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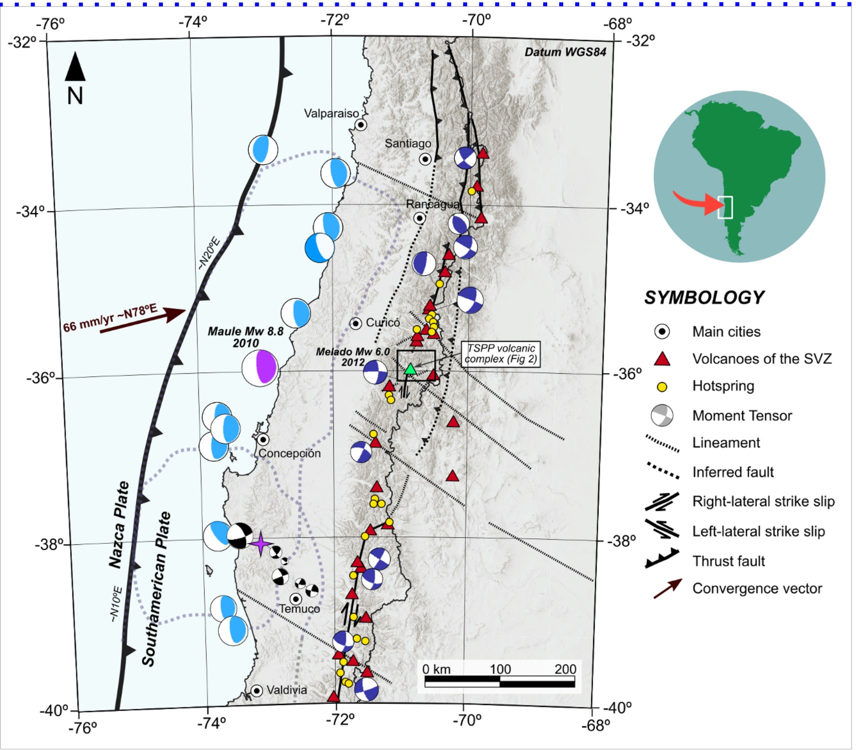
Faults and magma reservoirs along the Southern Andes Volcanic Zone (SAVZ): linking observations and numerical models of stress change controlling magmatic and hydrothermal fluid flow

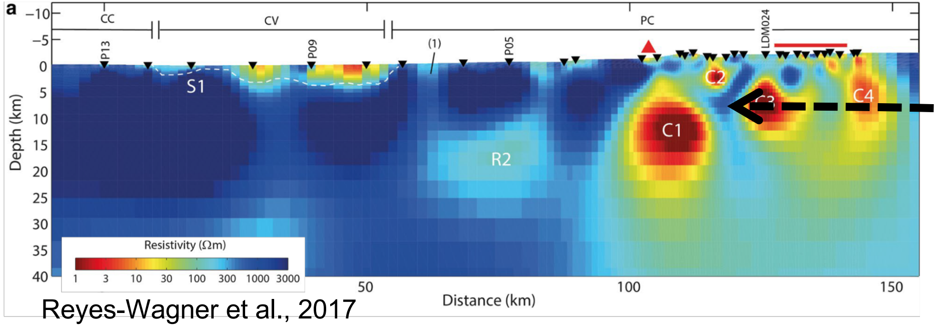


- Andean margin hosts >90 active volcanoes & >300 active geothermal systems.
- Dyking and volcanic activity spatially associated with fault zones, crustal earthquakes spatially and temporally related to volcanic activity.
- Many examples in the Andean margin!

What drives the interaction between magma reservoirs and fault systems over time-scales?

Field Case Study: Tatara-San Pedro-Pellado volcanic complex (36ºS)

- Pleistocene-Holocene volcanic complex (e.g. Singer et al., 1997)
- Dyking coeval with oblique slip tectonics (e.g. Sielfeld et al., 2019)



Reyes-Wagner et al., 2017

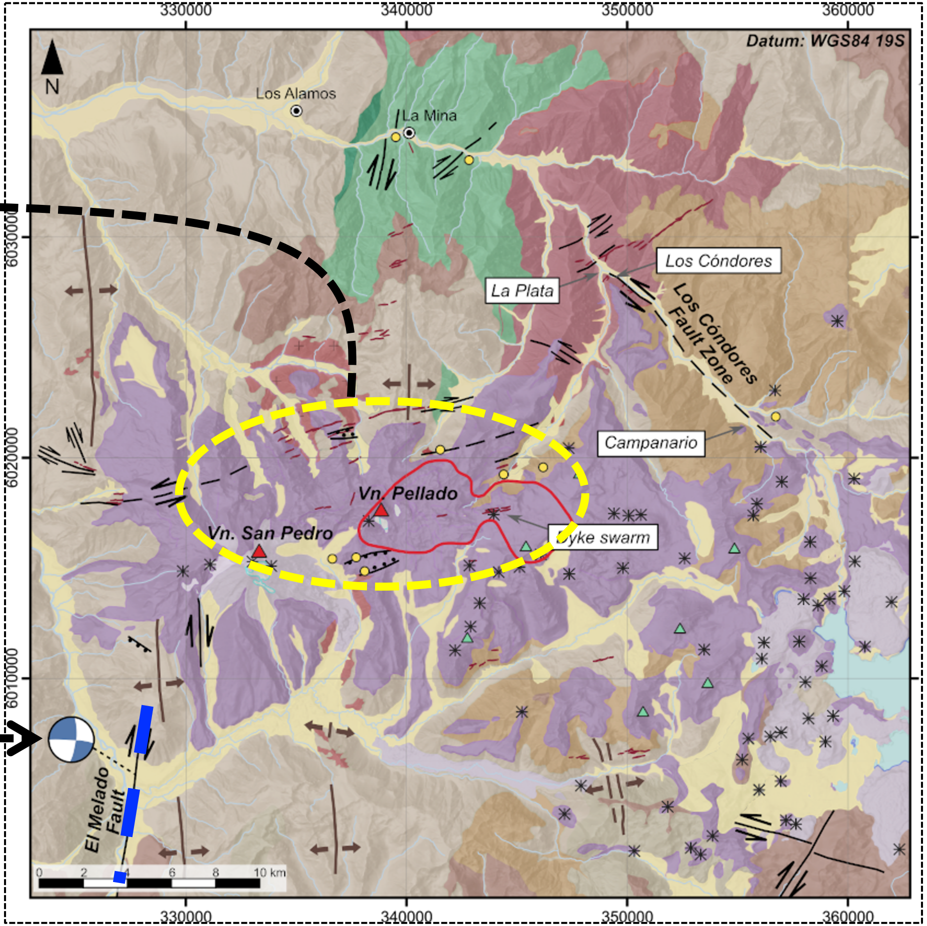
Crustal conductive anomalies indicate magmatic reservoir and active hydrothermal system.

Hickson et al., 2011; Reyes-Wagner et al., 2017

Active NNE-striking dextral fault (El Melado)

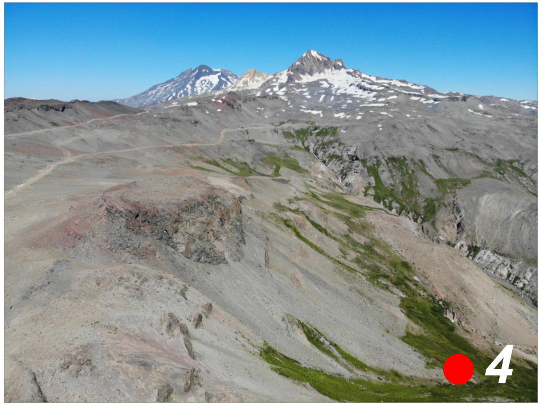
Cardona et al., 2018

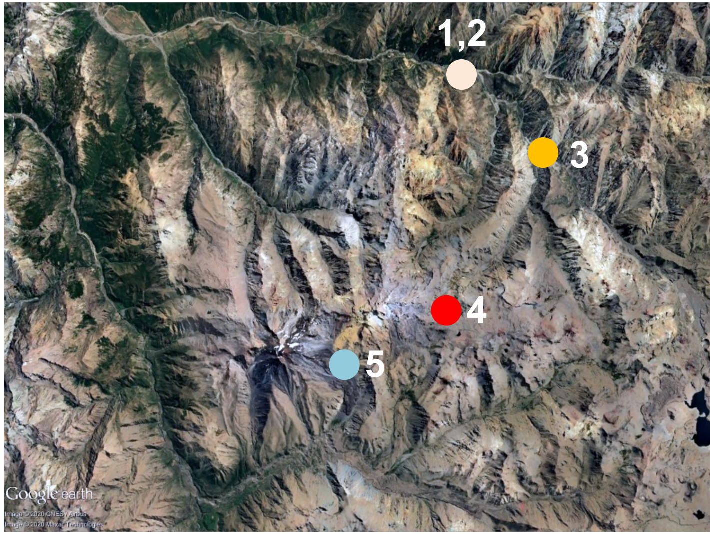
We simulate the interaction between an active fault and magmatic reservoir with 3D FEM.

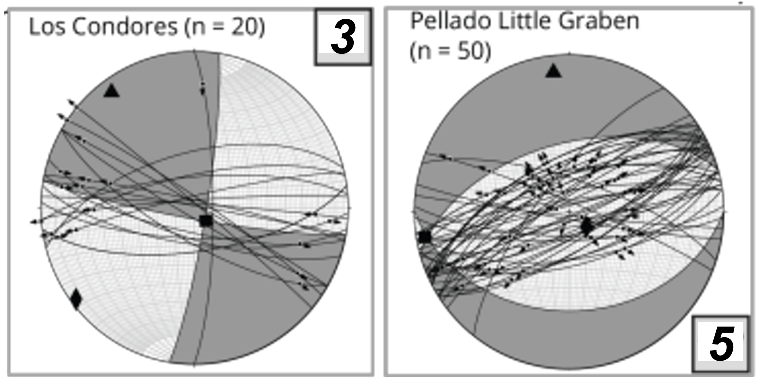


Modified from Sielfeld et al., 2019

Field Case Study: Tatara-San Pedro-Pellado volcanic complex (36ºS)







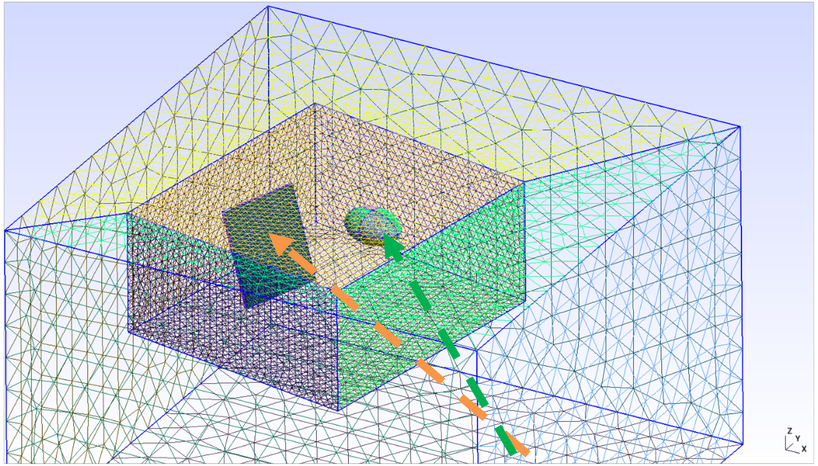
Kinematic analysis from fault slip data

Fault-hydrothermal vein networks, dykes, fault striae and paleostress and strain estimates ...

Numerical approach

Adeli3d, 3D FEM (Hassani et al., 1997, Gerbault et al., 2018)
- Dynamic relaxation method (Cundall & Board, 88)
- Drucker-Praeger non-associated elasto-plasticity.

Bedrock domain ~ 50^3 km^3 ~ 200k mesh elements
Fault zone ~ 10x10x0.3 km at ~2km depth
Magma cavity ~ shallow oblate, center at 6 or 10 km



Tested "mesoscale" rheological properties:
Bedrock & Fault zone: **E** (Youngs' modulus), **T-C** (tension & cohesion), φ (friction)

CONFIGURATION 1: Applied fault zone dextral (hanging wall southward) displacement induces deformation in the surrounding rock volume, potentially affecting the stability of a magma-filled cavity.

- **How much fault displacement is required to trigger failure at cavity walls in the intervening bedrock? Which mechanical properties characterize the bedrock intermediate volume?**

CONFIGURATION 2: Applied over-pressure (DP) from magma-filled cavity deforms the surrounding rock volume and potentially triggers displacement along a nearby crustal fault.

- **How much magma overpressure triggers fault displacement? Where does dilation occur?**

RESULTS

CONFIGURATION 1 : Applied fault zone dextral (Southward hanging wall) displacement

- 10 configurations tested
- Effect on a shallow cavity at 6 km depth

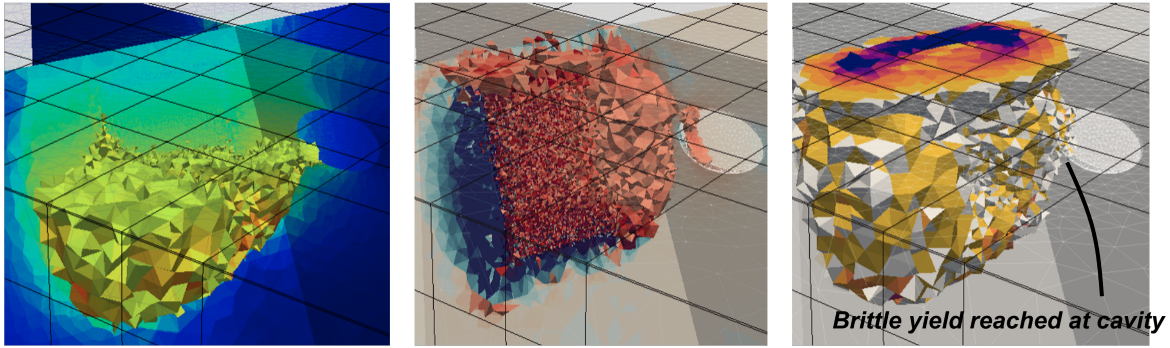
CONFIGURATION 2 : Applied over-pressure from magma-filled cavity at 6 km and 10 km depth.

- 10 configurations tested
- Effect of over-pressure from a shallow cavity on a crustal fault
- Effect of over-pressure from a deep cavity on a crustal fault

For each configuration, we evaluated the following:
Shear stress + volumetric dilatational strain + plastic strain +
maximum compressive principal stress

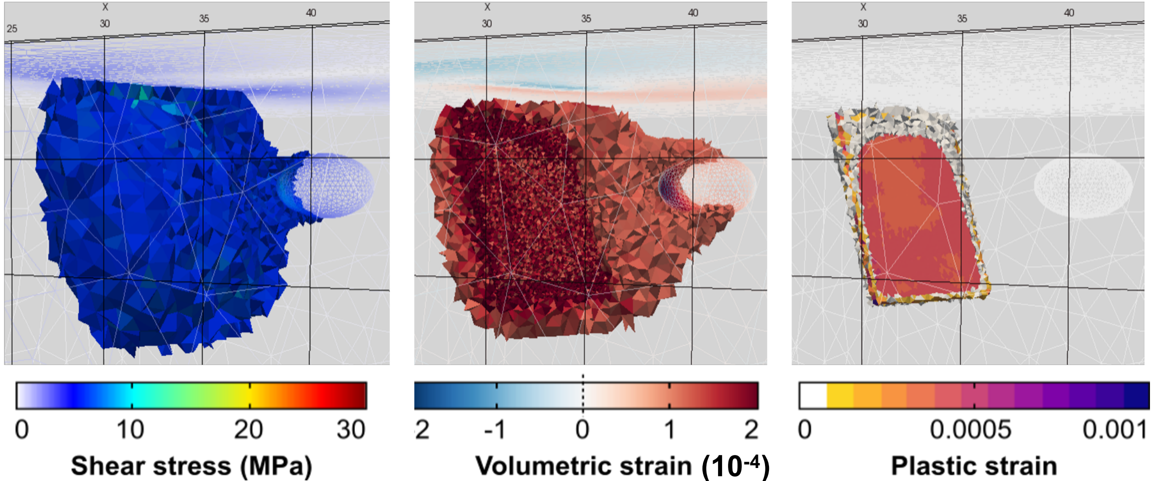
CONFIGURATION 1 : Applied fault zone dextral (Southward hanging wall) displacement

CFVF1: E=40 GPa, T-C=2-5 MPa, φ = 1°



- Most favorable condition for cavity failure after 20 m fault displacement ***(hence cumulated EQ/aseismic slip)***
- High E requires less fault displacement for cavity failure (more stress propagates further).
- Very low frictional strength eases cavity failure.

CFVF5: E=1 GPa, T-C=2-5 MPa, φ = 1°

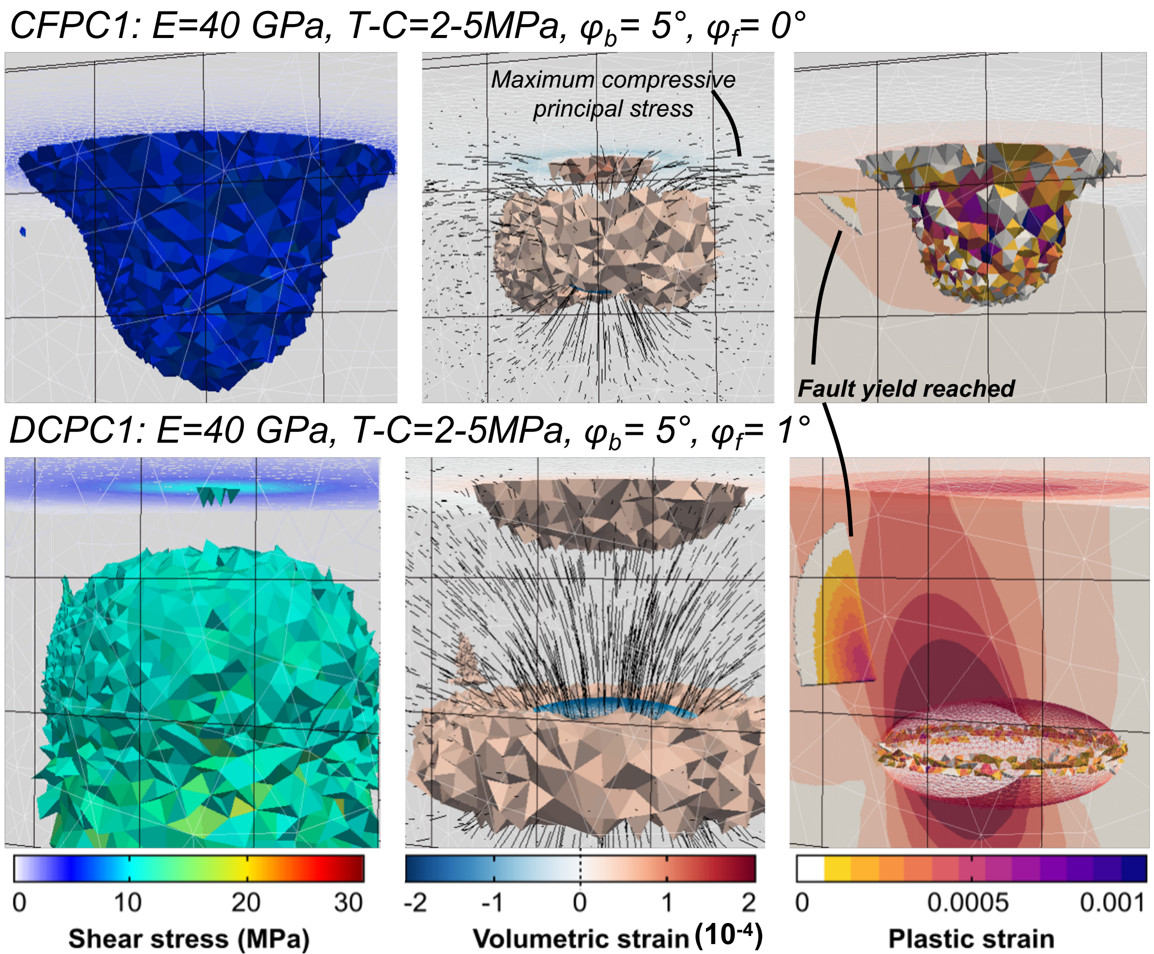


- **BUT! Even if cavity walls do not fail,** dilatational elastic strain affects the rock mass $\Delta \sim 10^{-5}$-10^{-4} (increases with 1/E)
- This dilation opens porosity and eases percolation of magmatic/hydrothermal fluids up to the surface!
- Next step, estimate volume available for inflowing fluids given a reference porosity, eg. :

$$dV_p \approx \phi_0 \int_{\Omega} \varepsilon_v d\Omega = 0.0004km^3$$

$$\Omega : x \in \Omega \mid \varepsilon_v(x) \geq 1 \cdot 10^{-5}$$

CONFIGURATION 2 : Applied over-pressure DP from magma-filled cavity



- Fault displacement (<5m) occurs for DP>40MPa, along with surface failure above the cavity.
- High E & high frictional strength of bedrock requires less DP for fault displacement.
- Extremely low strength of fault zone (ϕf~0!) is required.
- Diffuse volumetric dilatational strain reaches $\Delta \sim 2x10^{-5}$

- **What if the cavity is deeper & larger?** Rheological conditions are less restrictive.
- Elastic dilation of fault zone for DP~15MPa,
- Brittle failure occurs for DP~22MPa.
- Values in the range of worldwide estimates.
- Should be easily recoverable from geodetic measurements.

CONCLUSIONS

CONFIGURATION 1

- Depending on rock strength, tens to hundreds of meters of accumulated fault displacement can trigger sufficient dilation and magma reservoir failure within a lateral distance of 4 km.
- If all displacement is regarded as accumulated seismic slip, ~10-10^2 Mw 7 earthquakes would be required to trigger magma reservoir failure.
- Most likely, a combination of both seismic and aseismic slip are needed to achieve failure and open pathways for magmatic & hydrothermal fluids to the surface in timescales of several thousand years.
- Mesoscale elastic dilation without rock failure, is capable to open pore space and appears efficient in this fluid transfer.

CONFIGURATION 2

- It is difficult or impossible for an upper crustal magma inflation to trigger fault displacement located even 3 km away.
- However a mid-crustal magma inflation very easily breaks surface faults: good player!

CONCLUSIONS

- Other Andean volcano-tectonic systems: Cordón-Caulle, Callaqui stratovolcano, Villarrica stratovolcano, etc

- Crustal scale poro-elasto-plastic tectonics are coupled with magmatic reservoirs to open pathways for deep fluids towards the surface (no need of viscous compaction nor large scale extension)

- The long-term regional transpressive stress field also contributes and eventually affects these threshold values (eg. Iturrieta et al., 2017, Stanton-Yonge et al., 2019): there is a need to further evaluate relative contributions.

- Future work includes two-phase flow modeling and model/field work comparisons in order to better estimate the volumes of fluid transfer via diffuse vs. localized volumetric & shear strain, to feed into geothermal potential and volcanic risk assessment.

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