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The March 11, 2002 Masafi, United Arab Emirates earthquake: Insights into the seismotectonics of the northern Oman Mountains

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Abstract

A moderate (M ~5) earthquake struck the northeastern United Arab Emirates (UAE) and northern Oman on March 11, 2002. The event was felt over a wide area of the northern Emirates and was accompanied by smaller (felt) events before and after the March 11 main shock. The event was large enough to be detected and located by global networks at teleseismic distances. We estimated focal mechanism and depth from broadband complete regional waveform modeling. We report a normal mechanism with a slight right-lateral strike-slip component consistent with the large-scale tectonics. The normal component suggests relaxation of obducted crust of the Semail ophiolite (specifically, the Khor Fakkan Block) while the right-lateral strike-slip component of the mechanism is consistent with shear across the Oman Line. Felt earthquakes are rare in the region, however no regional seismic network exists in the UAE to determine local seismicity. This event offers a unique opportunity to study the active tectonics of the region as well as inform future studies of seismic hazard in the UAE and northern Oman.

Keywords: United Arab Emirates; Oman Mountains; Semail ophiolite; Arabian–Eurasian collision

1. Introduction

Active tectonics in the broad Arabian Gulf region is clearly dominated by the Arabian–Eurasian collision. This is most evident by the occurrence of earthquakes along the Zagros Thrust (Fig. 1, inset) making it one of the most seismically active continental regions on Earth. However, eastern Arabia, part of the Arabian Platform, is relatively aseismic. Most of the UAE (the western and central parts) is topographically flat and covered with sediments of the Arabian Platform, making geologic and seismic investigations virtually impossible. The remainder of the UAE is topographically high (the Oman Mountains) and is dominated by the Semail ophiolite. Because no regional seismic network exists in the UAE it has not been possible to assess local seismicity.

The Semail was a largely intact slice of hot young oceanic crust that was thrusted southwestwards or westwards onto the Arabian continental margin during the first stages of closure of the Neo-Tethys Ocean at the

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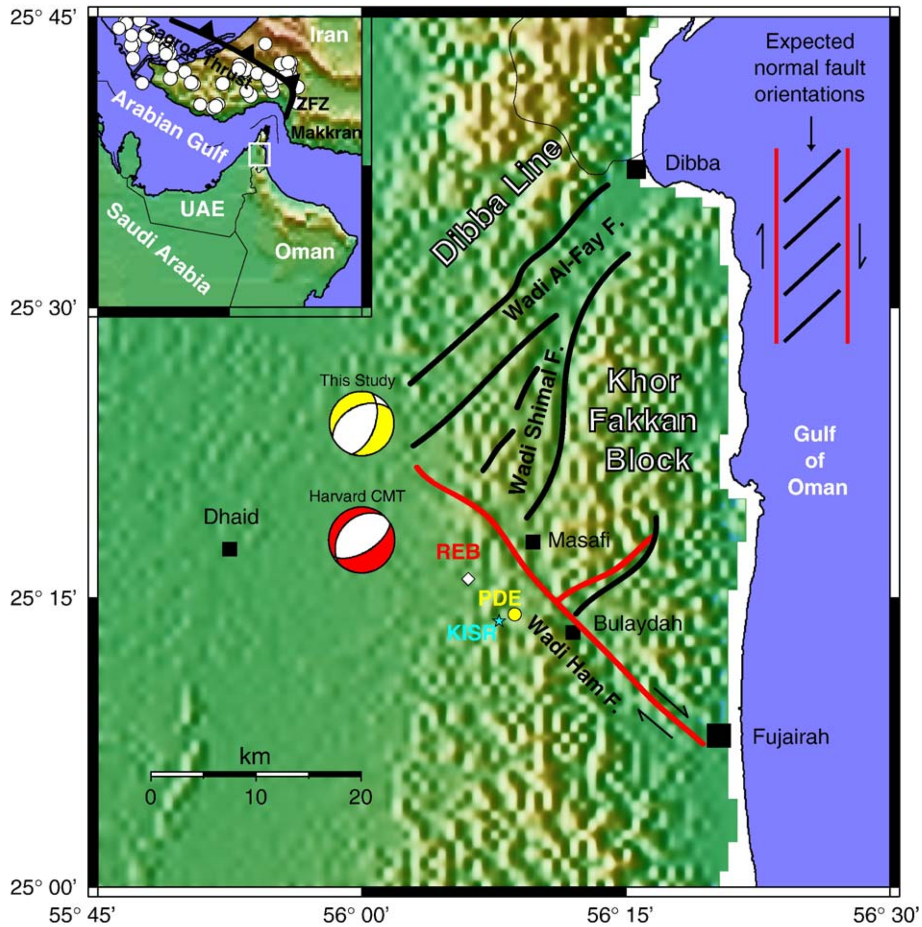

Fig. 1. Map of the northeastern United Arab Emirates (UAE) with locations of the March 11, 2002 earthquake (USGS-PDE, yellow circle; REB, white diamond; and KISR, cyan star), mapped faults and main geographic features. The focal mechanisms estimated by the Harvard CMT (red) and this study (yellow) are also shown. The Wadi Al-Fay, Wadi Shimal and other faults with late normal slip components (black) and other faults, including the Wadi Ham strike-slip fault (red) are shown. (Inset) Map of the UAE and surrounding region with tectonic plate boundaries and large earthquake locations (circles). The Zagros Thrust (black line), Makkran and Zendan Fault Zone (ZFZ) are shown.

end of the Cretaceous. Obductions are tectonically rare events, but the Semail is almost unique in its state of preservation. For this reason the geological studies of the Emirates and Oman have focused on the petrological details of the ocean crust (Lippard et al., 1986), and the structure and stratigraphy of the rocks below the Semail (Robertson et al., 1990; Searle and Cox, 1999) which record the stages of the obduction process. On the basis of these data sophisticated models for oceanic crust generation, intra-oceanic crustal detachment, partial subduction of continental crust and obduction of oceanic crust have been constructed for this region (Boudier et al., 1988; Hacker et al., 1996; Gnos and Nicolas, 1996; Gregory et al., 1998).

Following erosion and subsidence of the obducted mass, a period of quiet shallow water carbonate shelf deposition prevailed during the Eocene (Alsharhan and Nairn, 1997). A second compressional event affected the northeastern and northern margin of the Arabian Plate in the Oligocene–Miocene as a result of the final closure of the main tract of Neo-Tethys (Glennie et al., 1973). This event continues to the present day as a slow continent–continent collision responsible for the vast Alpine–Himalayan ranges of which the Zagros Mountains are one part (Şengör, 1987). The Alpine event produced the SW-verging thrusts of the Zagros and west-verging thrusts and associated huge N–S trending folds in the Tertiary limestone cover rocks in the Emirates and northern Oman (Searle, 1985; Warrak, 1996).

Unfortunately little research has been conducted in the northern Oman Mountains on neotectonics, and there are no detailed field surveys of the Tertiary faults or assessment of their seismicity. These fault structures include the Dibba Line (Glennie et al., 1990) and the

Wadi Shimal and Wadi Ham Faults (Gnos and Nicolas, 1996). These and associated faults lie within the Dibba–Masafi–Fujairah area of the northern UAE (Fig. 1).

On March 11, 2002 a moderate (magnitude ~5) earthquake struck the northeastern UAE. This event was detected and located by global seismic networks. Table 1 compiles the reported event parameters. These include global network locations by the United States Geologic Survey Preliminary Determination of Epicenters (USGS-PDE) and the Reviewed Event Bulletin of the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO-REB) and the regional network location by the Kuwait Institute for Scientific Research (KISR). The Harvard Centroid Moment Tensor (CMT) Project estimated a location and moment tensor for this event using well-established methods (Dziewonski and Woodhouse, 1983), although this event was probably near the low magnitude threshold for the CMT processing. The USGS-PDE, CTBTO-REB and KISR locations are broadly consistent, within 10 km of each other. This region is sparsely populated, however the event was felt throughout the northern Emirates. Reports of greatest damage were found near the town of Masafi (Fig. 1), suggesting that the network locations are reasonably close to the true epicenter. Many smaller earthquakes accompanied the largest event over a period of several months, the most significant being a foreshock (m_b 4.3) on January 09, 2002. A report on these events and the accompanying damages is provided by Othman (2002). A challenge to this study is the unknown uncertainty in the reported event locations from distance observations, especially when trying to associate the earthquake to a mapped geologic fault. Given that the damage was concentrated in the town of Masafi (north of the reported locations) we must accept uncertainties of the reported locations on the order of at least 10 km. The orientation of the inferred focal mechanism provides insight on the relationship of this earthquake with the known geologic structure.

In this article we present a double-couple focal mechanism for the March 11, 2002 Masafi earthquake estimated from complete regional waveforms. The focal mechanism is interpreted in terms of mapped faults in the northeastern UAE and provides insights into the active tectonics of the northern Oman Mountains.

Table 1
Locations and origin times for the March 11, 2002 Masafi earthquake

Catalog	Latitude	Longitude	Depth, km	Time	Magnitude
USGS-PDE	25.236	56.145	10	20:06:37.2	5.1 (m_b)
IDC-REB	25.2663	56.1009	0[a]	20:06:37.5	4.9 (m_b)
KISR	25.23	56.13	10	20:06:37	4.6 (M_S)
CMT	24.82	55.77	15	20:06:34.5	5.0 (M_w)

[a] IDC-REB procedures often fix depths at 0.

2. Source parameters from waveform modeling

Broadband complete (body and surface waves) regional waveforms are now widely used to estimate earthquake source parameters (e.g. seismic moment, focal mechanism and depth; see for example studies by Dreger and Helmberger, 1993; Walter, 1993; Randall et al., 1995; Ritsema and Lay, 1993, 1995). These methods typically use the reflectivity method (Randall, 1994) to compute Green's functions for a one-dimensional (plane-layered) earth model and can be applied to events with magnitudes as small as 4.0 and even smaller for near-regional distances. Accuracy of the method to produce reliable results depends on the accuracy of the earth model and signal-to-noise. Because regional seismic waves propagate through the crust and uppermost mantle (the lithosphere) and this outermost region of the earth is strongly heterogeneous, an accurate lithospheric velocity model is important, especially for periods shorter than about 20 s. Filtering the data diminishes sensitivity of the data to the velocity model. However sensitivity to focal parameters diminishes when using only long-period energy (longer than 35 s) particularly focal depth (Ritsema and Lay, 1995).

We obtained broadband waveforms from three stations at regional distances (<2000 km). Fig. 2 shows the stations and paths used in this study. Included in these data are waveforms from the Saudi Arabian National Seismic Network operated by King Abdulaziz City for Science and Technology (KACST, Al-Amri and Al-Amri, 1999) and the Kuwait National Seismic Network operated by the Kuwait Institute for Scientific Research (KISR; Bou-Rabee, 1999; Al-Awadhi and Midzi, 2001). Data from station ABKT (Alibek, Turkmenistan) were obtained from the Incorporated Research Institutions for Seismology Data Management System (IRIS-DMS). These three paths provide adequate azimuthal coverage to estimate the focal mechanism.

We used the USGS-PDE location and origin time (Table 1) for our source parameter estimation because this location was estimated from the most complete distribution of stations. The regional waveform data were converted to ground displacement. Synthetic seismograms were computed using the reflectivity computer codes written by Randall (1994). Paths within the

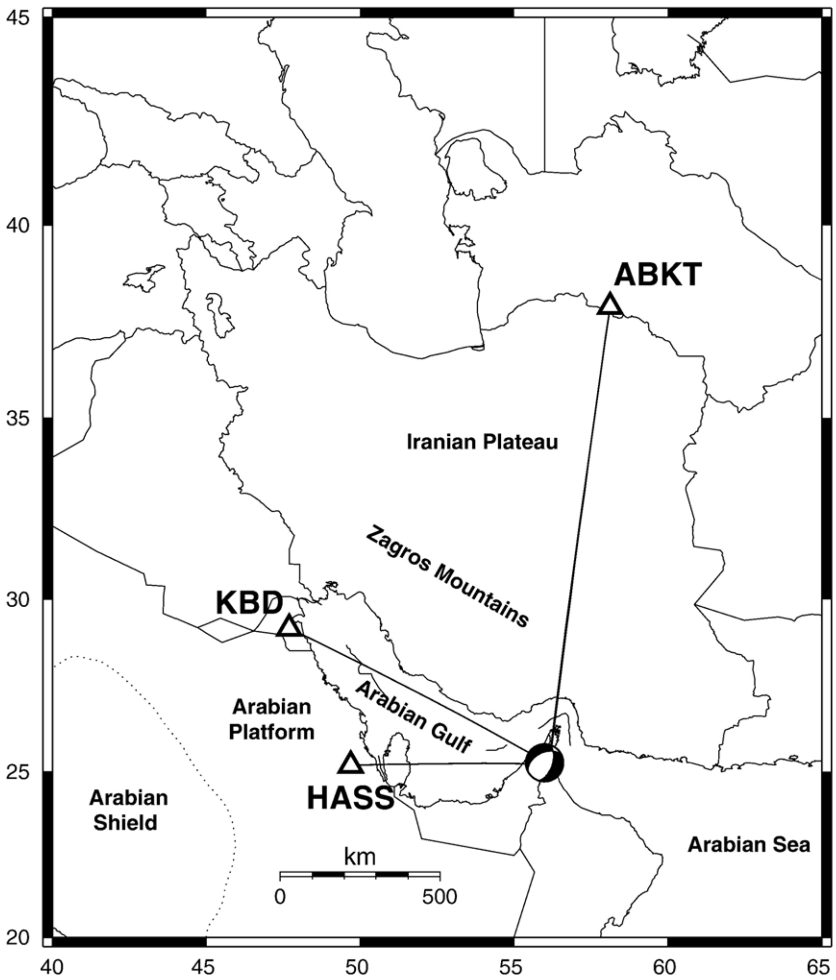

Fig. 2. Map of the Arabian Peninsula and southern Eurasia showing the event, stations and paths of regional waveforms considered in this study.

Arabian Platform (HASS and KBD) sample the sediments of the Arabian Platform, which thicken from the exposed basement of the Arabian Shield in the west to nearly 10 km near the Zagros Thrust in the east (Seber et al., 1997). The relatively slow and thick sedimentary structure plays a strong role in the surface wave dispersion of paths crossing the region. For the path to stations HASS (Al-Hasa, Saudi Arabia) we used the Arabian Platform velocity model of Rodgers et al. (1999). For the path to station KBD (Kabd, Kuwait) we used the Arabian Platform model but increased the sedimentary cover to 8 km (from 4 km). For the path to ABKT we used a model developed by William Walter (personal communication). The P-wave models used for the synthetics seismogram calculations are shown in Fig. 3 for comparison.

Seismic moment, focal mechanism and depth were estimated using the grid search algorithm of Walter (1993). We estimated the source parameters for individual three-component waveforms at each station and then jointly for three stations (HASS, KBD and ABKT). Data and synthetic were filtered between 80 and 30 s period (0.0125–0.033 Hz). The results for the individual station estimates show a consistent moment, mechanism and depth. Fig. 4a–c shows the focal mechanism, moment magnitude and scaled error as a function of source depth. The scaled error is the root mean-square (rms) difference between the data and synthetic (filtered) waveforms for all three components normalized by the rms amplitude of the data. A perfect fit would have a scaled error of zero. Station HASS has a minimum in the scaled error at 15 km with a right-lateral strike-slip mechanism. Station KBD shows a sharp reduction in the scaled error at 15 km, with a normal focal mechanism rotating to a strike-slip mechanism for deeper depths.

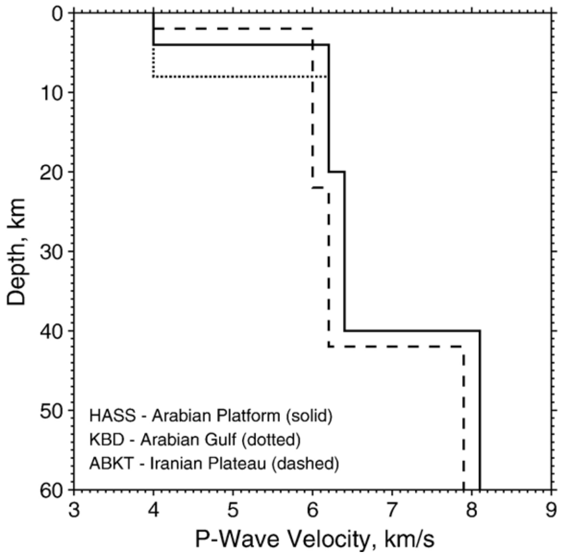

Fig. 3. Crustal P-wave velocity models used for the synthetic seismogram calculations.

Station ABKT is well fit with a strike-slip mechanism, but without a well-defined depth minimum. The mechanisms for the joint (3-station) grid search show a minimum at 15 km with a north–northeast striking normal mechanism with a slight right-lateral strike-slip component. The resulting moment magnitude, M_W, is 4.89 corresponding to a seismic moment of 2.43×10^{16} N-m. Our solution is generally consistent with the Harvard CMT solution. The double-couple focal mechanism solutions from the Harvard CMT and this study are given in Table 2. We found that our 3-station mechanism fit the waveforms slightly better than the Harvard CMT double-couple focal mechanism.

The resulting waveform fits for our preferred source model are shown in Fig. 5. The fits are quite satisfactory. In a separate test we could not fit the data as well with a single model for all three paths (not shown). In our preferred model, the body-waves are well fit especially for stations HASS and KBD. Station ABKT is nodal for Rayleigh waves and the observed waveforms suggest a quasi-Love wave on the vertical and radial component, possibly due to multi-pathing and/or anisotropy.

3. Discussion

The March 11, 2002 Masafi UAE earthquake provides a unique opportunity to investigate seismotec-

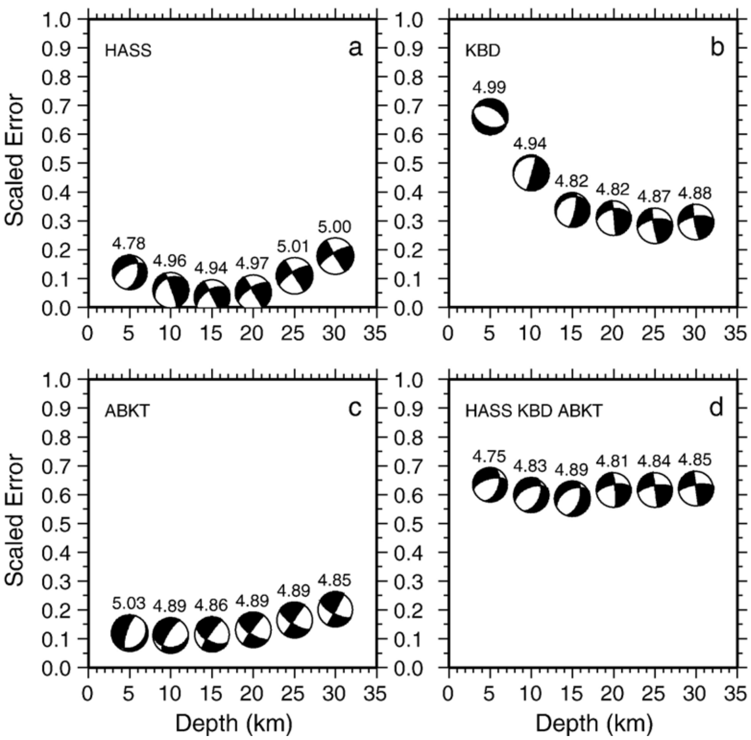

Fig. 4. Focal mechanism and misfit versus depth for single station estimates at (a) HASS, (b) KBD and (c) ABKT. The focal mechanism and misfit versus depth when all three stations are used is shown in (d). In each panel the moment magnitude at each depth is shown above each mechanism.

Table 2
Double-couple focal mechanisms form the Harvard CMT project and this study

Author	Strike	Dip	Rake	Depth, km	M_0, N-m	M_W
CMT	59°	59°	−82°	15	3.4e16	5.0
This study	18°	56°	−120°	15	2.34e16	4.89

tonics of the Oman Mountains. The focal mechanism of this event is mixed with both normal and right-lateral strike-slip components. The right-lateral strike-slip component of the mechanism is consistent with right-lateral motion along the Oman Line in Iran (e.g. Kadinsky-Cade and Barazangi, 1982). The Oman Line defines the boundary between continental collision of the Arabian and Eurasian Plates along the Zagros Thrust and oceanic-continental convergence in the Makkran region. Convergence along the Zagros Thrust is much faster than along the Makkran, leading to dextral motion along the Zendan Fault Zone (see Fig. 1).

The normal component is dominant and is consistent with brittle extension of the "Khor Fakkan Block", a massif of mainly Semail peridotite bounded to the west and northwest by the Wadi Shimal Fault, and bounded to the southwest by the Wadi Ham Fault (Fig. 1). The focal mechanism provides for northeast trending steeply southeast-dipping normal faults similar in orientation to an important pair of faults branching to the northeast from the Wadi Ham Fault (Gnos and Nicolas, 1996) (Fig. 1). These faults meet the Wadi Ham Fault at the town of Bulaydah between Masafi and Fujairah. The faults enclose a narrow block of granulite facies metamorphic rocks (the Bani Hamid metamorphic series) that originally lay beneath the Semail ophiolite, forming part of its metamorphic sole. These metamorphic rocks are quite high-pressure indicators suggesting a significant vertical component of fault displacement to raise the Bani Hamid metamorphic series and emplace them in the overlying Semail ophiolite.

Searle and Cox (1999) represent the two northeast trending faults at Bulaydah as reverse faults — the more northwesterly as a younger out-of-sequence thrust, and the other as part of the original Semail thrust in contact with its metamorphic sole. Gnos and Nicolas (1996) drew attention to the fact that the Bani Hamid metamorphics separate distinct upper and lower level sections of the Semail ophiolite. Searle and Cox's (1999) model is inconsistent with this latter observation, unless the more southeasterly fault bounding the Bani Hamid metamorphics was later activated as a normal fault, allowing a higher level of the Semail to be juxtaposed against them. In fact, normal slip sense is a common late reactivation of faults with northeast and north–south orientations in this region, e.g. the Dibba Line faults and the Wadi Shimal Fault (Searle, 1988).

It seems likely then that the Masafi earthquake was a result of normal fault reactivation of an older northeast trending fault, which was originally a compressional structure. Boote et al. (1990) may provide a mechanism for normal fault reactivation of the northeast trending structures. These authors argued for north–south trending dextral transpression along the transfer zone between the continent–continent collision west of the Straits of Hormuz, and the subduction of oceanic crust under Iran in the Makkran Gulf of Oman. North–south dextral shear strain is associated with NE trending normal faults, as suggested in Fig. 1.

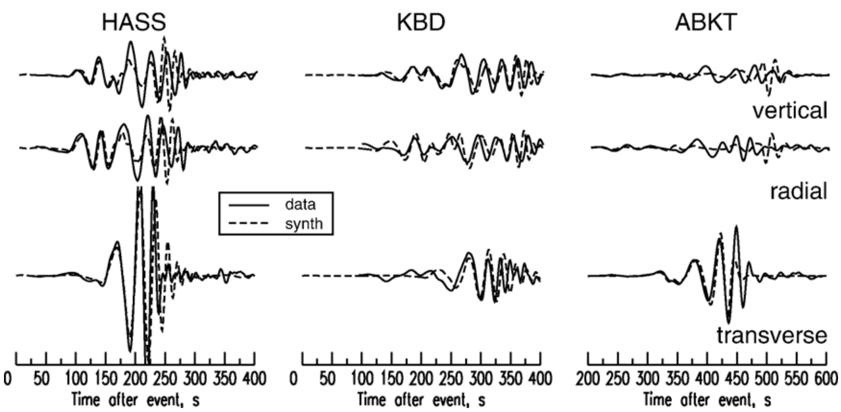

Fig. 5. Observed (solid) and synthetic (dashed) three-component waveforms for our preferred source model at all three stations. Data and synthetic were filtered 0.0125–0.033 Hz.

4. Conclusions

From complete regional waveform modeling we were able to estimate a focal mechanism of the March 11, 2002 Masafi, UAE, earthquake. The mechanism is consistent with relaxation of the Khor Fakkan Block as well as with a slight left-lateral strike-slip component. The event provides some constraint on active tectonics in the relatively aseismic northern Oman Mountains region. The large normal component is consistent with motion along preexisting thrust faults related to obduction of the Semail ophiolite. The strike-slip component is consistent with left-lateral motion across the Oman Line.

This earthquake caused considerable alarm in the northern Emirates and highlights the fact that damaging earthquakes can occur in this region. The recent installations of modern seismic networks in Saudi Arabia and Oman can improve studies of earthquake activity in the eastern Arabian Plate, however these stations are likely too far away to record low magnitude events in the UAE. A national seismic network in the UAE would provide the necessary data for evaluating earthquake hazard.

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