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The Wild and Wonderful Adventures of Applying Rock Mechanics to Volcanology

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ABSTRACT

The study of volcanology is traditionally covered by experimental volcanology, field volcanology, geochemistry, rheology, geophysics and analytical modelling. Recent developments have consisted of applying rock mechanics and rock engineering techniques to volcanology, including field, laboratory and numerical modelling techniques. This abstract highlights how laboratory experiments focussing on strength, stiffness and permeability have demonstrated the complexity of volcanic rocks. This abstract also presents how these laboratory results have been used to develop conceptual models of volcanic processes, which can help with decision making regarding volcano monitoring and hazard assessment.

Effect of porosity, texture and alteration on physical and mechanical properties

Volcanoes are spatially and temporally complex rock environments due to the dynamic processes which form, deform and destroy them (Figure 1). This presents a considerable challenge for characterising the rock masses in volcanic environments, while also presenting the opportunity to use rock mechanics and rock engineering tools to help better understand volcanic processes. The key geological characteristics that differentiate volcanic rocks are the texture and mineralogy, linked to the emplacement and subsequent alteration and weathering history.

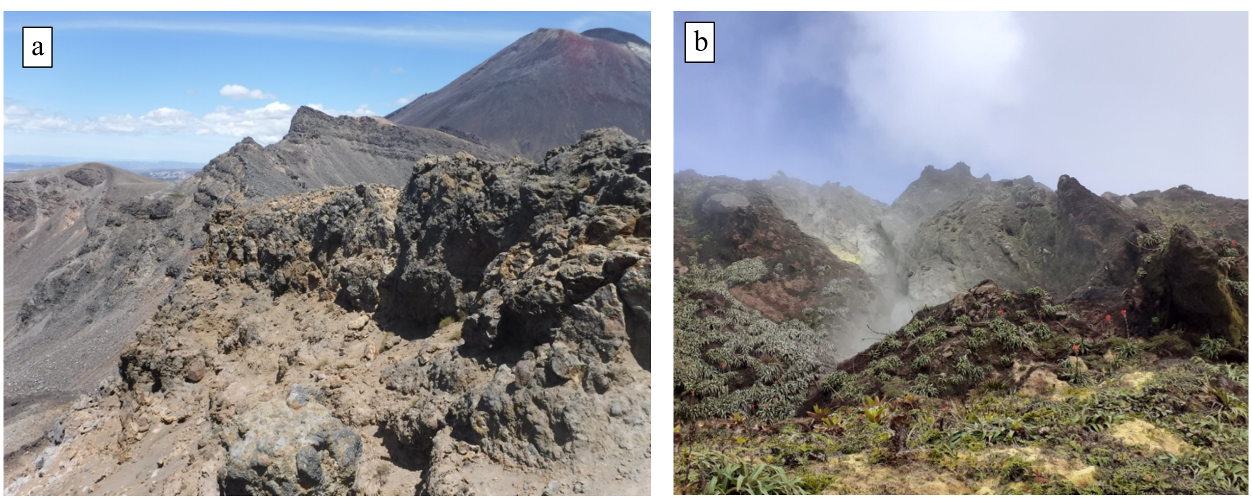

Figure 1: Highly variable rock masses in dynamic volcanic environments (a) lavas with variable texture and alteration on Tongariro volcano (New Zealand), with Ngauruhoe volcano in the background; (b) sulfuric fumarole on the lava dome of La Soufrière de Guadeloupe.

With a focus on andesite, which is an intermediate extrusive volcanic rock that forms many volcanic complexes, considerable laboratory experimentation has established that the physical and mechanical properties are affected by porosity, texture and alteration, as seen in Figure 2-4. Porosity consistently reduces strength and elastic stiffness (see reviews by Heap et al. 2020 and Heap and Violay, 2021), while increasing permeability (e.g. Villeneuve et al., 2019). Texture and alteration interact together to both increase and decrease strength, stiffness and permeability by concurrently reducing porosity through precipitation, increasing porosity through dissolution and changing the mineralogy by replacing primary minerals with higher porosity, lower strength and lower stiffness secondary minerals (e.g. Mordensky et al., 2019; Mordensky et al., 2022). Porosity, texture and mineralogy also affect the brittle to ductile transition, where rocks with higher porosity, such as brecciated lava, as well as more intensely altered dense lava transition to ductile behaviour at lower confinement than low porosity, unaltered lava (e.g. Mordensky et al., 2022).

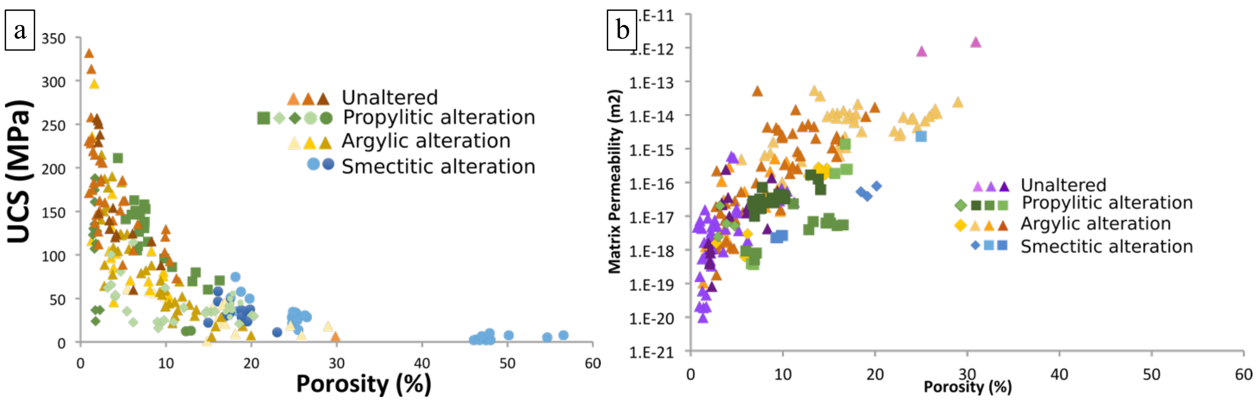

Figure 2: Effect of porosity, texture and alteration on strength (a) and permeability (b). (modified from Villeneuve et al., 2019).

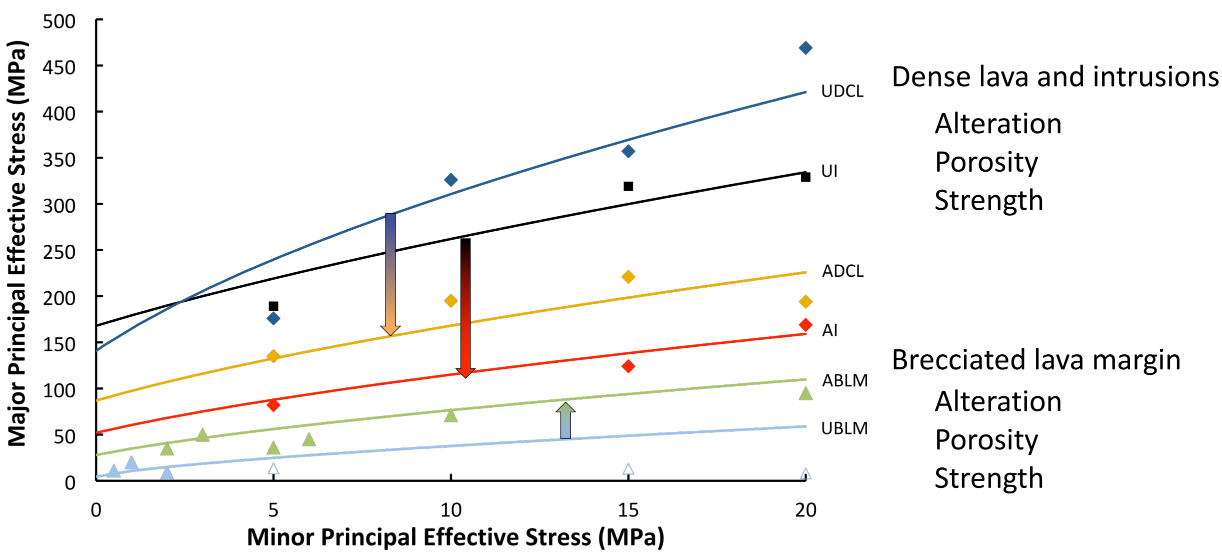

Figure 3: Effect of porosity, texture and alteration on failure criterion (modified from Mordensky et al., 2022)

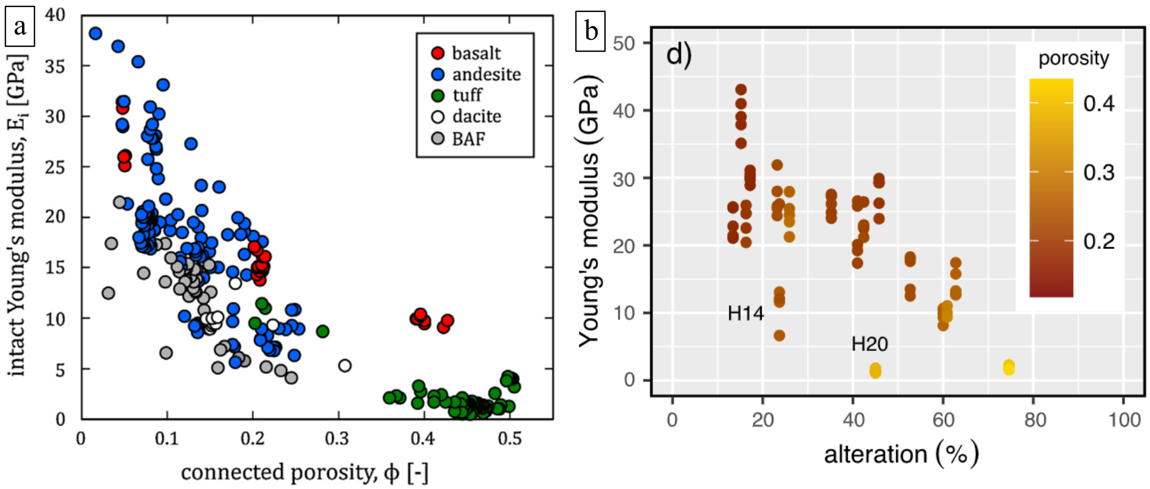

Figure 4: Effect of porosity and texture and alteration on elastic stiffness (a) (Heap et al., 2020), and effect of porosity and alteration on elastic stiffness (b) (Heap et al., 2021).

Rock mechanics helping to understand volcanological processes

The laboratory strength experiments on variably altered dense and brecciated andesite lava from Ruapehu volcano (New Zealand) provided evidence that altered lava behaves in a ductile manner at moderate confining pressures corresponding to 500 m to 1-2 km depth, and an explanation for the lack of pre-eruption seismicity in some altered volcanoes (Figure 5, a), like Ruapehu (Mordensky et al, 2019). Laboratory permeability experiments on intact and tensile fractured specimens demonstrated that altered, higher porosity andesite collected from the conduit at Whakaari volcano (New Zealand) have higher matrix permeability than unaltered, lower porosity andesite, however the tensile fractures for both rock types have similar permeability (Kennedy et al., 2020). In addition, the permeability of the tensile fractures in the altered andesite has a larger decrease with increasing confinement than those in the unaltered andesite. These findings were used to generate a conceptual model of opening and closing of fluid flow pathways related to dissolution, precipitation, tensile fracturing and crack closure within the rock mass comprising and surrounding the conduit at Whakaari volcano (Figure 5, b). Pressure builds up when flow pathways are closed, then is rapidly released as a phreatic eruption, followed by quiescence and renewed precipitation and crack closure (Kennedy et al., 2020).

Summary

A large number of physical and mechanical experiments on a variety of volcanic rocks has provided the basis for developing evidence-based conceptual models of volcanic processes. There remain many volcanic processes that will benefit from combining traditional volcanology with rock mechanics and rock engineering, and the generation of good quality data that reflects volcanic rocks' unique challenges will enable the development of well-supported conceptual models. Physical characteristics, such as porosity, primary and secondary texture, primary and secondary mineralogy, as well as alteration, are key to making rock mechanics data meaningful in complex, heterogenous and dynamic volcanic rock masses.

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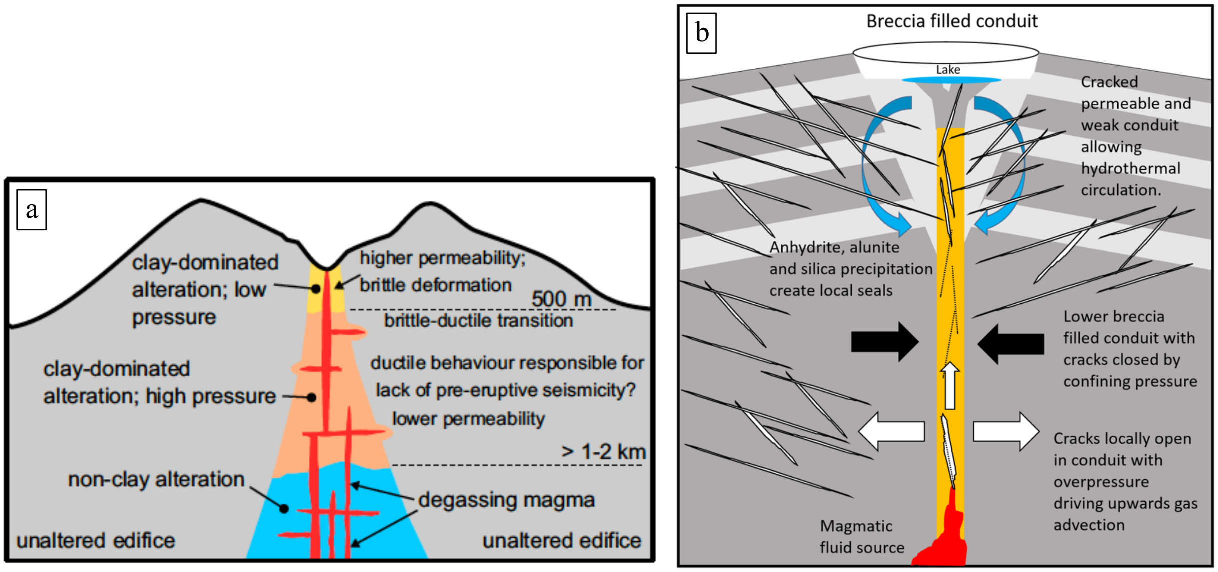

Figure 5: Conceptual models relating physical and mechanical parameters to volcanic processes. a) low seismicity at moderate depths in Ruapehu volcano resulting from ductile altered volcanic rocks at moderate confinement (Mordensky et al., 2019); b) over pressurisation in Whakaari volcano due to fluid flow pathway closure by precipitation in pores and fracture closure of soft altered rocks (Kennedy et al., 2020).

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