Re-energising the quest of drilling to the mantle

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Standfirst:

Drilling a complete section into the uppermost mantle of intact ocean crust formed at a fast spreading mid-ocean ridge would liberate fundamental knowledge into Earth processes. The activities and achievement will also inspire the future generations of geoscientists, who are essential to adapt to climate change and deliver the energy transition.

Main text

Scientific ocean drilling is one of the most successful enduring international collaborations and is responsible for delivering fundamental observations and key samples essential for major advances in Earth sciences. Insights from drilling projects include critical evidence for plate tectonics, the breakup of continents, the development of detailed biostratigraphic timescales and paleoclimate records [1], the mechanisms and consequences of the Chicxulub impact that extinguished the dinosaurs [2], and explorations of the frontiers of subseafloor life [3].

However, the seascape for ocean drilling research is turbulent. On 6th March 2023, it was announced that the flagship research vessel JOIDES Resolution, the globally roaming mainstay of scientific ocean drilling, will be retired in 2024. The 21-nation research alliance International Ocean Discovery Program (IODP) that co-ordinates global sea floor expeditions also comes to an end next year. These changes are of concern, especially for early career researchers for whom the formative experience of an ocean drilling expedition is often a key stepping-stone in many Earth science careers. Now more than ever, it is important to remember the critical advances ocean drilling has, and will, enable in the future. In this Comment, I highlight the necessity of continuing to explore the deep to uncover fundamental knowledge of Earth processes and inspire the next generation of Earth scientists.

Project MoHole Ocean crust covers 60% of Earth's surface and is formed and consumed by the dynamic processes of seafloor spreading and subduction. Decompression melting of the upper mantle at mid-ocean spreading ridges produces new ocean crust with remarkably uniform thickness (~6.5 ±1 km), compared to the thicker, older and highly variable crust of the continents (≥30 km). However, despite more than 50 years of ocean drilling, many of the details about the formation of ocean crust at mid-ocean ridges remain debated, including mantle melting and the movement, crystallisation and cooling of magmas. Even for ocean crust formed at fast spreading ocean ridges (Figure 1), the simplest tectonic setting on Earth, the geological nature of the seismologic Mohorovičić Discontinuity (or Moho, for short) and the transition from crust to mantle remains unknown. This uncertainty is principally due to a lack of in situ sampling of a complete section of intact ocean crust down into the upper mantle.

The concept of a MoHole, specifically drilling down through a complete unrifted section of ocean crust through the Moho and into the upper mantle, was first proposed in the 1950s, with the first attempts at scientific ocean drilling in 1962 (see [4]). Project MoHole managed to drill only a few metres into ocean floor basalts, but this first expedition to below the ocean floor highlighted the utility of drilling sediments and the crust beneath to better understand Earth processes. The penetration of ocean crust to the mantle has remained a core pillar of ocean drilling science plans ever since, through the various guises of international collaboration (Deep Sea Drilling Project 1968-1983; Ocean Drilling Program 1985-2005; Integrated Ocean Drilling Program 2006-2013; International Ocean Discovery Program 2014-2024).

However, to date, only two holes drilled into intact ocean crust have penetrated through the uppermost lavas and into the layer of sheeted dikes below (Holes 504B and 1256D at depths of 1,841 and 1,293 m sub-basement respectively). Only Hole 1256D in the eastern equatorial Pacific intersected the transition zone between dikes and lower crustal gabbros [5]. There are no samples from in situ cumulate gabbros, the cooling and crystallisation of which forms >70% of the ocean crust and powers hydrothermal systems that form black smoker sulphide deposits. No expedition has been able to reach the Moho, the seismologic boundary between the crust and mantle, and relate this transition to geological processes. Consequently, there are no pristine samples of the upper mantle that until recently (geologically, at least) was undergoing mantle convection.

In the new future 2050 Framework for Scientific Ocean Drilling [6], numerous of the Strategic Objectives and Flagship initiatives require deep coring and in situ observations. Yet – progress in the past decade of ocean drilling has been slow, and to date only one deep hole has been drilled into ocean crust in the latest phase of operations (Hole U1473A drilled to ~790 m below seafloor on at Atlantis Bank on the Southwest Indian Ridge).

Current challenges

Rejuvenation of the full crustal drilling concept came about in the 2000s through the development of the Mission MoHole and MoHole to Mantle proposals. However, community enthusiasm for the deep waned due to global financial and consequent funding crises, increased operational costs, and the slow implementation of essential geophysical site survey experiments. Since 2007 the JAMSTEC drilling vessel *Chikyu* has been available to the scientific drilling community. This large riser drillship was built with the specific vision of drilling to the mantle, and if endowed with operational funding and scientific resolve, might be able to drill into deep environments (>>2 km) and sample rocks in situ that hitherto have not been accessible. Our community's inability to utilise *Chikyu* to its potential has been the biggest hinderance to deep drilling. As a result, we have failed to take even the first incremental steps on the Road to the MoHole, such as developing essential skills in the installation of long lengths of protective casing into basalt-hosted holes or in ultra-deep water riser operations.

Some advances have been made by shallow drilling in the Hess Deep rift just off the East Pacific Rise [7], a tectonic window into disrupted lower ocean crust. This operation sampled primitive, modally layered gabbros, some with strong fabrics, that were the first samples of lower plutonic levels of fast-spread ocean crust. The upcoming IODP Expedition 399 will return to young gabbroic rocks exposed at the Mid-Atlantic Ridge, by deepening Hole U1309D to more than 2000 m. The young, hot rocks (< 2 million years old, >200°C) to be encountered during this project will be at temperatures above the known limits of microbial life and provide evidence (or not) for the abiotic formation of hydrogen, methane and other organic molecules that are essential building blocks for life [8].

There are also mature proposals to drill a deep 'pilot' hole into 80 million year-old crust on the north Arch of Hawaii (see [4]). Although this is not a perfect site for a MoHole due to the influence of magmatism from the Hawaiian Plume, the technical learning from drilling a >2 km hard rock hole with *Chikyu* would be invaluable and provide only the third in situ sampling of sheeted dikes. In late 2022, an Anglo-German geophysical cruise aboard the RRS *James Cook* collected seismic data for a potential MoHole site on the Cocos Plate in the eastern equatorial Pacific off the coast of Costa Rica (see [4]). This site has a simpler tectonic setting compared to Hawaiian options and targets crust that formed at the fast-spreading East Pacific Rise. Being relatively young ocean crust, at ~27 million years-old, temperatures in the upper mantle at the Cocos site would be much hotter (>200°C) than the proposed Hawaii site and would require specialist engineering.

Inspiration for the future

The mantle is just one of many pressing science goals requiring ultra-deep drilling. Better understanding of the rifting that leads to continental break up and the formation of new oceans requires deep drilling to ground truth seismic observations, identify and date key strata, rock types, and tectonic features to test contrasting mechanisms of extension. Most of *Chikyu*'s operations to date have investigated tsunamigenic regions above the Nankai-subduction zone [9], but arcs, large igneous provinces, and extended sedimentary records of monsoons and mountain uplift would all benefit from deep boreholes. All deep holes are major experiments for Earth sciences and will attract attention and excitement. However, in my experience at least, few targets have the inspirational history of Project MoHole and generate the exploratory zeal of drilling to the mantle.

At a time when society most needs geoscientists to respond to growing impacts of the climate crisis, the recruitment into geology, geophysics and other geoscience undergraduate programmes is declining in many parts of the world, including the US, UK and Australia [10]. Exciting and societally interesting explorations into the unknown, such as Earth's mantle, are imperative to inspire and recruit the next generation of geoscientists, who will be essential to tackle many of the major societal challenges confronting global society.

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Competing interests

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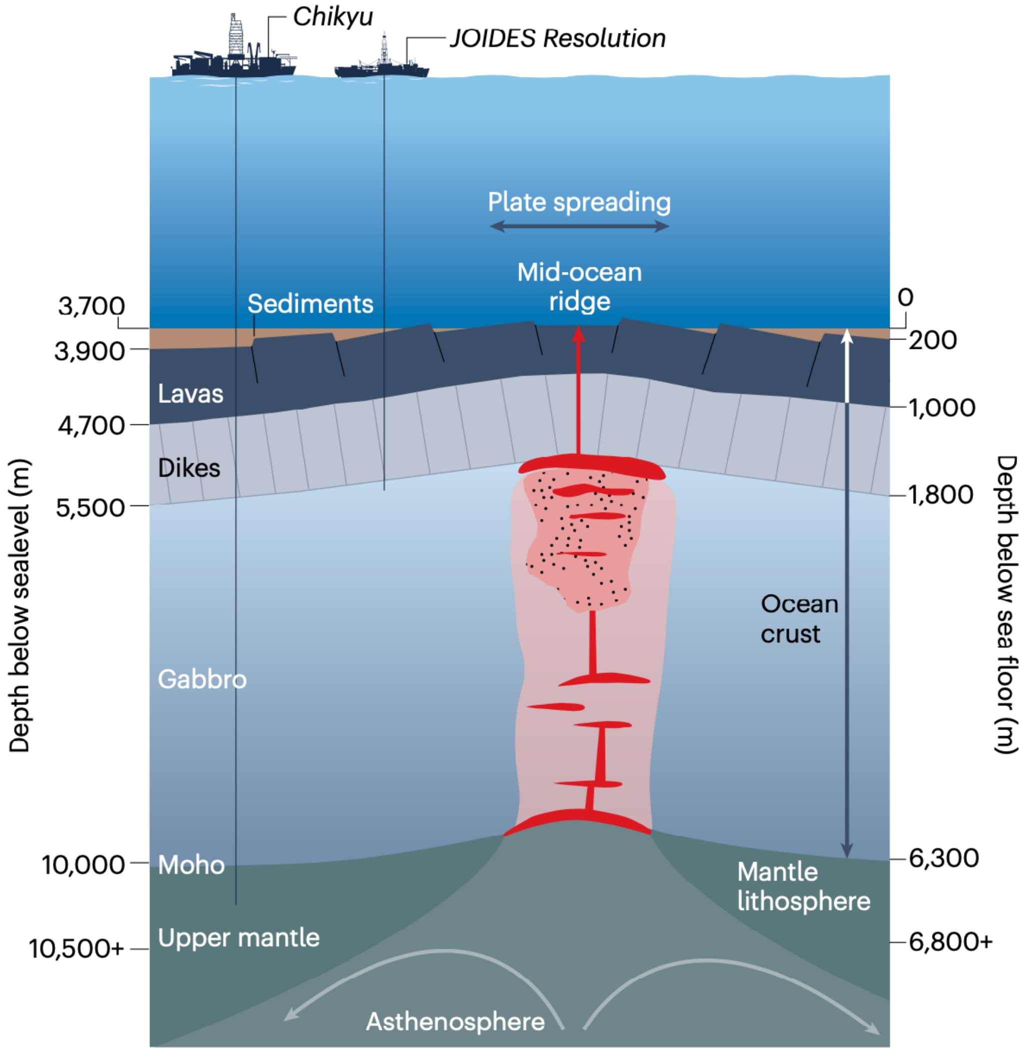

Figure 1. Drilling to the mantle in ocean crust formed at a fast-spreading mid-ocean ridge. Schematic diagram showing the approximate depths below sealevel required to reach Earth's mantle. Crust formed at a fast-spreading mid-ocean ridge is considered the best MoHole target as it comprises a relatively simple layer-cake of lavas, sheeted dikes and gabbros overlying mantle peridotites. Note, the distribution of melts in the lower crust remains debated.