Formation of the El Laco magmatic magnetite deposits by Fe-Si melt immiscibility and bubbly suspension flow along volcano tectonic faults

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Abstract

The origin of Kiruna-type magnetite-apatite deposits, which are thought to form by magmatic and/or hydrothermal processes, has recently come under renewed scrutiny. Geological and geochemical studies of volcanic-hosted magnetite deposits that include magnetite lava flows and ash layers at El Laco, a volcano in the Central Volcanic Zone, northern Chile, suggest a formation by eruptive emplacement of an iron oxide-rich melt. The generation of such exotic high density, low viscosity melts by dissociation from an andesitic host magma contaminated by shallow crustal sediments has only recently been shown experimentally. The dynamics of volcanic emplacement have remained enigmatic because the high density of iron-rich melts seems to negate their eruption potential. Yet, observations of ubiquitous vesiculation, degassing structures, and steam-heated alteration provide important clues that volatiles had a pivotal role in the volcanic emplacement. Here, we posit a scenario in which an iron-rich immiscible liquid gravitationally separates from its andesitic parent magma in a shallow magma reservoir and subsequently rises as a bubbly suspension along volcano-tectonic faults extending to the flanks of the edifice. We test this hypothesis through numerical models that capture both the deformation of the volcanic edifice as well as the melt transport within. Preliminary results indicate that separation of a low-viscosity, iron- and volatile-rich melt from a silicic magma within a reasonable time is possible only if an interconnected melt drainage networks forms at the granular scale. Results further suggest that magma reservoir deflation and/or minor local extension combined with the topographic load of the edifice may explain normal faults connecting the magma reservoir with magnetite flow locations on the volcano flanks. Finally, our models show that hydrostatically driven flow of iron-rich melts into these faults at depth may trigger volatile exsolution and bubble expansion to provide sufficient driving force for an eruptive emplacement. Although the case for such magmatic ore formation is perhaps strongest at El Laco, evidence from other localities suggests that similar processes have been at work. The new insights derived from our models may, therefore, apply more generally to Kiruna-type deposits elsewhere.

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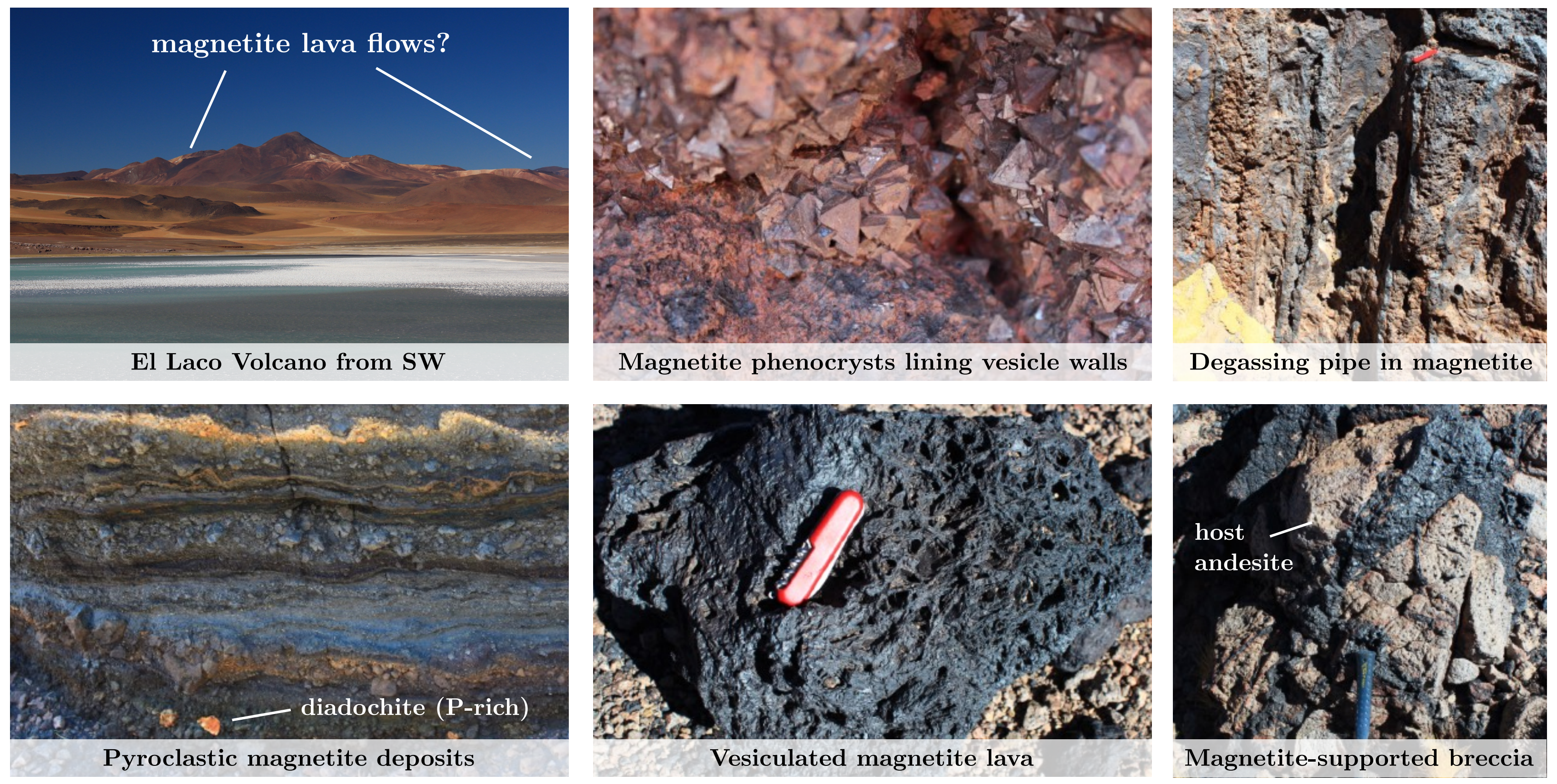
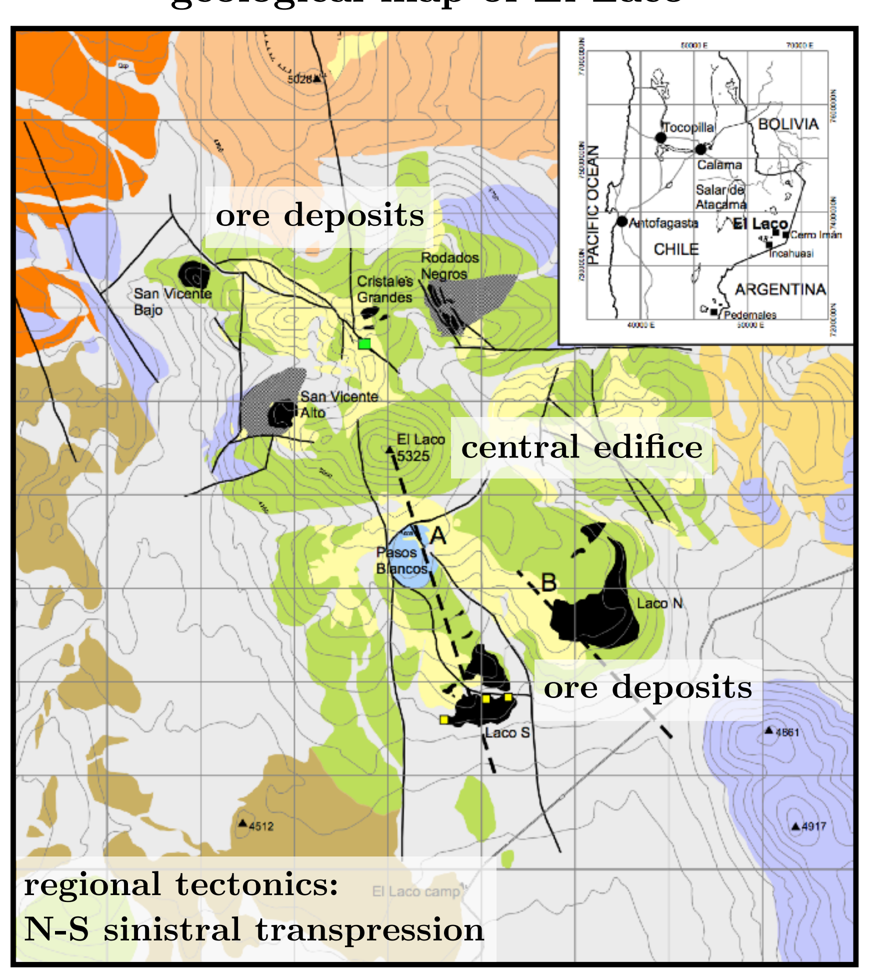
Magnetite-apatite (MtAp) deposits at El Laco



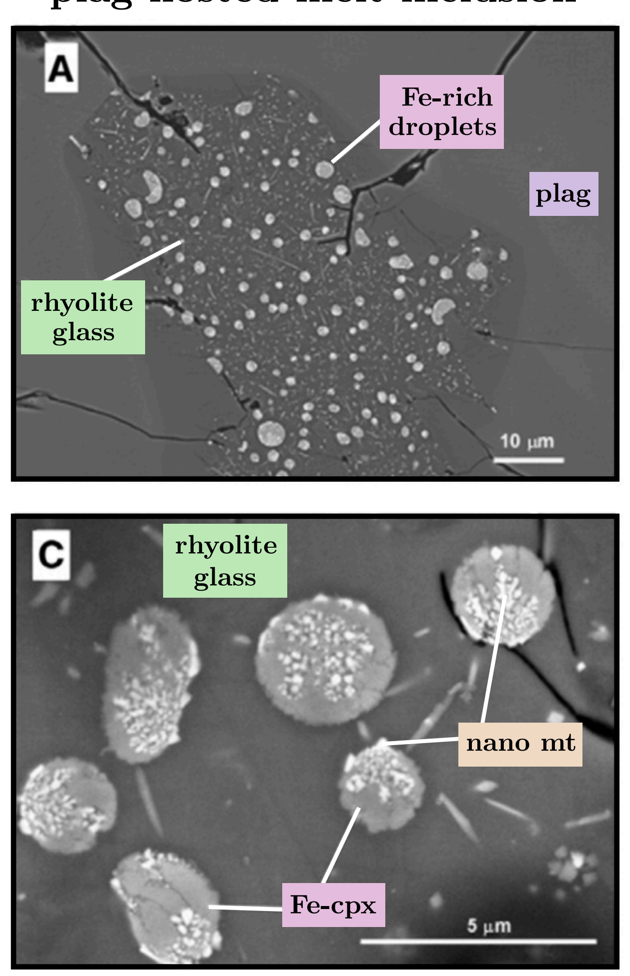
Geological context and observations

El Laco (ca. 3 Myr), **andesitic stratovolcano**, Central Volcanic Zone, Chile with **magnetite-apatite deposits** on its flanks. **Effusive to explosive volcanic emplacement**[1] indicated by lava flow textures, vesiculation, pyroclastics, degassing pipes, brecciation and alteration of host volcanics. **Fe-Si liquid immiscibility** evidenced by melt inclusions[2] in andesite. Built on thick continental arc crust[3], mantle-derived magmas likely contaminated by phosphorite[4], ironstone[5]. Regional tectonic environment predominantly sinistral transpression.

geological map of El Laco[2]



plag-hosted melt inclusion[3]



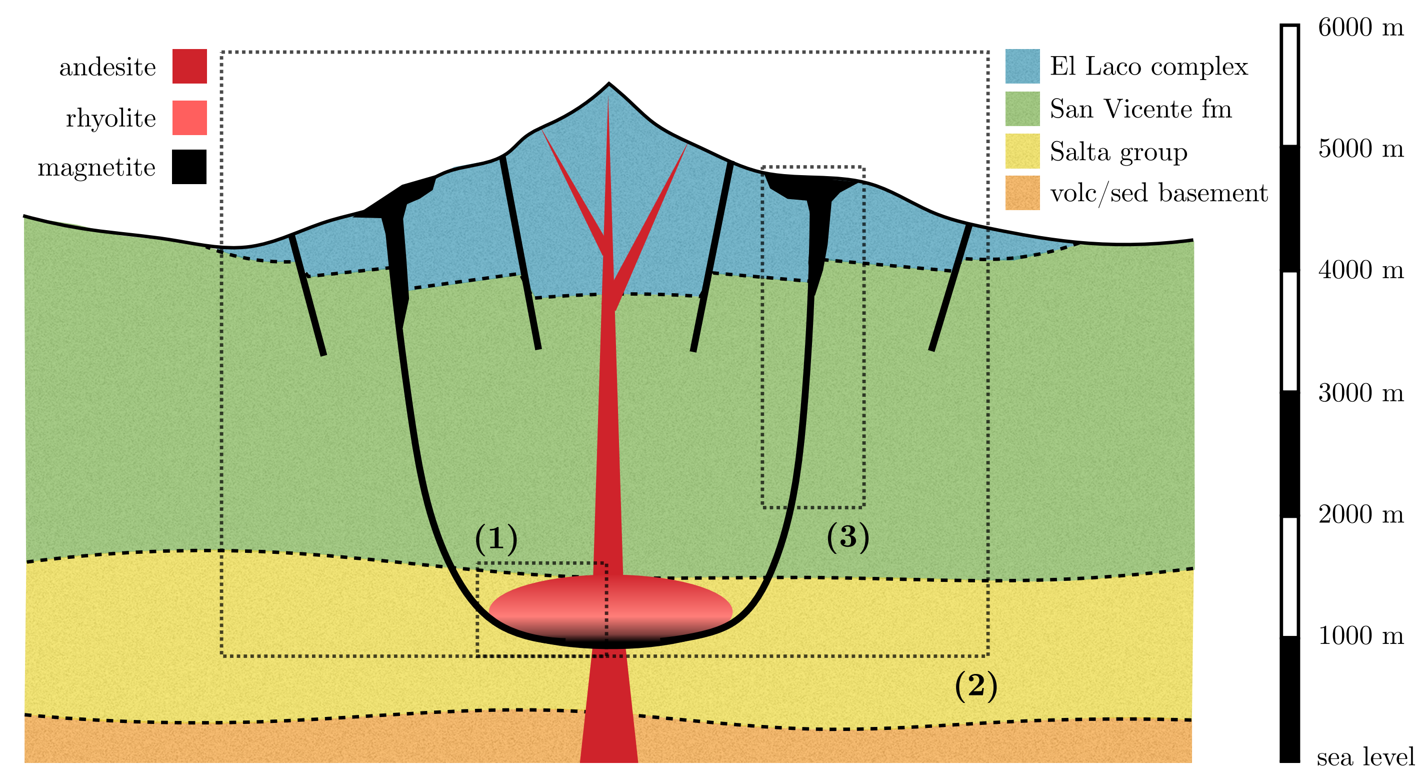
How can Fe-rich magmatic liquid form and erupt?

Can MtAp-deposits like El Laco be explained by the generation and volcanic emplacement of Fe-rich magmatic liquid? We test the following formation hypothesis:

(1) **Fe-Si liquid immiscibility** followed by gravitational separation forms low-viscosity, high-density, Fe-rich and high-viscosity, low-density, Si-rich liquids in subvolcanic magma body.

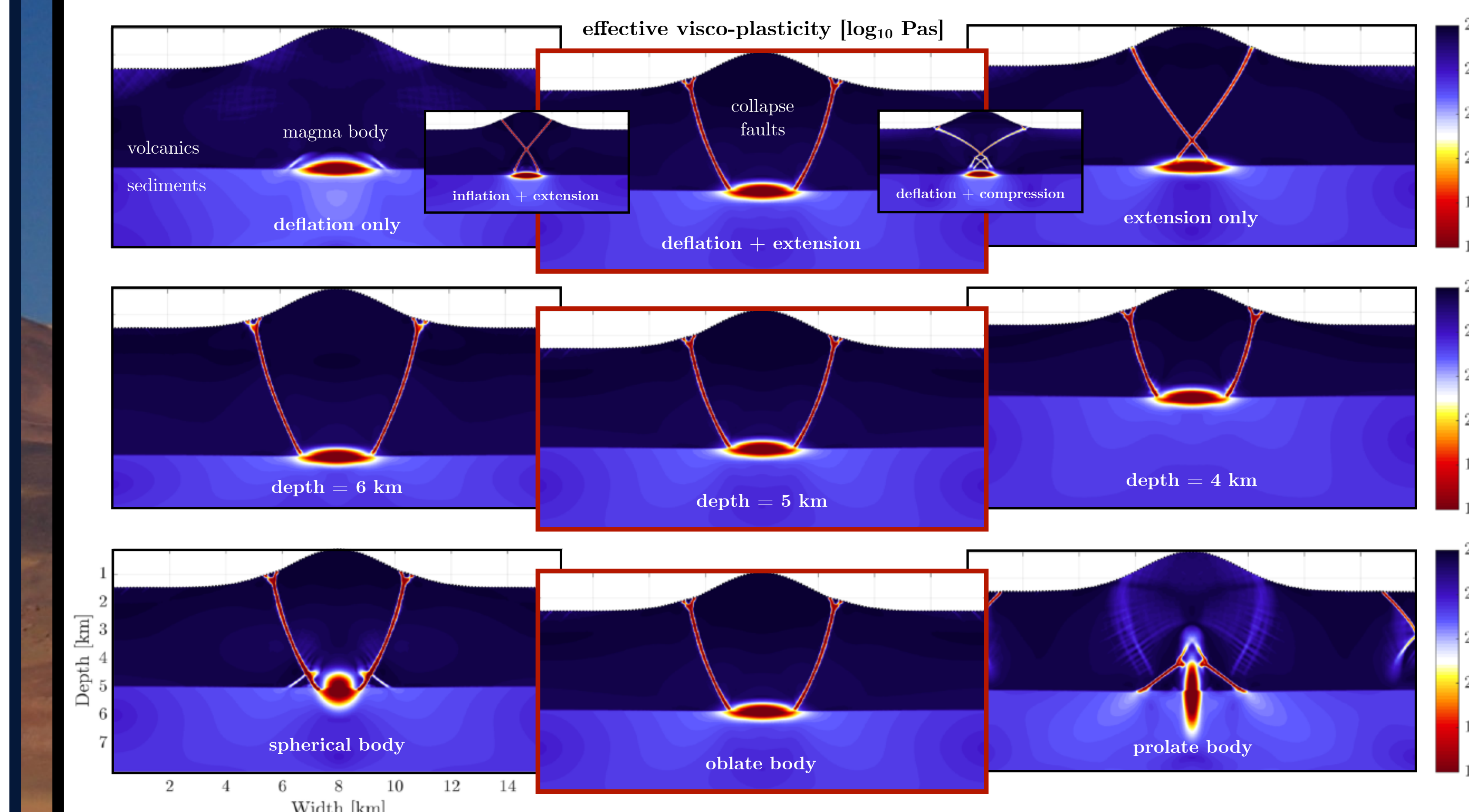
(2) **Volcano collapse faults** emerge around deflating magma body under the load of the stratovolcano edifice combined with regional tectonic stresses in the shallow crust.

(3) **Fe-rich liquids extrude** along collapse faults, initially driven by pressure of collapsing edifice but further enhanced by exsolution and decompression of magmatic volatile phase.



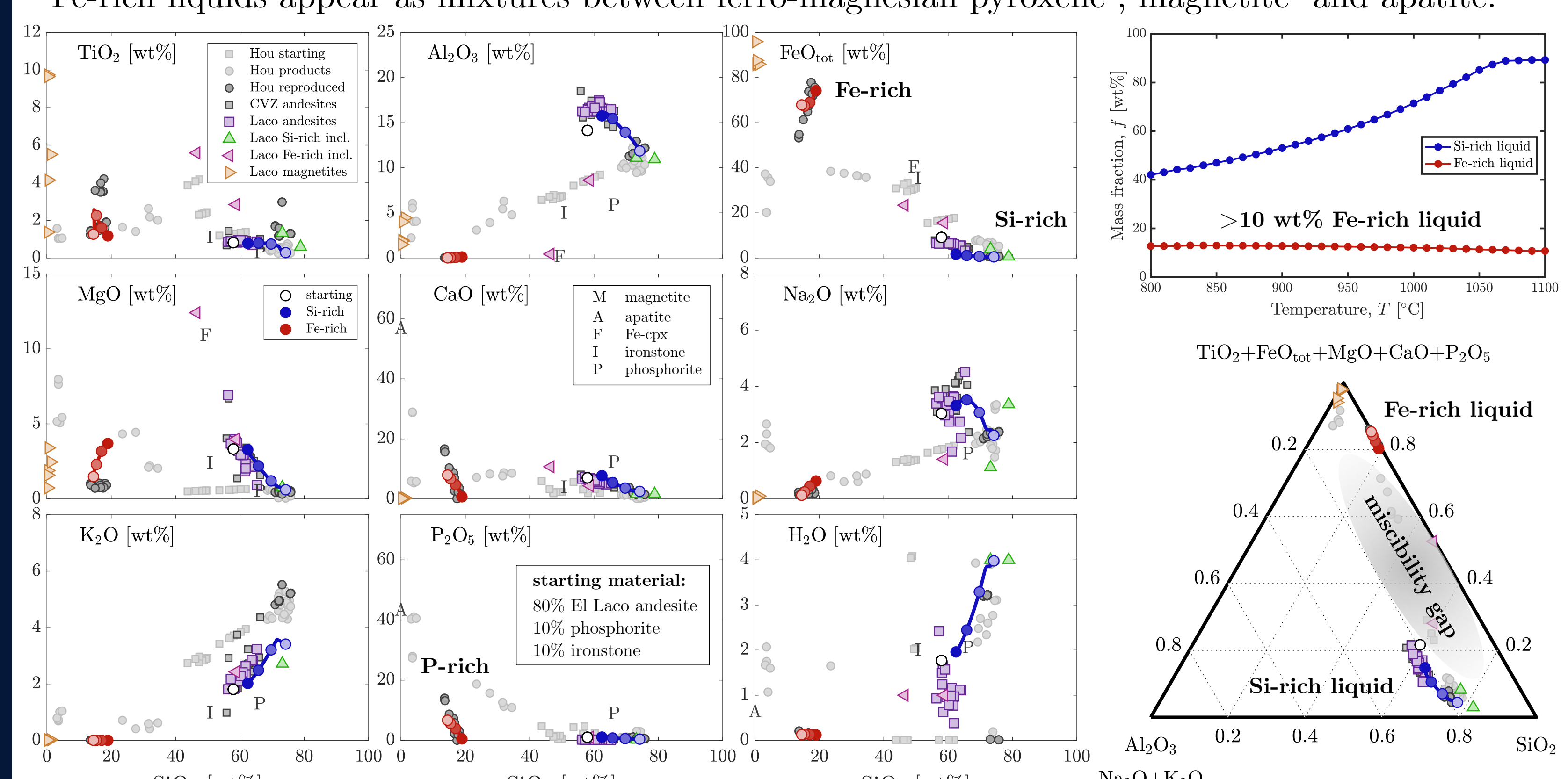
Collapse faults: rock deformation model

We model **visco-elastic/brittle-plastic Stokes flow** by 2-D **finite-element method**[9,10]; deflating body (magma) between stiffer upper (volcanics), weaker lower (sediments) layer; tectonic stress applied across domain. Results show that collapse faults provide fractured, permeable extrusion pathways connecting base of magma body with edifice flanks; best fit oblate body at 5 km, combining magma deflation (10^{-13} s^{-1}) and tectonic extension (10^{-15} s^{-1}).

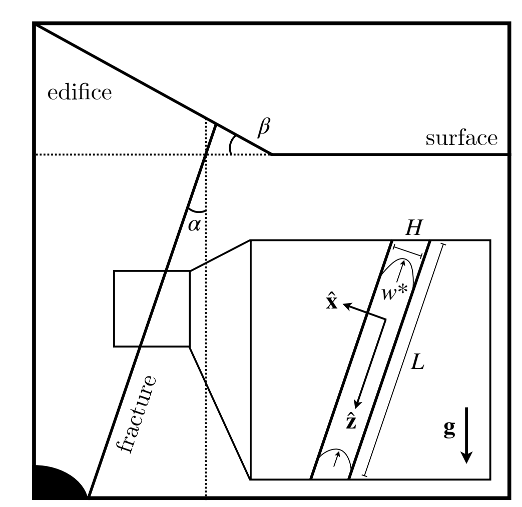


Melt immiscibility: thermodynamic model

We employ **alphaMELTS**[6,7] to reproduce experiments[8], test El Laco andesite[1] for immiscibility; Modelling predicts more extensive miscibility gap than observed; Si-rich liquids reproduced well; Fe-rich liquids appear as mixtures between ferro-magnesian pyroxene[2], magnetite[2] and apatite.



Volatile-driven extrusion: preliminary model



flow along inclined fracture

viscous stresses

$$\frac{\partial p^*}{\partial z} = \frac{\partial}{\partial z}\theta\frac{\partial w^*}{\partial z} + T2\theta w^*$$

gas expansion

$$\frac{\partial w^*}{\partial z} = B(1-\phi)\phi w^* + GR^{-1}\frac{(1-\phi)w^*}{1+B(1-\phi)z}$$

gas exsolution

$$\frac{\partial \phi}{\partial t} = \frac{\partial(1-\phi)w^*}{\partial z} + G(1-\phi)w^*$$

gas advection

positive feedback

Conclusion: Initial results support our new formation hypothesis. Petrological models show Fe-Si melt immiscibility consistent with experiments and melt inclusions. Mechanical models confirm collapse fault connecting base of magma body with edifice flanks. Moderate deflation consistent with thermal contraction sufficient combined with mild tectonic extension, which may have occurred on local NNW–SSE-trending faults within regional N-S-trending sinistral transpression. Preliminary analysis of volatile-driven extrusion suggests positive feedback leading enhancing extrusion along fracture once initiated by pressure of collapsing edifice. Volcanic emplacement of immiscible Fe-rich liquid may apply more generally to MtAp-deposits.

References: [1] Tornos et al., 2017; [2] Velasco et al., 2016; [3] Hildreth & Moorbath, 1988; [4] Moya et al., 2012; [5] Boso & Monaldi, 2008; [6] Ghiorso et al., 1983; [7] Asimow, et al., 2004; [8] Hou et al., 2018; [9] Kaus, 2010; [10] Keller et al., 2013.