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Relocation of Uppermost Mantle Earthquakes in the Atlas Mountains, Morocco

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Abstract

Upper mantle earthquakes are usually associated with plate boundary tectonics, but rarely occur beneath intracontinental orogenic belts. In the Moroccan Atlas Mountains, earthquakes determined at subcrustal depths are a controversial topic because they are few in number compared to subduction zones and are not related to plate boundary tectonics. A recent increase of broadband stations in Morocco has revealed numerous events below the Atlas belts, thought to occur from the upper mantle. Using additional available stations, these Atlas events were relocated and new epicenter resolutions were acquired following rigorous depth and RMS error criteria. 309 events were reprocessed and epicenter depths obtained were between 31 and 240 km during the last 23 years. Temporal variations of High Atlas events appear to be continually dipping while Anti Atlas events show no temporal variation trends. In addition, a recent strong event M6.8 occurred in September 2023 at the transition crust-uppermost mantle followed by several aftershocks which have been relocated at uppermost mantle depths. These events support delamination model under the High-Middle Atlas which could flow southward beneath the Anti Atlas lithosphere, and explain the large variation observed in lithosphere thickness between the High-Middle Atlas, and the Anti Atlas. Subcrustal events beneath the Atlas may be related to upper mantle earthquakes beneath the neighboring Canary Islands which have experienced recent swarms and eruptions. This possible correlation cannot be excluded since descending and ascending material is necessary for a regional geodynamic balance.

Keywords

Intraplate Earthquakes, Relocation, Delamination, Subcrustal Deformation, Atlas, Canary Islands

1. Introduction

The intra-continental deformation zones of the Atlas in northwest Africa are linked both to Euro-African convergence and to faults inherited from the Mesozoic age. The high topography reaching 4000 m in the Moroccan High Atlas does not seem linked to a thick lithosphere. Most geophysical studies suggest a thin lithosphere beneath the High and Middle Atlas Mountains [1]-[4] while the lithosphere-asthenosphere boundary (LAB) reached approximately 200 km below the Anti Atlas [3]. The process that can explain this unusual geodynamics varies from delamination [2] [5], to mantle upwelling [6] [7], to a large corridor from the Canary Islands to Betic Cordilleras crossing the Atlas zone [3] [8], and edge convection [9]. These models suggest thinning of the lithosphere beneath the underlying low-velocity zone of the Atlas, and are based on a passive image of the lithosphere from P-wave propagation, gravitational modeling, or volcanic components. However, an important data likely to constrain these models is the presence or not of earthquakes in the lower lithosphere. Since models dealing with vertical mantle rise or lateral corridor cannot account for descending lithosphere beneath the Atlas zone. One of the recognized evidence of descending lithosphere is observed in subduction zone with associated upper mantle earthquakes. As subcrustal earthquakes are rarely observed in intra-continental deformation zones, their occurrence remains questionable and generally linked to subduction of ancient oceanic lithosphere [10]. In the Atlas region, approximately 14 events have been suggested to occur at subcrustal depths [5], and 4 Atlas events suspected to be from upper mantle depths have been relocated at crustal depths and horizontally from the Atlas domain towards the neighboring Meseta plateau [11]. The recent expansion of seismic stations in the Moroccan network has provided arrival times from varying horizons and may improve the epicenter resolution. Depth resolution parameters could be better controlled and several earthquakes are revisited to resolve this enigmatic question of the presence or not of upper mantle earthquakes under the intracontinental Atlas system. Recent strong M6.8 event which caused severe human causalities and building damages occurred in September 2023 and was followed by hundreds of low magnitude aftershocks. This new seismic activity will increase the problematic of the Atlas lithosphere geodynamics since this major event ever recorded is located at the transition crust-upper mantle. As the presence of the uppermost mantle earthquakes in the Atlas constrain not only the western Mediterranean tectonics but also the volcanic unrest in the Canary Islands.

2. Data and Methods

Earthquake databases used are compiled from 2000 to 2023, in which 309 events are located in the Moroccan Middle, High and Anti Atlas, in addition to 6 events relocated in the continuation of the High and Anti Atlas Mountains beneath the continental margin (**Figure 1**). When investigating the Atlas events at subcrustal depths, there is considerable seismic activity during the last 23 years in the upper mantle of the Canary Islands, which led to swarms beneath Hierro Islands [13],

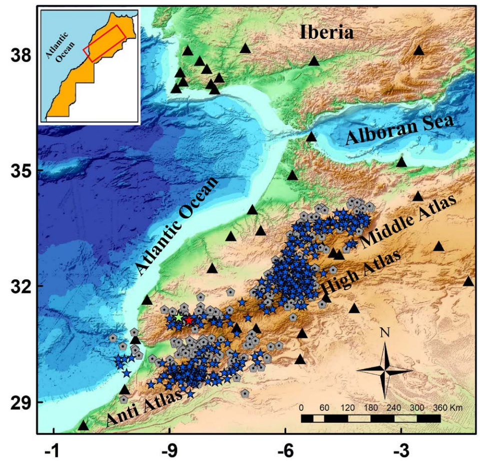

Figure 1. Subcrustal seismicity (gray) and relocated (yellow) during 23 years in the Moroccan Atlas area shown in the top left and recorded by regional station networks (triangles). Most events appear in the Middle Atlas, High Atlas, and the Anti Atlas) including a recent M6.8 event (red) that is relocated (blue). Base map used [12].

and recent eruption at La Palma in 2021. Data compiled from the IGN (Instituto Géographico Nacional) earthquake database [14], shows that subcrustal earthquakes of depth > 15 km are recorded and that their considerable volumes (16,000 events) reduce errors in depth estimates. Their contemporary occurrence with subcrustal events of the Atlas can be useful to investigate a possible correlation between intracontinental zones juxtaposed with oceanic volcanic system.

The Atlas events were recorded by the Moroccan network CNRST (National Center for Scientific and Technical Research), and cataloged by the International Seismological Center [15]. Seismic events estimated at depths greater than 30 km have magnitudes (m_L and m_b) varying from 0.2 to 4.2 in addition to the recent M6.8 event. However, they did not have sufficient resolution because the depth estimates of most events (83.4%) were determined from 5 to 8 stations and show large vertical (Erz) and horizontal (Erh) errors, or even absence of Erz values while RMS is often >1. By reprocessing the epicenter determination of these events through better regional coverage of stations, we used additional data from MDD (National Geographic Institute, Spain), INMG (Institute of the Sea and Atmosphere, Portugal) and CSEM (Euro-Mediterranean Seismological Center). We therefore defined a minimum of 10 stations for all relocations. When relocating events, we used updated Hypoinverse [16] based on minimizing the difference between observed and calculated travel times to determine the residual RMS amplitude considered as an estimate of the error. For better convergence of solutions during the relocation process, we searched for the initial velocity model that minimizes the average RMS value [17]. We used a model with four layers, a slow surface layer, an upper crust, a lower crust and the mantle. We also set a maximum for Erz and Erh at 5 km for depths greater than 30 km, and RMS < 1. On September 8, 2023, a strong event M6.8 beneath the High Atlas was located at about 25 - 28 km depth from several seismological institutions. Many hundreds crustal aftershocks have also been recorded, 14 of which appear to be located in the uppermost mantle. These events were relocated according to the criterion applied to events recorded in the period 2000-2022.

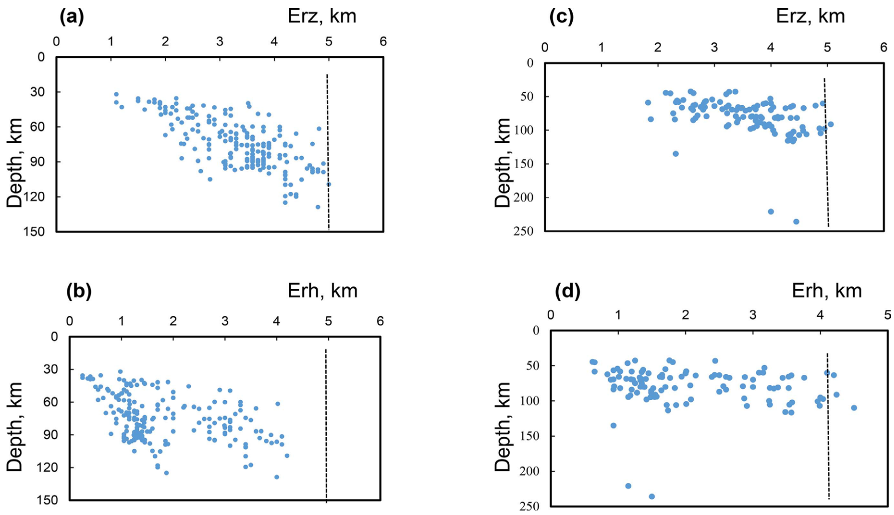

Figure 2. Resolution parameters obtained after relocation following strict criteria in errors (<5 km) to both Erh and Erz in the High-Middle Atlas (a) (b) and Anti Atlas events (c) (d).

3. Results

Uppermost mantle earthquakes over a period of no more than 23 years are relocated with strict criteria on resolution parameters. The processing used seems suitable for deciphering seismic activity beneath crustal depths in deformation zones of the Atlas. 195 relocated events appear below the crust of the High-Middle Atlas Mountains and 108 beneath the Anti Atlas while 6 additional events are located beneath the Atlantic margin. RMS and both horizontal and vertical errors are constrained by each epicenter relocation. Figure 2 shows the horizontal and vertical errors of relocated depths and associated RMS values which are compared to RMS values before relocation including recent seismic events of September 2023 (Figure 3). The magnitude ml of these seismic events is low and the depth is distributed from 40 to 130 km under the Middle and High Atlas and of 40 to 230 km beneath the Anti Atlas. Relocation of M6.8 event improved RMS from 1.99 to 0.9 while Erz and Erh obtained are 2.9 and 1.7 km respectively. Relative errors Erh and Erz are less than 8% for both the High-Middle Atlas and the Anti Atlas events. RMS of all relocated events are <1 which improved significantly RMS of previous epicenter determination. The temporal occurrence of these events shows a downward trend, particularly since 2014 under the High and Middle Atlas (Figure 4).

By latitudes, the temporal variations of events show dipping trends beneath the Middle and High Atlas latitudes while event progression appears horizontal under the Anti Atlas (Figure 5). The recent seismic crisis of September 2023 provided additional subcrustal events. The main event M6.8 was relocated at 31 km depth and was followed by hundreds of aftershocks; most of them are at shallow crustal depths. 16 relocated events were however distributed at subcrustal depths.

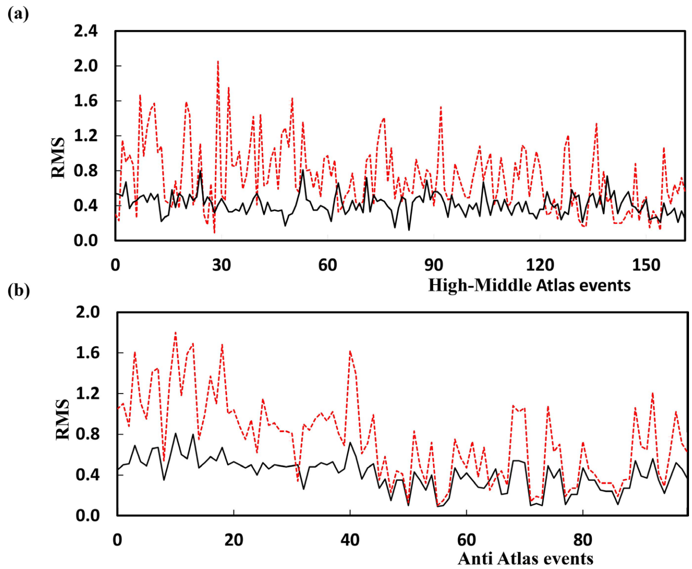

Figure 3. Resulting RMS before (red) and after relocalization (black) of the High-Middle Atlas (a) and Anti Atlas (b) subcrustal events.

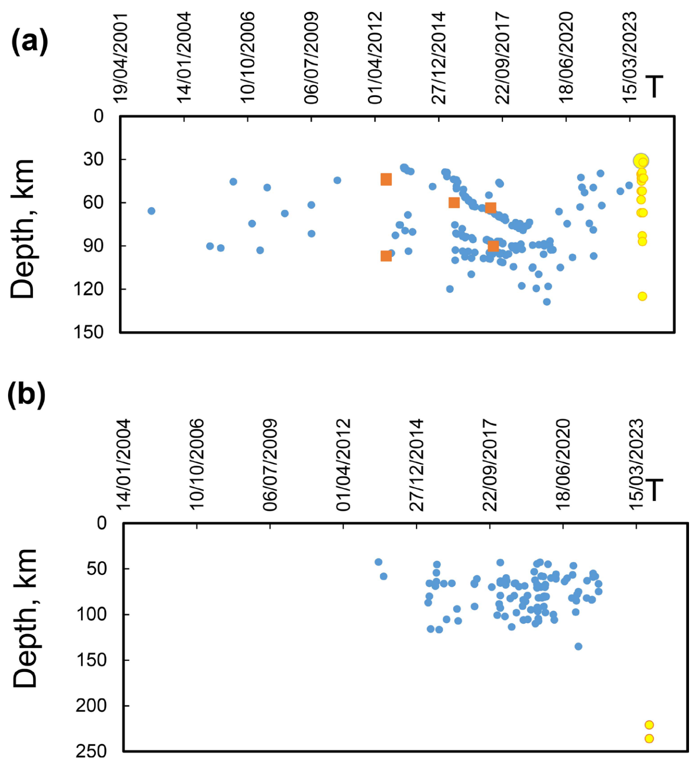

Figure 4. Temporal variations of upper mantle earthquakes at depth during the last 23 years in the High-Middle Atlas (a) and the Anti Atlas (b). Recent M6.8 seismic event and its aftershocks (yellow) are indicated and 6 events beneath the continental margin (red).

More significant observations are two events of magnitudes 3.5 and 3.4 which occurred 22 hours after the main event and relocated beneath the Anti Atlas at depths of 222 and 236 km with Erz of 4 and 4.45 km respectively. Another significant aftershock event was relocated at 125 km while the other subcrustal aftershocks displayed between 40 to 87 km depth. Subcrustal events under the Atlas Mountains show a particular spatial distribution adjusted by a correlation R^2 reaching 0.868 (Figure 6). Consequently, these seismic events highlight geodynamic process in the lithosphere and asthenosphere beneath the Atlas Mountains.

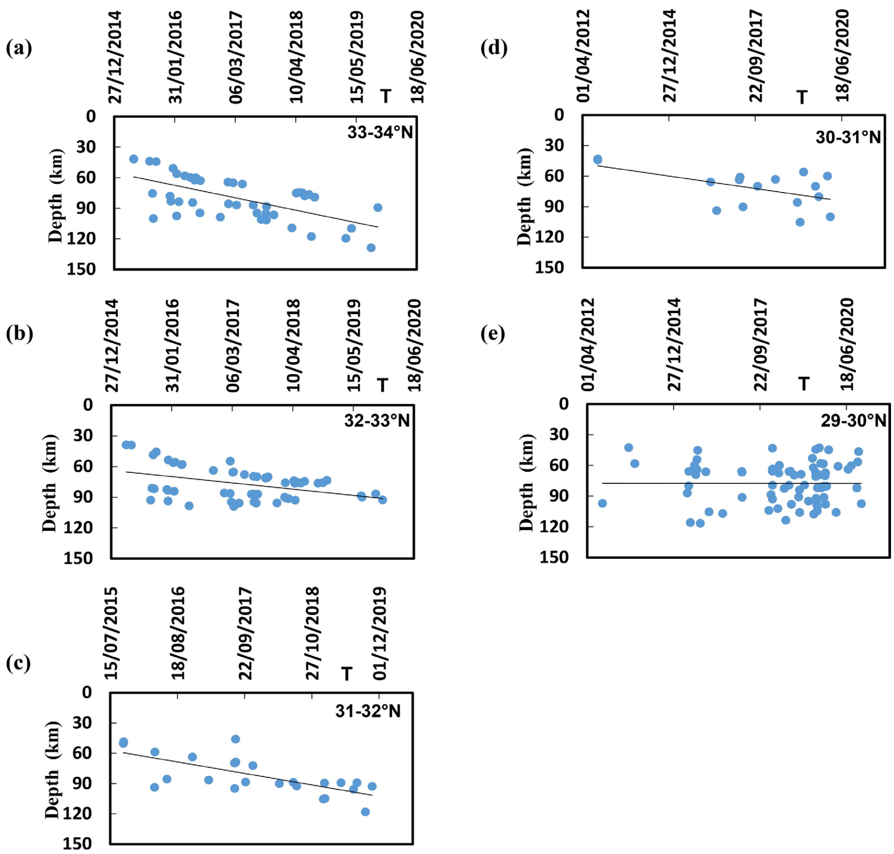

Figure 5. Temporal variations of deep earthquakes at depth are shown from varying latitude starting from Middle Atlas and High Atlas (33 - 31˚N), the junction High-Anti Atlas (30˚N), and the Anti Atlas (29˚N).

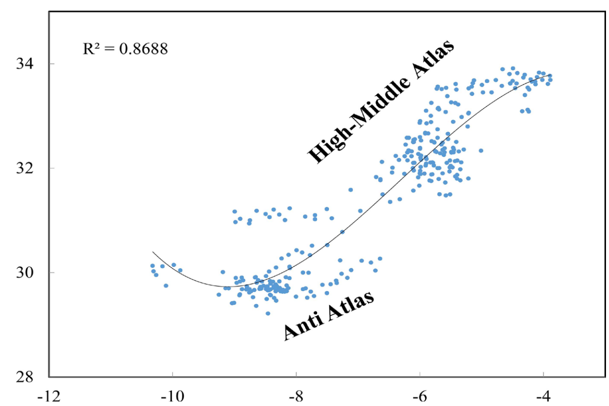

Figure 6. 3D image of upper mantle earthquakes (a) and their spatial relocation that shows high R^2 correlation between Middle-High Atlas and Anti Atlas zones (b).

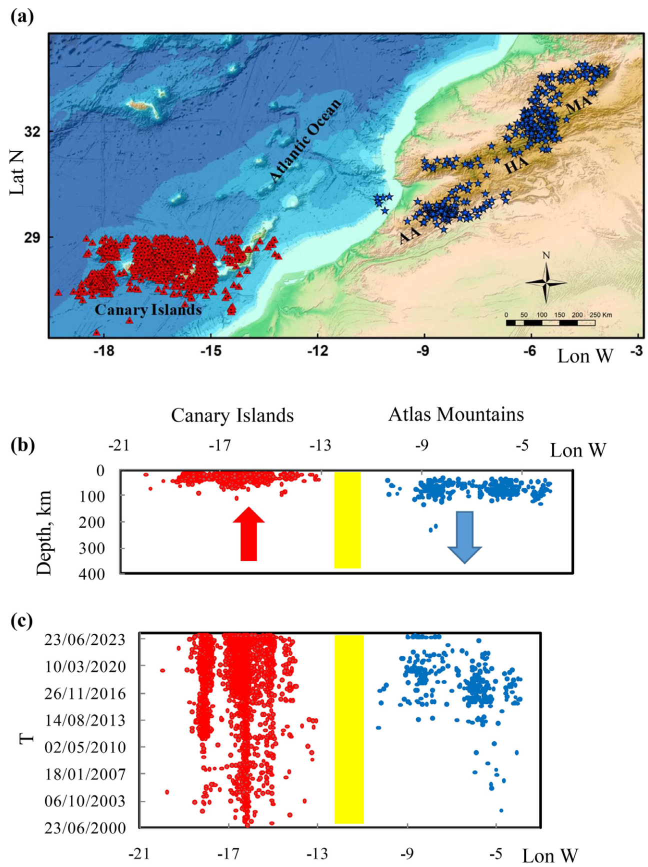

Figure 7. Upper mantle earthquakes recorded during the last 23 years in the Canary and Atlas (a) show deeper events (blue) beneath the Anti Atlas (AA), High Atlas (HA) and Middle Atlas (MA) compared to Canary events (red) and associated driving motions are indicated by arrows (b). Both systems are separated by a zone free from upper mantle earthquakes (yellow zone) (c).

4. Discussion

Seismic activity during the last 23 years is revisited and new more constrained epicenter relocations are obtained. Considerable relocated events provided depth estimates suitable to elucidate the presence of earthquake beneath the crust-mantle transition zone of the Atlas Mountains. Dipping zone of earthquakes observed after 2014 shows that such triggering process of events in depth may be related to progressive dipping motions. Recent events on September 2023 confirm the presence of earthquakes which occurred in the transition zone of crust-upper mantle and further events in the upper mantle. Two events recorded one day after the major M6.8 event are relocated at about 220 - 236 km depth which coincide with the upper limit of lithosphere thickness (250 km) beneath the Anti Atlas. This may be explained by interactions between deep earthquakes beneath the High and Anti Atlas. Low velocity anomaly observed by several tomography studies supported the upwelling mantle beneath this seismic zone in the Atlas. However, seismic events at these depths suggest that cold matter reacts under high P-T conditions, which could release kinetic energy. Such a mechanism is possible when a small amount of material is removed from the crust or lithosphere. Models that include coeval downward and upward movements in intracontinental environment support delamination models. A possible cause of this process could be an earlier thickening of the Atlas lithosphere. Instability of the thick lithosphere led to delamination in the lower lithosphere. Recent M6.8 event in the high Atlas suggests a new detachment piece at the lower boundary of the crust (31 km) followed by a set of events in the uppermost mantle with a vertical trend. Consequently, delamination appears to be affecting not only the lower lithosphere but also the deeper parts of the lower crust beneath the central High Atlas. Subcrustal events recorded in the northern limit of the Anti Atlas suggest that northern parts of the Anti Atlas juxtaposing the High Atlas could experience delamination, or that previous delaminated lithosphere of the High Atlas could cause earthquakes beneath the nearby lithosphere of the Anti Atlas. Azrou-Timahdita zone of the Quaternary volcanism of Plio-Quaternaryin the Middle Atlas [18] and Quaternary volcanic eruptions (Sargho) in the northern Anti Atlas express a final stage of mantle upwelling in Plio-Quaternary periods that were related to delamination phases [5]. Low velocity zones derived from tomography studies are due to heating from rising mantle, and dehydration reactions which release kinetic energy recorded as seismic events. As the downward flow related subcrustal seismicity of the Atlas is contemporary with mantle upwelling beneath the Canary Islands, their possible interactions could be possible to achieve a regional balance of movements (**Figure 7**). The Atlas events appear deeper than the Canary events, which suggest that descending material reaches high P-T conditions to trigger earthquakes, while upward movements in a volcanic context cause events at lower depths of the upper mantle during the final phase of eruptions. Even the presence of 6 events recorded beneath the continental margin, there is an earthquake-free zone between the Atlas and the Canaries which can be explained by a boundary zone where the motion varies from downward to upward flow. This could favor lateral propagation of mantle upwelling that reaches the surface of the Canary Volcanic Islands due to their thinner crustal thickness compared to the Atlas areas.

5. Conclusion

Relocation of uppermost earthquakes shows evidence for downward flow beneath the entire Atlas ranges. Such vertical movement is accompanied by an upwelling of the mantle to replace the delaminated material and maintain the topographic heights of the Atlas. Temporal variations of events observed at depth show a dipping motion that favors a loading process from the High Atlas to beneath the Anti Atlas crust. This downward movement from the High Atlas could flow beneath the Anti Atlas, leading to a deeper lithosphere-asthenosphere boundary (LAB) at more than 200 km.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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