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Review Article

Mapping the Moho with seismic surface waves: A review, resolution analysis, and recommended inversion strategies

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ABSTRACT

The strong sensitivity of seismic surface waves to the Moho is evident from a mere visual inspection of their dispersion curves or waveforms. Rayleigh and Love waves have been used to study the Earth's crust since the early days of modern seismology. Yet, strong trade-offs between the Moho depth and crustal and mantle structure in surface-wave inversions prompted doubts regarding their capacity to resolve the Moho. Here, we review surface-wave studies of the Moho, with a focus on early work, and then use model-space mapping to establish the waves' sensitivity to the Moho depth and the resolution of their inversion for it. If seismic wavespeeds within the crust and upper mantle are known, then Moho-depth variations of a few kilometres produce large (>1%) perturbations in phase velocities. However, in inversions of surface-wave data with no a priori information (wavespeeds not known), strong Moho-depth/shear-speed trade-offs will mask ~90% of the Moho-depth signal, with remaining phase-velocity perturbations ~0.1% only. In order to resolve the Moho with surface waves alone, errors in the data must thus be small (up to ~0.2% for resolving continental Moho). With larger errors, Moho-depth resolution is not warranted and depends on error distribution with period. An effective strategy for the inversion of surface-wave data alone for the Moho depth is to, first, constrain the crustal and upper-mantle structure by inversion in a broad period range and then determine the Moho depth in inversion in a narrow period range most sensitive to it, with the first-step results used as reference. Prior information on crustal and mantle structure reduces the trade-offs and thus enables resolving the Moho depth with noisier data; such information should be used whenever available. Joint analysis or inversion of surface-wave and other data (receiver functions, topography, gravity) can reduce uncertainties further and facilitate Moho mapping.

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1. Introduction

The Mohorovičić discontinuity, often referred to as the Moho, separates the Earth's crust from the underlying mantle. Compositional differences between the lighter crust and the denser upper mantle give rise to an increase in seismic velocities across the Moho, from the crust to the mantle. The discontinuity can thus be identified seismically as the location of the seismic-velocity increase (Mohorovičić, 1910).

During the century since the discovery of the Moho (Mohorovičić, 1910), the discontinuity, which can be either sharp or gradational, has been detected and imaged in numerous locations around the world, at various length-scales and with different seismic techniques. Controlled-source seismic surveys yield high resolution of the entire crust and the Moho by sampling them densely with rays of reflected or refracted seismic body waves, propagating between local sources and receivers (Prodehl and Mooney, 2011, and references therein). Relatively expensive and labour-intensive, controlled-source experiments can be complemented by "passive" seismic studies that use natural seismic sources (local or teleseismic earthquakes or ambient seismic noise). The passive imaging approaches include the analysis of *P*-to-*S* wave conversions at the Moho (e.g., Bostock et al., 2002; Kind et al., 2002; Nabelek et al., 2009; Stankiewicz et al., 2002; Zhu and Kanamori, 2000), surface-wave imaging, including inversions of surface-wave dispersion curves or waveforms and surface-wave tomography (e.g., Das and Nolet, 1995; Endrun et al., 2004; Yang et al., 2008), joint inversions of the *P*-to-*S* conversions (receiver functions) and surface-wave data (e.g., Julià et al., 2000; Tkalčić et al., 2012), local body-wave tomography (e.g., Koulakov and Sobolev, 2006), and even *SS* waveform stacking (Rychert and Shearer, 2010). Regional crustal models and Moho maps have also been constructed using combinations of both active-source and passive seismic data, as well as other geophysical and geological data (e.g., Grad et al., 2009; Kissling, 1993; Molinari and Morelli, 2011; Tesauro et al., 2008; Thybo, 2001).

Seismic surface waves are particularly sensitive to the structure of the crust and uppermost mantle — and, thus, to the depth of the Moho. Because these waves propagate along the Earth's surface, measurements of their speeds characterise average elastic properties of the crust and upper mantle between seismic sources and stations or between different stations. The Moho can thus be imaged even in locations with no stations or sources.

The two main types of surface waves are Rayleigh waves and Love waves (Aki and Richards, 1980; Dahlen and Tromp, 1998; Kennett, 1983, 2001; Levshin et al., 1989; Nolet, 2008). The speeds of Rayleigh waves depend primarily on the speeds of the vertically polarised *S* waves in the crust and mantle and, also, on *P*-wave speeds and density; the particle motion associated with Rayleigh waves in an isotropic, laterally homogeneous Earth model is within the great circle plane containing the source and the receiver. The speeds of Love waves depend primarily on the speeds of the horizontally polarised *S* waves and, also, on density; the associated particle motion is approximately perpendicular to the great circle plane.

The depth sensitivity of surface waves depends on their period: the longer the period, the deeper within the Earth the waves sample (Fig. 1). This makes surface waves strongly dispersive.

Dispersion curves of surface waves (their phase or group velocities plotted as a function of period or frequency) show a characteristic sharp increase with period associated with the Moho (Figs. 2, 3). This increase reflects the *S*-wave velocity increase across the discontinuity, and its period range depends on the depth of the Moho: it occurs at longer periods if the Moho is deeper. The depth of the Moho can thus be estimated roughly by a mere visual inspection of a surface-wave dispersion curve (Figs. 2, 3).

Inferences on the crustal structure and thickness have been drawn from surface-wave observations since the early days of modern seismology. It also became apparent early that the crustal models inferred from the dispersion data can be highly non-unique. Although the Moho depth has been an inversion parameter in numerous surface-wave studies, the data's sensitivity to the Moho and, in particular, the resolution of the Moho properties given by inversions of surface-wave data with measurement errors are still uncertain and not agreed upon.

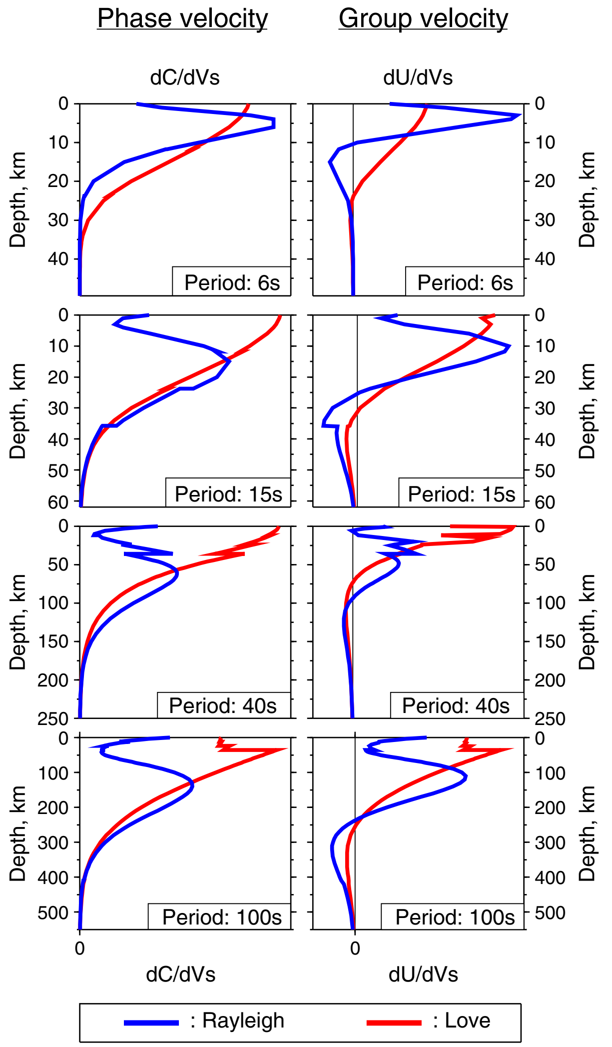

Fig. 1. Depth sensitivity of surface waves. The sensitivity curves are the Fréchet derivatives of the phase and group velocities of the fundamental-mode Rayleigh and Love waves with respect to S-wave velocities at different depths. The derivatives were computed for a continental, 1-D Earth model with a 37-km thick crust, at 4 different periods. Each graph is scaled independently.

In this paper we overview the classic surface-wave studies since the late 19th–early 20th century, as well as some of the more recent work focussing on the Moho. We then investigate in detail the sensitivity of surface-wave phase velocities to the Moho depth and the trade-offs between Moho-depth and crustal and mantle shear-velocity parameters in inversions of surface-wave dispersion. Exploring the model spaces in inversions of synthetic and real data, we examine the resolution of the Moho by surface-wave measurements as a data type. Finally, we discuss strategies for an accurate estimation of the Moho depth using surface-wave data and illustrate some of them with applications to phase-velocity measurements from southern Africa.

2. Surface-wave studies of the crust and the Moho

Rayleigh waves were identified on seismic recordings by Oldham (1899), and already at that time Wiechert (1899) speculated that