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An enigmatic earthquake in the continental mantle lithosphere of stable North America

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ABSTRACT

The existence of earthquakes within continental lithospheric mantle remains a highly controversial topic. Here, we present a detailed set of seismological analyses confirming the occurrence of a mantle earthquake beneath the Wind River Range of central Wyoming. Combining regional waveform inversion with the analysis of the delay and relative amplitudes of teleseismically-observed depth phases, we demonstrate that the 2013 Wind River earthquake – a M_W 4.7 highly-oblique thrust-faulting event – occurred at 75 ± 8 km, well beneath the base of the crust. The magnitude, mechanism, and location of this earthquake suggest that it represents simple brittle failure at relatively high temperatures within the mantle lithosphere, as a result of tectonic, rather than magmatic, processes.

1. Introduction

The occurrence and significance of earthquakes in the mantle lithosphere of stable continental regions has been a subject of much debate (e.g. Chen and Molnar, 1983; Wong and Chapman, 1990; Zhu and Helmberger, 1996; Maggi et al., 2000; Chen and Yang, 2004; Priestley et al., 2008; Sloan and Jackson, 2012), with their existence and location being used to argue for different rheological models for the continental lithosphere (e.g. Chen and Molnar, 1983; Jackson et al., 2008; Burov, 2010). Whilst earthquakes in the mantle of oceanic lithosphere are commonplace (e.g. Wiens and Stein, 1983; Craig et al., 2014), well-constrained examples from continental lithosphere are comparatively rare. Confirmed earthquakes in the continental mantle are limited to Utah (Zandt and Richins, 1979), northern Australia (Sloan and Jackson, 2012), and potentially northern India and Tibet (Chen and Molnar, 1983; Zhu and Helmberger, 1996; Chen and Yang, 2004; Priestley et al., 2008; Craig et al., 2012), although the precise location of deep earthquakes with respect to the local Moho in this latter case remains uncertain. Occasional other earthquakes at mantle depths in continental areas are reported in routine earthquake catalogues (e.g. International Seismological Centre, 2012; Engdahl et al., 1998). However, given the degree of precision required to differentiate earthquakes in the crust and uppermost mantle, and the uncertainties in such techniques, these often prove to be false or unverifiable when subjected to more detailed analyses aimed specifically at depth determination (Maggi et al., 2000; Engdahl et al., 2006). How widespread mantle seismicity in continental regions may be, and the depth extent over which it can occur, therefore remains a topic severely limited by a paucity of high-quality observational constraints.

As a result of the well-established thermal control on brittle failure of the lithosphere, potential mantle earthquakes in stable continental regions are expected to concentrate in the uppermost (and therefore coldest) few kilometers of the mantle, close to the Moho. The confirmation of an earthquake as occurring in mantle lithosphere, rather than in the overlying lower crust, thus typically requires precise knowledge of both the depth of the earthquake, and the depth of the Moho in the source region. Uncertainties in both parameters often result in earthquake depths within error of the local Moho, which cannot be conclusively identified as either crustal or mantle in origin.

Here, we present a comprehensive seismological study of an earthquake located near the Wind River range in central Wyoming, identified by the NEIC Preliminary Determination of Epicenters bulletin (NEIC hereafter) as having a potentially mantle origin. The location of this earthquake, within the continental United States, and the large amount of high-quality seismic data available make it ideal for a detailed analysis to confirm the preliminary NEIC depth. We combine regional seismological estimates of the earthquake focal mechanism and depth with teleseismic depth phase observations from both individual broadband stations and from small-to-medium aperture multi-instrument arrays to present conclusive

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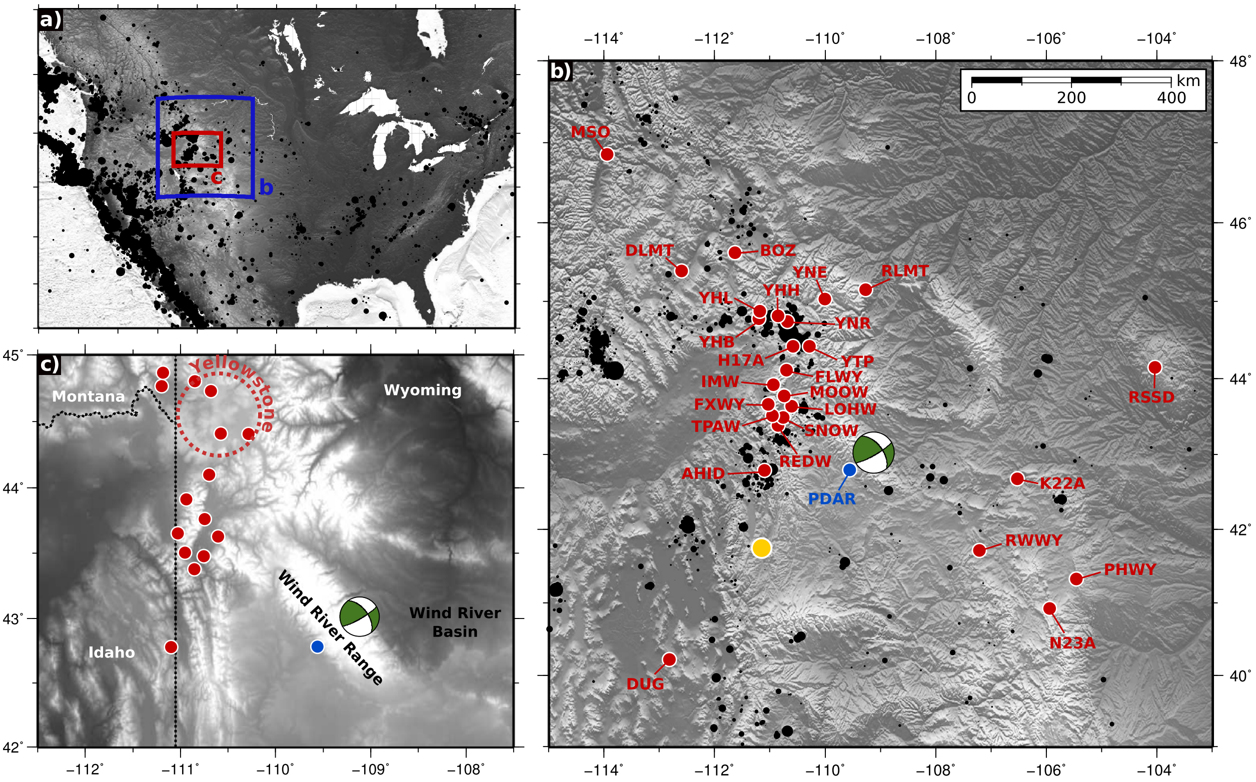

Fig. 1. (a) Location map. Black points indicate seismicity from the NEIC catalogue, scaled by magnitude. (b) Regional context. Black points are again NEIC catalogue seismicity. Green mechanisms indicates the Wind River earthquake. Yellow circle indicates the 1979 Randolphe, Utah, earthquake at 90 km depth (Zandt and Richins, 1979). Red circles indicate the locations of regional seismic stations used in the regional waveform inversion (Figs. 2, S1, S2). Blue circle indicates the location of the Pinedale seismic array (PDAR) used in the aftershock analysis (Figs. 8, S4). (c) Simple geological context, highlighting the location of the Wind River earthquake relative to the Wind River Range and Basin, and to the present location of the Yellowstone hotspot. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

evidence in favour of a hypocentre located significantly below the base of the crust in this region, well into the lithospheric mantle. We then briefly discuss the regional context of this earthquake, and how it may impact on current models for the rheology of continental lithosphere.

2. The 2013 Wind River Earthquake

This paper focuses on an earthquake that occurred in central Wyoming, between the Wind River Range and Wind River Basin (Fig. 1). The Wind River region is relatively seismically quiescent, with instrumentally recorded seismicity, covering a period of ∼60 yr, rarely exceeding M_L 4, and only once having reached M_L 5. The region lies within the central Wyoming Craton, near the complex western boundary of the cold, stable lithosphere which underlies much of northern North America, west of the Rocky Mountains (e.g. Sigloch, 2011; Porritt et al., 2014). The present day topography largely reflects deformation during the Late Cretaceous/Jurassic Laramide orogeny, of which the Wind River mountains represent a distal part. The Range itself is a basement-cored uplift, bounded by major (but inactive) crustal faults on its southwestern side, within the Archean Wyoming craton. The centre of the range comprises crystalline rocks of Archean age. The Wind River basin contains Paleozoic sediments, overlying the Archean basement. At present, the region is tectonically inactive, with the nearest region of significant seismicity being that related to the Yellowstone Hotspot (and associated track), some 200 km to the northwest.

At 13:16:33 UTC on the 21st September 2013, a moderate magnitude earthquake ($M_W \sim 4.8$) was reported in the area of the Wind River Range, Wyoming (42.974°N, 109.128°W; NEIC). Initial estimates of the earthquake depth, based on routine travel time inversion (NEIC) and surface and very-long-period body-wave inversion (www.globalcmt.org) indicated that this earthquake originated in the mantle lithosphere, at between 70 and 80 km. Hypocentral locations from both catalogues indicate a source beneath the margin between the mountains and the adjacent basin. Here, we undertake a detailed investigation aimed at confirming a source location in the mantle lithosphere for this earthquake.

A single aftershock was reported by the NEIC, occurring two hours after the initial earthquake. The reported catalogue depth of this event is similar (71 km) to that reported for the mainshock (76 km). Whilst the magnitude of this earthquake (M_L 3.0) makes it too small to be analysed with the methods employed here to study the mainshock, we use similarity in S–P arrival times and in apparent vector slowness across a regional array, to suggest that its depth is similar to that of the mainshock.

3. Earthquake source parameters

3.1. Velocity model

The seismological analyses conducted in this study are all heavily dependent on the near-source velocity structure. In the case of the regional inversion, a layered 1-dimensional model is used to calculate Greens functions for the computation of synthetic seismograms. For stations at greater distances, the same model is used to calculate depth-phase delay times and synthetic waveforms. The use of a simple one-dimensional velocity model fails to account for lateral variations in the velocity structure around the source. However, the precise details of the local velocity structure are largely unknown, and cannot be included accurately. The velocity model