GEODYNAMICS

Christmas recycling

The mechanisms for forming the abundant volcanic islands on ocean floors are debated. The geochemical signature of volcanic rocks from the northeast Indian Ocean suggests that seamounts there formed from melting recycled ancient continental rocks.

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The ocean floor is covered with tens of thousands of seamounts and flat-topped table mountains that are the eroded remnants of once-active volcanoes. At many seamount provinces, the cause of the volcanism is unclear. Possible mechanisms for driving eruptions on the seafloor include drifting of the rigid oceanic plate over a thermal anomaly in the underlying mantle and melting of the mantle as it rises beneath an actively spreading mid-ocean ridge, or melt seeping out from a crack that propagates through the plate. Writing in *Nature Geoscience*, Hoernle and co-workers[1] use measurements of the age and isotopic signature of lava samples taken from the Christmas Island Seamount Province in the northeast Indian Ocean to show that some of these seamounts were formed by the recycling of ancient continental material that was probably stripped from the base of the Australian continent.

The Christmas Island Seamount Province (CHRISP) is a little-known volcanic region that includes Christmas Island (Fig. 1). It covers a huge area of approximately 1,000,000 km^2. At first sight, the elongate nature of the volcanic province suggests that the islands might have formed as the Indian Ocean plate gradually drifted over a stationary thermal anomaly in the underlying mantle, such as a hot mantle plume. However, the elongate array of islands is also very broad, much wider than those typically observed to form above a mantle plume. Furthermore, there is no evidence of a vast outpouring of lava in the form of a large igneous province — a typical signature of the onset of plume activity — associated with CHRISP. Volcanism stemming from cracks in the ocean plate also seems unlikely. Existing fractures and faults in the northeast Indian Ocean floor have a north–south orientation, whereas CHRISP is elongated in an east–west direction.

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Figure 1 | Lavas on Christmas Island, north-east Indian Ocean. Hoernle *et al.*[1] suggest that some seamounts and ocean islands in the Christmas Island Seamount Province formed from the melting and recycling of ancient continental material stored in the upper mantle. The continental remnants could have been stripped off the base of Australia during the continental breakup that started 150 million years ago.

Hoernle *et al.*[1] carry out high-precision ^{40}Ar/^{39}Ar age determinations, together with Sr-, Nd-, Pb- and Hf-isotopic analyses of lava samples collected from CHRISP in an attempt to unravel its origin. The age data show that the seamounts formed over a long time interval, from about 140 to 40 million years ago. The seamounts are youngest in the west and older towards the east, as would be expected if the Indian Ocean plate had drifted over a stationary mantle plume. However, the data also reveal that many of the seamounts are similar in age to the oceanic crust on which they sit, and most likely formed at a mid-ocean ridge contemporaneously with the generation of new oceanic crust. They then moved gradually eastwards as the oceanic crust spread away from the ridge. Formation at a mid-ocean ridge, however, cannot account for all of the ocean islands and seamounts. The youngest in the province, including Christmas Island, are more than 25 million years older than the underlying oceanic plate and must have formed away from the mid-ocean ridge in an intra-plate setting. Formation of the entire CHRISP therefore requires a mechanism that can generate volcanic activity both at a mid-ocean ridge and in an intra-plate setting.

Many CHRISP lavas exhibit isotopic ratios that are typical of mid-ocean-ridge basalt, but some also show enriched isotopic signatures. In particular, some of the seamount basalts have elevated ^{207}Pb/^{204}Pb ratios. This enriched signature is thought to result from the recycling of ancient continental lithosphere or deeply subducted oceanic lithosphere and sediments in the mantle. This isotopic signature has been observed in the basaltic rocks that erupt to form seamounts and ocean islands, such as those at the Walvis Ridge in the South Atlantic and on Pitcairn Island in the South Pacific Ocean[2]. Although at these locations the enriched component is thought to have undergone melting in an upwelling mantle plume, there is no definitive surface expression of a thermal anomaly beneath CHRISP.

To explain these apparently contradictory observations, Hoernle *et al.*[1] argue that the islands formed from the melting of ancient continental lithosphere, possibly derived from the base of the Australian plate, which has been recycled in the shallow upper mantle. Plate tectonic reconstructions show that 150 million years ago, CHRISP was located at the point of separation of west Burma from Australia and Greater India. During continental breakup, enriched continental material from the base of the Australian lithosphere could have detached and remained in the upper mantle as the new Indian Ocean basin formed above. The continental material would be more readily fusible than the surrounding mantle, melting preferentially as the mantle upwelled beneath the nascent spreading centre. It could thus have been recycled into the CHRISP seamounts that formed at the mid-ocean ridge.

The presence of a recycled continental signature in the much younger, 4 million-year-old Christmas Island basalts (Fig. 1), which did not form at the mid-ocean ridge, suggests that delaminated ancient continental material may still be present beneath this part of the northeast Indian Ocean. The continental remnants may have melted to source lava flows on Christmas Island. Hoernle *et al.*[1] suggest that shallow recycling of ancient continental material can therefore explain the formation of the entire CHRISP without the need for a deep mantle plume.

There are some inconsistencies in the proposed model, however. Given that volcanism on Christmas Island formed in an intra-plate setting, far away from mantle that is passively upwelling and melting beneath the mid-ocean ridge, it is unclear what drove the continental remnants to melt there. Some of the volcanism occurred above 100-million-year-old lithosphere, which would be almost 100 km thick[3]. The enriched lower continental lithosphere is only likely to melt at these depths if it is incorporated into hot upwelling mantle, as has been suggested for the Tristan plume beneath the south Atlantic Ocean[4,5]. Detailed numerical modelling of combined element and isotopic data, together with an assessment of melt volumes, is therefore required to constrain the precise conditions of mantle melting beneath large seamount provinces such as CHRISP.

Shallow recycling of ancient, delaminated continental material could have helped form seamounts in ocean basins across the globe. This mechanism is probably more prevalent in ocean basins that have formed from recent continental breakup, such as the Atlantic and Indian Oceans. Here, the supply of enriched continental material is likely to be more abundant compared with older ocean basins, such as the Pacific, where the supply of continental remnants may have long been exhausted. Where readily fusible continental material has been recycled by mantle melting and has erupted at the surface, a measureable residue similar to those recently found at the Gakkel Ridge in the Arctic Ocean[6] may be left behind. This refractory material may therefore provide another means for tracing continental recycling in other ocean basins.

Hoernle *et al.*[1] suggest that some volcanic seamounts in the northeast Indian Ocean formed from the shallow recycling and preferential melting of delaminated continental material beneath a mid-ocean ridge. This mechanism could explain the origin of some of CHRISP. Other volcanic islands in oceans underlain by young thin lithosphere may have formed in a similar way. ❐

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EARLY EARTH

Snowballs limited by weathering

A series of extreme cooling episodes, starting 750 million years ago, could have repeatedly turned the planet into an ice-covered snowball. Carbon cycle modelling suggests that the timing of the glaciations can be explained by chemical weathering rates.

A. Joshua West

Ice invaded the tropical latitudes during the Neoproterozoic series of glaciations that occurred between approximately 750 and 550 million years ago[1]. The Snowball Earth theory argues that ice was so extensive during this time that the planet was entirely frozen, reflecting an outstandingly dramatic shift in Earth's climate. Transitions into and out of snowball glaciations may have been governed by changes in the concentration of atmospheric carbon dioxide: once glaciation was triggered, extensive ice cover allowed atmospheric CO_2 to build up until the planet warmed enough to melt the ice. Once the ice retreated, the excess CO_2 would have been consumed by chemical weathering, eventually pushing levels low enough for ice sheets to regrow. Curiously, the durations of ice-free gaps between proposed snowball glaciations are orders of magnitude longer than expected for typical rates of CO_2 drawdown by weathering. Writing in *Nature Geoscience*, Mills *et al.*[2] suggest that the aftermath of the Neoproterozoic glaciations effectively overwhelmed the planet's ability to soak up CO_2 from the atmosphere through chemical weathering, delaying the return to the $p\mathrm{CO}_2$ concentrations required for glacial inception.

Chemical weathering of silicate rocks releases dissolved cations and removes CO_2 from the atmosphere by driving the sequestration of carbon in carbonate minerals. Rates of weathering are generally climate dependent: warm and wet conditions lead to faster weathering, along with rapid removal of atmospheric CO_2. Conversely,