Student questions: SESE Postdocs colloquium

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"Geology and history of the Malea Planum region: A new view of Mars' oldest large volcanic province"

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What methods are you able to use to age date the structures you're studying through just remote sensing?

Excellent question. Relative dating is done via stratigraphic analyses, i.e., looking at satellite images to see which unit overlaps/embays what other units. However, remote sensing greatly limits our capability to assign **absolute** ages to surfaces und landforms. Nevertheless, like with any other dating technique (from radiometric dating to counting tree rings), we look at what a continuous and ubiquituous process leaves behind and then calculate how much time must have passed since the process began. By far the most common and widespread of such processes on planetary surfaces is impact cratering, i.e., by counting craters on a geologic unit or landforms, we can estimate an absolute "model" age. This was made possible by the Apollo missions, which returned lunar samples that were radiometrically dated in labs on Earth. These ages were then assigned to the crater densities found on these units on the Moon. This calibration was eventually extrapolated to other bodies, including Mars. Bear in mind, that this technique, called "crater size-frequency distribution measurements", has caveats and limitations, but currently remains our only method to assign absolute ages to entire geologic units or landforms on other planets.

Speaking of the geology of mars and that we have a lot of information on the planet currently, is it possible to 100% determine what causes it to have two faces where one is heavily cratered and the other is smooth with low elevation?

If a planet shows two distinct faces that is called a "dichotomy". Mars' dichotomoy is thought to have formed as the result of a giant impact (or possibly multiple impacts), that caused the northern hemisphere to be lower than the southern one. As a result of this, the northern lowlands were later filled with deposits, which now cause it to appear smoother and younger (less cratered) than the southern hemisphere.

Are the floors of the Calderas you are studying younger in age than the surface material?

The floors of the paterae in the Malea Planum region, i.e., potential calderas, show the same age as their surrounding plains. The reason for this is the wrinkle-ridged plains unit, which was emplaced after patera formation and therefore superposes the patera floors, their rims, as well as the surrounding surface. Dating the floors of the paterae (e.g., via crater counting), can therefore not deliver the actual formation age of the paterae, but only a minimum age.

When you are referring to ice sheets covering the region, since you are close to South Pole, are they water ice or CO_2 ice?

As my landscape formation model invokes the past presence of ice sheets in the area in order to explain glacial and fluvial deposits and erosion features, these would have been composed of water ice (CO_2 ice melts only under very high pressures and would therefore not produce liquids, even under a denser martian atmosphere). Furthermore, the the accumulation of water ice sheets in my mapping area was predicted by atmospheric models.

What future work can be done to clarify whether the channels are glacial, volcanic, or both?

Good questions. We would need to look at the actual geology of the channel levees (the raised rims around the channels) and see whether they are made of volcanic materials or fluvial sediments. This would probably require in-situ observations, i.e., a rover. Orbital observations might reveal spectral signatures of such materials, but it would remain unclear whether they are primary (true volcanic deposits), or secondary, i.e., volcanic rocks that were re-deposited after fluvial transport.

Are these ash deposits proof of previous volcanism or are these volcanoes erupting in recent times?

Judging by the subdued/degraded appearance and cratering of the paterae/calderas and the potential ash deposits, any associated volcanism should have ceased by ~3.5 billion years ago.

Do you think Mars' lower gravity might influence the size of those large calderas?

The size of a caldera is mostly determined by the size and shape of the collapsing magma chamber at depth. However, the depth at which a magma chamber should be is greatly affected by gravity, as Mars' lower gravity causes lithostatic pressure and therefore compaction rate and density to increase slower as you go deeper. On Earth, there is a preferred depth for magma chambers (neutral buoyancy) given certain parameters; on Mars the same parameters would result in ~3 times the depth.

What are the limitations of Mars missions with in situ sampling/future sample return capabilities helping with the development of geological/morphological maps in place of field work?

On Earth, geological maps are at least partially informed by field work, i.e., in-situ analyses of outcrops. On Mars, this knowledge is largely absent, except for the very few landing locations. Nevertheless, the observations by the Curiosity rover in Gale crater have already enabled the formulation of "true" geologic maps in the area, i.e., remote sensing based mapping efforts that use limited ground truth to produce comprehensive local maps and stratigraphic columns. With more missions populating the martian surface with more point sources of such ground truth, we will be able to assess a greater variety of rock types in correlation with what these units look like from orbit. This can then allow us to produce more accurate maps, wherever else we might see a similar unit. Field work and gathering ground truth is not a sprint, but a marathon. In general, the accuracy and detail of geologic maps of Mars will steadily increase with the growing amount of ground observations (as it has since the first lander missions 45 years ago). Sample return will specifically help to further refine the martian chronology to better calibrate our crater count-based dating of units (see answer to first question).

What rate of exoplanets could we reasonably expect to also have magmatic activity?

Short answer: We are not sure yet. Longer one: Judging from our own Solar System, where almost all bodies show some sign of current or past volcanic activity (including cryovolcanism), we might very well expect volcanism to be a rather common feature of planets troughout our galaxy. In fact, it is difficult to imagine a planetary body that is at least the size of our Moon, to be devoid of volcanic activity. The tough question is: How long do planets and moons of given size stay volcanically active? There seems to be a certain size treshold, below which planets become volcanilly dormant relative early in their evolution. In general, I would expect every terrestrial (i.e., made of mostly silicates, not ice) planet or moon out there that is at least the size of Earth to be volcanically active, even if they already formed billions of years ago.

Did you use a particular Earth caldera to compare your findings on Mars?

I looked at several ones in situ and via remote sensing/literature research. The ones that I looked at up close included Valles Caldera in northern New Mexico, Crater Lake in Oregon, and the central caldera of Mount Vesuvius in Italy. All of these share certain aspects with the paterae on Mars. Only rarely are there "perfect" analogs; nevertheless, looking at Valles Caldera proved to be very insightful and I highly recommend it a trip there!

Where do you see this research going as technology continues to improve?

It is less about limitations by technology but more about the political will to conduct new missions with the technology we already have and use. Of course, landing, touching, drilling, and bringing back is always the ultimate call a planetary geologist can make. Realistic improvements in the near- to mid-term could be a higher resolved gravity map of Mars. We recently conducted a dedicated gravity mapping mission around the Moon (GRAIL); doing something like that around Mars would enable countless scientific breakthroughs. For instance, the paterae, can have distinct gravity signatures, e.g., positive anomalies, but our current data can barely or not resolve them.

Could mars have been cold and icy but punctuated by multiple short periods of warmth caused by volcanism or impacts?

That is indeed what the majority of the scientific community currently suggests in order to solve the "Mars dilemma". The geologic evidence suggests that warmer periods allowing for liquid water to be stable on the surface should have lasted 100s of 1000s of years (e.g., time needed to build up certain deltas). While impacts, even very large ones, can inject high amounts of energy that can significantly increase ambient temeperatures for millennia, only continuous, large-scale volcanism seems to have the potential to sustain a warmer climate for that long. In that context, the outgassing of H_2 as a potent greenhouse gas is of particular importance.

For the Hella basin you indicated that source of volcanism was likely mantle-sourced from an impact event -- do you see any indications of impact-induced volcanism elsewhere on Mars such as the Tharsis Rise region?

The mantle-volcanism I suggest was not "triggered" by the Hellas impact event, but the impact faults it created eventually enabled it by providing zones of weakness penetrating the entire crust. This is comparable to the reason why we find clusters of volcanos in northern Arizona, where tectonic forces created faults that acted as pathways for ascending magma. Still, you wouldn't say the tectonics "triggered" the volcanism. The Tharsis rise on Mars is a very diverse area, with different styles of volcanism that were undoubtedly sourced from different depths. In general, the Tharsis rise was formed by mantle upwelling pushing up the crust. Some specific volcanoes on the Tharsis rise have been associated with a mantle source, e.g., Alba Patera. However, the largest of the Tharsis edifices, Olympus Mons, was likely fed by a very shallow magma chamber.

If the fluvial outflow channels you noted are from the melting of a glacial cover, does this help support other global glaciation hypotheses about Mars's ancient climate?

Yes, although we must be careful to avoid circular logic: Ancient glaciation → channels should have been formed by glacial meltwater → channels imply ancient glaciation. The observation at hand is the distribution of channel networks across the martian southern highlands. This, coupled with the cold and ice climate models, motivated the model of massive ancient glaciations feeding meltwater channels during intermittent warm phases. While this allows us to explain many morphologic and mineralogic observations, we must be mindful that it is still a house of cards we are building pending further investigation that will eventually necessitate in-situ observations.

What part of your research into the Malea Planum region did you find the most difficult and how did you get around this? P.S: I am still loving the Star Trek shirt you wore for the talk!

As with any investigation that is centered around a comprehensive mapping, getting started is always the toughest thing. You literally start with a blank sheet, and finding a sensible starting point, i.e., the first landforms to map, can sometimes be overwhelming. Usually I simply choose the most abundant and prominent features, e.g. wrinkle ridges, and start outlining them. Something that made looking at Malea Planum specifically tough, is the ubiquitous coverage by thick dust-ice mantling. While that stuff itself is pretty interesting, it obscures the geology and makes the assessment of contacts very difficult. The only ways out sometimes are to simply acknowledge the resulting ambiguity (i.e., drawing an "approximate contact") or to decrease the mapping scale so you are less affected by superficial mantling. Live long and prosper.

Are there any notable differences in the geomorphologic landforms of Mars compared to Earth's analogues due to the differences in gravity and atmosphere?

Definitely. For instance, slopes tend to be much more stable on Mars, as its lower gravity triggers less landslides. Therefore, if you see abundant slumping along a relatively gentle scarp on Mars, you may deduce that the material must be very weak. One geologic effect of the currently thin atmosphere is that active dunes, i.e., those that are currently moving, have to comprised of extremely fine material, so they are actually "dust dunes" and not sand dunes. This is because Mars thin air can exert only little kinetic force and particles that could easily be lifted up on Earth remain stationary or are limited to saltation (tumbling around).

Is it known when tectonic activity and convection ceased on Mars, and could that also have an effect on climate change (due to disruption in the magnetic field and loss of atmosphere)?

Tectonic activity might still be ongoing on Mars, as we are actually detecting Mars quakes with the currently active Insight lander. However, most of the large tectonic features are alder than ~3.5 billion years. Convection in the mantle should also still be ongoing according to geodynamic models. However, the rotation of the outer core, which is what causes the dynamo effect that forms a more or less dipolar planetary magnetic field, appears to have shut down ~4 billion years ago. The lack of a relatively strong magnetic field is one of the main reasons suggested for why Mars lost most of its atmosphere, as this allows the solar wind to slowly strip it away.

Is mantle source volcanism thought to be a rare or common occurrence on terrestrial planets?

Good question. I would not say it is very rare. What makes it significant though, is where exactly it occurs, as it has several implications. The lunar maria (the dark areas) were likely derived from the mantle. On Earth, most of the mantle-fed volcanism takes place along the mid-oceanic ridges, where the crust is extremely thin. However, there is also some mantle-fed volcanism within the continents, where the lithosphere is very thick, so it is important to find out why. Mars has no mid-oceanic ridges and a thick lithosphere, so finding mantle-fed volcanism has interesting implications.

When studying the Caldera (and other geomorphic features on Mars), is it safe to use Earth analogues as a reference point?

No, it is never "safe" to use analogs, which is why we must always stay cautious and sceptical. Nevertheless, terrestrial analogs can reveal important insights as they are much more accessible than the surfaces of other planets (at the moment at least). Sometimes, terrestrial analogs have led researchers on a wrong path. The craters on the Moon were initially thought to be of volcanic origin, as volcanic craters on Earth seemed to be the best analog at first glance. Nevertheless, terrestrial analogs are (still) much more accessible than their planetary counterparts, thus offering insights that are currently not possibly otherwise. Seismic profiles through a caldera, for instance, are only available on Earth… Those are very informative and can certainly help to understand similar strucuture on Mars.

What type of timescale would it take glaciers to make these types of geological shapes?

That depends on the erosional resistivity of the ground material. Depending on that, the observed channel network might have been carved within several decades to a few 1000s of years.

You stated that computer models gave results that the Martian surface would have been too cold for running water to have produced the current features you displayed. Is it possible that Ice Melt from nearby volcanic activity could have been the cause?

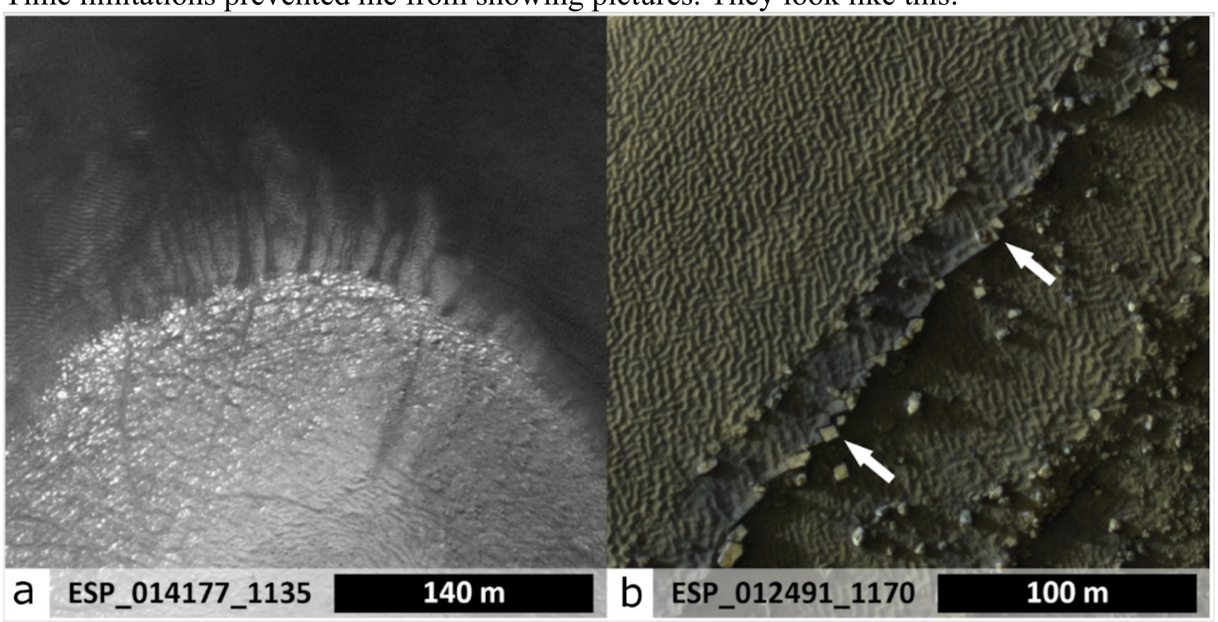
Yes. Heat intruduced by volcanic activity, e.g., via direct lava-ice interaction or indirect warming from nearby dikes, can lead to massive melting events on Earth (Iceland, Alaska, etc.). Certain features on Mars could be explained by that. However, there are some landforms and desposits that require a very steady water supply over 100s of 1000s of years at least, which is not what we would expect of glacial melting by volcanic heat. Here, longer term effects by volcanic outgassing and resulting greenhouse effects come into play.

Does increased resolution of the DEM further your investigation? You alluded to it's importance, but I wasn't sure if it met some critical minimal resolution threshold as-is, or if a resolution improvement would further support this work.

Better resolution is always better! The DEM I used has a resolution of ~330 m/pixel or better. Given the size of landforms I mapped and analysed this was sufficient, although it has to be kept in mind when looking at features that are smaller than few kilometers. If necessary, we can also produce DEMs with ~50/pixel or better at a local scale. I did that for looking at sub-km landforms on the Hellas basin floor a few years ago.

What do the ash deposits associated with this explosive volcanism look like?

Time limitations prevented me from showing pictures. They look like this:



The black streaks in (a) are likely granular flows sourced by an exposed layer of ash. The blocky, jointed, and bright material above it looks a lot like tuff, a form of pyroclastic deposits. The angular blocks in (b) marked by the white arrows a likely due to angular jointing, which only occurs in cooling volcanic material, including massive ash layers.

If the compositions are known of the material from the Malea Planum region, and knowing the, or modeling the, depth of the magma chamber to be 60 km, can an ascent rate of the magma be predicted for this ancient volcanism?

We would need to know the gas content and vesicularity of the material, both of which require laboratory analyses, i.e., in-situ samples. Would love to have some!

What do you predict drove these ancient, massive eruptions in the near south pole region? Is this due to large impacts rejuvenating and mobilizing the magma to trigger an eruption or something else?

As on Earth, large-scale volcanism is usually driven by mantle flows, i.e., convection including occassional hot spots. The Hellas impact event certainly affected these mantle flows. On Earth, volcanism can also be driven and/or focused by mantle flows that are being deflected, less by giant impacts but often by subducting mantle slabs (the Cascades for instance). The Hellas impact event likely caused mantle upwelling (bit like a water drop causing backsplash); this coupled with a thinned lithisphere that was penetrated by deep, circum-basin faults is the right recipe for massive volcanism. What you might mean with "rejuvenating" might actually refer to impact melt. While Hellas should still have massive amounts of solidified impact melt sitting under its younger deposits, that itself is not considered volcanism, nor did it trigger it.

What types of instrumentation are you using to analyze the geography of Mars, and is the research that you are doing in anyway going to be used to explore regions in which we may set up habitats for future manned missions to Mars?

Planetary remote sensing in general utilizes both passive and active sensors operating across different parts of the electromagnetic spectrum. The simplest one might be a common camera taking pictures in the visible spectrum. We also have cameras seeing ultraviolet, infrared, and beyond. These are all passive instruments, i.e., the detect reflected sunlight or thermal radiation from the surface. A common active istrument is a laser altimeter, which shoots laser pulses at the surface and we then see how long they travel. This tells us the distance between the spacecraft and the surface, which, in turn, allows us to compile a digital terrain model (DTM). Another active instrument is Radar. Concerning future manned mission: While the Malea Planum region probably has lots of water ice stored in the underground permafrost, I would actually not recomment it as a landing site for humans, at least not for the first missions. The region is very far south and thus receives less sunlight than the equator (just like central Canada gets much less sunlight than Mexico), which would greatly limit energy production and cause further habitation challenges due to much lower average and peak temperatures.

Is there an idea of why the possible channels are not in a regular pattern the way they are here on Earth?

What will you do with all this information of volcanoes?

Volcanism affects pretty much everything, from climate, to soil, to earthquakes. By learning more about volcanoes on Mars, we also learn about them on Earth and any other body. So all this information on Martian volcanoes can be stitched together to formulate a more complete picture of climatic and geologic evolution. For example, I already used what I have found out about the Malea Planum region to contribute to a paper about climate effects of volcanic outgassing on Mars, in which I suggest that this area alone contributed several mbar of H_2 to the Martian atmosphere, which might have increased ambient temepratures by 10s of degrees. Pretty rad.

Unlike Mars, we don't have exploration data (actual geological samples) on Venus. What method do you think could investigate geological processes on Venus?

We yet have to return samples from Mars, but at least we have meteorites that we think came from there. Other than that, we have in-situ chemical analyses of rocks made by landers and rovers. The same is true for Venus, where several landers of the Soviet Venera program touched down and performed basic analyses of the ground around them. Although the resolution of the data was low, the composition of the rock was found to be ultra-mafic basalt. Moreover, one of the landing sites showed what appeared to be cinder on the ground, thus implying gas exsolution took place during an at least somethot explosive eruption. Going forward, what we need are high-resolution radar maps of Venus (only good way to peek trough the thick smog; current radar data is good, but could be better) and derived topographic maps (current ones are very low resolution). Further, a renewed program of Venus landers/rovers, each with soil analyses instruments and possibly a seismometer, would be extremely vital to better understand Venus' geology.

Is the process of evolution of similar types craters in different planets comparable with respect to period of evolution, topography, etc?

With "craters" I assume you mean the paterae, i.e., potential calderas. As far as we know, the way calderas form is basically the same on any planet, i.e., the ground collapses above an emptying magma chamber, the size of which heavily influences the size of the resulting hole in the surface. So if we see what looks like a caldera, e.g., most of the paterae on Mars, this is the process we assume. The subsequent evolution, however, including erosion, infilling with deposits, and tectonic overprint, is drastically different, thus resulting in differently looking structures after some time. The paterae of the Malea Planum region on Mars are over 3.7 billion years old. Absolutely no caldera from that long ago survived to the present day on Earth, as our planet's tectonism, erosion, and deposition is significantly more intense. That is way look at the Moon and Mars is so valuable. It help us understand old processes whose record has been all but erased on Earth.

How are you able to detect faults and determine rock units remotely, and where is your confidence level when making these observations?

Faults can be remotely detected as they are usually associated with a topographic relief, i.e., a distinct ridge or step in the landscape. Further morphologic analyses are necessary to come to a reliable interpretation, but this is the essence of it. The same procedure is also used on Earth to detect and analyze faults in remote sensing data. As for rock units, remote sensing can only deliver a set of data that would be consistent with a rock type, e.g., basalt or sandstone, but a definite lithologic characterization is only possibly on the ground, as you need to see the fine-scale texture of the rock in an actual outcrop. That is why planetary mapping tries to be as cautious as possible, e.g., I do not call what I think to be basalt plains “basalt plains”, but give it a more descriptive term pending ground verification such as “highland plains”.

With respect to one of the questions regarding the Ash distance at the Paterae. Is the distance a multi-function reason such as lack of atmosphere, gravity, materials, and kinetic energy of the ejecta? Thanks

Yep. All these parameters influence ash dispersal. Volatile content of the erupting magma is also a big factor. In general, we would expect ash deposition to reach farther on Mars than on Earth due to the lower gravity and air friction.

Why did tectonic and volcanic activity cease on Mars?

Neither ceased, i.e., there are hints that both are still going on today (seismic signals, potential outgassing signatures, extremely young volcanic landforms). However, both seem to have drastically declined in instensity after ~3.5 billion years ago. This is because these activities are driven and enabled by the internal energy of a planetary body, of which little Mars already lost much more than big Earth. The decreased heat flux caused Mars’ lithosphere to get very thick, which hinders the ascend of magma and hence eruptions. Caused by this cooling, Mars is also shrinking, which causes its lithosphere to be in a compressive state, i.e., being squeezed like the skin of an old apple, which further prevents magma to rise to the surface.

What if any impact does Mars's lesser atmosphere have on the welding of ashfall deposits?

Good question. Welding, i.e., a form of cementation, can be the result of high emplacement temperatures causing melting on the surfaces of grains or of compaction from higher pressure, e.g., when an ash layer gets buried deep under a stack of younger deposits. The former only happens if ash is still very hot, i.e., relatively close to the source vent. The maximum distance for melt-welding might be shorter on Mars, as its lower atmophere might enable ash to stay airborne longer. The thin atmosphere, however, might somewhat counteract this by offerig less friction and more insulation, as thinner atmosphere transport heat less efficiently. Sounds like a research project! Compaction welding should work on Mars, but due to the lower gravity you would need three times the stack of superposing deposits to create the same pressure compared to Earth.

Are there any current plans on any of the Mars missions to gather information on these volcanoes' mineral composition?

Not specifically. We continuously observe Mars' surface with hyperspectral cameras that can detect mineral signatures from orbit (on Mars Recon. Orbiter and on Mars Express). Although those observations have so far been compromised by dust, I remain hopefully that one day we might snatch a usable image of the Malea Planum paterae.

Are volcanoes located closer to the equator less altered by erosion via glacio-fluvial processes? How might future missions to Mars, or sample return, help to further your work?

The volcanic centers closer to the equator of Mars tend to be more pristine, although that is mostly due to them being younger. The Malea Planum region is most likely the oldest of Mars' volcanic provinces. The Elysium volcanoes, however, are relative close to the equator, significantly younger then Malea, and also show signs of intense overprint by massive channels and associated deposits, which have repeatedly been interpreted as glacio-fluvial in origin akin to big lahars on Earth (when volcanoes melt snow and ice, triggering mud floods).

Are there any other possibly similarly mantle-sourced calderas in regions other than the Malea Planum that may indicate wider volcanic activity across Mars?

There are other large paterae, i.e., potential mega-calderas, on Mars. One might actual be larger than the ones in the Malea Planum region. It is located in the center of Syrtis Major Planum (the big dark spot if you look at Mars through a telescope). Although now dedicated analyses have been done on that feature yet, I would not be surprised if it also was mantle-sourced. Much younger and pristine paterae, i.e., likely claderas, can also be found on the summits of the big Tharsis volcanoes. Zeus Patera on Olympus Mons, for instance, has previously been interpreted to be the result of a very shallow magma chamber collapse. Models showed that mantle.sourced volcanism should have been possible on Mars, and it has been suggested to explain signatures of Ca-rich olivines and other mantle-typical minerals. However, to my knowledge, mantle-fed volcanism has not previously been associated with a specific caldera.