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Investigating La Réunion Hot Spot From Crust to Core

Whether volcanic intraplate hot spots are underlain by deep mantle plumes continues to be debated 40 years after the hypothesis was proposed by *Morgan* [1972]. Arrivals of buoyant plume heads may have been among the most disruptive agents in Earth's history, initiating continental breakup, altering global climate, and triggering mass extinctions. Further, with the temporary shutdown of European air traffic in 2010 caused by the eruption of Eyjafjallajökull, a geologically routine eruption in the tail end of the presumed Iceland plume, the world witnessed an intrusion of hot spot activity into modern-day life.

The larger interest in intraplate hot spots stems from the suspicion that their volcanism is fueled by mantle plumes, which are deep-seated, columnar upwellings of hot rock, possibly originating from the core-mantle boundary. Depending on their numbers and typical heat fluxes, mantle plumes could be major factors in Earth's heat budget, providing direct cooling to the core. Seismology could settle the controversy regarding their existence and significance by imaging plume conduits—or lack thereof—in situ, but the most promising hot spots are located well into the oceans, and large-scale instrumentation of the seafloor has been coming into reach only recently.

In an effort to learn more about plume origins and dynamics through seismology, scientists from France and Germany are focusing on the Indian Ocean's La Réunion Island. Its close proximity to major landmasses (Madagascar and mainland Africa) allows for excellent seismic illumination, reducing the need for expensive ocean bottom sensors to record earthquakes around the globe. The Réunion Hotspot and Upper Mantle–Réunions Unterer Mantel (RHUM-RUM) project aims to seismologically image the crust and mantle under the island at all depths. Through what is thus far the most expansive attempt to work out the deep plumbing of hot spots, RHUM-RUM scientists may be able to clarify the feeding mechanism for hot spot volcanism, estimate ascending material and heat fluxes, and document interaction with the overlying African plate and with neighboring mid-ocean ridges.

RHUM-RUM: The Biggest Seismological Plume Hunt So Far

La Réunion Island in the western Indian Ocean (Figure 1) is among the most active volcanoes in the world and a very strong candidate for a hot spot underlain by a deep, “classical” mantle plume [e.g., *Courtillot et al.*, 2003]. Its location has been the site of geochemically characteristic intraplate

volcanism for 65 million years, and its 5500-kilometer-long, time-progressive volcanic track leads northward to the Deccan Traps of India, one of the most voluminous flood basalt provinces on Earth and the presumed manifestation of plume head arrival. The hot spot sits atop one of two “superswells” in the lowermost mantle, the suspected origin regions for most deep plumes.

RHUM-RUM relies on island and ocean bottom seismometers deployed on and around La Réunion to piece together finely scaled plume structures directly below the hot spot. Existing land instrumentation on Africa and Madagascar extends the effective array aperture to several thousand kilometers. The wide view gained by stations far afield is needed to image into the lowermost mantle and sets RHUM-RUM apart from previous oceanic plume imaging efforts [*Barruol et al.*, 2002; *Suetsugu et al.*, 2009; *Wolfe et al.*, 2009].

To illuminate the mantle structures under the island down to about a 1000-kilometer depth, RHUM-RUM researchers deployed 57

broadband ocean bottom seismometers over an area of 1500 × 2000 square kilometers on a monthlong cruise in October 2012 (Figure 1). Scheduled to record for 13 months, this ocean bottom component is supplemented by 20 existing and 10 new stations on La Réunion Island as well as 27 RHUM-RUM stations on Mauritius, Rodrigues, the southern Seychelles, Madagascar, and the Iles Eparses in the Mozambique Channel. In total, around 120 broadband seismometers are currently operating in the western Indian Ocean until the end of 2013, making RHUM-RUM the largest attempt to image an oceanic mantle plume so far.

RHUM-RUM's German-French collaboration taps into complementary scientific expertise, technical means (for example, providing land and ocean bottom seismometers and local support), and logistics (the French and German research ships *Marion Dufresne* and *Meteor*, respectively). The project is led by Institut de Physique du Globe de Paris and the University of Munich, collaborating with the Alfred Wegener Institut Bremerhaven; Mauritius Oceanography Institute; and the universities of Antananarivo, Bonn, Brest, Frankfurt, La Réunion, Montpellier, Münster, Nice, Orsay and Strasbourg. Serendipitously,

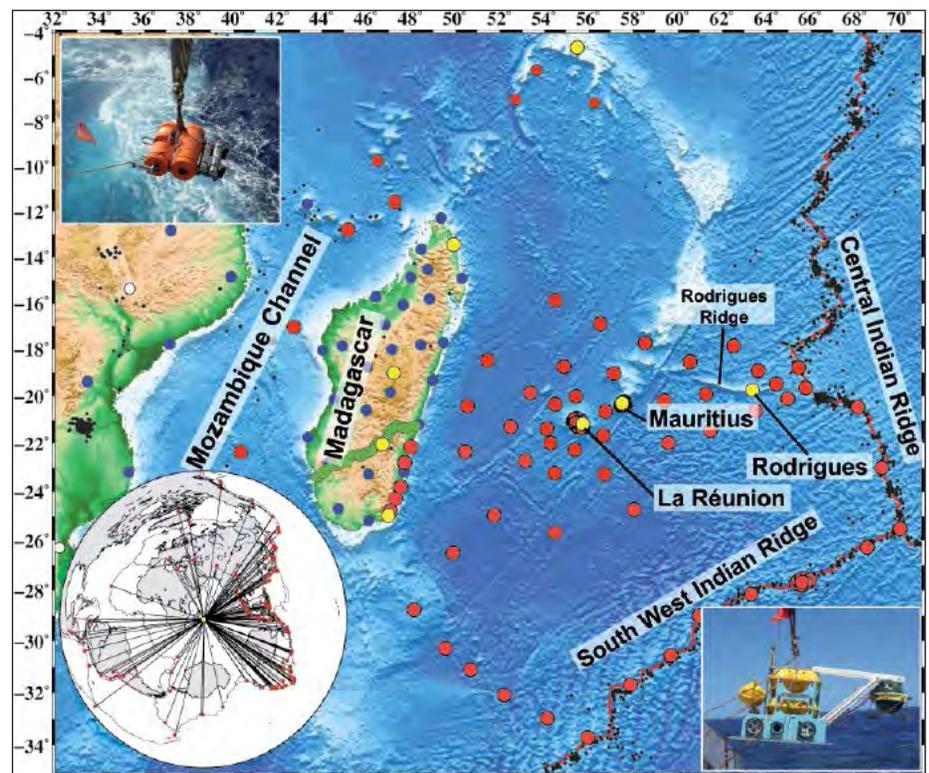


Fig. 1. Seismological broadband stations in the southwestern Indian Ocean. Red circles indicate ocean bottom and land seismometers deployed in 2012 by the Réunion Hotspot and Upper Mantle–Réunions Unterer Mantel project. Yellow circles indicate permanent stations run by the Incorporated Research Institutions for Seismology, Geoscope, Geofon, and the Observatoire Volcanologique du Piton de la Fournaise. Blue circles indicate the Madagascar Comores Mozambique Array, deployed by Washington University in St. Louis, Mo. Green circles indicate the Madagascar Seismic Profile, deployed by GeoForschungsZentrum Potsdam, Germany. White circles indicate AfricaArray stations. Black dots indicate regional seismicity (1990–2010, body wave magnitude $M_b > 4.0$). Bottom left inset shows the teleseismic earthquake distribution for 1 year (2009, $M_b > 6.0$, distances 30° to 160°), and the top left and bottom right insets show two types of broadband ocean bottom seismometers that were deployed (German model and French model, respectively).

two other seismological experiments—the Madagascar-Comores-Mozambique Array, led by Washington University in St. Louis, Mo., and the Madagascar Profile, run by GeoForschungsZentrum Potsdam, Germany—are deploying 50 more broadband stations in Madagascar in 2011–2014 (Figure 1). Sharing these data and data from recent initiatives such as AfricaArray (<http://www.africaarray.psu.edu>) should significantly improve resolution of the lower mantle under La Réunion. RHUM-RUM data will become freely available 3 years after the end of the experiment.

Scientific Targets

Deep plume stems are challenging imaging targets because their presumed diameters are only on the order of 100 kilometers, i.e., close to the wavelengths of the seismic body waves that are available for sampling the plume. Much of the controversy surrounding the existence and locations of plumes concerns true depth extent: Are plume stems not yet detectable, or are they not present? Are these conduits continuous, tilted, pulsating, or ponding? Claimed detections in the lower mantle [Montelli *et al.*, 2004; Wolfe *et al.*, 2009] have met with skepticism because artifacts due to sparse sampling and steep wave incidence might feign plume conduits.

The RHUM-RUM project strongly emphasizes developing imaging methods that address these challenges. Cutting-edge wave-form tomography methods, which account for scattering of wave energy around narrow conduits, will be adapted to data from the seafloor and islands. Hemispheric-scale inversions will include all available regional data, including very deep diving waves that are diffracted along the core-mantle boundary. In addition, project researchers will investigate the transition zone between the upper and lower mantle for anomalous topography of mantle discontinuities, which can indicate temperature perturbations induced by a plume originating from the lower mantle.

When rising plume flow approaches the surface, it may erode the overlying lithosphere, pond in the asthenosphere, and/or

spread away from the hot spot. Researchers will investigate these scenarios by combining numerical and analog modeling with observables such as surface wave and body wave tomography as well as the study of seismic anisotropy through shear wave splitting.

La Réunion served as an early illustration of the hypothesis that hot spots interact with their nearest mid-ocean ridges [Morgan, 1978]. In this hypothesis, heat rising from a plume may be diffused most efficiently by channelized flow to spreading ridges, which serve to remove heat from mantle convection cells. Flow channels might explain an array of anomalous surface observations on spreading ridge segments adjacent to La Réunion hot spot (for example, the very recent volcanism on Rodrigues Island, the protruding shape and smooth morphology of the Central Indian Ridge segment between 17°S and 21°S (Figure 1), and the geochemical signature of rocks dredged along this ridge segment [e.g., Dymant *et al.*, 2007]), but the hypothesis awaits seismological confirmation because it requires instrumenting the seafloor between the hot spot and ridge. To this end, the RHUM-RUM network extends eastward and covers Rodrigues Ridge (Figure 1), a linear bathymetric high that supposedly represents the surface expression of leaky flow in the asthenosphere since 30 million years ago, from La Réunion hot spot to the Central Indian Ridge. The most recent volcanism on Rodrigues Island dates to only 1.5 million years ago, so the channel should still be operating and will hopefully become the first to be clearly imaged.

A Forthcoming Rich Data Set

By seismologically imaging the entire mantle column under La Réunion hot spot, RHUM-RUM should exemplarily provide answers to hotly debated questions surrounding oceanic hot spots, including their origin and geometries at depth and how they can remain active and stationary for more than 100 million years. Early results are expected in 2015. More information about RHUM-RUM can be found at <http://www.rhum-rum.net>.

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