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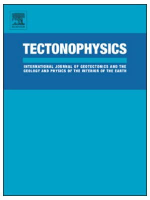

Apparently-deep events in the Middle Atlas resolved to be shallow: Implications for lithospheric deformation

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ABSTRACT

The occurrence of intermediate depth seismicity in intracontinental settings is rare, but it has been postulated with various degrees of certainty in several regions. One such region is the Middle Atlas of Morocco. Since 1960, 75 intermediate depth earthquakes have been reported in this region by Spain's National Geographic Institute (IGN). The apparent deep nature of these events is hard to reconcile with well-established geophysical evidence of a thin lithosphere under the Middle Atlas, but has been associated with mantle delamination processes. We relocate 4 events with IGN-reported depths >80 km that were recorded by a relatively dense temporary deployment; using a recent regional 3D velocity model obtained through teleseismic body and surface wave tomography. The relocation procedure uses a grid-search approach to minimize the mean normalized misfit, where each travel-time misfit is normalized by the estimated pick uncertainty. We find that our observed arrivals are much better fit by shallow (<5 km) depths than the reported depths of >80 km. We propose that these shallow foci earthquakes are the result of regional crustal deformation of this region caused by the present convergence between Africa and Eurasian Plate. We infer that if there are any ongoing delamination processes in the area, they are aseismic. This study is an example of how local earthquake locations in tectonically complex areas can be significantly improved by using a dense local seismic array and a well-constrained 3-D velocity model.

1. Introduction

The occurrence of deep seismicity is a long-standing puzzle in the Earth Sciences. Crustal earthquakes are the result of brittle failure and frictional sliding, but at depths exceeding ~70 km pressure and temperature conditions are such that deformation is accommodated by ductile flow rather than brittle failure (Green and Houston, 1995). However, the existence of deep seismicity has long been recognized (e.g. Gutenberg and Richter, 1954; Frohlich, 2006) and is generally divided into intermediate-depth seismicity (hypocentral depths between 70 and 300 km) and deep-focus seismicity (hypocentral depths over 300 km). The vast majority of intermediate-depth seismicity has been associated to subduction zones, where older and colder oceanic crust descends into the convecting mantle. Deep seismicity in intracontinental settings, not related to subduction in any way, is much rarer but there are some well documented examples: the 1979 Randolphe, Utah earthquake at 90 km (Zandt and Richins, 1979), > 40 km into the mantle, the 2000 Arafura Sea earthquake, at 61 ± 4 km, >25 km into the upper mantle (Sloan and Jackson, 2012), and the Wyoming earthquake beneath the Wind River Range of Central Wyoming at 75 ± 8 km (Craig and Heyburn, 2015), well beneath the base of the crust. The intracontinental Middle Atlas range in northern Morocco is another region where intermediate depth seismicity (75 events in the broader area having a focal depth > 50 km since 1960, *IGN catalog*) has been reported with no association to subduction processes (Hatzfeld and Frogneux, 1981). The tectonic significance of these events is heavily dependent on their hypocentral depth. Early studies attributed this deep seismicity to elevated crustal thickness and unusually cold mantle lithosphere (Chen and Molnar, 1983). However, subsequent studies have found no evidence for either thickened crust or high velocity lithospheric material beneath the Middle Atlas (Seber et al., 1996; Teixell et al., 2005; Missenard et al., 2006; Fullea et al., 2010; Bezada et al., 2014; Palomeras et al., 2014).

Cenozoic magmatism, gravity anomalies, high heat flow, and the absence of a crustal root have all been interpreted in terms of lithospheric delamination and/or lithospheric thinning beneath the Middle Atlas region (e.g. Ayarza et al., 2005; Teixell et al., 2005; Missenard et al., 2006; Fullea et al., 2010; Bezada et al., 2014; Palomeras et al., 2014). Ramdani, (1998) proposed that the intermediate-depth seismicity in the area was also a result of the delamination process. Using seismic tomography results, Bezada et al. (2014) proposed that the presence of hot mantle enabled the lithospheric foundering beneath the Middle Atlas and central High Atlas, leaving behind lithospheric cavities in this region. These

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findings are in conflict with reports of intermediate-depth earthquakes given that the volume within which these events are reported to occur is imaged as asthenosphere, where there are no known mechanisms that would induce seismic slip.

The distribution of permanent seismic stations in northern Morocco is relatively sparse, and the seismic velocity structure exhibits a high degree of lateral heterogeneity (Bezada et al., 2014; Palomeras et al., 2014), which makes it seem plausible that conventional event location algorithms may be mislocating some crustal events as deep. In order to clarify the relationship between delamination processes and seismicity, well-constrained hypocentral depths for the Middle Atlas events need to be determined.

In this study we take advantage of dense station coverage from the deployment of temporary seismic networks and of recently developed 3D velocity models of the crust and uppermost mantle to relocate four presumably deep events. We find compelling evidence to suggest that these events have shallow crustal origins.

2. Seismo-tectonic setting

Presently, Africa and Eurasia converge at a rate of ~5 mm/yr. Relative to a fixed Eurasia, the convergence direction is NNW (Stich et al., 2006) or NW (Nocquet, 2012). The plate boundary in southern Iberia and Morocco is diffuse, with deformation and seismicity distributed over a zone ~350 km wide extending from southern Spain to the High Atlas in Morocco (e.g. Buforn et al., 1995, 2004). In accordance with the relative plate motions, the regional stress field determined from earthquake focal mechanisms exhibits NW to NNW directed compressional axes, although a diversity of focal mechanisms is observed (e.g. Buforn et al., 1995, 2004). In particular, EW tension axes are common in southern Spain and also dominate in the Alboran region. Strike-slip mechanisms occur as well in Northern Morocco, with horizontal compressional axes compatible with the convergence direction (e.g. Buforn et al., 1995, 2004). Scarce to moderate amounts of seismicity are observed in the Middle Atlas, High Atlas and the Moroccan Meseta. These earthquakes exhibit a variety of focal mechanisms but are nonetheless broadly consistent with Africa-Eurasia convergence (Medina and Cherkaoui, 1991; Buforn et al., 2004; Bensaid et al., 2014). Based on GPS measurements, it is estimated that the Middle and High Atlas accommodate 1–2 mm/yr of this convergence (Fadil et al., 2006; Stich et al., 2006; Serpelloni et al., 2007).

Intermediate-depth seismicity as it has been reported in the region can be divided into three zones. The most abundant intermediate-depth events occur in a NS-trending block, ~50 km wide, to the east of the strait of Gibraltar. These events, exhibiting mainly vertical tension axes and depths of up to ~150 km (Buforn and Coca, 2002; Buforn et al., 2016), occur within the Alboran slab which has been imaged with high resolution by several recent studies (Bezada et al., 2013; Bonnin et al., 2014; Villaseñor et al., 2015). A second zone, in transitional and oceanic lithosphere west of the strait of Gibraltar, occur within a ~100 km wide band with an EW trend (e.g. Buforn et al., 2004). Some of these events have recently been located using ocean-bottom seismometers and their occurrence at mantle depths has been confirmed (Grevemeyer et al., 2016). The third zone, the focus of this paper, is northern Morocco; specifically the Middle Atlas and Moroccan Meseta region. Given the small magnitudes of these events (88% with local magnitude $M < 4$), the corresponding focal mechanisms have not been calculated.

3. Data set and method

We use data from temporary deployments occurring between 2009 and 2013 (Fig. 1). Within the time frame of deployment we recorded four local events in the Middle Atlas/Eastern Moroccan Meseta region with reported depths >80 km, all with magnitude smaller than 3.5 (mb) (Table 1). Catalog depths for these events were determined from the records of up to 21 stations, all of them at epicentral distances of at least 2.5°. In contrast, the majority of the four events were recorded by up to 45 stations from our temporary array. The exception is the fourth event (Table 1) which was recorded at only 27 stations as it occurred after demobilization of part of our network. Importantly, the majority of our stations are located within an epicentral distance of 2° from the events. The recorded seismograms are of high quality and the first breaks are extremely clear for the stations near the epicenter (Fig. 2).

P and S arrivals were picked on the vertical and horizontal components respectively (Fig. 3). Some of the records from stations with greater epicentral distances did not yield arrival times given their poor signal-to-noise ratios. Picking uncertainties were estimated visually for each P and S pick. Uncertainties are very small for first arrivals recorded in stations with small epicentral distances (≤50 ms). As can be expected, uncertainties are larger for S arrival times and for stations with larger epicentral distances.

To find the event locations that are most consistent with the observations we first obtain the P and S travel times from each station to a volume of nodes (spaced at ~10 km in every direction) surrounding the original location. Each of these nodes represents a candidate location and the travel time calculation is done using a ray-tracer based on graph theory (Moser, 1991; Toomey et al., 1994), a tomographically derived 3D P-wave velocity model (Bezada et al., 2014), and a constant Vp/Vs ratio of 1.8. For each station, the two travel time volumes (P and S) are converted into misfit volumes by subtracting the observed travel times, which are picked from the records assuming the reported origin time. Since the true origin time is unknown, for each candidate location the mean of all residuals (P and S for all stations that recorded the event) is removed. This adjusts the origin time for each candidate location to minimize the misfits. After this adjustment, the misfits are normalized by the corresponding pick uncertainty and averaged in order to produce a single misfit volume for the event. We then find the minimum value of the combined misfit volume and up-sample the volume around the minimum value using spline interpolation in order to increase the resolution of the location. The location that provides the minimum normalized misfit in the up-sampled volume becomes the preferred location. This approach has the advantage of providing the misfit values for points surrounding the preferred location, which facilitates the analysis of location uncertainties and the generation of error surfaces. The method is also computationally efficient because the travel time calculations are done only once for each station. The ray tracing method yields the minimum travel time to every point inside the velocity model, so once this calculation has been done, any number of events anywhere within the velocity model can be located using the approach described above.

4. Results

The grid-search method we employed found global minima for all of the four events that correspond to shallow (≤5 Km) hypocentral depths (Table 1). With the preferred, shallow, locations we can reproduce the observed travel times much better than with the original, deep, hypocenters. This is evidenced by a much narrower distribution of the misfits (Fig. 3), a substantial reduction of the largest misfit in each case, and a reduction of the RMS misfit values (Table 1). Changes in epicentral location are less dramatic but nonetheless significant, with changes of 18 to 57 km with generally easterly azimuths.

Fig. 3 shows the observed and calculated P and S arrival times for the previous and preferred locations for two stations per event. It is clear that arrival times predicted from our preferred locations are much more consistent with the waveform data than those calculated from the previous locations.

We note that there are two ways in which the new locations prove particularly advantageous over the previous ones: A) Stations with small epicentral distances are much better fit by the new locations; especially for events 1 and 3, that were recorded by several stations with

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