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Seismic wide-angle constraints on crustal thickness and structure at Ocean Drilling Program Site 1256: How typical are its features for oceanic crust?

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ABSTRACT

Ocean Drilling Program Site 1256 was drilled in the Guatemala Basin, eastern Pacific Ocean, sampling superfast-spreading crust. It is one of the deepest drill holes sampling intact oceanic crust and the only site that has penetrated gabbroic rocks away from a tectonic window. Two gabbroic units were sampled at 1157 m and 1283 m below the basement. We collected seismic refraction and wide-angle reflection data across the drill site, and the resulting tomography models show that the first encountered gabbro does not mark the top of the seismic boundary between the upper (layer 2) and the lower (layer 3) crust, which we observe 500–600 m deeper. We propose that the drilled gabbroic rocks may represent either shallow intrusions or depth variations of the magma lens, marking the upper limit of a layer 2–layer 3 transition zone. Seismic tomography and wide-angle migration of mantle reflections reveal rather thin crust of 5 ± 0.2 km (i.e., ~1.5 s two-way traveltime), being 1 km thinner than normal oceanic crust. The crustal deficit occurs solely within the lower crust. The observed thin crust distinctly differs from typical fast-spreading crust and may indicate the occurrence of a depleted mantle source. Yet, our preferred interpretation is that at superfast spreading rates of >200 mm/yr, the melt transport through the mantle is too slow to provide enough melts to form 6 km of oceanic crust.

OCEANIC CRUST AND OCEAN DRILLING PROGRAM SITE 1256

The oceanic crust underlying Earth's ocean basins is the largest geological formation on our planet, showing a large degree of variability as a function of plate age and geographical location. Its structure and hence the observed variability are primarily derived from the interpretation of seismic refraction experiments (e.g., Grevemeyer et al., 2018; Christeson et al., 2019) defining an upper crust (layer 2) and a lower crust (layer 3) of basaltic and gabbroic composition, respectively. Our geological understanding of its crustal architecture is still based mainly on ophiolites as an analog for the oceanic crust because their lithological sequences (basaltic lavas, sheeted dikes, gabbros, and ultramafics) are similar to those sampled in ocean basins (e.g., Moores and Vine, 1971). Over the last decades, ocean drilling became a major factor in understanding processes governing the nature of the oceanic crust by drilling deep into the upper crust (e.g., Alt et al., 1996) and sampling the lower crust and upper mantle in tectonic windows (e.g., Dick et al., 2000; Lissenberg et al., 2024). Yet, the only in situ section drilled through the upper crust into gabbroic rocks was at Ocean Drilling Program (ODP) Site 1256 in the Guatemala Basin to the west of Central America (Wilson et al., 2006).

This site was chosen for drilling because the seafloor was formed at an interval of superfast spreading rate of ~220 mm/yr full rate (Wilson, 1996). Sampling the fastest possible spreading rate was desirable to test the prediction that the melt lens occurring at the crests of fast-spreading mid-ocean ridges gets shallower at higher spreading rates (Purdy et al., 1992). The upper-to-lower crustal transition is a consequence stemming from the rate of magma supply from below and hydrothermal cooling by seawater from above (Morgan and Chen, 1993), and melt lenses are suggested to control the formation of the lower oceanic crust (Henstock et al., 1993; Morgan and Chen, 1993). As a consequence, it is expected that the basaltic upper crust gets thinner and the lower crust gets thicker as spreading rate increases (Christeson et al., 2019), and hence lower crust at superfast spreading rates would be reachable at shallower depth than elsewhere. Site 1256 found the expected shallow first occurrence of gabbro at 1157 m (Wilson et al., 2006), while it occurs deeper elsewhere in crust formed at lower spreading rates (e.g., Carbotte et al., 2021).

Drilling Site 1256 and sampling gabbros in situ took the ODP and the Integrated Ocean Drilling Program (IODP) three campaigns, spending nearly five months at sea, resulting in a big success. However, pre-site survey data failed to place drilling results into the context of total melt generation because seismic data did not provide a reliable estimate of crust thickness of the 15-m.y.-old crust (Hallenborg et al., 2003). Today, superfast-spreading crust is produced at the southern East Pacific Rise at ~150 mm/yr, and its thickness averages 5.7 km at 16°S–17°S (Canales et al., 1998) and 6.1 km at 14°S (Grevemeyer et al., 1998). These estimates match the globally observed average crustal thickness of ~6 km (e.g., Christeson et al., 2019), suggesting that crust of mid-ocean-ridge basalt (MORB)–like composition is the result of decompression melting of a mantle source composed of dry

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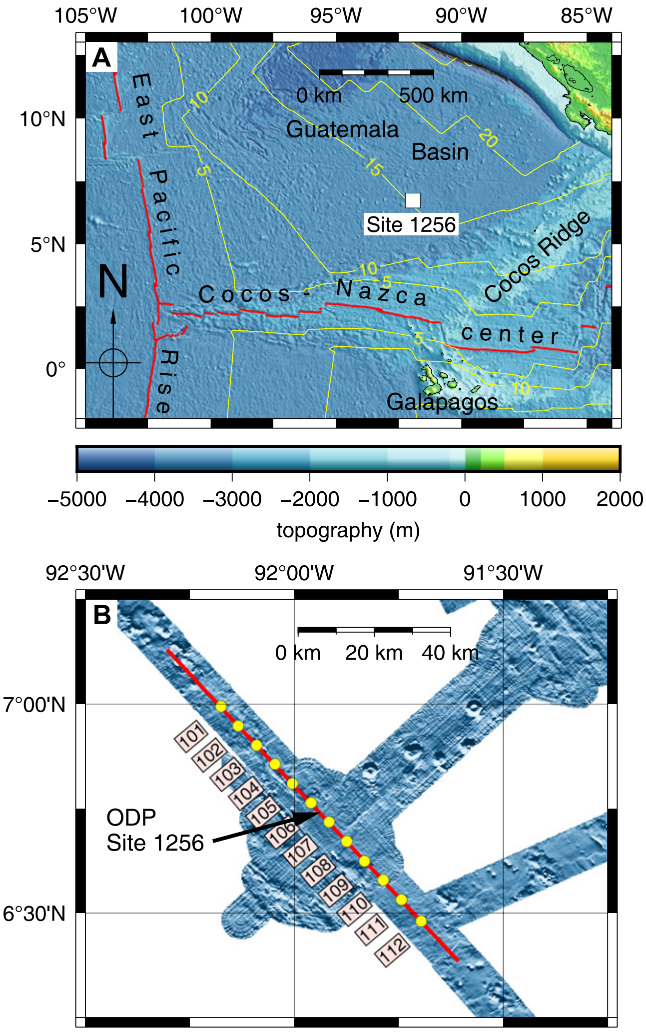

Figure 1. (A) Regional bathymetric map outlining tectonic setting of Ocean Drilling Program (ODP) Site 1256. Yellow lines give seafloor age in millions of years (Müller et al. 2019). Bathymetry is predicted from satellite altimetry (Tozer et al. 2019). White box shows location of study area in B. (B) Seismic survey across Site 1256 (red line). Numbered boxes mark positions of ocean-bottom seismometers. Bathymetry is from shipboard measurements.

pyrolite with a mantle temperature of ~1300 °C (McKenzie and Bickle, 1988). However, crust formed at the East Pacific Rise >22–12 m.y. ago, occurring today in the Guatemala Basin, may have resulted from a mantle source that had experienced melt extraction in the vicinity of the Galápagos hotspot before it melted farther beneath the ridge crest of the East Pacific Rise (Geldmacher et al., 2013). Such a depleted mantle may generate rather thin crust and could explain thin fast-spreading crust measured 500 km to the east of Site 1256, ranging in thickness from only 4.8 km to 5.5 km (e.g., Ivandic et al., 2008; Grevemeyer et al., 2007). If Site 1256 were to show a similar pattern, it may deviate profoundly from average fast-spreading crust.

We present constraints from seismic refraction and wide-angle reflection data collected in 2022 in a joint German-UK survey aboard RRS *James Cook*, providing shots recorded on ocean-bottom seismometers (OBSs) along a seismic profile running parallel to the strike of the paleo–East Pacific Rise and crossing Site 1256 (Fig. 1). We constrain velocity structure and crustal thickness from both seismic traveltime tomography and migration of wide-angle reflections turning at the crust-mantle boundary (PmP phase).

SEISMIC CRUSTAL STRUCTURE

Along profile JC228-p100, 12 OBSs spaced at 7 km received shots from a tuned airgun array of 5000 in^3 fired at 60 s interval (~150 m spacing) at a pressure of 150 bar, recording seismic wide-angle reflection and refraction P- and S-wave data of excellent quality (see the Supplemental Material[1]). Traveltimes were inverted using TOMO2D software (Korenaga et al., 2000) to yield a high-resolution image of the crustal structure and crustal thickness. Our preferred model is the average from a Monte Carlo inversion of 100 starting models (Fig. 2; Supplemental Material).

Below 250 m of sediment, seismic P-wave velocity (Vp) increases rapidly from 4.3 km/s to 6.1 km/s at 1.2 km below basement, the depth predicted from drilling to mark the top of the gabbroic layer 3 (Fig. 3A). The occurrence of a continuous gabbroic body was inferred after Site 1256 drilled two gabbroic units with 52 m and 24 m thickness at 1157 m and 1283 m below basement, respectively (Wilson et al., 2006; France et al., 2009). Although thin features like the drilled gabbros cannot be imaged in seismic wide-angle data, the bulk seismic velocity structure itself is indicative of the dominant crustal lithology. Based on our seismic data, a continuous gabbroic formation can only be inferred 500 m below the drilled sills at 1.7 ± 0.2 km, where a Vp of 6.7 km/s is reached, approximating the top of the lower crust (e.g., Detrick et al., 1994). Using the transition from a high-gradient upper crust to lower-gradient lower crust as an alternative definition of the layer 2–layer 3 transition, it occurs at a similar depth of 1.8 ± 0.3 km below basement and hence a few hundreds of meters deeper than the gabbroic rocks sampled by drilling. Starting models introducing a shallow layer 2–layer 3 transition at the depth where the gabbros were sampled cause a worse misfit for crustal arrivals, while models issuing a layer 3 near 1.6 km below basement, as found elsewhere in superfast-spreading crust (Christeson et al., 2019), perform best. However, the seismic wide-angle data provide a rather smooth representation of the subseafloor structure and average the structure laterally over several kilometers and vertically over several hundred meters, providing a certain degree of ambiguity in the vicinity of the layer 2–layer 3 boundary (Fig. 2B), while drilling represents a single point measurement.

In the lower crust, the average Vp is on the order of 6.9 km/s and hence at the lower limit of Vp found in the lower oceanic crust formed at fast and intermediate spreading rates (Grevemeyer et al., 2018). The thickness of the lower crust averages 3.0–3.4 km along the profile (Fig. 2A). Total crustal thickness is 5 ± 0.2 km (Fig. 3B) and hence rather thin considering that the average oceanic crust is ~6 km thick (Christeson et al., 2019). The S-wave velocity (Vs) structure supports the stratification and thickness of the crust and crustal layers, yielding a Vp/Vs ratio of 1.7–1.86 for crustal rocks (Figs. S5 and S6 in the Supplemental Material). The uppermost mantle shows a Vp of 7.8 km/s and Vs of 4.5 km/s both sampling the slow direction of an anisotropic mantle.

To provide additional constraints on the crustal structure, we use seismic mirror imaging of the OBS data (Grion et al., 2007) to yield the sedimentary structure and basement morphology. In addition, to constrain the crustal thickness, we use the sparsely spaced OBSs and time migrate Moho wide-angle reflections (Supplemental Material) in a procedure similar to the approach introduced by Shiraishi et al. (2022).

[1]Supplemental Material. Information about the processing and figures. Please visit https://doi.org/10.1130/GEOL.S.31120216 to access the supplemental material; contact editing@geosociety.org with any questions.

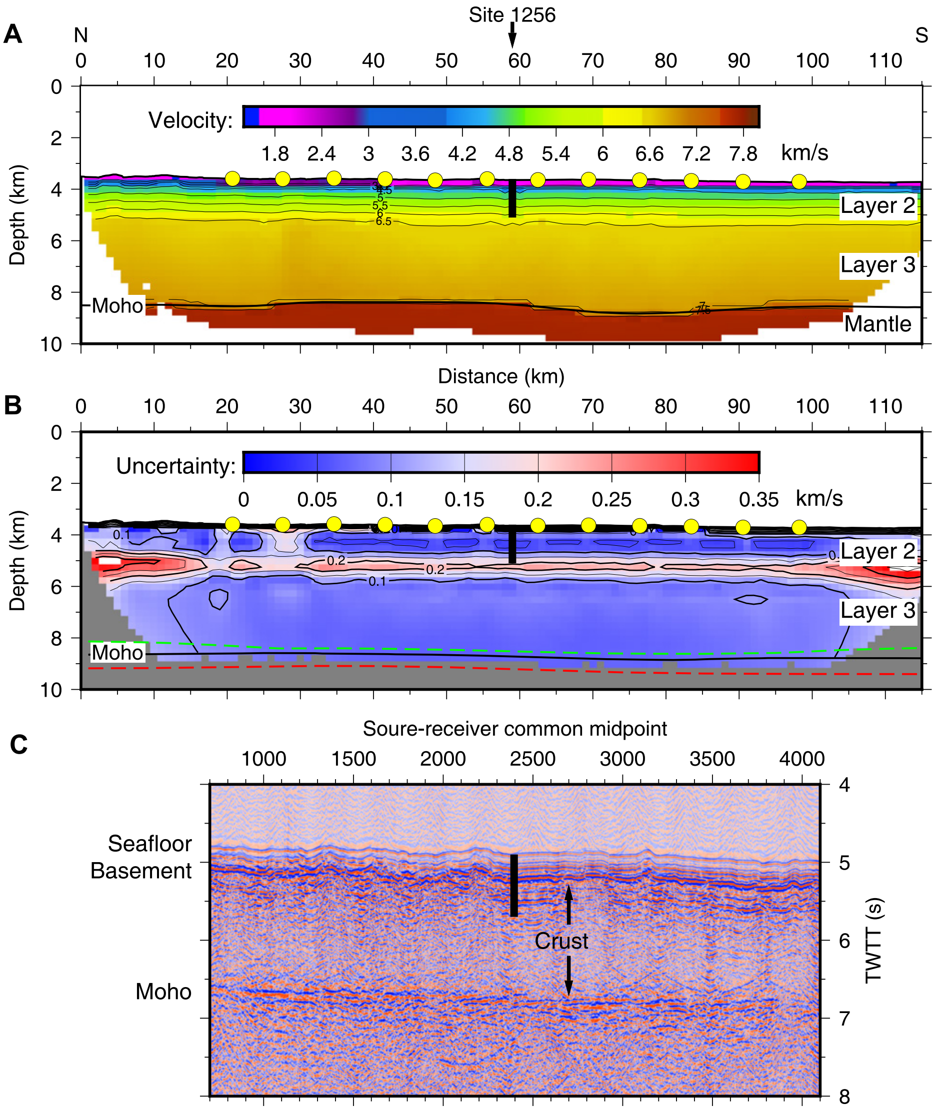

Figure 2. Seismic results. (A) P-wave velocity model; thick black line marks seismic Moho. (B) P-wave velocity model uncertainty. (C) Crustal structure constraint from mirror imaging and migration of wide-angle reflections of ocean-bottom seismometer (OBS) data; distance scale is as in A and B. TWTT—two-way time. Penetration of Ocean Drilling Program Site 1256 is shown by bold black line; yellow dots are OBS sites.

In the vicinity of Site 1256, multichannel seismic reflection imaging failed to show clearly the crust-mantle boundary (Hallenborg et al., 2003), but some lines in the vicinity of the drill site revealed reflections interpreted as seismic Moho at ~1.5 s two-way traveltime (TWTT) and hence ~5 km below basement. Our wide-angle imaging supports a seismic reflection Moho at 1.4–1.6 s TWTT (Fig. 2C) and hence corroborates observations from the traveltime tomography, arguing for a rather thin oceanic crust showing only minor changes in crustal thickness along the profile.

DISCUSSION

For decades, the nature of the layer 2–layer 3 transition zone has been debated (e.g., Detrick et al., 1994). Based on the stratigraphy of ophiolites (e.g., Moores and Vine, 1971) and observations at tectonic windows into the oceanic crust (e.g., Hayman and Karson, 2007, 2009; Karson et al. 2023), it is generally considered that the boundary between the upper and lower crust is characterized by a change in lithology, where the upper crust is formed by basaltic lavas and dikes while the lower crust is composed of gabbroic rocks. Geological fieldwork on the ocean floor in these tectonic windows suggests that this lithological transition occurs at ~1.6 km below basement in fast-spreading crust (Hayman and Karson, 2007) and at 1.2–1.4 km in superfast-spreading crust (Hayman and Karson, 2009; Karson et al., 2023). A global compilation of seismic data for fast- and superfast-spreading crust reveals a layer 2 thickness of 1.86 km and 1.56 km, respectively (Christeson et al., 2019). Thus, it might be reasonable to suggest that modern seismic measurements overestimate upper crust thickness with respect to geological observations by a few hundred meters, perhaps indicating a transition zone rather than a sharp lithological boundary. In contrast, inferences drawn from ODP Site 504B drilled into 5.9-m.y.-

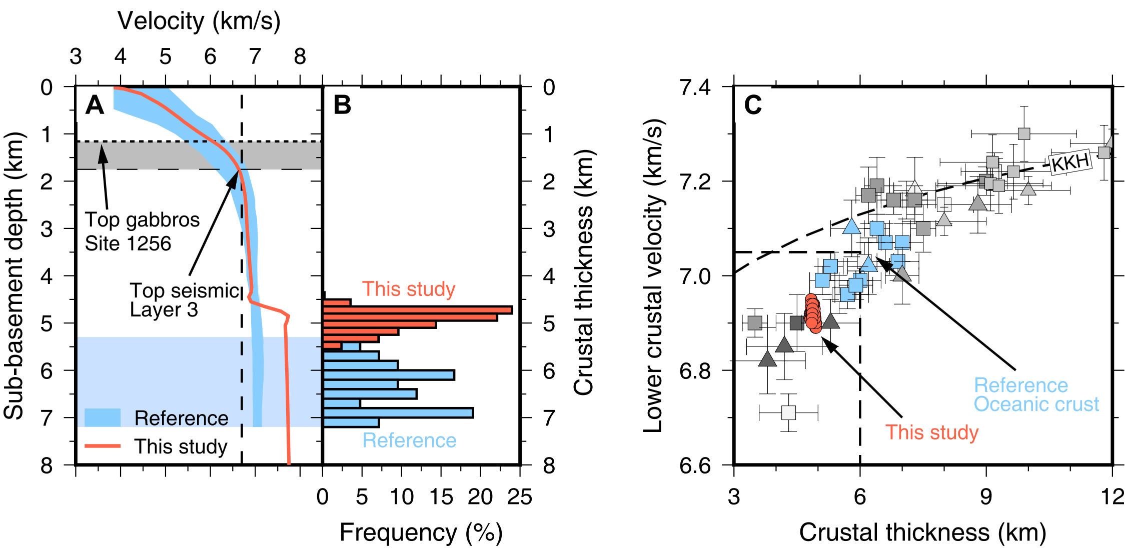

Figure 3. Crustal properties at Ocean Drilling Program Site 1256 (red) compared to normal oceanic crust (blue). (A) Seismic velocity versus depth. (B) Crustal thickness from Monte Carlo inversion. (C) Lower crustal velocity versus crustal thickness; error bars reflect the variability found in the measurements (gray symbols and reference crust: compilation of Grevemeyer et al., 2018). KKH—prediction of the model from Korenaga et al. (2002).

old crust formed at the Cocos-Nazca spreading center showed that the seismically defined layer 2–layer 3 transition occurred within the sheeted dikes and hence would not mark a lithological boundary (Detrick et al., 1994).

A transition zone of basalt that is frequently cut by gabbroic sills above the layer 2–layer 3 lithological boundary could be explained by spatial variations of the depth to the magma lens reflector (e.g., Hooft et al., 1997), suggesting that the sill depth varies as a function of magma supply and hydrothermal activity and hence time. In this scenario, the drilled gabbroic units may occur near the top of the transition zone. Alternatively, a transient intrusion of shallower gabbroic lenses, which are found in the Oman ophiolite (France et al., 2021) and were recently imaged in high-resolution seismic reflection volume at the East Pacific Rise at 9°50′N (Marjanović et al., 2023), may indeed generate a transition zone of mixed basaltic and gabbroic composition rather than a sharp lithological boundary. From our data alone, it is not possible to discriminate between fluctuating and constant shallower sill emplacement, but based on our well-constrained velocities, we argue that the two gabbroic intrusions drilled at Site 1256 during IODP Leg 312 (Teagle et al., 2006; Wilson et al., 2006) must be embedded in the transition zone above a homogeneous gabbroic lower crust because the seismic layer 2–layer 3 transition occurs roughly 500 m deeper than inferred from the first encounter of gabbro and hence well below the drilled gabbro (Fig. 3A).

It is always difficult to relate constraints from seismic techniques, averaging features over large areas, to the precise but local constraints from a single drill site. The most distinct feature found in the crustal structure occurs below the depth sampled by drilling and is expressed in the thickness of the lower crust. Christeson et al. (2019) found that the lower crust is globally on the order of 4.3 km thick, reaching 4.6 km in superfast-spreading crust, yielding a ratio between the thickness of the lower to upper crust of $\sim$3, which decreases with decreasing spreading rate to $\sim$2.2 at slow-spreading ridges. Instead, our study supports a seismically defined lower crust that is 3.4 ± 0.2 km thick and shows a ratio of lower to upper crustal thickness of just 2.0 ± 0.1. Because the total thickness of the oceanic crust is dominated by the lower crust, the thin lower crust corresponds to a rather thin igneous crust with a thickness of 4.8–5 km, revealing a crust that is >1 km thinner than the average oceanic crust flooring the ocean basins (Christeson et al., 2019). Consequently, the seismic structure supports unusual melting conditions. The relationship between lower oceanic crustal Vp and crustal thickness is commonly used to assess melting conditions (e.g., Korenaga et al., 2002). When compared to global patterns, the thin crust found at Site 1256 reveals significant differences (Fig. 3C) and hence may indicate a mantle source deviating from a pyrolytic source melting at a normal mantle temperature, generating 6 km of crust.

Thin oceanic crust was also found in the Wharton Basin of the Indian Ocean, where crust with a thickness of 3.5–4.5 km was formed 55 m.y. ago. Singh et al. (2011) proposed that the presence of a depleted mantle affected the emplacement of that crust. Based on numerical simulations, they discussed a scenario in which a curtain of cold downwelling of depleted mantle material developed at the edges of the Kerguelen hotspot, which was later entrained into the spreading center. A similar setting can be envisioned for the crust in the Guatemala Basin, where rocks sampled at Site 1256 reveal a paradox of isotopic enrichment but incompatible-element depletion of Early Miocene–aged East Pacific Rise lavas (Geldmacher et al., 2013). To explain the geochemical characteristics, Geldmacher et al. (2013) proposed a scenario where depleted plume material from the Galápagos hotspot affected crustal formation at the East Pacific Rise. However, melt transport beneath mid-ocean ridges is still a matter of debate (e.g., Rabinowicz and Toplis, 2009). Hence, an alternative scenario might be related to sluggish magma transport at superfast spreading rates, happening in the form of dunite channels (Lissenberg et al., 2024), where a network of melt-transporting channels extract and transport melts from the mantle to the crust (Kelemen et al., 1995). In the crust, melts mix within a magma chamber to form the oceanic crust. Little is known about the time scale of the melt transport through the mantle, but one interpretation of the generation of thin crust might be that this process is not keeping pace at superfast spreading.

Independent of the processes governing crustal formation in the Guatemala Basin 15 m.y. ago, we conclude that the oceanic crust drilled at Site 1256 is rather thin, deviating in its structure distinctly from normal fast-spreading crust, showing a low degree of melt generation that was controlled by either anomalous mantle properties or poorly understood melt extraction at superfast spreading rates of $\sim$220 mm/yr.

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