Tectonophysics 609 (2013) 314–330

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Review Article

The Mohorovicic discontinuity in ocean basins: Some observations from seismic data

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ARTICLE INFO

Article history:
Received 8 October 2012
Received in revised form 7 February 2013
Accepted 7 February 2013
Available online 26 February 2013

Keywords:
Oceanic crust
Crust-mantle boundary
Marine seismology
Plate tectonics
Seafloor spreading
Crustal evolution

ABSTRACT

Since the late 1970s studies of the oceanic crust using airgun sources and towed hydrophone arrays have been conducted in a wide range of ocean basin settings including mid-ocean ridges and old oceanic crust. The very earliest studies were performed at the fast-spreading East Pacific Rise (EPR) and revealed a very distinct almost continuous vertical incidence reflection event at a depth corresponding to the crust–mantle transition as inferred from seismic refraction studies. This suggested that the transition was quite sharp in comparison to the source wavelength. That Moho was observed very close to or even exactly beneath the ridge crest implied that it was formed at essentially zero age. Since then, many experiments using progressively improving airgun arrays and streamer systems have expanded these observations. Here we review the literature presenting studies of "normal" oceanic crust produced at mid-ocean ridges with the objective of assessing the age of formation of Moho and the nature of variability of Moho signature in multi-channel seismic data. Moho is observed as a consistent feature for all spreading rates but appears quite variable, being very distinct in some areas, complex in form in others and absent in many regions (as much as 40%). Although fast-spread crust is associated with the strongest, simplest and most laterally continuous Moho images we see significant variability at almost all spreading rates and ages. Where Moho is absent from vertical incidence data this cannot be fully explained by the effect of scattering or attenuation in the crustal section above. Moho can be observed at zero age in only a small number of areas at or near Overlapping Spreading Centers on the EPR. After three decades of marine seismic studies many fundamental questions remain concerning the nature of the Moho that will require targeted experiments to solve.

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http://dx.doi.org/10.1016/j.tecto.2013.02.018

1. Introduction

The purpose of this paper is to examine two specific questions about the nature of Moho in the oceans:

1. At what age is Moho created in oceanic crust (and whether the age of formation depends on factors like spreading rate) and,
2. How variable is the crust mantle-boundary that gives rise to the Moho?

We acknowledge that this is a reduced set of questions that might be raised about the nature of the oceanic Moho but these questions are critical to understanding the nature of Moho in the oceans and can be reasonably addressed with available marine seismic data.

Specifically, we will examine the nature of the Moho at the base of the oceanic crust produced at mid-ocean ridges and hence this contribution does not include consideration of Moho in regions such as large oceanic plateaus like the Ontong–Java or Manihiki Plateaus formed by unusually massive volcanism (Taylor, 2006, for instance), and it does not include analysis of oceanic island chains like the Hawaiian Islands or Marquesas that are created by hot-spot processes. The ridge environments we study are those present in major ocean basins and not back-arc basins.

We will discuss what evidence there is for differing characteristics of Moho formed at ridges producing crust across a range of spreading rates and the nature of changes that can be observed in association with ridge segmentation such as fracture zones, overlapping spreading centers and smaller discontinuities. We will also comment on changes with respect to crustal age. The primary data type we will examine is multi-channel seismic (MCS) reflection images and so we are commenting on the nature of the so-called “reflection Moho”. We use evidence from seismic refraction studies in a supportive way where those data are coincident with reflection data. Methods for acquiring these types of data are well known and are described for instance in Sheriff and Geldart (1995), Jones (1999) or Mutter (1986).

To our knowledge no seismic study in the oceans has aimed specifically at investigating the oceanic Moho. Many have focused on the formation of oceanic crust in the near ridge-crest region and considerable attention has been given to the role of magma systems and especially the axial magma chamber (AMC) in processes of oceanic crustal formation. These studies typically provide images of Moho but the geographic distribution of observations is often very tightly focused around the ridge axis and so encompass crustal ages to at most a few million years. Images of Moho from studies of older regions of oceanic crust produced at both slow and fast-spreading centers are also available and these will be discussed as well. Our review does not include observations from surveys conducted at subduction zones. Very distinct vertical-incidence Moho reflection images exist from settings such as at the Middle America Trench (Hinz et al., 1992; Ranero et al., 2003), the Sunda margin (Lüschen et al., 2011; Singh et al., 2008, 2011) or the Alaska–Aleutian trench (Shillington et al., 2011). Also clear wide-angle oceanic Moho reflections are typically recorded by such surveys, which along with crustal and mantle refracted phases are used to derive crustal velocity structure at the trench, allowing to study hydration of the incoming plate (e.g. Ivandic et al., 2008). A more comprehensive study of oceanic Moho, beyond the scope of this contribution, should include analysis of these observations.

The distribution of observations of oceanic Moho, even including subduction zone settings is sparse and irregular. An ideal set of experiments designed specifically to examine the nature of the oceanic Moho would have a far different distribution of observations from what is presently available for study. The available set of observations was made over a period of several decades. Comparison of observations from early to more recent data (some of which reoccupy the same sites) is made difficult because during this period there has been considerable evolution in seismic airgun sources from simple so-called unturned arrays to large tuned arrays. Similarly hydrophone arrays have advanced from relatively short (2.4 km) analogue streamers to the present arrays that record many more channels (>400) at finer spacing over much greater offsets (>6 km) and in digital format. Seismic reflection and refraction observations form largely independent data sets with relatively few coincident observations. These uneven characteristics of the available data substantially limit our ability to draw generalizable conclusions on the nature of the Moho boundary and prompts us to restrict the questions posed to the two described above.

2. Early observations at the East Pacific Rise

The first multi-channel seismic reflection images of Moho at the base of oceanic crust that we are aware of were obtained in June 1976 on the East Pacific Rise (EPR) between 9°N and 10°N by Herron et al. (1978, 1980) and described further by Stoffa et al. (1980). These observations have been cited numerous times in the literature and formed the essential basis for several studies that followed in the 1980s and 1990s.

The Moho, often designated the M discontinuity in papers from that period (as in Fig. 1b) was observed as a distinct high-amplitude event in reflection response throughout and was also readily observed very close to the axis of the ridge where a magma chamber reflection could also be observed (R4 in Fig. 1b) in the upper crust. Herron et al. (1980) made most emphasis of this latter observation and suggested that Moho was “formed immediately under the magma chamber, at about 6 km below the seafloor, presumably by gravity settling of crystals from the melt”. At the time these first images were made it was widely believed from studies of ophiolites and from seismic refraction studies (Herron et al., 1980 reference Cann, 1974; Orcutt et al., 1975, 1976) that the magma chamber beneath the ridge was very large, extending several kilometers away from the ridge crest. The observation of Moho in reflection images very close to the ridge axis therefore suggested that Moho was fully formed within the large magma chamber itself. R4 was thought to represent the very top of the magma body whose sides were not visible in the images perhaps because they were either too steep or that its boundary with the solid crust was gradational, the latter being the preferred explanation.

Designation of the M reflection as the boundary between crust and upper mantle, as is necessary to consider the event to be Moho was based on fairly tenuous associations with the velocity structure of the crust as it was known at the time. Stoffa et al. (1980) describe the result from one sonobuoy refraction station (C116 20) that shows post-critical wide-angle events that give two-way time to a layer with 8.0 km/s velocity that coincides closely with the M event on line 25 (their Fig. 4). A number of other sonobuoy experiments were made that show mantle arrivals at around the same two-way time as a typical M reflection but none are at the locations coincident with observed M reflections. Orcutt et al. (1975, 1976) had reported the presence of a broad low velocity zone (LVZ) beneath the EPR at this location and their observations also derive Moho depths that are roughly similar to those implied by the observations from reflection events. Compilations of refraction data from oceanic crustal settings such as that of Rosendahl et al. (1976) clearly implied that the oceanic crust was expected to be around 6 km thick and the observed M event matched that depth to a good approximation.

The acquisition system used to obtain these images comprised a 24-channel analogue streamer (digitization occurred on board the vessel in the recording system) with a maximum offset of about 2.4 km (100 meter groups). Processing employed relatively simple approaches using software developed at the Lamont–Doherty Earth Observatory and the images shown were derived from 24-fold common midpoint (CMP) stacks. Stoffa et al. (1980) show pre-stack migrated gathers in which the M event is very clearly visible at zero source-receiver offset but the streamer length was insufficient to