KILAUEA CALDERA ON MAY 10 2009: HALEMA'UMA'U CRATER IS APPROXIMATELY 100 M DEEP

Taking up the **mantle**

Dr Dominique Weis explains the foundations of her research into the geochemistry of the Earth's mantle, via mantle plumes, which probe the deep, hidden interior of the planet

Firstly, can you outline the context from which your research has emerged?

The mantle represents about 84 per cent of the Earth's volume, with the core representing around 15 per cent and the crust just 1 per cent. The mantle only rarely reaches the surface and as a result, it is mostly un-sampled, except for basalts or xenoliths (solid pieces of the mantle). In fact, there have been numerous attempts to directly sample and analyse the mantle, but they have been mostly unsuccessful. This leaves room for exciting work to be done, uncovering the composition of the largest part of the Earth.

Your latest investigation focuses on the intraplate volcanism of the Hawaiian Islands. Can you explain why you study mantle plumes?

Mantle plumes are hotter than the surrounding material and rise from deep in the mantle, all the way from the core-mantle boundary in some cases, a movement of around 2,890 km. When the plume head begins to melt near the surface, at a depth of about 100 km, it forms a large igneous province or oceanic plateau comprising huge volumes of magma. Oceanic islands are another manifestation of mantle plumes; the study of their composition tells us much about the Earth's mantle. Mantle plumes are probes of the deep mantle, and this is why I study them.

You have observed significant geochemical differences between volcanoes of Kea and Loa trends. Can you explain what is meant by this?

The first geographically-derived evidence for the existence of two chains of volcanoes dates back to Dana in 1849, then Jackson in 1972. It was later shown that these two chains also show distinct lead isotopic differences, but without an explanation for the source of these differences. The disparities were puzzling, especially considering that the two chains of volcanoes are separated by only about 50 km, while the sampling zone of the plume is roughly 100 km. Temperature, upwelling rate and more general physical parameters of the plume are concentrically zoned, so a lateral compositional and isotopic difference between the two sides did not make sense.

With a significant database of high-precision analyses of around 600 samples of shield lavas, we have been able to show that there are also differences in other isotopic systems, including strontium, neodymium and hafnium. We have also made a connection with the presence of an anomalous zone (low seismic velocities) at the core-mantle boundary to account for the different signature of Mauna Loa, the largest volcano on Earth.

Why do late-stage volcanoes allow for a different understanding of the isotopic systematics of the Earth's mantle?

On Hawaii, the evolution of a volcano presents a typical cycle, usually over 1-1.5 million years, with: a pre-shield stage with alkalic compositions (Loihi seamount); a shield stage with tholeiitic compositions that represent over 95 per cent of the volume of the volcano (Mauna Loa and Kilauea are in this stage now) when the volcano grows above sea-level, and; a post-shield stage with a return to alkalic compositions. Sometimes, there is a resurgence of volcanism long after the volcano has moved away from the centre of the hotspot, and this stage is also alkalic.

Post-shield and rejuvenated volcanism corresponds to significantly lower degrees of partial melting in the mantle than shield volcanism and because of that, they are more

susceptible to sample small heterogeneities in the mantle source. This is due to the fact that heterogeneities have a tendency to concentrate in the small fraction of melt, below 1 per cent, while a larger melt fraction of around 10 per cent means that they are more diluted.

What wider geochemical applications does this research have in the understanding of Earth's reservoirs and the environment?

Geochemistry is at the interface of many Earth and environmental science disciplines. It provides the tools to trace sources ('fingerprinting'), quantify processes, establish natural levels, quantify anthropogenic contributions and constrain the nature and timing of processes that control the past, present and future evolution of Earth and its environments. For example, geochemical principles, tools and techniques can be applied to studies ranging from the extent, rate and impact of global climate change to environmental pollution tracing and mitigation/remediation, mineral and hydrocarbon resource exploration and exploitation, and timescales of repeating natural hazards such as earthquakes and volcanic eruptions.

Island investigations

A team at the **University of British Columbia** is using the unique geochemistry of the Hawaiian archipelago to conduct pioneering research into the dynamics of the Earth's mantle that results in island formation

THE GEOCHEMICAL AND geophysical processes that occur within the Earth's mantle remain hidden and difficult to investigate. A team at the University of British Columbia is using Hawaii as a focus for their study and is beginning to uncover these problematic mechanisms. Their focus is on mantle plumes, which are formed in response to cooling of the Earth's core, and then rise up as solid material through the mantle. Melting in the plume heads forces huge volumes of lava to the surface over a short period of time while their tails create chains of volcanoes that can stretch for thousands of kilometres. Hawaii is the product of such a plume, a 6,000 km island chain formed over ~80 million years. Volcanoes within the Hawaiian archipelago occur in two parallel chains that are both geographically and geochemically distinct. Named after the largest volcanoes in each chain, the Loa and Kea trends demonstrate directionally asymmetric composition in the plume conduit, which provides a challenge to established views about concentrically zoned models of mantle plumes in Hawaii and elsewhere, and how material from the deep mantle is brought to the surface. Consequently, the work being done by the team is changing perspectives about the nature of the Hawaiian plume, and is beginning to influence global understanding of mantle dynamics.

Using precise geochemical techniques, the team analyses isotopic compositions of ocean island basalts in order to uncover some of the hidden intricacies of mantle dynamics. In fact, the 1,000 km wide bathymetric swell that surrounds Hawaii is associated with the presence of a sub-lithospheric hot, buoyant mantle plume, which extends well into the lower mantle and possibly as far as the boundary between the mantle and the core itself, at a depth of 2,890 km.

OVERCOMING GEOPHYSICAL BOUNDARIES

The team is confronted by a number of challenges in accurately documenting plume depth, particularly as seismic waves lose resolution at such depths in the mantle. By documenting clear compositional differences between the Loa and Kea chains, the research group is able to begin elucidating the structure of the mantle plume that feeds the volcanoes and how it relates to the dynamics of the deep mantle. The investigation has dealt with a subject as large as Mauna Loa, the largest active volcano on Earth, with a volume of around 80,000 km^3. The researchers have carefully analysed 120 samples taken from a range of locations, including a mile-high submarine landslide section, that allows for continuous stratigraphic collection across a range of ages, as well as sub-aerial prehistoric and historic lavas. The distinct nature of these basalts has resulted in the group's conclusions about the deep mantle, proposing previously unknown sources for the compositional differences within the Hawaiian mantle plume.

The investigators in British Columbia, fronted by Dr Dominique Weis, endeavour to continue their groundbreaking analysis to further probe the intricacies of the Hawaiian system. When projected into the deep mantle, the Hawaiian mantle plume straddles an area known by geophysicists as the Pacific large low-shear-velocity province (LLSVP), made of steep-sided and compositionally distinct material that is located towards the Loa side of the plume. It appears from the work conducted thus far that this repository of enriched mantle could have been caused either early during the differentiation of the Earth, or by the presence of subducted material at

SUNSET ON WEST MAUI, FROM THE TOP OF HALEAKALA the core-mantle boundary. Further studies will be required in order to determine which interpretation is correct. High-precision isotopic studies have thus far only been produced for the 5 million years of the volcanoes on the islands of the Hawaiian archipelago, which represents only a recent snapshot of Hawaiian plume volcanism.

There appear to be differences in eruption type between the volcanoes studied and the Emperor Seamounts, which comprise material produced between 85-42 million years ago. Where the basalts of the older chain seem to have a relatively constant rate of eruption and only Kea compositions, the volcanism of the Hawaiian archipelago demonstrates Kea-Loa compositional asymmetry and a drastic increase in the magma production rate. Through further probing the older rocks along the Hawaiian chain, the team aims to uncover the behaviour of the mantle plume, and the internal chemistry of the Earth, through deep time.

TRACER ELEMENTS

The process at the centre of this pioneering investigation refers to 'source fingerprinting', a technique that involves radiogenic isotope ratios. As the melting process within the mantle leads to chemical fractionation, it does not change the ratio of radiogenic isotopes. The UBC team has therefore measured radiogenic isotope compositions, a precise methodology that provides an extremely powerful tracer for the source of the mantle plume, given that the mantle is heterogeneous on scales ranging from centimetres to thousands of kilometres. Providing a 'fingerprint' of the source, these isotopes are able to generate an enormous amount of information about the time-integrated history of the mantle, including the presence of subducted or recycled material.

Due to the vast timescale that must be considered when studying mantle processes, this study required the use of isotopic systems with extremely long half-lives. Used in combination, the decay from parent to daughter isotopes provides a detailed analytical tool for thier research. Parent isotopes include ^{87}Rb, ^{147}Sm, ^{176}Lu and ^{238}U, ^{235}U and ^{232}Th, with their respective daughter isotopes being ^{87}Sr, ^{143}Nd, ^{176}Hf and ^{206}Pb, ^{207}Pb and ^{208}Pb. The daughter isotope ratios record the long-term history of basalt source components and reservoirs in the mantle. The differences that the team has documented in oceanic basalts provide the data required to discuss the composition of mantle plumes in unprecedented levels of detail. This leads into ideas of the sources for the differences between the islands, and finally the dynamics of mantle geochemical cycling. Through their work on the complexities of the Hawaiian island chains, the team is beginning to discover these sources, working further towards deciphering the chemical and physical processes that take place in the mantle.

FINDING THE SOURCE

Through their efforts to establish the source of compositional differences within plumes, the research group has been able to propose that they originate at the boundary between the core and mantle at the edge of two LLSVPs – one of which is under Africa, and the other is the team's study location.

A major breakthrough made by the study links the enriched signature that has been found in the Hawaiian islands with the presence of the ultra-low velocity zone, a sub-division of LLSVP. In fact, similarly enriched mantle ('type 1') has been found in Hawaii and Pitcairn in the Pacific, and Kerguelen and Tristan on either side of the African anomaly. This connection is beginning to show the ways in which the compositional differences of the mantle can be studied through their sampling by mantle plumes, as Weis explains: "I inferred that these deep velocity anomalies at the core-mantle boundary might be the repositories for enriched components in the mantle and are brought to the surface by strong mantle plumes, such as Hawaii and Kerguelen".

The remotely operated vehicle (ROV) Jason 2 was designed and built by Woods Hole Oceanographic Institution Deep Submergence Laboratory. Jason's manipulator arm allows for the collection of basalt, that is then put in the vehicle's basket.

> The team's work is using precise geochemical techniques, analysing ocean island basalts in order to uncover the previously obscure intricacies of dynamics in the Earth's mantle

PROBING PLUMES

Beyond these connections with LLSVP, the findings suggest further mechanisms to account for the presence of compositional heterogeneities within individual mantle plumes. Their analysis is proposing a source for the Loa side of the Hawaiian mantle plume connected to the ultra-low-seismic-velocity zone (ULVZ), less than 50 km across. Within this region, P- and S- wave velocities can be reduced by up to 10 and 30 percent respectively. The ULVZ is concentrated close to the edge of the LLSVP pile. Weis is enthusiastic about the potential implications of the connection between the ULVZ and mantle plumes: "We have proposed the link between the presence of this anomalous zone and the enrichment of the Loa component in the Hawaii mantle plume. Collaboration and dialogue between researchers is key to further progress in the understanding of the Earth's deep interior". Weis and her collaborators are working on generating this dialogue, with the aim of developing new knowledge about these complex deep mantle processes.

JOINT INVESTIGATIONS

This project has required a range of different skill sets, leading to productive collaborations. Two key partners are Dr Mike Garcia of the University of Hawaii at Manoa and Dr Mike Rhodes at the University of Massachusetts at Amherst, USA. As specialists in Hawaiian volcanoes, each with different focuses, the collaboration results in much more than the sum of the parts. Garcia brings a detailed knowledge of the field, history and processes of the volcanic activity within the Hawaiian Islands. Conversely, Rhodes provides expertise on the elemental geochemistry of lavas on the islands. This partnership was created over a decade ago, after Weis became renowned for her work on the Kerguelen mantle plume in the Indian Ocean. This led to the use of the powerful radiogenic isotope tracers that are driving their research at present.

Another prominent contributor is Dr Don DePaolo of the University of California in Berkeley, who has been co-leading the Hawaii Scientific Drilling Project in which Weis has been involved. The HSDP project was highly

TRAINING AT THE PCIGR ON THE NU ATTOM HR-ICP-MS BY AN ENGINEER FROM NU INSTRUMENTS LTD

successful and its results have provided breakthroughs in understanding the Hawaiian mantle plume.

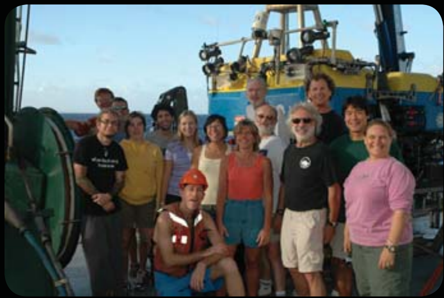
NEXT GENERATION

These major collaborators comprise an extremely important part of the work being conducted. However, a great many other notable researchers are involved in these efforts. Dr Mark Jellinek and Dr James Scoates, both of the University of British Columbia in Canada, have joined the team, contributing their expertise in geophysics, fluid and mantle dynamics, and in the field and petrology, respectively. These fruitful partnerships have allowed the scientists to bring their work forwards, constantly pushing the range of knowledge available to them and, as always, students and postdoctoral fellows have played an important role. Weis believes that training and teaching is a particularly important component of her scientific work: "Students and young scientists are a big part of what keeps me on my toes, and they contribute to the drive to keep renewing scientific challenges". As our understanding of geochemistry increases, it is these students who will lead the future application of this knowledge to other fields, including the environment and the human body.

ONGOING EXPLORATION

The work will continue for some time, and this is an exciting transition point for their projects. The Pacific Centre for Isotopic and Geochemical Research at University of British Columbia has just acquired six new instruments at the forefront of technological and analytical development. Weis is enthusiastic about the new directions that these will afford: "Funding is being provided to allow for a series of new research projects centred on the themes of fragile ecosystems, hidden resources and windows into the Earth".

Placed in new, custom-built clean laboratories, the vision is to both provide a research and development facility for mass spectrometry, in partnership with Nu Instruments Ltd, and to establish the University of British Columbia as a world leader in geochemistry. Weis is also furthering her investment in student training through a new Canadian funding opportunity (NSERC-CREATE) by launching the Multidisciplinary Applied Geochemistry Network (MAGNET), which integrates the capabilities of six cutting-edge laboratories and 10 collaborators across Canada. The programme will train more than 20 students and young researchers every year, and will help in producing the next generation of researchers. It is important to maintain a view on the long-term direction of work being conducted, but this is something that Weis is very mindful of: "Ultimately, it is my hope that geochemistry will be increasingly used to address issues of economic and societal importance". Such work can be taken up by government and industry, and may ultimately affect the treatment of natural resources, as well as terrestrial and aquatic ecosystems. The team hopes that their work, revealing the secrets within the planet, will contribute to such an undertaking.



Northern Hawaiian Islands science team, in front of Jason 2. The four-week marine expedition was led by the University of Hawaii (Drs Garcia and Ito) and sponsored by the US National Science Foundation.

INTELLIGENCE

FINGERPRINTING THE EARTH'S MANTLE

OBJECTIVES

- To improve our understanding of planetary evolution and the Earth's environment
- To model the geochemical and isotopic variations of the Earth's mantle through a comparative study of large igneous provinces and more recent hotspots or volcanic centres
- To determine the origin, source and pathways of mantle plumes, and their variations through time

KEY COLLABORATORS

Dr Mike Garcia, University of Hawai'i at Manoa • **Dr Mike Rhodes**, University of Massachusetts at Amherst • **Dr Don DePaolo**, University of California, Berkeley • **Dr Mark Jellinek** and **Dr James Scoates**, University of British Columbia

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DOMINIQUE A M WEIS attained her BS at the Université Libre de Bruxelles, Belgium, in 1979, quickly followed by a PhD in Sciences in 1982 and habilitation in geochemistry in 1992. Post-doctoral fellowships (Université Paris VII, France, California Institute of Technology, USA) allowed her to perfect her training in geochemistry. She moved to Canada, University of British Columbia in 2002. Her research has been recognised by a number of awards, including Canada Research Chair Tier I (2002, 2009), American Geophysical Union Fellow and Daly Lecturer (both 2010), Geochemical Fellow (2011) and recently ECORD Distinguished Lecturer (2010-now).

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