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Review Article

Moho, seismogenesis, and rheology of the lithosphere

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ABSTRACT

The Moho is not always a sharp interface; but seismic phase *SsPmp* yields robust, physically averaged estimates of crustal thickness (virtual deep seismic sounding, VDSS). In S. Tibet where the Moho is as deep as 75 km, bimodal distribution of earthquake depths, with one peak in the upper crust and the other below the Moho, generated much interest in how lithological contrast affects seismicity and rheology. Generally seismicity is limited by distinct temperatures (*Tc*): 350 ± 50 °C in the crust and 700 ± 100 °C in the mantle (Earthquake Thermometry). Laboratory experiments show that distinct *Tc* reflect the onset of substantial crystal plasticity in major crustal and mantle minerals, respectively. Above these *Tc*, frictional instability ends due to velocity weakening of slip. So the seismic to aseismic transition is closely linked with brittle-ductile transitions in the crust and in the uppermost mantle, where the strength of the continental lithosphere is expected to peak ("Jelly Sandwich"). Plasticity depends exponentially on temperature (which evolves over time), so interplay between the geotherm and crustal thickness could result in concentrated seismicity in the upper crust — the only portion of a very warm lithosphere where temperature is below ~350 °C ("Crème Brûlée"). Conversely, where the entire crust is below ~350 °C (and the uppermost mantle is also below ~700 °C), then earthquakes could occur over a wide range of depths, including the entire crust and the uppermost mantle ("Caramel Slab").

Contents

1. Introduction

The Mohorovičić discontinuity, or the Moho, is a global feature that lies at depths between about 15 to 75 km and 5 to 10 km under the continents and the oceans, respectively (e.g., Brown and Mussett, 1993). There are only two locations where the Moho is

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exposed on the surface over large areas: the Troodos ophiolite in Cyprus and the Semail ophiolite in Oman. In both cases, relics of oceanic lithosphere overthrust onto the continent, providing rare opportunities for direct inspections (Fig. 1). These rare outcrops confirm the interpretation that the Moho is the transition between the crust and the mantle where mafic or even less magnesium- and iron-rich rocks change to ultramafic assemblages below (Brown and Mussett, 1993; Christensen and Mooney, 1995).

In a well-known article, Benioff (1954) associated the cessation of deep earthquakes with the position of the Moho. In this hypothesis a seismogenic, true "mega-thrust" extends from oceanic trenches down to a depth of about 700 km where the Moho lies. While both earlier work and later research clearly showed that inclined bands of deep earthquakes occur in the interior of subducted oceanic lithosphere (Isacks and Molnar, 1969, 1971; Wadati, 1927), and that nowhere is the Moho deeper than about 75 km (e.g., Anderson, 2007; Tseng et al., 2009), the relationship between the Moho and seismogenesis has received a considerable amount of renewed attention since the discovery of unusually deep earthquakes at depths near 90 km beneath the Tibetan plateau where the thickest crust (~75 km) is found (Chen et al., 1981).

The connection between the Moho and generation of earthquakes is through rheology of rocks. Since there is a marked contrast in lithology across the Moho, and lithology is an important factor in the thermo-mechanical properties of rocks, the Moho marks a region near where a crucial change in the instability of fault slip could occur. There is continual research on this subject (e.g., Afonso and Ranalli, 2004; Burov and Watts, 2006), including a recent review by some of the same authors (Chen et al., 2012). Here we first briefly review important means to investigate the nature of the Moho and the distribution of earthquake depths. Besides providing the necessary background information, these discussions emphasize new results or perspectives. We then connect rheology and seismogenesis in terms of slip instability, putting empirical rules of "earthquake thermometry" on firm grounds: The limiting temperatures for seismicity, T_c, are about 300–400 °C and 600–800 °C in the crust and in the upper mantle, respectively. Finally, we discuss emerging topics of current interests, including the so-called slow earthquakes and their possible relationship with the Moho and rheology.

2. The Moho: in the eyes of the beholder

When Andrija Mohorovičić discovered the first major discontinuity of the Earth's interior, he relied on the method of seismic refraction. The principle of this method now widely appears in introductory texts (e.g., Brown and Mussett, 1993): by noting the cross-over distance beyond which refracted arrival above the Moho is overtaken by refraction below the discontinuity, and by measuring the slopes of these two branches of travel-times, one can measure both the depth of the discontinuity and the speed of seismic waves above and below it.

On a global scale, much of what we know about the Moho is still gathered from seismological/geophysical means. Advances in technology have revealed a wealth of information. For instance, the Moho is not always a simple interface. Deep seismic reflection has been effective in illuminating crustal structures but the Moho itself can be elusive to this particular method. Moreover, the characteristics of the Moho are quite varied; including gradual transitions between the crust and the uppermost mantle (e.g., see a recent review by Eaton (2006) and references therein).

In the past two decades, it has become routine to investigate the Moho using seismic waves from distant ("teleseismic") earthquakes. Under the general, generic name of "receiver functions" (RFs), these methods use a variety of secondary wavefields scattering off heterogeneities beneath seismic stations to investigate the subsurface. While RF cannot achieve the high frequency-content and dense spacing of conventional seismic reflection, it has several advantages: The deep-penetrating power of seismic waves generated by earthquakes is unrivaled; the broadband nature of earthquake sources facilitates multi-frequency, and therefore multi-scale studies; and the cost of deployment is modest, with minimal impact on the environment.

Fig. 2a shows an example of a long seismic profile using earthquake sources. Over a distance of about 1000 km across the north China craton, wide-angle reflections off the Moho clearly reveal large variations in crustal thickness not expected from modest changes in elevation (Yu et al., 2012). The strong signal from the Moho is the so-called *SsPmp* phase in the coda of the *S*-wave train (Fig. 3b). This phase received only passing interest in the past as a useful element in RF because its amplitude is weak when the source–receiver distance is large, beyond about 55° (e.g., Owens and Zandt, 1997; Zhou et al., 2000). Lately, in order to investigate deep-seated Moho beneath thickened crust of Tibet, Tseng et al. (2009) used the large amplitude of *SsPmp* from earthquake sources that are between about 35°–50° away to construct deep-penetrating seismic profiles over a distance of more than 500 km over Tibet.

There are two keys in this approach. First, at distances less than about 50°, the last leg of *SsPmp* is a post-critical reflection off the top of the Moho, resulting in amplitude of vertical ground motion that is comparable to that of the direct *S*-arrival, or phase *Ss* (Figs. 2a and 3b). Second, the "*Ss*" portion of the ray-paths for these two phases is near-identical (Fig. 3b). By aligning the *Ss* phase to the Earth's surface,

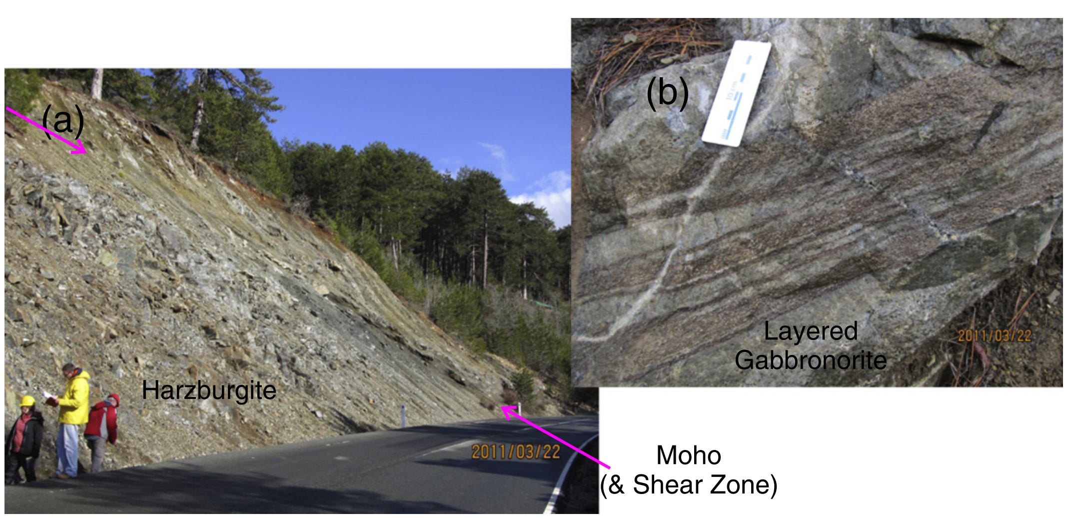

Fig. 1. Photographs of Moho outcrop in the Troodos ophiolite, Cyprus. (a) The top of the ultramafic, harzburgite massive is the "Moho", with some serpentinization and local evidence for an extensional shear zone. (b) A clear example of layer gabbronorite (mafic crust), seen about 400 m to the right of the Moho. The length of the scale is 100 mm. (Photos taken by the first author.)