Program

Start	End	Title	Speaker
9:30	9:50	Opening remarks あいさつ、研究集会開催趣旨説明	Kazutaka Mannen
9:50	10:50	Fluid pathways and flow dynamics in magmatic-hydrothermal regimes: insights from ancient, exhumed hydrothermal systems and contemporary seismicity 邦題：　マグマ性ー熱水系における流体経路と流動ダイナミクス：過去の露出した熱水系と現代の地震活動からの考察	Prof. Stephen Cox
10:50	11:50	Testing hypotheses with hydrothermal modeling 邦題：　熱水モデリングによる仮説の検証	Dr. Steve Ingebritsen
11:50	13:00	Lunch	
13:00	14:00	Magmatic-hydrothermal eruptions: Evidence from active volcanic-hydrothermal systems, and eroded metal deposits 邦題：　マグマ性熱水噴火：活動的火山熱水系および侵食された金属鉱床にみられる痕跡	Prof. Jeffrey Hedenquist
14:00	15:00	Experiences using the Volcanic Unrest Index in 2022-23 for Taupo caldera volcano, New Zealand 邦題：　ニュージーランド・タウポカルデラ火山における 2022～2023 年の VUI 適用の経験	Dr. Sally Potter
15:00	15:15	short break	
15:15	16:15	Pressure Cooker beneath the Tatun Volcano Group of Taiwan 邦題：　台湾大屯火山群直下の圧力鍋	Prof. Cheng-Horng Lin
16:15	17:15	discussion	

Fluid pathways and flow dynamics in magmatic-hydrothermal regimes: insights from ancient, exhumed hydrothermal systems and contemporary seismicity

Stephen F Cox (Research School of Earth Sciences, Australian National University)
Yohei Yukutake (Earthquake Research Institute, University of Tokyo)
Drew Whitehouse (National Computational Infrastructure, Australian National University)

A variety of ore deposit types form in response to high fluid fluxes at depths between the top of fluid-producing magmatic intrusions and near-surface regimes in magmatic-hydrothermal systems. The spatial distribution of these deposits and their internal structures provide insights about the architecture of fault/fracture-controlled fluid migration, as well as the dynamic coupling between fluid pressure, deformation processes, permeability evolution and fluid pathways in intrinsically low permeability rocks in sub-volcanic regimes.

The exsolution of overpressured fluids during crystallisation of magmatic bodies is critical in driving permeability enhancement. Slip on faults and opening of fracture networks, that act as fluid conduits in the overpressured parts of these systems, occurs in response to episodes of fluid injection and related fluid pressurisation that are rapid relative to the rates of tectonic loading. Nevertheless, the geometries of activated faults and fractures are controlled by the ambient stress field. Permeability destruction due to sealing of newly-activated faults and fractures by deposition of minerals from supersaturated fluids is fast compared with the lifetimes of hydrothermal systems. Accordingly, regeneration of permeability by repeated episodes of fluid pressurisation is required to sustain the fluid fluxes necessary to generate ore deposits in magmatic-hydrothermal systems.

Deep fluid injection experiments in low permeability, crystalline rocks provide insights about deformation processes, as well as the dynamics of fluid flow, that are associated with migration of overpressured fluids within activated fault zones. Fluid pressurisation associated with injection drives earthquake swarm seismicity involving many thousands of low M_w earthquakes. Seismicity fronts associated with active injection migrate away from injection sources at rates governed injection rates; the distance of the seismicity front from the injection source follows a √(time) law. Importantly, deep injection experiments demonstrate that the cumulative seismic moment release is directly proportional to the injected fluid volume. This relationship allows estimation of injected fluid volumes and injection rates in natural, injection-driven earthquake swarms.

Seismicity beneath Hakone caldera (Japan) exhibits characteristics that are diagnostic of migratory, injection-driven swarm seismicity in overpressured fault networks. Swarm seismicity occurs over an area of 40 km^2 and down to depths of 4 to 6 km within the central and western parts of the caldera. Below this depth, fluid migration is aseismic. The eastern half of the caldera is seismically quiescent. Most seismically-activated faults are strike-slip faults that are near-optimally oriented with respect to the far-field, NW-trending maximum principal stress. Segments of faults are repeatedly activated during individual swarms, as well as during successive swarms.

Nine major, injection-driven swarms between 1995 and 2020 have each involved between approximately 500 and 12,500 seismic events in the range $-1.0 \leqslant M_w \leqslant 3.7$. The smaller, simpler swarms (eg, the August 2009, 2019 swarms) are localised within just a few small, clustered faults and usually involve up to several thousand rupture events with $M_w > 0$. These swarms have durations up to about 10 days and involve injection of up to 35,000 m^3 of fluid at rates up to about 0.2 m^3s^{-1}. Larger, more complex swarms (eg, the 2001, 2013 and 2015 swarms) activate networks of many hundreds of small fault segments in numerous fault clusters that are widely distributed in both the Central and Western Seismic Zones. The 2015 swarm, for example, had a duration in excess of 120 days and involved 12,500 events with $M_w > -1.0$ during injection of a total of approximately 300,000 m^3 of fluid. The swarm involved 17 distinct, spatially and temporally clustered sub-swarms and associated bursts of fluid injection. During 10 hours around the time of the 2015 phreatic eruption, approximately 130,000 m^3 of fluid was injected rapidly into a complex network of small fault segments at depths between 200 m and 5500 m bsl, beneath the Owakudani eruption area. Injection rates were transiently as high as 4 m^3 s^{-1}.

The maintenance of fluid overpressures and inhibition of large phreatic eruptions during swarms in this shallow magmatic-hydrothermal system requires the presence of a low permeability lithocap that persistently impedes upward rupture propagation, seal breaching and associated development of hydraulic connectivity with the near-surface, hydrostatic-pressure regime.

These results have implications for better understanding the fluid pathways and potential phreatic eruption hazards within Hakone caldera. The results also provide new insights about the dynamics of permeability evolution, fluid flow and reaction, as well as the architecture of fluid migration associated with ore formation in the overpressured parts of magmatic-hydrothermal systems beneath active volcanoes.

Testing hypotheses with hydrothermal modeling

S.E. Ingebritsen (U.S. Geological Survey, retired, and Kyoto University Institute for Geothermal Sciences, Beppu, Japan)

"Major improvements in understanding and forecasting are possible through enhanced monitoring combined with advances in experimental and mathematical models... Models of volcanic processes provide a basis for closing observational gaps and hence could help improve forecasting.... Mathematical models offer a guide for what observations will be most useful [and] may also be used to make quantitative and testable predictions, supporting forecasting and hazard assessment" [1]

The hydrothermal system itself can pose hazards and create disasters (*cf*. Ontake-san, White Island) and, almost always, the hydrothermal system affects the various geophysical monitoring data (seismic, geodetic, *etc*.) that we rely upon for forecasting.

We will review some of the pertinent theory and key parameters and consider examples of geysering, volcanic unrest (distal volcano-tectonic earthquakes, Lassen 2014-15) and eruption (Kilauea 2018), as well as a generic cooling-pluton example. Questions (hypotheses) addressed include: Can geysers predict earthquakes? What caused the hydrothermal outburst at Lassen in 2014? Will explosive eruptions occur when the Kilauea lava lake drops below the water table? Are precursory dVTs potentially caused by aquifer pressure changes? And, what are the possible implications of dynamic permeability changes for phreatic eruptions and geothermal resources?

[1] U.S. National Academy of Sciences, Engineering, and Medicine, 2017, *Volcanic Eruptions and their Repose, Unrest, Precursors, and Timing:* Washington, D.C., The National Academies Press, 122 p., https://doi.org/10.17226/24650

Magmatic-hydrothermal eruptions: Evidence from active volcanic-hydrothermal systems, and eroded metal deposits

Jeffrey W. Hedenquist (University of Ottawa)

Volcanologists study the fresh rocks of active volcanoes, as well as their geophysical and geochemical characteristics, including those of high-temperature vapor discharged from associated volcanic (i.e., magmatic) hydrothermal systems; MT evidence (≤0 Ω-m resistivities), particularly from Japan, indicates that these extend to 4-5+ km depth with diameters of 2-3+ km, below summits or on the flanks of volcanoes. By contrast, economic geologists study metal deposits that form in these magmatic-hydrothermal systems, which originate in the roots of volcanoes and are driven by intrusions, with apophyses as shallow as 1-2 km depth. Once extinct, the system erodes to expose altered volcanic and intrusive rocks, with those at <1 km paleodepth altered by the strongly reactive condensates of volcanic vapor. The altered rocks can be brecciated from magmatic-hydrothermal and hydrothermal processes, potentially leading to eruptions, with the associated sharp pressure decrease in part triggering metal deposition. Hydrothermal eruptions (no juvenile component) initiate from 10s m depth (at the water table) to 500+ m depth, based on stratigraphic evidence from NZ, with eruption velocities up to 200+ m/s. They are driven by P_{H2O} and P_{CO2} of the hydrothermal solution, where $P_{hydrostatic}$ is exceeded (e.g., due to rupture of mineral sealing by seismic triggering, etc.). At ~500 m depth (250°C), P_{H2O} = 40 b, and if 1 molal CO_2 is in solution (common in NZ geothermal systems at depth), P_{CO2} = 54 b. By contrast, magmatic-hydrothermal breccias may form as deep as ~1-4 km, based on observations from porphyry and epithermal deposits, caused by dikes intruding the hydrothermal system; many breach the surface with their juvenile component still recognizable. Mapping these clast to matrix-supported mono- to polymictic breccia pipes provides information to better understand magmatic-hydrothermal and hydrothermal eruptions from active systems, including altered ejecta as well as geophysical signatures.

Experiences using the Volcanic Unrest Index in 2022-23 for Taupō caldera volcano, New Zealand

Sally Potter (Canary Innovation Ltd., New Zealand)

Taupō volcano in New Zealand showed signs of activity in 2022 in the form of increased seismicity and deformation. Low levels of activity such as this are often recorded at active volcanoes, causing difficulties in deciding whether the volcano is in a state of normal background activity or 'unrest'. The Volcanic Unrest Index (VUI) was developed in 2014 to help define unrest. This was utilized by GNS Science, New Zealand's volcano monitoring agency (now called Earth Sciences New Zealand), alongside a historical catalogue of unrest and it's impacts to determine that the volcano was indeed experiencing unrest.

Due to the most recent eruptive episode in 232 AD being a catastrophic caldera-forming eruption, there was concern that communicating about its unrest, and raising the Volcanic Alert Level from zero (no unrest) to one (minor unrest) for the first time at this volcano, would in itself cause adverse impacts to society and the economy. The VUI was used together with a package of other tools, including unrest and eruption forecasts, to help communicate the raising of the Volcanic Alert Level in late 2022.

This presentation will describe how the historical unrest catalogue and VUI were used to contribute towards the decision to change the Volcanic Alert Level. It will also include the challenges experienced with this approach, and how the VUI was communicated to both the public and emergency management agencies throughout the unrest sequence.

Pressure Cooker beneath the Tatun volcano group of Taiwan

Cheng-Horng Lin (Institute of Earth Sciences, Academia Sinica, Taiwan)

The Tatun Volcano Group (TVG) at the northern tip of Taiwan is linked to the Taipei metropolitan area, which is home to over 7 million residents. Although there has been no recorded volcanic eruption in the TVG throughout human history, recent seismic observations show that it may still be active. In addition to detecting magma reservoirs from different seismic methods such as S-wave shadow, low-velocity zone and seismic reflections, it is interesting to note that clustering earthquakes have been observed beneath Mt. Chishin and the Dayoukeng fumarole. In particular, the heartbeat-like seismicity has been repeatedly detected beneath the Dayoukeng fumarole. To further evaluate possible relationship between seismicity and volcanic activity in the TVG, we conducted a 4-dimensional seismic tomography using abundant seismic data collected from 2014 to 2021. Our results show that the dramatic increase in seismicity in 2019 followed an increase in seismic velocity in the Dayoukeng fumarole area and Mt. Chihsin in 2018. This increase in seismic velocity may have been caused by higher pressure beneath the TVG, resembling a pressure cooker on a flame. Thus, the sequential rise in both seismic velocity and seismicity strongly suggests that careful monitoring of temporal velocity variations in the volcanic area might provide an early warning of potential seismic swarms or volcanic activity in the future.