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Review Article

100 years of seismic research on the Moho

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ABSTRACT

The detection of a seismic boundary, the "Moho", between the outermost shell of the Earth, the Earth's crust, and the Earth's mantle by A. Mohorovičić was the consequence of increased insight into the propagation of seismic waves caused by earthquakes. This short history of seismic research on the Moho is primarily based on the comprehensive overview of the worldwide history of seismological studies of the Earth's crust using controlled sources from 1850 to 2005, by Prodehl and Mooney (2012). Though the art of applying explosions, so-called "artificial events", as energy sources for studies of the uppermost crustal layers began in the early 1900s, its effective use for studying the entire crust only began at the end of World War II. From 1945 onwards, controlled-source seismology has been the major approach to study details of the crust and underlying crust–mantle boundary, the Moho. The subsequent description of history of controlled-source crustal seismology and its seminal results is subdivided into separate chapters for each decade, highlighting the major advances achieved during that decade in terms of data acquisition, processing technology, and interpretation methods.

Since the late 1980s, passive seismology using distant earthquakes has played an increasingly important role in studies of crustal structure. The receiver function technique exploiting conversions between P and SV waves at discontinuities in seismic wavespeed below a seismic station has been extensively applied to the increasing numbers of permanent and portable broad-band seismic stations across the globe. Receiver function studies supplement controlled source work with improved geographic coverage and now make a significant contribution to knowledge of the nature of the crust and the depth to Moho.

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1. Introduction

The investigation of the crust–mantle boundary, termed the Mohorovičić discontinuity (short "Moho") after the first person to observe it (Mohorovičić, 1910), started at the beginning of the 20th century by the application of advanced methods of earthquake research.

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It was recognized in the early 1910s as a worldwide boundary separating rocks with fundamentally different physical properties, e.g. seismic wave speed or density, and it was soon discovered that its depth distribution shows substantial variations.

The Moho soon became the target of controlled source seismology investigations, where location and time of events were exactly known. A detailed history of controlled source seismology from its beginnings at around 1850 to its advanced stage of knowledge in 2005 was recently published as Memoir 208 of the Geological Society of America (Prodehl and Mooney, 2012). The following short history of research on the Moho outlines in brief the most important results, and the reader is referred to this Memoir for more details about controlled source techniques. The Memoir contains an Appendix with a collection of controlled-source seismology data, reproductions of rare historic publications, as well as a reproduction of the publication of Finlayson (2010) who has compiled a complete collection of references to deep seismic sounding experiments in Australia.

Passive seismic methods exploiting distant earthquakes have become increasingly important for studies of the Moho in recent years. We introduce the major approaches in current use, notably receiver functions, and describe the applications across the globe to 2005 to match the coverage of the controlled source experiments.

The origin of the Moho has been debated since its discovery, and the debate is still ongoing. From seismic results, it must represent a relatively abrupt change in physical parameters, primarily seismic velocities and density (Oliver, 1982), but also changes in seismic anisotropy (Jones et al., 1996) and scale lengths of heterogeneity (Enderle et al., 1997) may occur across this boundary. Petrologically, it is mostly interpreted as a change in composition between the felsic crust and the mafic mantle, and this transition is often termed the petrological Moho (O'Reilly and Griffin, this volume). However, the Moho may also be shallower or deeper if the lower crust or upper mantle have been subject to metamorphic reactions. A shallower seismic than petrological Moho may occur where mafic to ultra-mafic lower crustal material has been transformed into eclogite facies (Griffin and O'Reilly, 1987); in which case the seismically determined Moho may correspond to the transition between an undisturbed mafic lower crust and similar material in eclogite facies. Such transition has been proposed for the Moho in Variscan Central Europe (Artemieva and Meissner, 2012; Mengel and Kern, 1992), in an area of the southern North Sea (Abramovitz et al., 1998), and at several passive margins (Mjelde et al., this volume). The seismic Moho may also be deeper than the crust–mantle boundary if the upper mantle has been metamorphosed into low-velocity rocks, such as serpentinite depending on the degree of metamorphosis (Coleman, 1971). O'Reilly et al. (1996) describe a case at the Rockall Trough where a substantial part of the upper mantle rocks has been partially metamorphosed into serpentinite, although with velocity close to mantle velocity. Serpentinization is believed to have major importance in subduction zones (Kamiya and Kobayashi, 2000; Bostock, this volume). Tectonic shear localisation may further shift the location of the seismic Moho away from the crust–mantle boundary by introducing localized anisotropy with high velocity in preferred directions (Jousselin et al., 2012; Vauchez et al., 2012). An example of such shear zones may be found in the MONA LISA data set (England et al., 1997). In the following we discuss the historical development of seismic research on the Moho.

2. The first 40 years of Moho research

In 1909 Andrija Mohorovičić at Zagreb, while studying seismograms of a strong local earthquake, constructed a travel-time–distance plot. This event occurred on October 8, 1909 in the nearby Kulpa Valley (approximately 40 km south of the observatory) and had many aftershocks recorded throughout central Europe. Mohorovičić noticed that exclusively for distances between 300 km and 720 km an additional P-wave and a corresponding S-wave could be identified (Fig. 1), from which he deduced a discontinuity with a velocity jump from 5.68 to 7.75 km/s at a depth which he calculated to be 54 km. He stated: "Since the P^{-}-wave can only reach down to a depth of 50 km, this depth marks the limit of the upper layer of the Earth, the Earth's crust. At this surface, there must be a sudden change of the material which makes up the interior of the Earth, because there a step in the velocity of the seismic wave must exist" (Mohorovičić, 1910). This boundary, based on the phase P^{-}, later labeled P_n, was shortly thereafter defined as the crust–mantle boundary and was named the Mohorovičić discontinuity (subsequently shortened to "Moho") that separates the crust with average velocity of 6.0–6.8 km/s from the uppermost mantle with velocities of around 8 km/s.

Fifteen years later, the internal structure of the Earth's crust was detected for the first time. In 1925, when investigating the records of the Tauern earthquake of November 20, 1923, Victor Conrad of Central Meteorological Institute in Vienna detected a phase P^* which he interpreted to originate from an intracrustal discontinuity (Conrad, 1925). He could establish its existence in his later studies, but at different depths when he investigated a 1927 earthquake (Conrad, 1928). Subsequently many other investigators worldwide confirmed this discontinuity and it was named the Conrad-discontinuity. The early seismic measurements were sparsely distributed because only few seismometers existed and they were generally not mobile (Figs. 2 and 3).

In his book "The Earth", Jeffreys (1929) discussed in much detail the subdivision of the crust based on near-earthquake observations in continental regions. In his summary on the upper layers of the Earth he concludes that three layers are concerned: an upper layer, 10 km thick, with P-velocities 5.4–5.6 km/s, an intermediate layer, 20 km thick, with 6.2–6.3 km/s and a lower layer with 7.8 km/s and, comparing the velocities with laboratory measurements on the compressibility of rocks, he suggested that the three layers are probably composed of granite, tachylyte (glassy basalt) and dunite, and that there is probably no layer of crystalline basalt. Though the conditions below the oceans had been "less thoroughly studied", he saw evidence that the granitic layer there was thin or absent.

From 1923 onwards, large explosions, e.g., quarry blasts or explosions carried out for construction purposes were recognized as ideal sources (controlled "artificial earthquakes") for systematic recording of seismic waves for studies of the Earth's crust in detail (e.g., Angenheister, 1927, 1928; Wiechert, 1926, 1929). Similar methods were applied in California and the eastern United States, but results were not published until 1935. Most investigations of artificial events, however, did not observe the base of the earth's crust. The only study of that time in the USA, which

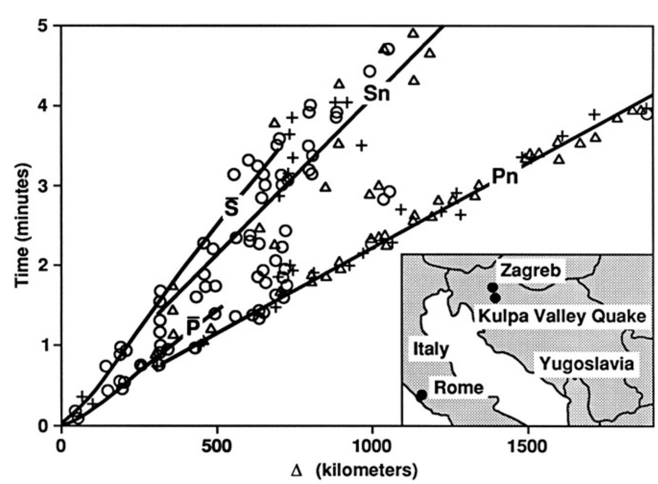

Fig. 1. The traveltime plot by Mohorovičić (1910) from which he deduced the existence of the Moho as an interface between layers with velocities 5.7 and 7.8 km/s. After Jarchow (1991); published by permission of the author.