Crewman "Swimmer Ken" and Alvin pilot Anthony Tarantino preparing the craft. Photo by Ken Sims.

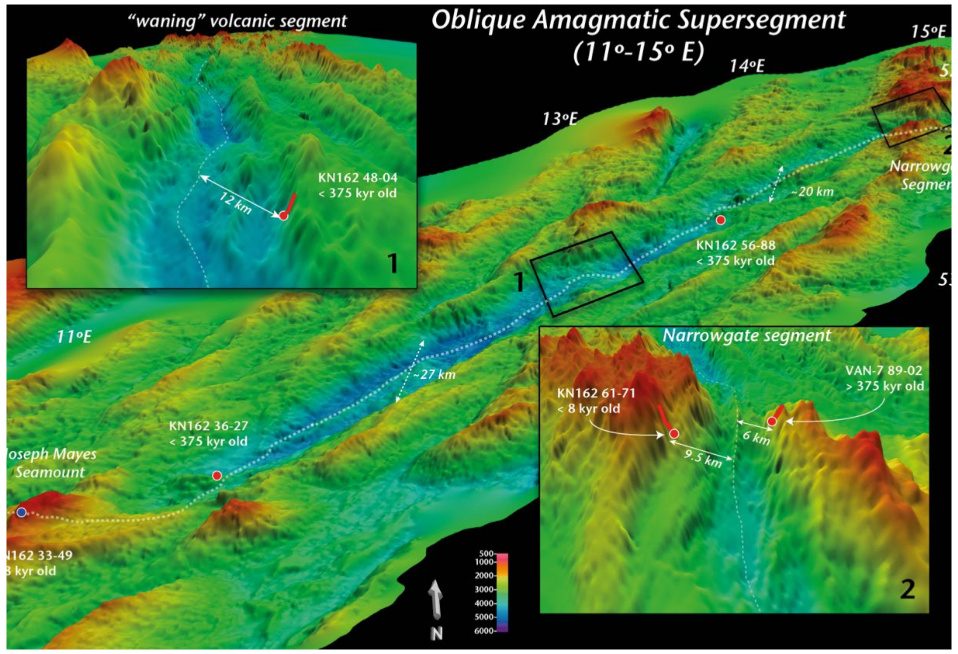
Pushing the boat out: Taking mid-ocean ridge science to new depths

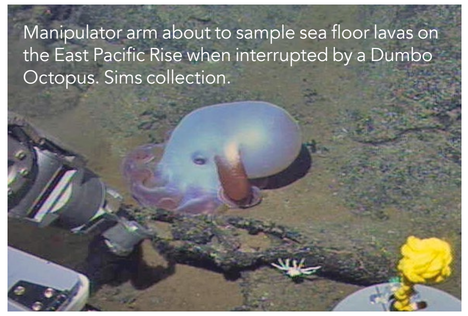
Magmatism is one of the most fundamental dynamic processes on Earth, and mid-ocean ridges account for 70% – 80% of Earth's annual magma output. Physical models of mid-ocean ridge processes have traditionally suffered from poorly constrained time scales of magmatic processes. At the University of Wyoming, **Professor Kenneth W. W. Sims** and his students are using longer-lived daughter isotopes of the U-decay series to constrain previously unobtainable time-dependent parameters. Their findings are providing critical insights into ridge construction, magma genesis, and magma transport, allowing for more realistic models of mantle melting and flow.

Scientific progression is punctuated by paradigm shifts, fundamental changes in understanding that invert the old-world order. From acceptance of the sun (not the Earth) as the centre of the solar system, to Darwin's theory of natural selection, such events do not come along often.

The most recent paradigm shift began in 1915, when meteorologist Alfred Wegner suggested that continents change position over time. He offered five lines of evidence (jigsaw, geological, and tectonic fits of the continents; fossils; glacial deposits); however, he could not offer a credible mechanism and his work was widely discredited. Not until the mid-20th century was Wegner vindicated, when technical advances revealed that: firstly, earthquakes occur along defined lines (i.e., plate boundaries); and secondly, that Earth's oceanic crust is magnetically 'stripy' and has preferential alignments of magnetic minerals that record polar wanderings (the North magnetic pole moves ~10 km a year) and periodic polarity reversals (every 2 – 300,000 years). Different continents record different movement trajectories, a fact that can only be explained by movement of the continents themselves.

The volume of evidence supporting plate tectonics theory has grown to be irrefutable. Of note was the discovery of mid-ocean ridges, away from which ocean floor age increases with distance. Today, plate tectonics theory is so engrained that it surprises many to learn it only became accepted within their lifetime, or within that of their parents. However, scientists are still ironing out the details, assisted by ever more advanced technologies, from real-time





Manipulator arm about to sample sea floor lavas on the East Pacific Rise when interrupted by a Dumbo Octopus. Sims collection.

Sampling hydrothermal vents among a city of tube worms on the East Pacific Rise. Sims collection.

Above left: High-resolution three-dimensional bathymetry for 11–15 E on the SWIR. The samples' ages are quantitative age limits based upon U-Th-Ra disequilibria measurements (modified from Standish and Sims, Nature Geoscience 2010). These young ages show that eruptions are happening a considerable distance off the centre of the axis and even up high along the valley wall on faults.

GPS measurements of plate movement, to deep-sea submersibles that give access to hidden worlds.

One such scientist is isotope geologist Professor Kenneth Sims of the University of Wyoming. Volcanology, rarely off lists of 'coolest' jobs, is no stranger to those who push physical and academic boundaries, but even within this rarefied sphere there are some who take their work to new extremes. Professor Sims is a National Geographic Explorer who has used his mountaineering skills to access sites more remote than ever before, from deep within volcanic craters with active lava lakes to atop the world's southernmost active volcano, Mt Erebus in Antarctica.

Recently, Professor Sims and his colleagues have, quite literally, pushed the boat out, turning their attention to mid-ocean ridge basalts (MORBS). Their work is revealing new insights in mantle melting, magma ascent, and the construction of new crust, deep within our oceans.

DATING MID-OCEAN RIDGE VOLCANISM

Magmatism is one of the most fundamental dynamic processes on Earth. Estimates put the number of submarine volcanoes at over a million, with mid-ocean ridges accounting for 70% – 80% of Earth's annual magma output. Physical models to describe this activity often suffer from a lack of knowledge on time scales of magma genesis (e.g., rates of melting, transport, crystallisation, and degassing). Professor Sims and his students and colleagues are addressing this issue using isotope geochemistry. The half-lives (time taken for 50% of the atoms of a radioactive material to convert into daughter atoms) of isotopic systems traditionally used for dating (e.g., U-Pb) are too long for investigating most MORBS; therefore, they have developed a U-(uranium-) series dating technique. Half-lives of longer-lived daughter isotopes within this series (e.g., 230Th = 75 thousand years [kyr]; 231Pa = 32 kyr; 226Ra = 1.6 kyr) encompass time scales over which MORB genesis occurs, allowing the constraint of previously unobtainable time-dependent parameters.

ABERRANT YOUTH: OFF-AXIS VOLCANISM

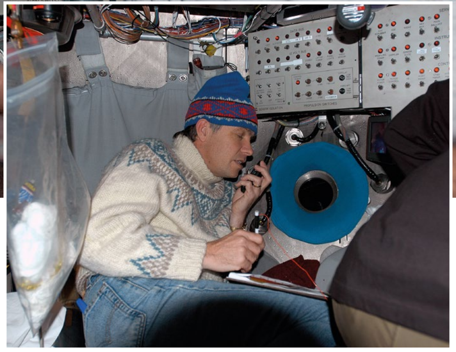
In classic mid-ocean ridge models, magma rises in the middle (the axial ridge) and spreads out; however, a key finding of Professor Sims and his team has been the high level of off-axis activity. At the fast-spreading East Pacific Rise (EPR), student Chris Waters has found off-axis lavas extending 4 km from the central axial ridge, despite being < 8 kyr. Furthermore, Professor Sims and his colleague, Robert Sohn, developed quantitative models to explain apparent off-axis volcanism up to 25kms off axis. On the slow-spreading South West Indian Ridge, Professor Sims and student Jared Standish identified young volcanism associated with fault systems high on the flanks outside the central axial valley. These findings have provided critical time constraints on ridge construction, improved understanding of magma genesis and transport, and allowed for more realistic 2D models of mantle melting and flow.

MORB PETROGENESIS

There are two end-member theories for MORB formation: (1) a 'dynamic' process where melt becomes isolated from the crust and is transported to the surface when a critical porosity threshold is attained; and (2) a 'reactive' process where melt percolates through porous crust resulting in chemical exchange and the formation of high-porosity conduits.

U–decay series data are key to informing on these opposing theories, but until recently have been limited by insufficient age resolution. By collecting samples with high locational accuracy, Professor Sims' team greatly improved the data resolution. Focusing on young (< 200 kyr) MORB samples from the EPR, they found that isotope data can distinguish between the effects of source

> **Scientific progression is punctuated by paradigm shifts, fundamental changes in understanding that invert the old-world order**



Above: Scientist Maurice Tivey recording his observations while diving to the East Pacific Rise in the submersible Alvin. Photo by Ken Sims.

variability and melting processes. Furthermore, they have shown that U–Th and Th–Ra disequilibria are inversely correlated and vary with major- and trace-element compositions. These findings confirm that magmas were formed by mixing of two melts – harzburgite melt from the uppermost mantle (< 70 km) and deeper garnet peridotite melt (> 70 km) – and are consistent with reactive transport.

TAKING SCIENCE TO NEW DEPTHS

A particular strength has been the use of high-resolution imaging and bathymetry, made possible by unmanned and manned deep-sea submersibles such as ABE and Alvin. Access to this technology had allowed the team to put samples into geological context (i.e., accurate knowledge of sample locations, geological settings, and relative ages), thereby eliminating large uncertainties in isotope data interpretation.

Such a targeted approach to sample collection has allowed the team to focus on ever smaller features; for example, hydrothermal vents, which form along mid-ocean ridges, facilitating the transfer of heat and mass from crust to oceans, and supporting rich biological communities.

Single method isotope dating has long been used for determining chimney growth rates; however, lack of knowledge about vent behaviour cast doubt over the ages derived and in addition there was a lack of concurrence between different dating systems. This lack of agreement is not surprising as these chimneys are continuously growing and dissolving and so to get a true age one needs to incorporate this open-system understanding in the age calculations. Along with colleagues from the Woods Hole Oceanographic Institution Susan Humphris and Meg Tivey, Professor Sims is using his understanding of hydrothermal systems to rigorously assess the assumptions central to high-precision U- and Th-decay series dating. The results will explore the applications and limitations of the methodology, allowing for more reliable dating.

Taken together, the body of work produced by Professor Sims and his colleagues is greatly advancing our understanding of the interconnected products and processes encountered at mid-ocean ridges.

Magmatism is one of the most fundamental dynamic processes on Earth

Q&A

What is the youngest age you can reliably date using your refined isotope-dating methods?

Because the ocean is opaque we know very few details about the short order timescales of ocean floor volcanism. Of course, time is an essential aspect of understanding geological processes. Dating volcanics from spreading centres is problematic, however, because conventional dating techniques are inapplicable. Such dates are essential to address such questions as: the age of lava flows of different ridge segments; how ages vary with spatial position within a ridge segment; the across-axis distribution of volcanism; and, how tectonic and bathymetric ridge expressions are related to the age and size of volcanic outpourings. There may also be relationships between the age of volcanic activity and the depth and strength of the axial magma chamber reflector and volcanic eruptions. And finally, since hydrothermal activity and biological communities derive their energy from volcanism, these aspects of the ridge system may also depend critically on the timing of volcanism. Clearly, a host of scientific questions about the ridge system can only be addressed once temporal constraints are in place.

U-series dating, which my laboratory specialises in, is the current method that provides the best age constraints for young ridge volcanism. U-series disequilibrium is created by fractionation of the parent and daughter nuclides during the melting process. Regardless of how the disequilibrium is created or enhanced, in the absence of secondary processes (e.g. post-eruptive alteration), any disequilibria generated by magmatic processes ceases to be produced once the lava is erupted. Thus, upon eruption the lava acts as a radioactive "stop-watch" with parent and daughter isotopes moving back toward secular equilibrium, which is attained after about five half-lives. While absolute ages are often problematic with this method, good age constraints can be obtained by making use of different radionuclides with different half-lives. The fundamental principle of this method is that when melting occurs parent-daughter elements (which are also isotopes) in the multi-step U- and Th-decay series isotopes become fractionated, or perturbed, from a state of radioactive equilibrium (a steady-state determined by radioactive principles https://en.wikipedia.org/wiki/Decay_chain) and then after eruption these isotope-element, parent-daughter pairs return back to this state of equilibrium at a rate that is proportional to the daughter isotope's half-life. Since secular equilibrium is achieved after ~5 half-lives, we can put some very tight bounds on the ages of the lavas based on the different parent-daughter isotope pairs. Using these radioactive principles, our research has established unique, paradigm-shifting eruption ages across the Earth's ocean basins (e.g., the East Pacific Rise, Southwest Indian Ridge, the Arctic Gakkel and Kolbeinsey Ridges). In fact, as we have shown for submarine seamounts in Samoa, because the half-life of 210Po is only 138 days, we can use the 210Po-210Pb chronometer to establish the eruption dates of lavas that are less than two years old with an uncertainty of just a few weeks.

What is the fastest spreading ridge on Earth, and how much new oceanic crust does it produce each year?

The speed at which a mid-ocean ridge creates new material is known as the "spreading rate". This spreading rate, measured in mm/yr, varies across the globe and is subdivided into fast, medium, and slow with values generally being >80 mm/yr, 80 – 50 mm/yr, and 50 – 20 mm/yr, respectively. The spreading rate of the Mid Atlantic Ridge is ~25 mm/yr, while the East Pacific Rise varies from 80 – 160 mm/yr. Ridges that spread at rates <20 mm/yr are referred to as ultraslow spreading ridges (e.g., the Gakkel Ridge in the Arctic Ocean, or the Southwest Indian Ridge).

Global magma production rates on Earth, averaged over the last 180 million years, are calculated by various researchers to be between 26 and 34 cubic km/yr, with about 75% of this total being contributed by ocean-ridge magmatism (e.g., see Crisp, JVGR, 1984). These types of calculations are estimates as they require knowledge of two parameters with large variations: eruption dimension/ geometry and eruption duration. For example, if we take the fastest spreading ridge segment on the Earth (~160mm/yr), which is along the East Pacific Rise, assume an average crustal thickness of 6km, one calculates a magma production rate of ~0.001 cubic km/yr per 1 km of ridge length. But this value is for only 1km of the most active part of the ridge. In comparison, the magma production rate for the entire ridge is ~22 cubic km/yr when incorporating the different spreading rates of the different ridges.

How much does the geochemistry of MORBs vary among spreading centres (i.e., can you fingerprint a spreading centre from the composition of the basalts erupted?). If there are variations, what is the main cause (source composition, pre-eruptive processes, etc.)?

Mid-ocean ridge magmas are the product of substantial melting of the Earth's mantle, which is made of the minerals olivine, pyroxene, and garnet. This process creates tholeiitic basalts which are, by comparison with other volcanic rocks, rather similar across all of the ocean basins. That being said, these mid-ocean ridge basalts display a wide range of subtle chemical and isotopic differences that are well correlated with the depth from the ocean surface to the ridge, the estimated thickness of the oceanic crust, the spreading rate and even where the ridge is located on the Earth (see e.g., Schilling…; Hart, … and Langmuir…). There are also variations that reflect small differences in the extent of melting that occurred to create the basalt and what the different proportions of pyroxene and garnet were in the mantle before and after melting.

How deep is the deepest subsea volcano, and can you reach this depth with Alvin (or any other submersible)?

The ocean floor is all volcanic. Maybe the cool question to ask here is what is the deepest part of the ocean and have we ever seen it or been there? To which the answer would be, the Marianas Trench is the deepest part of the world's oceans, reaching a maximum depth of 10,994 metres (36,070 ft) ± 40 metres [130 ft]) at a small slot-shaped valley known as the Challenger Deep. Four expeditions have successfully reached the bottom, the first of which was the most heroic when Don Walsh and Jacques Piccard reached the bottom in 1960 in the "Swiss designed, Italian built, Navy owned" bathyscaphe – Trieste. Two subsequent ROV descents for scientific expeditions occurred in 1996 (JAMSTEC's Kaikō) and 2009 (WHOI's Nereus). This was followed on by film director James Cameron's personal quest in 2012.

What's next for your research?

My newest research direction is Yellowstone, which is not only a massive super volcano that threatens our very existence but also hosts the world's most profound example of an active continental hydrothermal system with a surface expression. Despite its pre-eminence among continental hydrothermal systems, scientific understanding of how the Yellowstone hydrothermal system operates and how it generates such profound geochemical and microbial diversity is still in its infancy. Geologic processes are ultimately responsible for enabling this geochemical and biological diversity. Following on my work studying the ages of hydrothermal systems on ocean floors, I have become involved in a collaborative effort involving a microbiologist, Eric Boyd from Montana State, and a geophysicist, Brad Carr from the University of Wyoming, to investigate how geologic processes influence geochemical and microbial diversity in active hydrothermal systems in Yellowstone.

Detail

RESEARCH OBJECTIVES

Professor Sims' ultimate goal is to better understand the genesis and evolution of Earth's volcanoes with an eye toward forecasting future eruptions. His diverse field experience ranges from ocean floor geology using manned and unmanned submersibles to geologic studies of active volcanoes at high altitudes in technical terrain.

FUNDING

National Science Foundation (NSF)

COLLABORATORS

Janne Blichert-Toft: Ecole Normale Superieure de Lyon
Peter Kelemen: Lamont-Doherty Earth Observatory
Maurice Tivey: Woods Hole Oceanographic Institution (WHOI)
Margaret Tivey: WHOI
Daniel Fornari: WHOI
Susan Humphris: WHOI
Chris Waters: WHOI
Sean Scott: University of Wyoming High Precision Isotope Laboratory
Lynne Elkins: University of Nebraska -Lincoln

BIO

Dr Sims earned his BA in Geology from Colorado College, his MSc from the Institute of Meteoritics at the University of New Mexico, and his PhD from the University of California, Berkeley. Ken is also an avid climber and former high-altitude mountain guide, which has enabled him to sample where few other geologists venture.

CONTACT

Kenneth WW Sims
Professor of Isotope Geology
Wyoming High Precision Isotope Laboratory
Dept. of Geology & Geophysics
University of Wyoming
Laramie WY 82071
USA

E: ksims7@uwyo.edu
T: +1 307 766-3306
W: www.uwyo.edu/geolgeophys/faculty/ken-sims.html