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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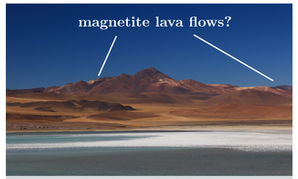
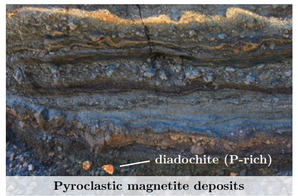
Magnetite-apatite (MtAp) deposits at El Laco



El Laco Volcano from SW


Magnetite phenocrysts lining vesicle walls


Degassing pipe in magnetite



Pyroclastic magnetite deposits

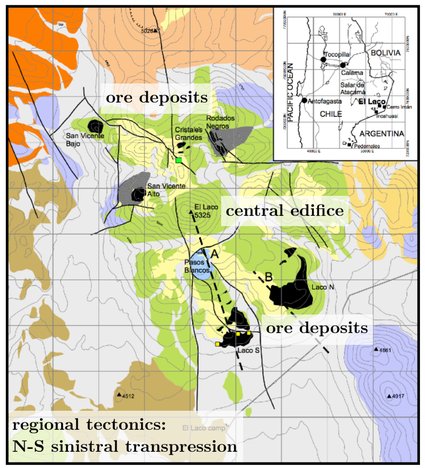

Vesiculated magnetite lava

Magnetite-supported breccia

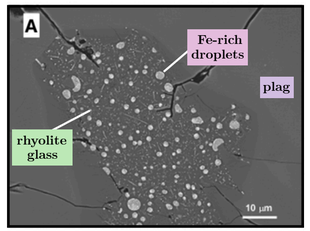
Geological context and observations

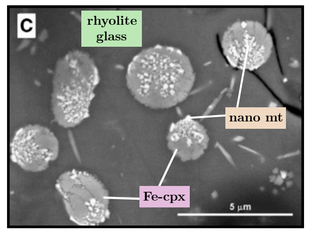
El Laco (ca. 3 Myr), **andesitic stratovolcano**, Central Volcanic Zone, Chile with **magnetite-apatite deposits** on its flanks. **Effusive to explosive volcanic emplacement**[1] indicated by lava flow textures, vesiculation, pyroclastics, degassing pipes, brecciation and alteration of host volcanics. **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]





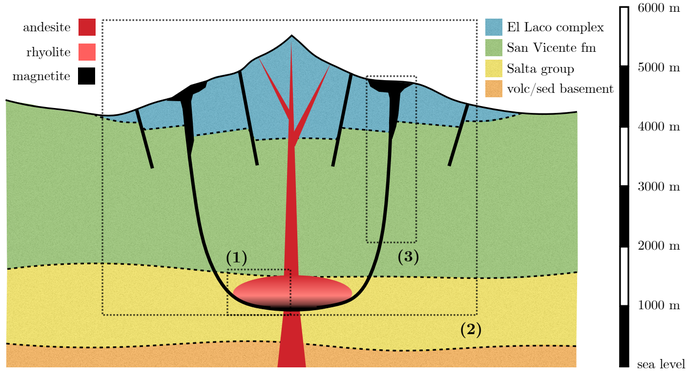
How can Fe-rich magmatic liquid form and erupt?

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.

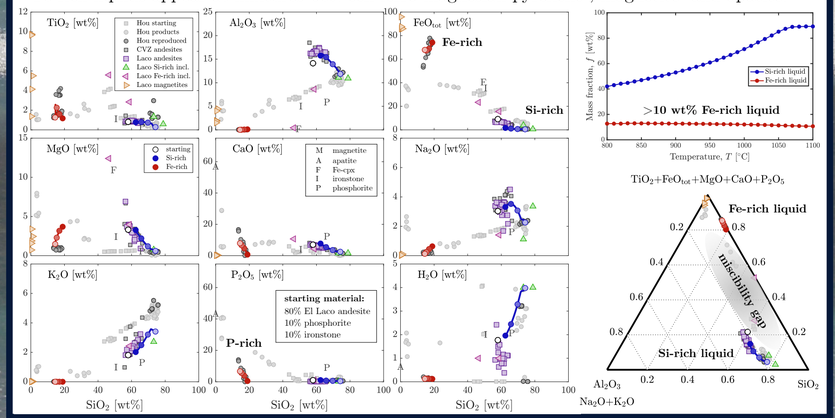
(2) **Volcano collapse faults** emerge around deflating magma body under the load of the stratovolcano edifice combined with regional tectonic stresses in the shallow crust.

(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.



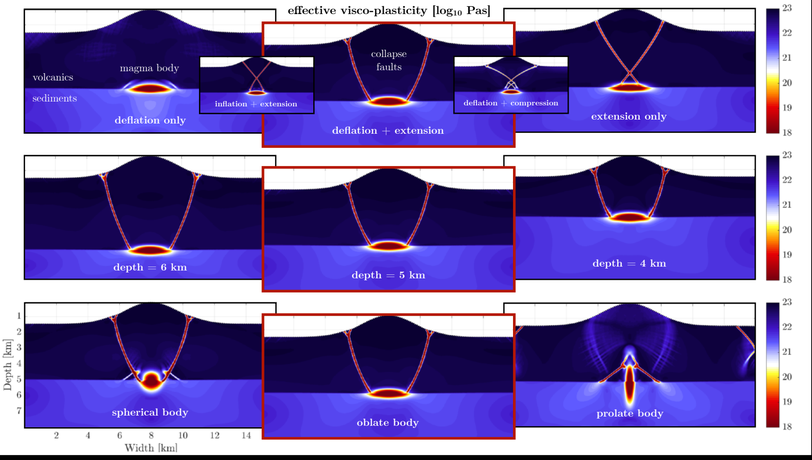
Melt immiscibility: thermodynamic model

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.

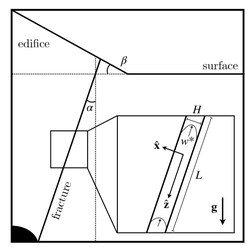


Collapse faults: rock deformation model

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}).



Volatile-driven extrusion: preliminary model



viscous stresses — flow along inclined fracture

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

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

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

gas expansion — gas exsolution — positive feedback — gas advection

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.