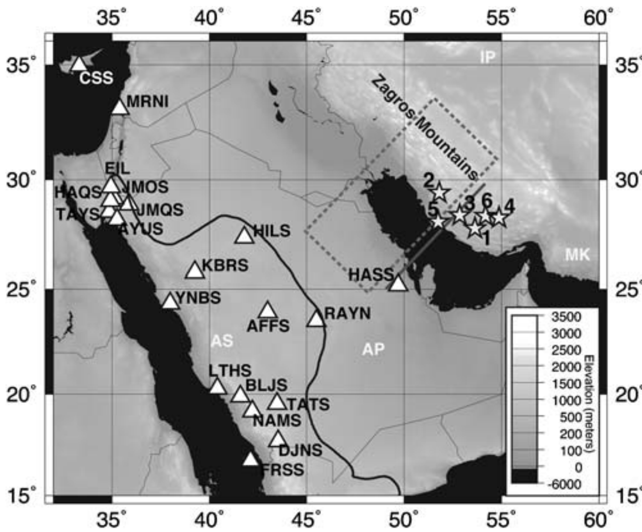

Figure 1. A map showing the Zagros Mountains, nearby tectonic features, and earthquake locations. White triangles are the regional stations used for moment tensor inversion, and the stars are the six events studied. The solid black line indicates the border between the Arabian platform and shield. The solid gray line indicates the location of a combined receiver function and local *P*- and *S*-wave traveltime study (Hatzfeld *et al.*, 2003), and the dotted gray box indicates the location of a gravity and seismic study (Snyder and Barazangi, 1986). Geologic regions are labeled in white as follows: Arabian shield (AS), Arabian platform (AP), Iranian platform (IP), and Makran (MK) regions.

The Arabian platform and the Arabian shield comprise the Arabian Peninsula to the south of the Zagros Mountains where the majority of the seismic stations used in this study are located. The Arabian platform lies southwest of the Persian Gulf. Sedimentary thickness on the platform increases toward the Persian Gulf where it reaches a maximum thickness of nearly 10 km (Seber *et al.*, 1997). Total crustal thickness in this region is modeled to be 40 km (Rodgers *et al.*, 1999). The Arabian shield is uplifted relative to the platform to its north in spite of having a thinner crust (36 km). This anomalous uplift and the presence of recent volcanism in the shield indicate the existence of mantle upwelling in this region (Camp and Roobol, 1992).

Datasets and Methods

Datasets

The data used in this study come from a collection of both open and closed seismic networks at regional and teleseismic distances. The majority of the data for determining moment tensors comes from the SANDSN (Fig. 1). This network consists of 11 short-period and 27 broadband three-component seismometers located in the Arabian shield and plateau. Data for this study were provided by the SANDSN for the seven years from 1997 to 2003. Complimentary broadband seismic data for the same time period were also used from open stations (e.g., CSS, EIL, RAYN) in the region belonging to the Global Seismic Network (GSN) and other international cooperative networks. The teleseismic waveforms used for modeling depth phases were obtained from GSN stations as well as from Norwegian Seismic Array (NORSAR).

Earthquakes were considered for inversion if they occurred during the time frame for which we had access to SANDSN data, if they were listed as having depths of at least 15 km in the ISC catalog (Table 1), if they were located within the central Zagros region where crustal structure is best constrained by previous studies (Fig. 1), and if they were well recorded by at least three regional stations.

Methodology

For each earthquake, moment tensor inversion was used to determine source mechanisms from the regional waveforms, filtered between 0.02 and 0.029 Hz, using the method of Randall *et al.* (1995). Because the earthquakes studied here have moderate magnitudes ($4.9 < M_w < 5.7$), the source time function was assumed to be a delta function. Regional seismograms were selected based upon visual inspection of quality throughout the wavetrain. Moment tensor inversion was performed for each event over a depth range of 0 to 80 km in 1 to 5 km increments. Root mean square (rms) error and visual inspection of the fit of synthetic seismograms to the data were considered to determine the best source depth for each earthquake.

A single velocity model was used for the calculation of the Green's functions (Table 3). The velocity model uses the crustal structure for the Arabian platform from Rodgers *et al.* (1999) and the IASP91 mantle model (Kennett and Engdahl, 1991). This model was chosen because the largest portion of the event-to-station travel paths lie within the Arabian platform.

To confirm and refine source depths, arrival times for teleseismic *pP* and *sP* phases recorded between distances of 30° and 90° were modeled using ray theory. The goal of modeling depth phases was only to constrain the source depth, so no source time function or instrument response was included; efforts at modeling focused on matching arrival times of the depth phases. A second velocity model representative of structure in the central Zagros was used in this modeling (Table 4). The model consists of crustal structure from Hatzfeld *et al.* (2003) over a half-space mantle.

To find clear teleseismic depth phases for each event, data from a wide range of GSN stations were examined after

Table 3
Velocity Model Used for Moment Tensor Inversion

Depth (km)	*P*-wave Velocity (km/sec)	*S*-wave Velocity (km/sec)
1–4	4.00	2.31
4–20	6.22	3.59
20–38	6.44	3.72
38–42	7.30	4.21
42–74.5	8.04	4.48

Table 4
Velocity Model Used for Modeling Teleseismic Depth Phases

Depth (km)	*P*-Wave Velocity (km/sec)	*S*-Wave Velocity (km/sec)
1–11	4.70	2.71
11–19	5.85	3.38
19–46	6.50	3.75
mantle	8.00	4.62

filtering between 0.5 and 3 Hz, in addition to stacked waveforms from NORSAR. Because of the moderate size of the earthquakes in this study, only a small number (1–3) of short-period waveforms were found for each event that showed clear depth phases.

A simple grid search was used to find the source depth that best matched the timing of the observed depth phases. In this grid search, the best-fitting strike, dip, and rake obtained from the moment tensor inversion for a given depth were used to generate half-space synthetics of the *pP* and *sP* arrivals. The best-fitting source depth range was determined by the match of either the *pP* or the *sP* arrival time or both to the observed waveforms.

Discussion and Conclusions

Table 2 gives the depths and moments for the six events examined, and Table 5 provides the moment tensor elements for the events. Figure 2 shows the results of the moment tensor inversion and depth phase matching for one sample event. Ⓔ Results for additional events can be found in the electronic edition of *BSSA*. For all events, focal mechanisms indicate a thrust-faulting source with some degree of strike-slip motion, as has been observed previously for the central Zagros by many studies. No systematic change in quality of fit with increasing station distance is found. Depths from moment tensor inversion are less well constrained than those from depth phase modeling. We attribute this difference to the inherent difficulty of constraining depths from surface waves and therefore prefer the depths calculated by depth phase modeling, a method designed to better constrain source depths. In all cases, where rms error from moment tensor inversion has a clear minimum, the range of optimal depths determined by moment tensor inversion and from depth phase modeling shows broad agreement, allowing source depth to be constrained to within a few kilometers.

The six events have source depths between 2 and 11 ± 2 km. Based on *a priori* knowledge of the crustal structure of the central Zagros Mountains (Snyder and Barazangi, 1986; Hatzfeld *et al.*, 2003), all the events nucleated within the sedimentary upper crust, a finding that agrees with recent studies of seismic deformation in the area (e.g., Lohman and Simons, 2005; Nissen *et al.*, 2007). These results indicate that deformation in the upper crust is not restricted to ductile folding as suggested by some studies (e.g., Hatzfeld *et al.*, 2003; Tatar *et al.*, 2004).

Tables 1 and 2 can be used to compare source depths from this study in relation to depths reported for the same events in other catalogs. For all six events, the depths reported in the catalogs were deeper than those obtained in our analysis. Consequently, our results are consistent with other seismological studies of the region that have found that seismicity is limited to the upper crust within the Zagros Mountains (Maggi *et al.*, 2000). In contrast with the discrepancy of earthquake depths, we find no systematic increase or decrease between the moment magnitudes we obtained and those obtained in other catalogs, and in all cases, our magnitudes differ from those published in the CMT catalog by 0.2 magnitude units or less (Table 1).

The moment tensor solutions calculated for these six events include some degree of non-double-couple motion that is proportionally similar to the non-double-couple components listed in the CMT catalog. Part (d) of Figure 2 shows the double-couple component of our best solution and for the CMT solution. Although the solutions are broadly similar, there are some differences in nodal plane orientations.

Comparison of the source depths calculated via moment tensor inversion of the regional surface waves and from modeling of teleseismic *pP* and *sP* depth phase arrival times shows good agreement between the two methods. The smaller of the events presented here approach the minimum magnitude threshold for which teleseismic waveforms can be used for moment tensor inversion or for depth phase modeling. The good agreement between depths obtained from moment tensor inversion and depth phase modeling achieved for these six moderate events indicates that our method of modeling regional waveforms bandpassed between 0.02 and 0.029 Hz to accurately estimate source depths may be applied to other moderate events in this area for which teleseismic depth phases are not available for constraining source depth.

Table 5
Moment Tensor Elements (dyne cm)

Event Number	Depth	Mxx	Mxy	Mxz	Myy	Myz	Mzz	M_0
1	5	0.847×10^{24}	0.205×10^{24}	-0.152×10^{25}	0.634×10^{23}	0.753×10^{24}	-0.911×10^{24}	1.93×10^{24}
2	5	0.237×10^{24}	0.114×10^{24}	-0.569×10^{24}	0.258×10^{24}	-0.105×10^{25}	-0.495×10^{24}	1.34×10^{24}
3	8	0.181×10^{24}	-0.397×10^{23}	-0.202×10^{23}	-0.167×10^{23}	0.278×10^{24}	-0.164×10^{24}	3.87×10^{23}
4	9	0.179×10^{24}	0.432×10^{23}	0.118×10^{24}	0.234×10^{23}	-0.300×10^{23}	-0.202×10^{24}	2.31×10^{23}
5	4	0.380×10^{24}	0.199×10^{24}	-0.393×10^{24}	0.550×10^{23}	0.561×10^{24}	-0.435×10^{24}	8.23×10^{23}
6	5	0.271×10^{25}	-0.212×10^{24}	0.225×10^{25}	-0.607×10^{24}	-0.328×10^{25}	-0.210×10^{25}	4.69×10^{24}

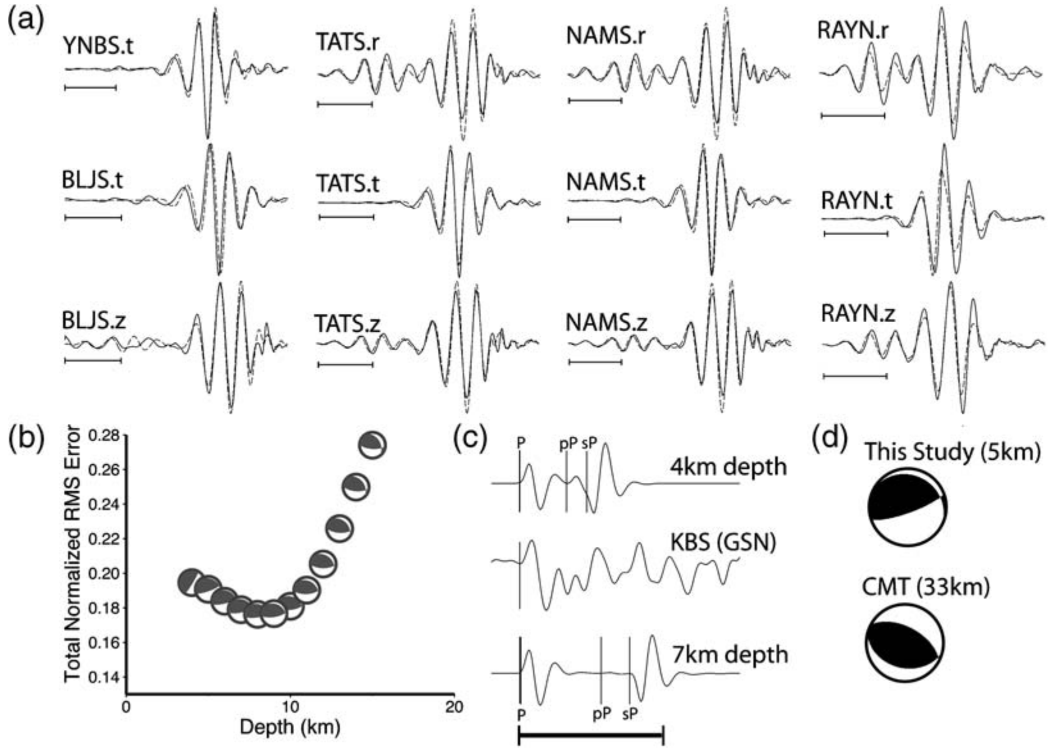

Figure 2. (a) Fit of full waveform synthetics to observed data from moment tensor inversion. Observations are shown as a solid line, while synthetics are shown as a dashed line. The bar beneath each set of waveforms indicates a scale of 100 sec. (b) The best-fitting focal mechanism at each depth is shown plotted against rms error. (c) Observed depth phases are shown bracketed by synthetics for the maximum and minimum possible source depths. The bar beneath the seismograms indicates a time scale of 5 sec. Records from NORSAR arrays are stacked to improve signal-to-noise ratios, but where GSN stations are used, records from only a single station are shown. (d) Our best double couple solution and source depth are shown along with the double couple CMT solution and source depth.

We acknowledge that the focus on matching surface wave amplitude and timing may limit our ability to model potentially deeper events, as these events typically excite surface waves with smaller amplitudes that may not be well recorded with high signal-to-noise ratios at regional distances and therefore cannot be modeled with the methodology in this study. This and the limited number of earthquakes modeled prevent us from eliminating the possibility that some deeper earthquakes may occur in the Zagros Mountains.

In summary, we find no evidence from this study for lower crustal or mantle events in the central Zagros Mountains but find a systematic overestimation of depths in global catalogs. This finding supports previous work that calls into question the existence of lower crustal and mantle earthquakes beneath the Zagros Mountains and contributes to recent papers that study small to moderate sized earthquakes that may not be accurately represented in global catalogs (e.g., Lohman and Simons, 2005).

Data and Resources

Data used in this study were from the Saudi Arabian National Digital Seismic Network (SANDSN, http://www.norsar.no/, last accessed February 2009), the Norwegian Seismic Array (NORSAR), and the Global Seismic Network (GSN, http://www.iris.edu/hq/programs/gsn, last accessed February 2009). Plots were created using Generic Mapping Tools.

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