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This 1961 effort to drill right through Earth's crust didn't succeed. Half a century on, geologists are ready to try again.

Journey to the mantle of the Earth

On the 50th anniversary of the first attempt to drill into Earth's mantle, **Damon Teagle** and **Benoît Ildefonse** say that what was once science fiction is now possible.

Retrieving a sample of Earth's mantle has been an overarching ambition of the geoscience community for more than a century. In 1909, the Croatian meteorologist Andrija Mohorovičić noticed that seismic waves travelling below about 30 kilometres underground move faster than those above that depth, indicating a fundamental change in the composition and physical properties of the rocks. He had discovered the upper boundary of Earth's mantle, now known as the Mohorovičić discontinuity, or 'Moho' for short. This boundary marks the start of the bulk of Earth's interior, which extends from the base of Earth's crust — at 30–60 kilometres under the continents but just 6 kilometres under the thinner crust of the oceans — to the core 2,890 kilometres below.

Drilling down and retrieving samples directly from the mantle would provide scientists with a treasure trove comparable to the Apollo lunar rocks, giving insight into the origins and evolution of our planet. But this has proved as difficult, perhaps more difficult, than going to the Moon. So far, no one has drilled deeper than about 2 kilometres into the ocean crust, or a third of the way to the mantle. The first effort to drill into the mantle, 'Project Mohole', foundered in a geopolitical quagmire and did not achieve its goal.

A new Mohole campaign is now under way, thanks to improved technology,

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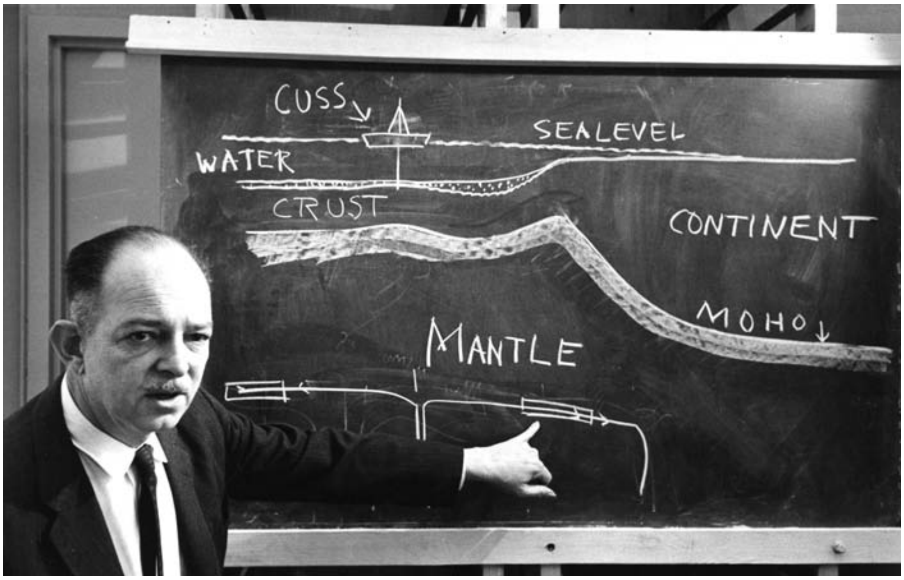


Harry Hess, a founding father of the theory of plate tectonics, explains Project Mohole.

▸ a better understanding of the rocks far below our feet and a deeper appreciation of the challenges of drilling through them. Over the next few years, geophysical surveys will be conducted at three Pacific Ocean locations that are in contention to be the site of the first deep hole to the mantle (see 'Drilling sites'). Drilling down to the mantle will require a huge amount of ship time and will be very expensive — far more expensive than a current single drilling expedition, although far cheaper than a Moonshot. But if funding can be found, and the scientific commitment maintained, drilling could begin within the decade, and be completed within 15 years. In the meantime, next month, we will be leading an expedition to the Pacific to bore further into the oceanic crust than ever before.

INSPIRED IDEA

The first serious plans to drill down to the mantle were concocted in the late 1950s by a handful of post-war American geoscience grandees under the guise of the American Miscellaneous Society — an informal group of US National Academy of Science members, sometimes referred to as a 'drinking club'. The idea came primarily from Harry Hess, one of the founding fathers of the theory of plate tectonics, and Walter Munk, who pioneered studies of how winds drive ocean currents and explained why one side of the Moon is locked towards Earth. Frustrated by what they saw as a stream of worthy yet pedestrian research proposals in their field, they sought to undertake something more ambitious and innovative.

At a wine breakfast at Munk's home in La Jolla, California, on a Saturday morning in April 1957, they came up with Project Mohole, a scheme to drill, for the first time, right through Earth's crust and into the upper mantle.

Back then the nascent offshore petroleum industry had not yet begun to contemplate deep-water drilling. The Mohole project required the development of new technologies such as dynamic positioning, which would allow a drill ship to keep its position steady. The group obtained funding from the US National Science Foundation and commissioned the best ship available for the job: the drilling barge *CUSS 1*, named after the oil companies that had developed it, Continental, Union, Shell and Superior. Within four years of the project's proposal, propellers had been installed on the side of *CUSS 1* and a system developed that allowed these to keep the ship in position.

Between March and April 1961 scientists took their first core from the uppermost hard rock of the oceanic crust, or 'basement', off Guadalupe Island in the eastern Pacific Ocean, thanks to the daring and innovative engineering efforts of Willard Bascom and his colleagues. From beneath 3,800 metres of water and 170 metres of sediment, they pulled up a few metres of basalt, at a cost of US$1.5 million (about $40 million in 2009 dollars, in terms of its share of the total US economy). This remarkable accomplishment was reported in *Life* magazine (14 April 1961) by the novelist and amateur oceanographer John Steinbeck, who was aboard *CUSS 1* during these first operations.

This was the only ocean core that Project Mohole succeeded in drilling. After the expedition, the management of the project changed, some poor decisions were made about which drilling technologies to pursue, and costs spiralled out of control. In 1966, Project Mohole collapsed when the US Congress voted to cancel its funding.

Nevertheless, the project coincided with a growing acceptance of plate-tectonics theory. Interest in the formation and evolution of the oceanic crust was booming. Project Mohole proved that scientific drilling into the ocean basement was possible. This contributed to the establishment, and continuance over four decades and running, of international collaboration in scientific ocean drilling. The Integrated Ocean Drilling Program (IODP; www.iodp.org) and its predecessors, the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP), form arguably the most successful, long-term international scientific collaboration in any field.

THE DEEP FRONTIER

The mantle holds some 68% of the planet by mass. Its sheer volume makes an accurate knowledge of its composition and variability essential for understanding how Earth was formed and has evolved. Almost all of Earth's surface crust — the material that makes up the sea floor and the continents — originally came from the mantle.

Some pieces of the mantle have been thrust up to Earth's surface during tectonic mountain building, where they are available for study. Other mantle pieces, encased in lava, have been ejected from volcanoes, and sea-floor spreading has brought some to the ocean floor. These pieces show that the mantle is composed mainly of rocks called peridotites, made of magnesium-rich, silicon-poor minerals such as olivine and pyroxene. They also suggest, together with far-field seismic measurements, that the mantle's composition varies from place to place, but the extent of this variation remains unclear. The available samples have all been chemically altered by the processes that brought them to the surface or by exposure to sea water. Concentrations of many of the key elements and isotopic tracers (including water, uranium, thorium, lithium, carbon, sulphur, silicon, potassium, the noble gases and the iron oxidation state) that might be useful in reconstructing Earth's evolution are highly labile. A few kilograms of fresh peridotite from beneath the crust would provide a wealth of new information.

"Drilling to the mantle is the most challenging endeavour in the history of Earth science."

Getting to the mantle requires drilling through a full section of oceanic crust, which will also be a boon for geologists. The formation of crust is the foundation of the plate-tectonic cycle. It is the main mechanism by which heat and material is dredged up from the interior of Earth, resurfacing some 60% of our planet every 200 million years. Currently, the thermal, chemical, and perhaps biological, exchanges occurring deep in the oceanic crust remain poorly understood because of the lack of direct observations *in situ*.

The technology to drill a hole a few inches wide through 6 kilometres of crust now exists or is feasible to develop[1,2]. A promising candidate technology is on the Japanese drilling ship *Chikyu*, launched in 2002. The vessel has a riser system: an outer pipe surrounds the drill string — the steel pipe through which cores are recovered. The drilling mud and cuttings are returned up to the vessel in the space between the two pipes. This helps to recycle the drilling mud, control its physical properties and the pressure within the drill hole and helps to stabilize the borehole walls. It also means that cuttings can be evaluated for scientific purposes. *Chikyu* is a giant ship, capable of carrying 10 kilometres of drilling pipes, and is equipped for riser drilling in 2.5 kilometres of water.

Over the next decade, researchers and engineers will have to design and develop new drill bits, lubricants and wireline instruments to make coring into the mantle possible, at pressures as high as 2 kilobars and temperatures up to 300 °C, and beneath about 4 kilometres of water. In particular, this will require a riser system capable of going deeper than *Chikyu*'s current equipment, or a different mud-circulation system, with part of the equipment installed on the sea floor.

To find the best site for the new Project Mohole, a large number of factors need to be considered. Ideally, it would be in the shallowest possible water overlying oceanic crust, which means going as close as possible to the mid-ocean ridge where new crust is formed. It should also be in the coldest possible crust, which is away from the ridge. These constraints limit the possible sites to three — off the coasts of Hawaii, Baja California and Costa Rica, respectively. All have pros and cons. The site near Hawaii, for example, is the coolest, but also the deepest, and close to recent volcanic activity that might have chemically altered the mantle and perturbed the overlying crust. All the sites are in the Pacific Ocean because the crust there is formed faster than in other oceans, which makes for the simplest, most uniform basement architecture. Seismic and geological studies hint that fast-spreading ocean crust should be relatively uniform and conform most closely to textbook models. We hope to find material that conforms to these models of a simple crust: a layer cake of rock types called lavas, dikes and gabbros.

Meanwhile, the ocean-drilling community continues to core as deeply into the crust as is feasible using the conventional, non-riser technology available on the drilling vessel *JOIDES Resolution* — the recently rebuilt workhorse of the IODP.

THE LOWER CRUST

Fifty years after John Steinbeck sailed on *CUSS 1* with the pioneers of ocean-crust drilling, we are the co-chief scientists on an expedition to obtain for the first time a section of the lower oceanic crust — the material lying just above the mantle. IODP Expedition 335 is due to sail from 13 April until 3 June[3].

The site chosen for this mission is on the Cocos plate off the coast of Costa Rica (ODP site 1256). This site is in ocean crust that formed superfast — at more than 20 centimetres a year, much faster than any present-day crust formation. That makes the upper crust there much thinner than elsewhere, so it is possible to reach the lower portions without having to drill very deep. Three previous expeditions to Hole 1256D have drilled down to more than 1.5 kilometres below the sea floor, into the transition zone between dikes and gabbros[4,5].

This spring we plan to deepen the hole at least another 400 metres, and recover for the first time gabbros from the lower crust, which will be the deepest types of rock ever extracted from beneath the sea floor. (The hole itself is not the deepest ever drilled into the sea floor; that was Hole 504B, which reached 2,111 metres below the bottom of the eastern Pacific off Colombia.)

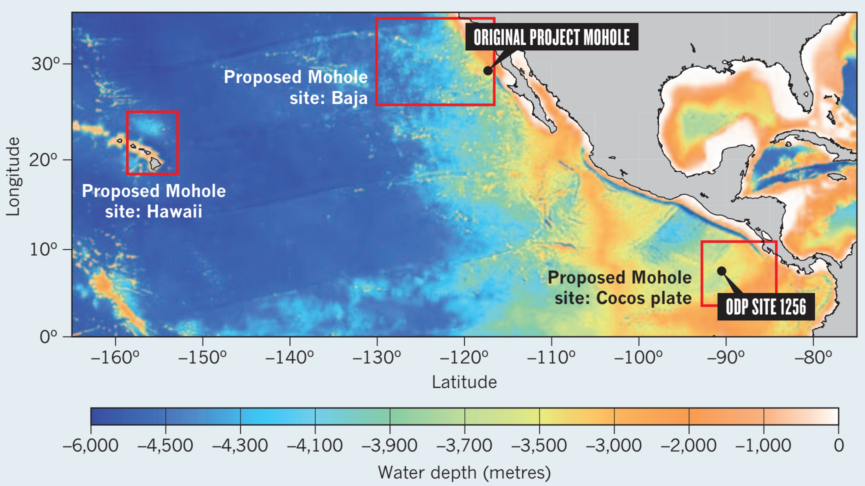
The mission should help to settle many debates: how crust is formed at mid-ocean ridges; how magma from the mantle is intruded into the lower crust; the geometry and vigour of how sea water can pull heat from the lower oceanic crust; and the contribution of the lower crust to marine magnetic anomalies. We will still be 3.5 kilometres shy of the Moho, but the project will provide further impetus for, and confidence in, deep ocean crust drilling, as well as crucial information for planning a full penetration through the Moho and into the upper mantle.

Drilling to the mantle is the most challenging endeavour in the history of Earth science. It will provide a legacy of fundamental scientific knowledge, and inspiration and training for the next generation of geoscientists, engineers and technologists. There is a surprising level of interest from the world's media and engagement by the general public in this frontier endeavour. And it may be only the beginning of a bigger project. As the crust and the mantle are both likely to be different from place to place, we will ultimately want a number of such holes. That may seem a distant dream, but ultra-deep drilling will only get more routine and cheaper with time and experience.

As Harry Hess told a US National Academy of Science meeting in April 1958, when defending the first Mohole Project against detractors: "Perhaps it is true that we won't find out as much about the Earth's interior from one hole as we hope. To those who raise that objection I say, if there is not a first hole, there cannot be a second or a tenth or a hundredth hole. We must make a beginning." ■

DRILLING SITES

Three areas are under consideration for drilling into the mantle. One includes the original Project Mohole drilling site. Another includes a site (ODP site 1256) where scientists will drill this year into the lower crust.



SOURCE: REF. 1

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Further reading accompanies this article online at go.nature.com/b2ehus.