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Review Article

Constraints on the Moho in Japan and Kamchatka

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ABSTRACT

This review collects and systematizes in one place a variety of results which offer constraints on the depth and the nature of the Moho beneath the Kamchatka peninsula and the islands of Japan. We also include studies of the Izu–Bonin volcanic arc. All results have already been published separately in a variety of venues, and the primary goal of the present review is to describe them in the same language and in comparable terms.

For both regions we include studies using artificial and natural seismic sources, such as refraction and reflection profiling, detection and interpretation of converted-mode body waves (receiver functions), surface wave dispersion studies (in Kamchatka) and tomographic imaging (in Japan). The amount of work done in Japan is significantly larger than in Kamchatka, and resulting constraints on the properties of the crust and the uppermost mantle are more detailed.

Japan and Kamchatka display a number of similarities in their crustal structure, most notably the average crustal thickness in excess of 30 km (typical of continental regions), and the generally gradational nature of the crust–mantle transition where volcanic arcs are presently active.

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1. Introduction

The primary purpose of this brief review is to collect, systematize and present in a common format a variety of results which offer constraints on the depth and the nature of the Moho beneath Kamchatka and Japan, which form the eastern margin of the Asian continent. These areas have been studied for decades, with a variety of geophysical methods, including active and passive seismic methods, gravity and other techniques.

The Moho and the upper mantle structures in and around Japan have been well investigated both from active and passive seismic source studies including marine expeditions. Earlier results on these subjects (1960–1970s) were mainly presented from seismic refraction experiments (Yoshii, 1994). The advance of technology in data acquisition and processing systems in 1980 and 1990s brought us a large amount of high quality seismic data (Yoshii, 1994; Iwasaki et al., 2002). In active source experiments, the receiver spacing became much denser (less than 2–3 km), which enabled us to identify many seismic phases including reflections from the Moho (PmP phase) and improve the constraints on the nature of the Moho boundary. After the 1995 Kobe earthquake, a new and denser seismic network has been established in Japan. It was subsequently used to carry out detailed tomography analyses and receiver function investigations that provided constraints on the lateral variations in Moho geometry and the uppermost mantle velocity beneath Japan.

Due to the strategic importance of Kamchatka during the Cold War, and the general culture of research publications in the former Soviet Union, many published results on the crustal structure are somewhat cryptic, especially where spatial locations are concerned. In this review we undertook an effort of digitizing and geo-referencing all published results available in the peer-reviewed literature, in both Russian and English languages. No attempt was made to locate local publications or archival copies of technical reports that potentially contain some of the primary data. In other words, we are presenting results as they have been published, and provide only a minimum of commentary.

Hereafter, we present several important features of Moho and upper-mantle structure beneath Japan and Kamchatka from various methodologies that are described in the following section. For each region we present, in turn, a brief overview of relevant tectonic features, and subsequently describe specific constraints on the Moho. We conclude this review with a discussion of similarities and differences between these two regions.

2. Summary of methods

2.1. Compressional wave refraction and reflection

The primary method for detecting the crust–mantle boundary relies on observations of refracted compressional waves. This technique is commonly employed with artificial sources (blasts on land or air guns at sea), and a common practice is to interpret both refracted and post-critically reflected waves, identified on record sections on the basis of their apparent velocities. A version of the method commonly used in the USSR during the second part of the XX century was referred to as the Deep Seismic Sounding (DSS) technique. After 1980–1990s, ray tracing technique became a standard tool for seismic refraction/wide-angle reflection profiling. By combining travel time and amplitude data, we could obtain detailed structure of the deeper part of crust and upper-mantle. Near-vertical reflection profiling is quite an effective tool to image crust and upper-mantle structure particularly in the continents. In Kamchatka or Japan, however, it is quite rare to obtain clear image around the Moho boundary due to high seismic attenuation arising from their complex structures and intense volcanic activities.

2.2. Mode conversion in body waves

Records of compressional seismic waves from distant earthquakes typically contain both compressional- and shear-polarized waves within their coda. The shear-polarized phases are understood to arise from mode conversions between compressional and shear waves that take place when compressional waves encounter sharp gradients in seismic impedance (density–velocity product) (Phinney, 1964; Vinnik, 1977). The Moho is expected to give rise to a prominent P-to-S converted phase. Recognition of this phase, and timing of its arrival with respect to the “parent” compressional wave, offers a constraint on the depth to the converting boundary (e.g., Langston, 1981). Frequency, amplitude and signature of the waveform associated with the Moho P-to-S converted wave can be used to assess the nature of the boundary (e.g. vertical extent of the gradient in impedance). A “receiver function” technique (e.g., Ammon, 1991) relies on the similarity in waveform shapes of parent P and daughter S waves, and employs time-series manipulation algorithms to isolate the latter in digital records of teleseismic P waves. Results of such processing are records of shear waves in “relative time” that may be interpreted as a proxy for the depth to a converting interface. A common practice is to combine multiple observations, and to explore the changes in timing and appearance of converted phases with respect to direction of propagation (back azimuth and angle of incidence), making sure that the phase being interpreted is indeed a direct P-to-S converted wave. The timing of converted phases is subject to a trade-off between the depth of the converting interface and the ratio of P and S wave speeds (e.g. Gurrola et al., 1995).

2.3. Surface waves

In a layered medium with depth-variable seismic properties surface waves propagate with the speed dependent on their period. Waves with progressively longer periods (and consequently larger wavelengths) sample progressively deeper parts of the Earth. A resulting relationship of speed vs period (known as a “dispersion relationship”) can be interpreted in terms of the vertical distribution of speed. Key assumptions that are involved in this approach are a) that the medium is horizontally stratified and b) the properties change only vertically in the volume enclosing both the source and the receiver. A common strategy is to divide the region of study into areas containing distinct source–receiver paths, and to develop independent velocity–depth profiles for them. In this approach, the depth to the Moho can be estimated, either as a depth of a strong gradient in speed or, alternatively, a depth where the speed reaches a value characteristic of the upper mantle rock.