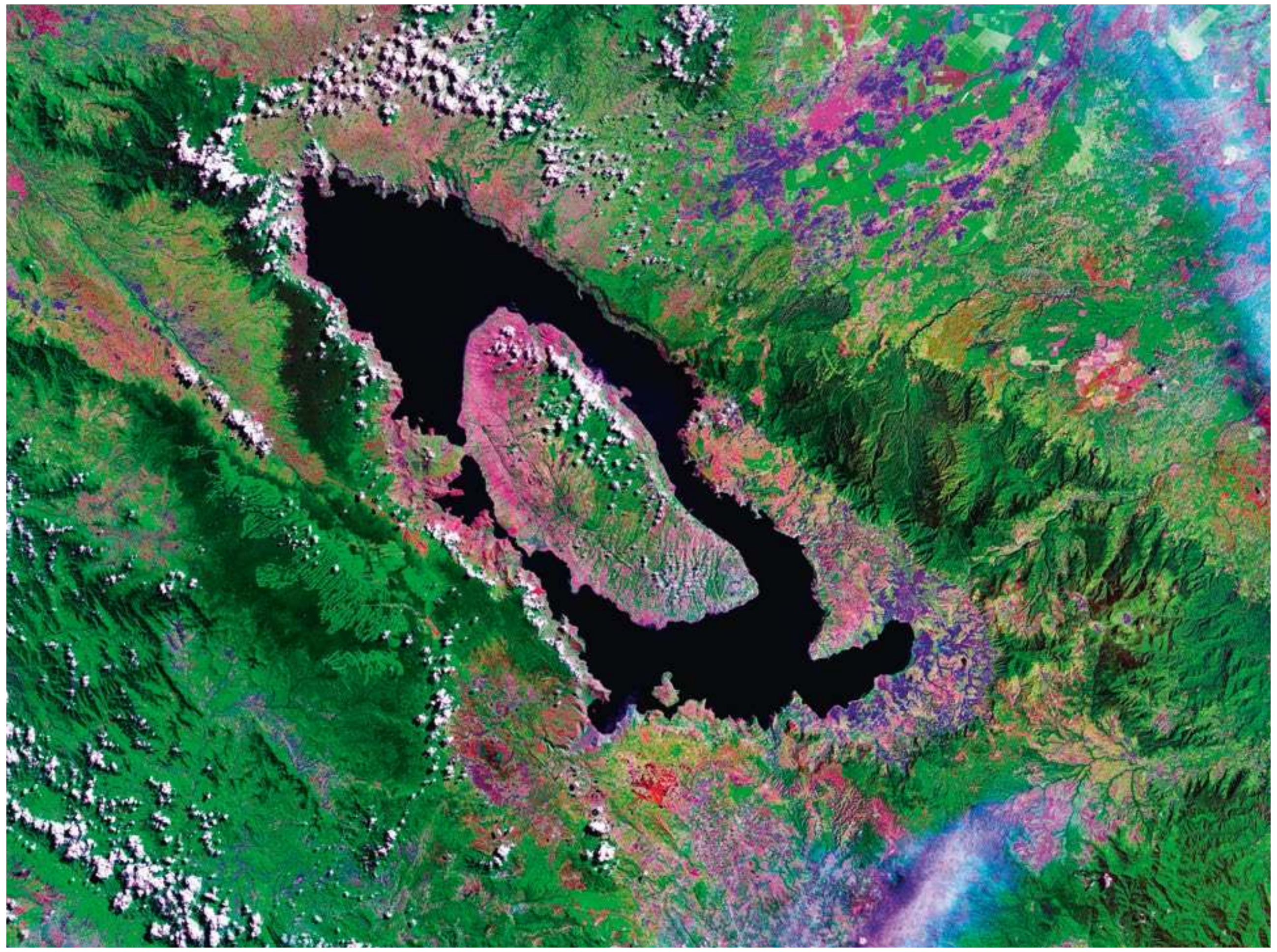
Supervolcano Forensics:

unravelling the mysteries of the Earth's biggest natural catastrophe

To many, if not most, the word 'forensics' invokes images of the very small – DNA, fingerprints, etc., – but for ***Professor Shanaka de Silva*** *and his colleagues at the College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, 'forensics' is being used to investigate something altogether bigger. The team is using a multidisciplinary approach to reveal the secrets of 'supervolcanoes' and supereruptions, calling on expertise in the fields of geophysics, geochronology, petrology, geochemistry, and numerical modelling.*

Next to asteroid impacts, supervolcanoes are the most catastrophic natural hazard on Earth. On average, supereruptions have occurred on Earth approximately every 100,000 years, blanketing surrounding regions with thousands of cubic kilometers of volcanic material and affecting the global climate. During these eruptions, collapse of the magma chamber roof leaves a caldera (a crater tens of kilometers in diameter). In the following decimillennia, the volcano recovers as magma readjusts to the disturbance (rather like the surface of water when something is dropped into it) causing the ground above to swell ('uplift') and deform – a process known as resurgence. Earthquakes, lake tsunamis and fresh eruptions characterise this recovery, posing significant and continuing hazards.



The Earth's largest volcanic lake, Toba (Sumatra, Indonesia) fills the 100 kilometres long and 30 kilometres wide Toba caldera that formed 74 ka in the Earth's largest recent supereruption. Samosir Island, in the center, is the caldera floor that was uplifted almost a kilometer during post-superuption resurgence. GeoCover Landsat 7 satellite image in infrared and visible light courtesy of NASA.

Pyroclastic flows from Sinabung volcano on the 2nd August, 2017. Sinabung lies just 20 miles to the north of Toba and shares geochemical and age characteristics with Toba.
Credit: Shanaka de Silva

The potential impacts make understanding supervolcanoes a task of the utmost importance, and one that is being tackled by Professor Shanaka de Silva and his colleagues at the College of Earth, Ocean, and Atmospheric Sciences, Oregon State University. In particular, the group are addressing a number of questions:

1. Magma bodies that feed supereruptions are likely at least an order of magnitude larger than the calderas they form and develop over hundreds of thousands to millions of years. Questions remain as to how such large volumes of magma can accumulate in the crust and eventually erupt, rather than cool and solidify into a granite.
2. The very conditions that promote the growth of large magma bodies demote the likelihood of eruptions. Why then do these magma systems eventually fail and erupt?
3. After catastrophic supereruptions, the system recovers during the 'resurgence' and 'restlessness' stages (or as Professor de Silva describes it, 'the afterparty after the big dance'). Why does this happen and what are the driving mechanics and time scales? Since all currently active calderas (e.g., Yellowstone, Campi Flegrei, Long Valley, Toba) are resurgent and restless, how long will this last and what is the hazard posed?
4. Since many large calderas erupt repeatedly, going through cycles of eruption and recovery, what is the relationship between supereruptions and resurgence?

PIECES OF THE PUZZLE

Professor de Silva and his colleagues are gathering information using different scientific techniques – an approach they have termed Supervolcano Forensics – at calderas around the world. Students and postdoctoral researchers have conducted much of this ground-breaking work, examples of which include:

1. Geochronology (led by graduate students Casey Tierney, Chris Folkes, Jamie Kern, Jason Kaiser, Rodrigo Iriarte and collaborators Axel Schmitt and Martin Danišík), which uses the decay of radioactive isotopes in magmatic minerals (i.e., crystals within the magma; for example, zircon) to date volcanic processes. This work has focused on calderas in the Central Andes and has shown that: (a) crystals can form in the storage region several 100,000 years before eruption; and (b) most magma in the storage region actually remains non-erupted.
2. Geochemistry and petrology (including work by graduate students Dale Burns, Stephanie Grocke, Chris Folkes and collaborator Jan Lindsay), which uses the chemistry and textures of both liquid magma and magmatic minerals to understand magma history (e.g., storage depths, temperature, water content, interaction with other magma, speed of ascent). The team has confirmed (a) the multi-stage evolution of magma chambers, with distinct changes in volume, composition, and heterogeneity; and (b) that thermally and chemically homogenous magmas reside in the storage region both before and after a supereruption, and drive resurgent activity. These magmas do not solidify owing to regular periodic injections of fresh, hot magma from depth.
3. Geophysics (led by collaborators from the PLUTONS project), including the use of seismic waves (i.e., waves produced by earthquakes and magma movement) to generate 3D images of the crust below calderas. This work has confirmed the presence of large low velocity zones (i.e., partially molten areas) that extend hundreds of kilometres across and tens of kilometres deep.
4. Numerical modelling (led by collaborator Patricia Gregg), that uses mathematical models to predict how systems will behave under given conditions. This work has shown that: (a) the rheology (whether brittle or ductile) of surrounding rock is a controlling factor; (b) negative feedbacks between magmas' thermal energy, rock plasticity, internal pressurisation and likelihood of eruption promotes growth rather than eruption; (c) eventual failure of large magma chambers (i.e., eruption onset) is a function of roof rheology and geometry; once reservoir volumes reach 10^4–10^5 km^3, the crust is unable to support them and the roof collapses, producing calderas of up to 10^3–10^4 km^2, consistent with the largest calderas on Earth.

The work of Professor de Silva's group, grounded firmly in field-based observation of the deposits and stratigraphy (the relative temporal and spatial relation of events) is showing that supervolcanoes are surface manifestations of crustal scale magmatic activity. The development and longevity

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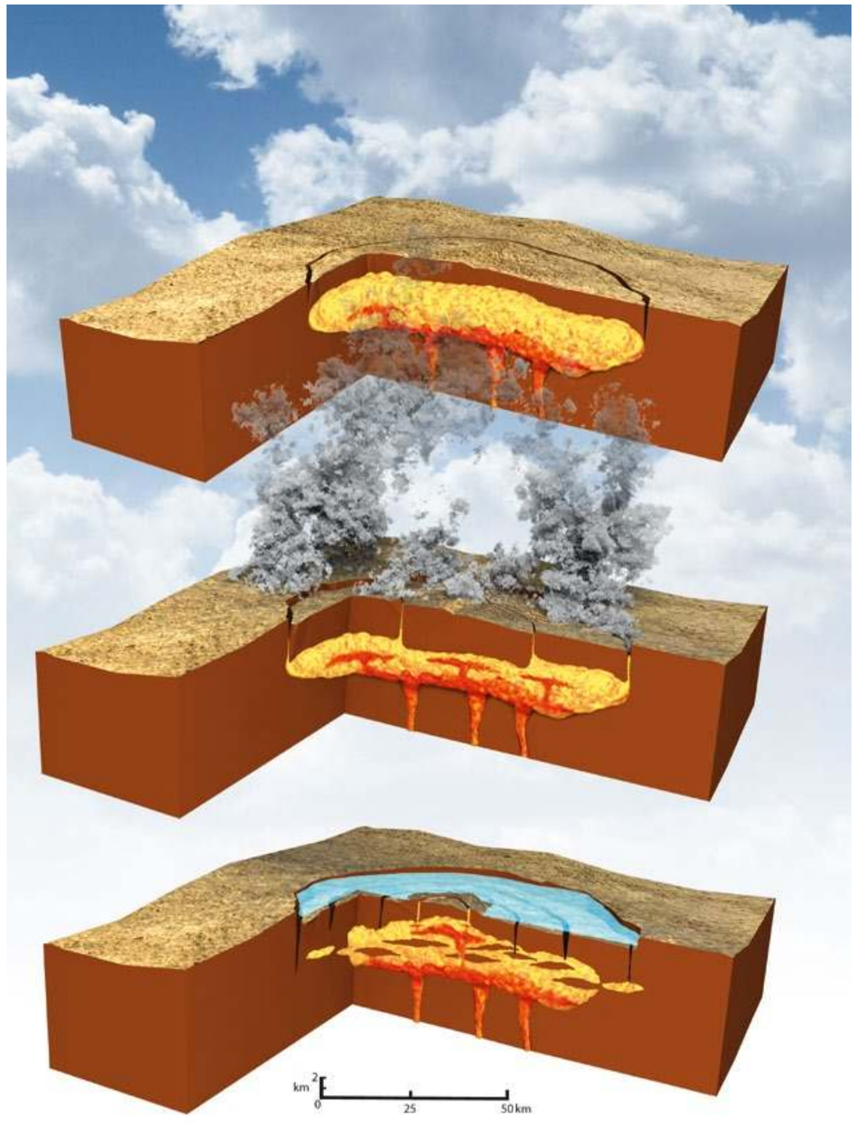

The life cycle of a supervolcano like Toba caldera. Top – As magma accumulates the crust of the earth is upwarped and stretched. Faults propagate from the surface downwards. Magma is kept hot by continued intrusion from deep (red) (105 to 106 years). Middle – Supereruption - Eventually the faults intersect the magma and eruption initiates as the roof blocks collapse into the magma chamber acting like a plunger to force the vesiculating magma out as ash, gas, and pumice at supersonic speed (days to weeks). Bottom – Resurgence. The caldera may fill with water. The magma system and crust readjust uplifting the collapsed roof blocks and leaking small eruptions through the collapse faults (104 to 105 years)

of supervolcano magmatic systems depend on the interplay between heat transfer and the mechanical strength of the crust. Without this feedback, magma could not be stored in large volumes; it would erupt in small events, or solidify too early. This in turn controls the eventual size of the eruptions and calderas.

As an integrative framework and with an eye to hazard assessment, Professor de Silva and his colleagues are developing a simple model that frames calderas behaviour as a reaction to changes in the balance of forces in the crust and magma system. In this model, the caldera cycle is a continuous loop. An exciting possibility is that since the temporal and spatial scales of deformation associated with pre-eruptive development of large magma systems is quite different from those associated with restlessness, the transition from resurgence and restlessness to pre-eruption build-up could, in principle, be detected. Part of the challenge is nailing down the temporal and spatial scales of the different stages and their surface representations.

NEW RESEARCH FOCUS

To specifically improve understanding of resurgence and restlessness, Professor de Silva and his team have now turned their attention to Toba, Indonesia. Approximately 74 ka (thousand years ago), Toba experienced the most catastrophic eruption of the last 100,000 years, during which at least 2800 km^2 of magma was erupted (that is 28,000 times the amount erupted during the 1980 eruption of Mt St Helens!), forming a caldera 30 km wide and 100 km long. Since then, the caldera floor has experienced well over 1 km of vertical uplift, forming the island of Samosir. This project, which won the support of the National Science Foundation, aims to test the hypothesis that resurgence is fed by magma left over after the climactic eruption.

> ***Professor de Silva and his colleagues are gathering information using different scientific techniques – an approach they have termed Supervolcano Forensics***

So far, graduate student Adonara Mucek has used geochronology to date zircon crystals and lake sediment deposits, revealing that resurgence began at least 30 ka and continued until at least 2.7 ka. Eruptions fed by remnant magma rejuvenated by fresh magma from deep continued for at least 20,000 years after the climactic eruption. New work by graduate students Katharine Solada and Jade Bowers is further constraining lake sediment history, and expanding our understanding of resurgent eruptions, including possible relationships with the actively erupting Sinabung volcano.

Behind the Bench

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Bio

Shanaka de Silva is a Professor of Geology and Geophysics at Oregon State University. With fieldwork as a point of departure, Shan, students, and collaborators have adopted a "forensics" approach to understanding supereruptions and supervolcanoes in the Central Andes, Japan, China, Sumatra, New Zealand and the Italian Alps.

Collaborators

- Patricia Gregg, University of Illinois
- Axel Schmitt, University of Heidelberg, Germany
- Martin Danišík, Curtin University, Australia
- Ray Cas, Monash University, Australia
- Jan Lindsay, University of Auckland, New Zealand
- Graduate Students: Adonara Mucek, Stephanie Grocke, Jason Kaiser, Dale Burns, Rodrigo Iriarte, Jamie Kern, Katharine Solada, Chris Folkes, Jade Bowers
- PLUTONS Team (various collaborators) http://plutons.science.oregonstate.edu

Research Objectives

Professor Shanaka de Silva and his many collaborators are currently investigating the most devastating natural events on Earth, supereruptions. With this project, Prof de Silva and his team are working to gain a clear understanding of the processes and timescales of these supervolcanoes as this is vital for our ability to address potential hazards in the future.

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Q&A

Where (and when) will be the next supereruption?

The most likely place for a future supereruption is a location where there has been such an eruption in the past. We know that large calderas like Toba and Yellowstone have had multiple eruptions in essentially the same location. If the factors that led to their formation and evolution remain the same (largely controlled by plate tectonics), these calderas are the most likely location.

Current statistics suggest that the Earth experiences a supereruption (Magnitude, M 8) approximately every 100,000 years. However, there have been at least two such eruptions in the last 74 ka, and it is likely that our inventory of Earth's supereruptions is incomplete. Calderas appear to be cyclic, but their periodicity varies rapidly. Our best strategy is to be vigilant at the currently active systems and pay attention to volcanic areas around the Earth that have shown this type of activity in the last two million years or so.

What would be some of the local, regional, and global impacts of a supereruption today?

Our understanding is that everything within a 100 km radius will be devastated by pyroclastic flows. Beyond this, depending on the prevailing winds there could be continent scale impacts on transportation, power infrastructure, water resources, and agriculture. Communication will almost certainly be limited and air traffic limited due to airport inoperation. Global impacts are debated, but it is commonly thought that significant cooling (due to atmospheric aerosols) for many years that will adversely impact agriculture, the food chain, and human activities is the most likely global impact. Given the interconnectedness of the global economy, a supereruption in any part of the globe is likely to be a global "Black Swan" event.

What is the radius of total destruction for a supereruption?

About 100 km is a generally agreed value.
How far away could you be from a supereruption and still hear it?
The M 4.5 1883 eruption of Krakatau is often quoted as the loudest sound ever produced on Earth. It was apparently clearly heard up to 3,000 miles away and the pressure spike (an acoustic wave) created by the eruption was recorded around the globe for about five days. So technically the "sound" of this eruption was heard around the world for several days. A supereruption is at least 1000 times as intense as the Krakatau eruption, therefore, the "sound" could be expected to be significantly "louder" and intense.

What new technologies and/or scientific advances will help us to better understand supervolcanoes?

We are still in infancy when it comes to understanding volcanoes, not just supervolcanoes. Critical to understanding this is what is happening in the magma systems. While we are beginning to understand some of the signals volcanoes broadcast, the problem with supervolcanoes is that they operate on much longer time scales than normal volcanoes and over much larger spatial scales. This is a huge challenge, but advances are being made on several fronts from understanding how magma systems are built and evolve, the time scales over which these systems develop, the rates and time scales of magmatic processes, and what leads to eruption versus storage. While we are improving our ability to read signals from restless calderas, two as yet insurmountable challenges are to predict exactly when (if) an eruption will occur and how big it will be. Methods and technologies that help answer these two questions are critical. One exciting area of development is the use of satellites to measure signals associated with volcanoes. Given the global distribution of restless calderas and the long time and spatial scales over which they operate, constant surveillance and measurements by satellites maybe a key direction in our effort to understand supervolcanoes.