A 3-D, Technicolor Zombie: Joint Analysis of Multidisciplinary Geophysical and Geochemical Data at Uturuncu Volcano, Bolivia Reveals Active Hydrothermal System and Possible Sulfide Deposition

Patricia MacQueen[1], Thomas Hudson[2], Ying Liu[3], Elizabeth Eiden[1], Karissa Rosenberger[4], Scott Henderson[5], Matthew Comeau[6], Joachim Gottsmann[7], Matthew Pritchard[1], Michael Kendall[2], Martyn Unsworth[8], Tobias Fischer[4], and Jonathan Blundy[2]

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Abstract

Uturuncu volcano in southern Bolivia is a member of a distinctive class of volcanoes – systems that show unrest despite not having erupted in the Holocene. Uturuncu has not erupted in 250 kyr, but has been deforming (uplift with a moat of subsidence) for several decades, along with seismic swarms and active, sulfur-encrusted fumaroles. Our work builds on previous geophysical imaging at Uturuncu by jointly analyzing multidisciplinary datasets, focusing on imaging the shallow (<15 km depth below surface) structure of the system with geophysical and geochemical data. Whereas previous research pointed to andesite melt at depths >15 km depth, results were ambiguous as to what proportions of melts vs. brines are present at shallower depths. Identifying fluids (melt, brine, etc.) and structures at shallow depths is key for evaluating the hazard potential of the volcano and understanding the source of the unrest. We present new results from gravimetry, seismology (hypocenter relocation, seismic velocity and attenuation tomography), gas geochemistry, and InSAR observations. The results point to an extensive and active hydrothermal system extending ~20 km laterally and ~10 km vertically from Uturuncu, with possible connections at depth to the deeper magmatic system. A combined view of the new density, seismic velocity and attenuation models, and the existing resistivity model is crucial for revealing key features of the hydrothermal system: a vapour-rich conduit beneath Uturuncu (low resistivity/high attenuation column extending from 1.5 to 12.5 km depth), an extensive alteration zone surrounding Uturuncu (complex zone of annular shaped anomalies surrounding Uturuncu from 1.5 to 12.5 km depth), and a possible zone of sulfide deposition just below the western flank of Uturuncu at 1.5 km depth (high density/low resistivity/high attenuation). High fluxes of diffuse CO2 degassing at sub-magmatic temperatures and a small area directly above a low resistivity anomaly subsiding from 2014 to 2017 show that the hydrothermal system is currently active. Analyzed jointly, this multidisciplinary data set suggests that current activity within the shallow structure at Uturuncu is dominated by hydrothermal, rather than magmatic processes.

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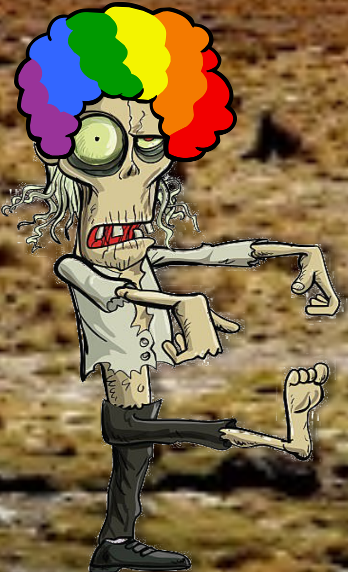
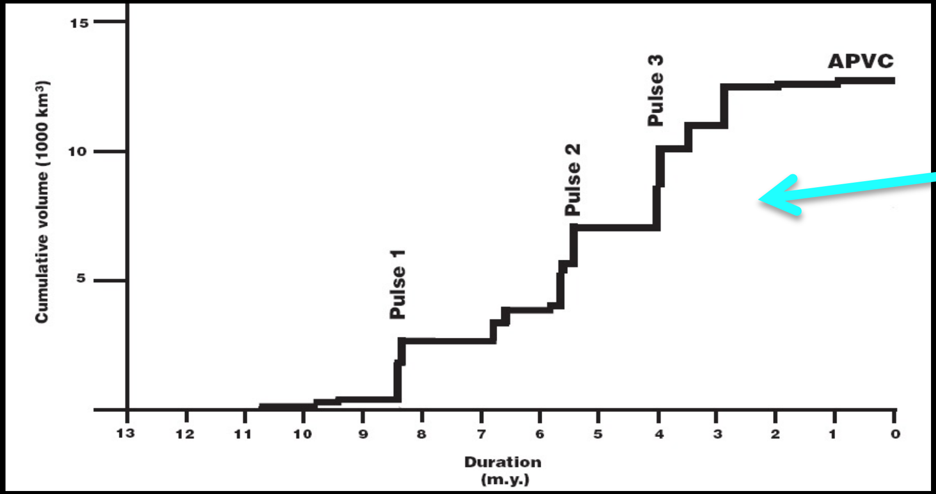


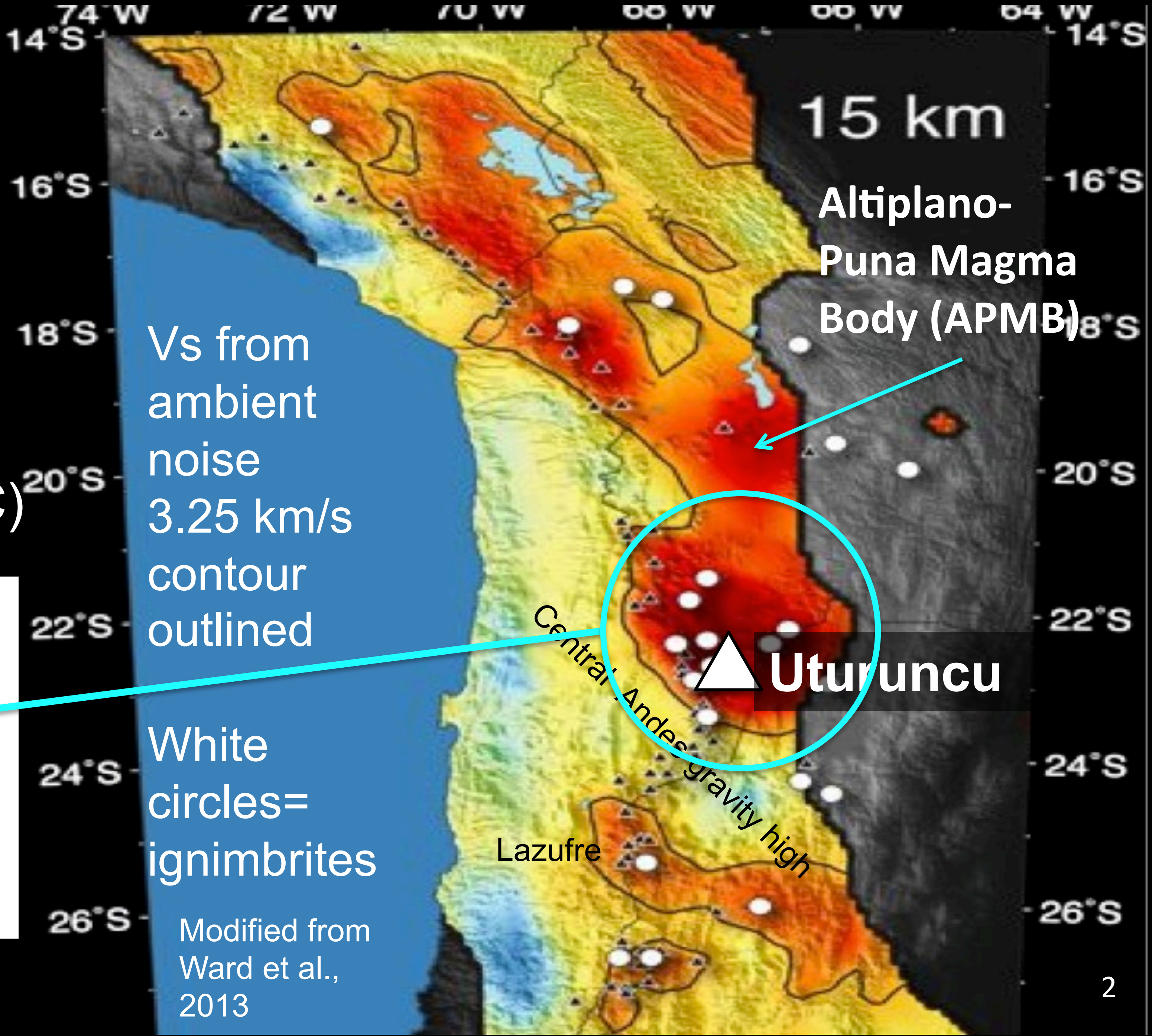
Zombie Cartoon: Anton Brand
Wig: Club Penguin Rewritten

Central Andes: Ignimbrite flare-up & Crustal partial melt from geophysics

Ignimbrite erupted volume:
Altiplano-Puna Volcanic Complex (APVC)



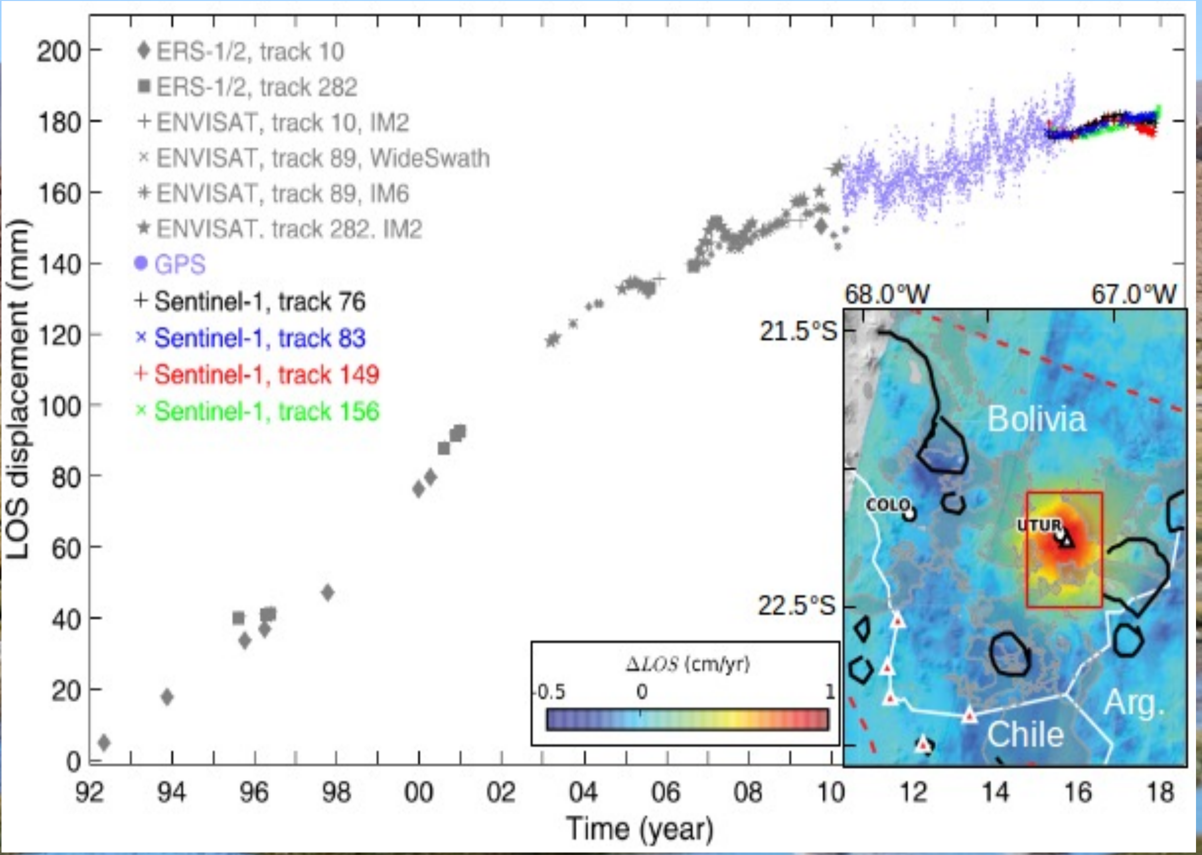
From: Salisbury et al., 2010



Uturuncu, Bolivia

Dormant for ~250,000 years (Muir et al., 2015)

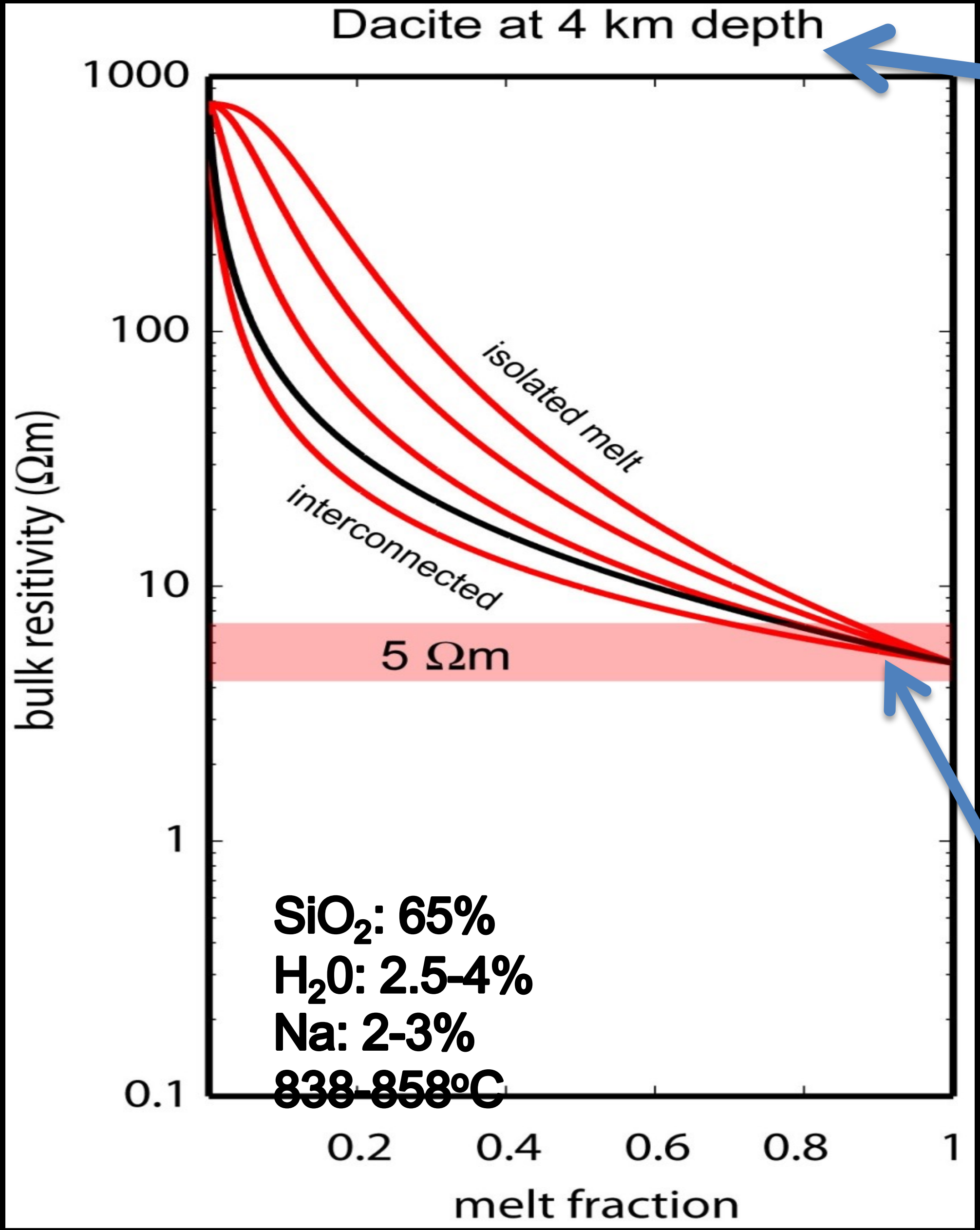
Deforming for ~50 years! (Gottsmann et al., 2018)

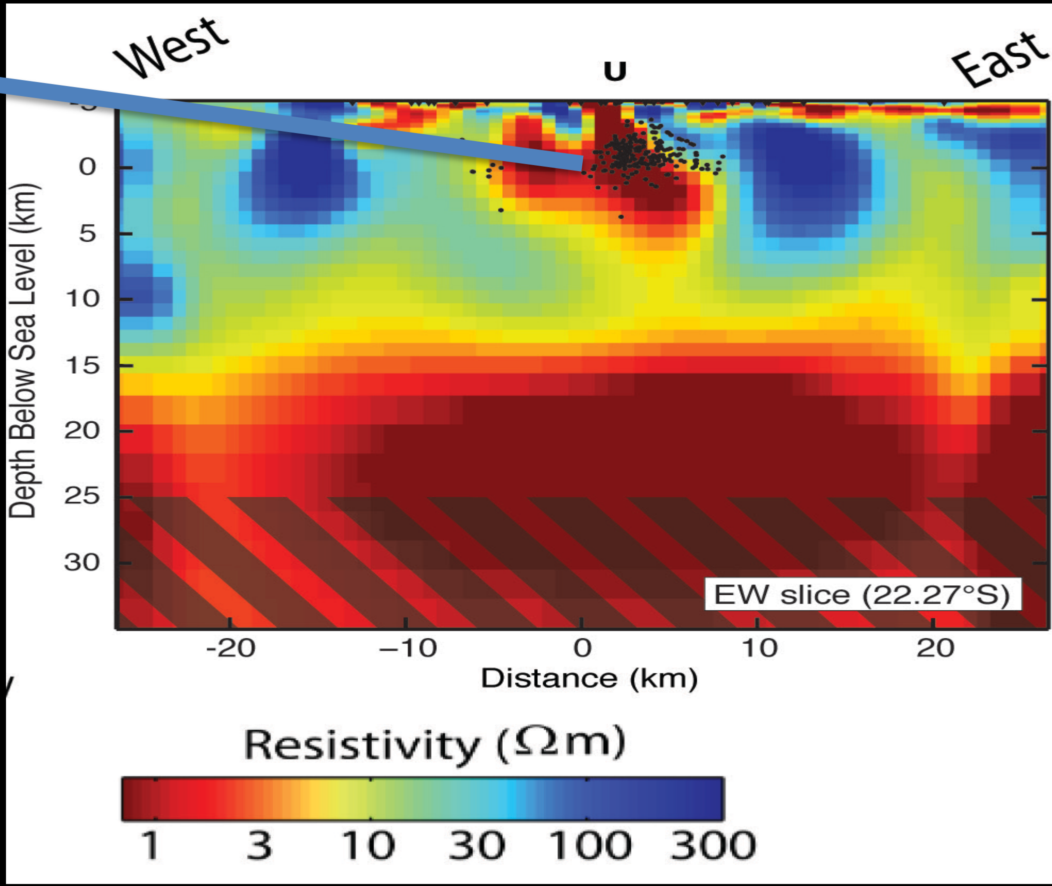


(Lau et al., 2017; Henderson and Pritchard, 2013, 2017)

Photo by Tom Fournier

Melt and Brines Beneath Uturuncu

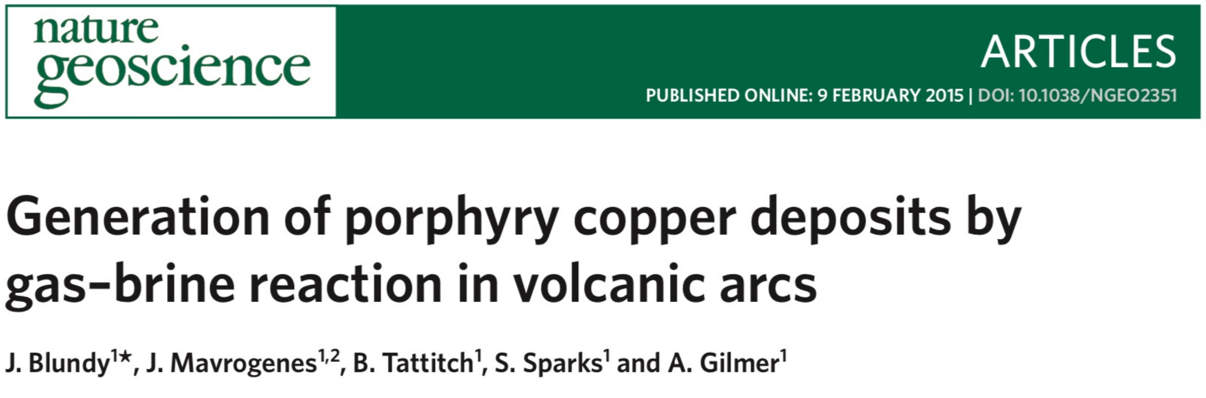




Brine needed!!

Comeau et al., 2015; 2016
Lamonier et al., 2016
Geochemical data from
Muir et al., 2014, 2015;
Sparks et al., 2008

Brine lenses and ore formation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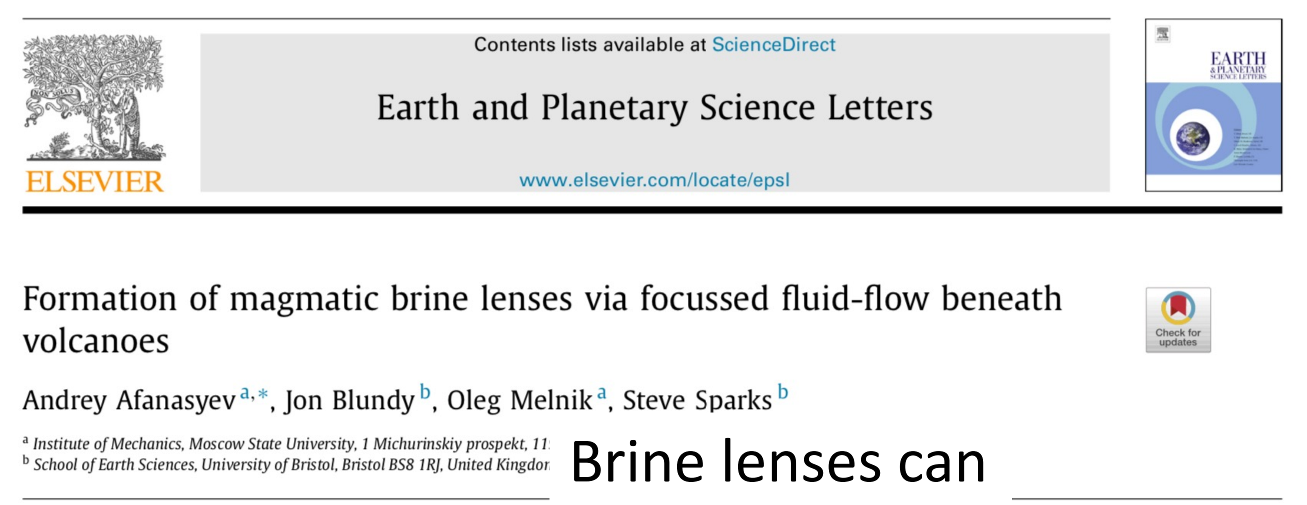
Generation of porphyry copper deposits by gas–brine reaction in volcanic arcs

J. Blundy[1*], J. Mavrogenes[1,2], B. Tattitch[1], S. Sparks[1] and A. Gilmer[1]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Formation of magmatic brine lenses via focussed fluid-flow beneath volcanoes

Andrey Afanasyev[a,*], Jon Blundy[b], Oleg Melnik[a], Steve Sparks[b]

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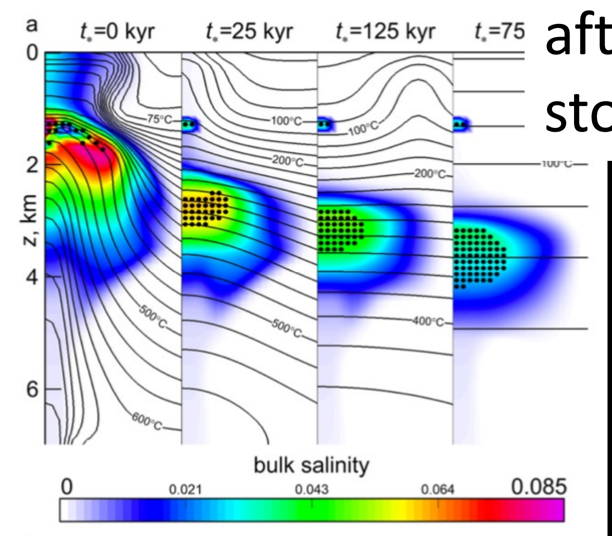
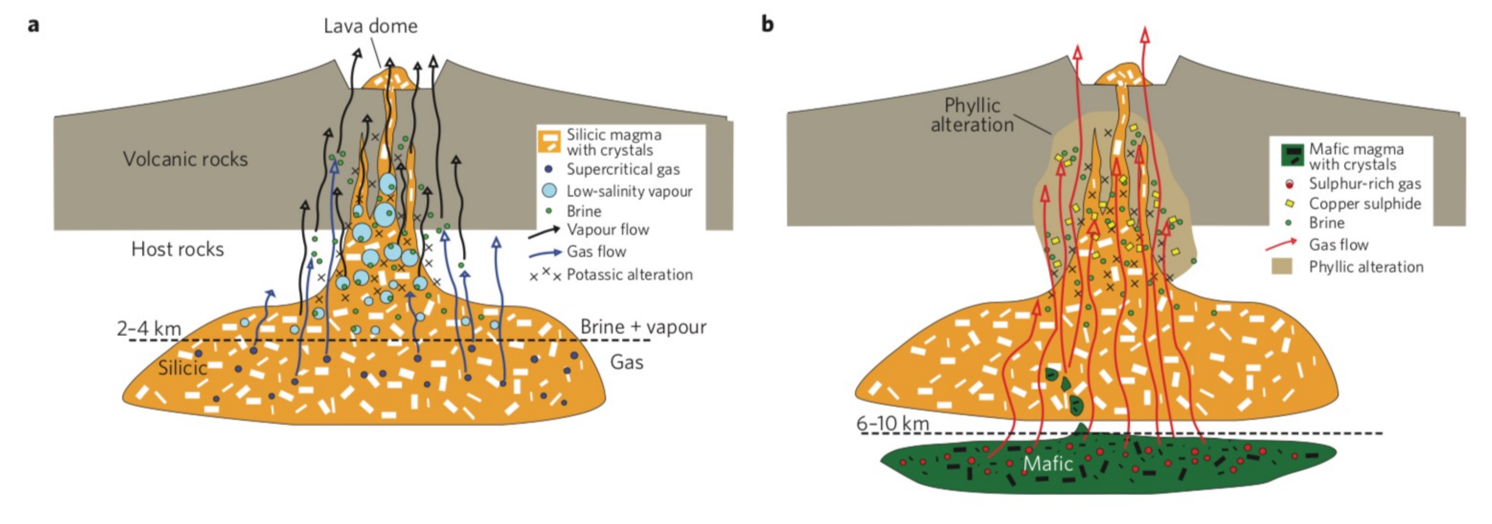
Pulses of brines and gasses could create ore deposits

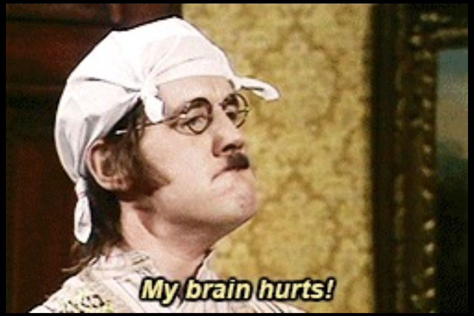
Brine lenses can persist long after degassing stops





The geology problem

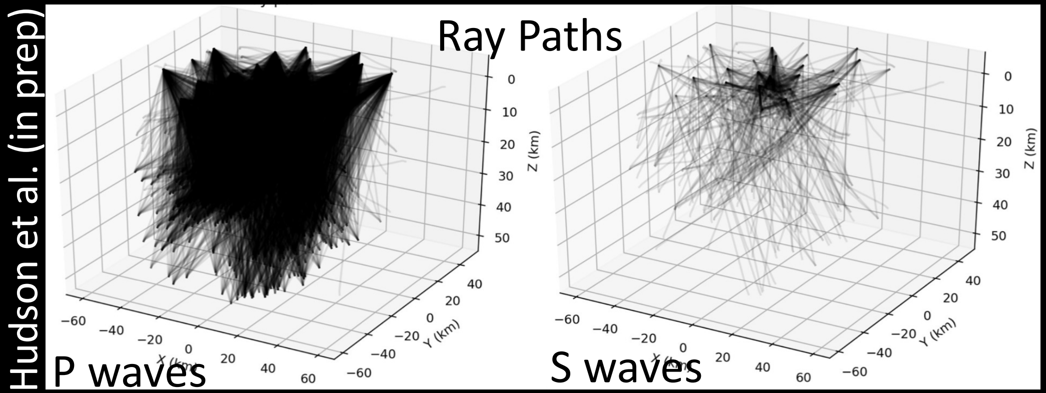
- What's driving unrest at Uturuncu?
  - Long repose interval
  - Previously unobserved post-eruptive process?
    - hydrothermal activity ± magma crystallization ± ore formation?
    - Depth is key!
- What's DOWN there, anyway??
  - Partial melt?
  - Saline fluids?
  - Crystallized pluton?
  - Mature ore body?



Geophysical and Geochemical data at Uturuncu

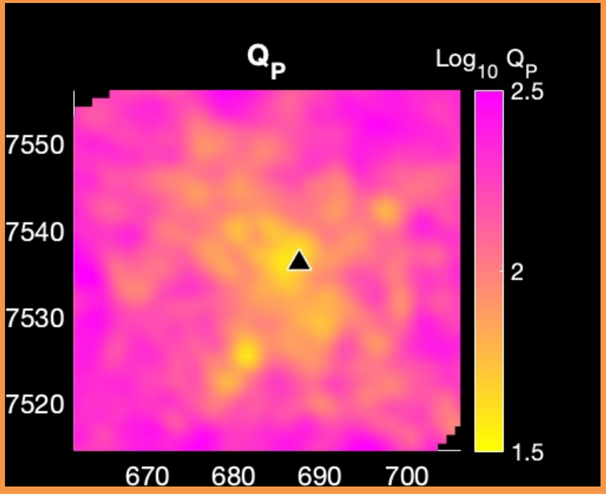
- Resistivity model (Comeau et al., 2016)
- Density model (MacQueen et al., 2021)
- NEW seismic tomography models (Liu et al., in prep)
- NEW seismic attenuation model (Hudson et al., in prep)
- InSAR - Uplift currently waning, subsidence moat gone (**See poster V15H-0144**; Eiden et al. 2022, in prep)
- Gas geochemistry (Tobias Fischer) – sub-magmatic temperatures (250°C)
- Time-lapse gravity – minimal mass change 2010-2013 (Gottsman et al., 2017)

NEW seismic tomography models

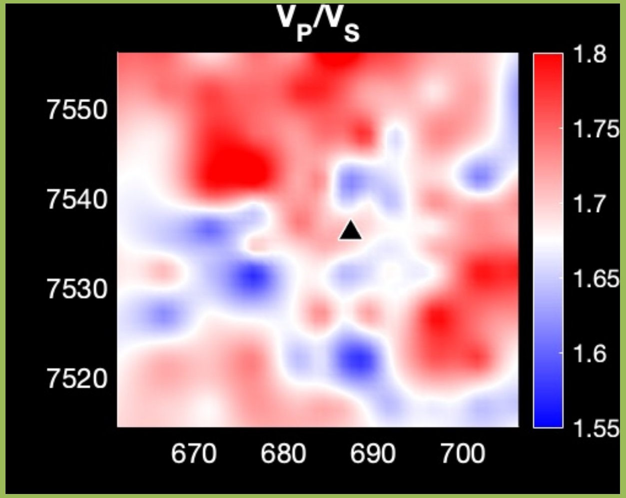


- Using updated seismic catalog from Hudson et al. (2022)
  - Two deployments 2009-2012, 42 stations
  - ~2000 local earthquakes (Mw 0 to 3.5)

3-D P-Wave Attenuation Tomography (Hudson et al, in prep)



3-D Velocity tomography (Liu et al, in prep)



← Direct inversion for Vp/Vs (Guo et al., 2018)

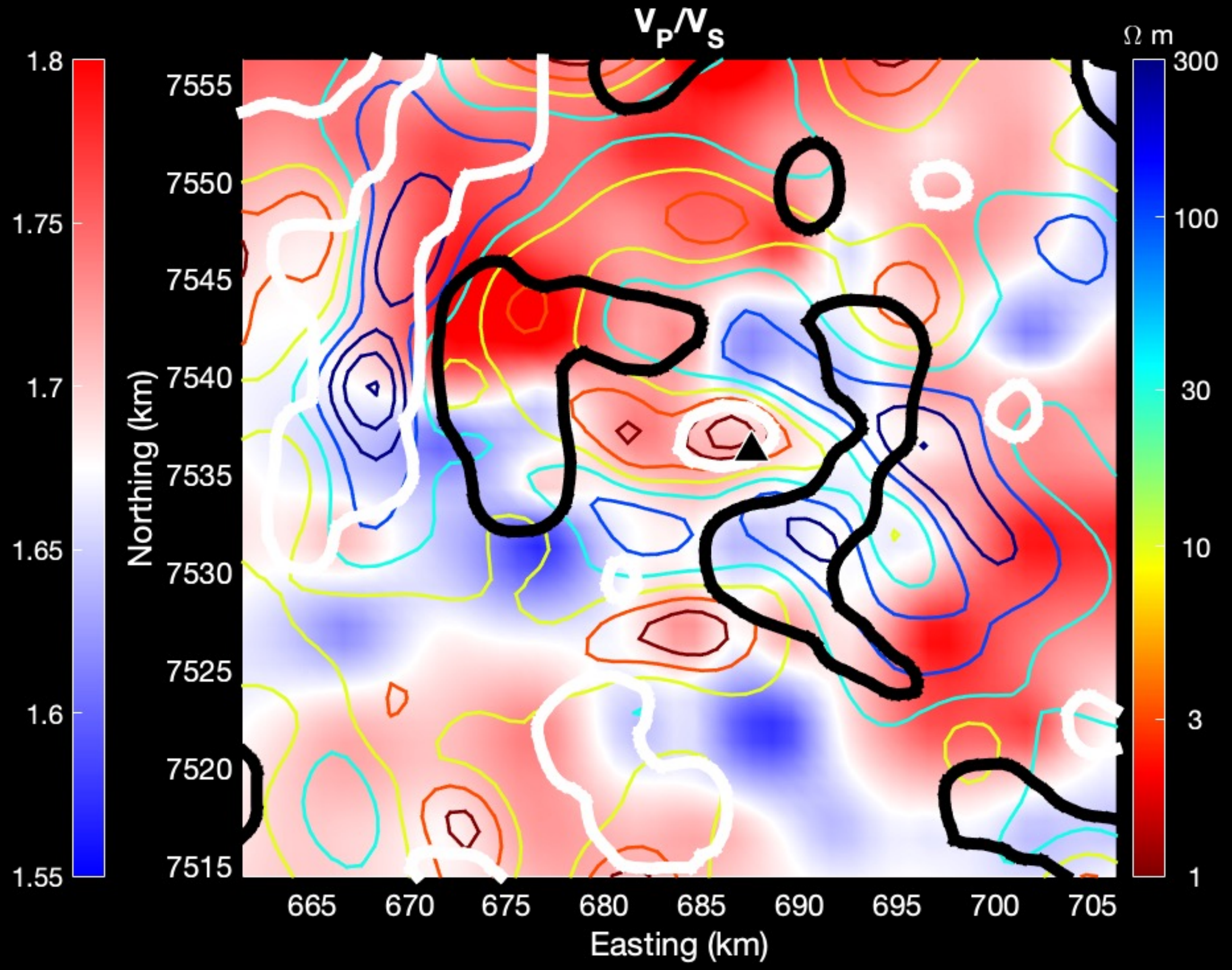
Slices at 1 km. above sea level

The data problem

- Interpretation: How to translate geophysical properties to geology?
  - One property: Ambiguity!
  - Ex: Low resistivity = brines/metallic minerals/clays
  - More properties: less ambiguity!
- How to meaningfully combine (six!) geophysical models without being overwhelmed?

Overlaying models/Co-rendering

Slices at 1 km. above sea level



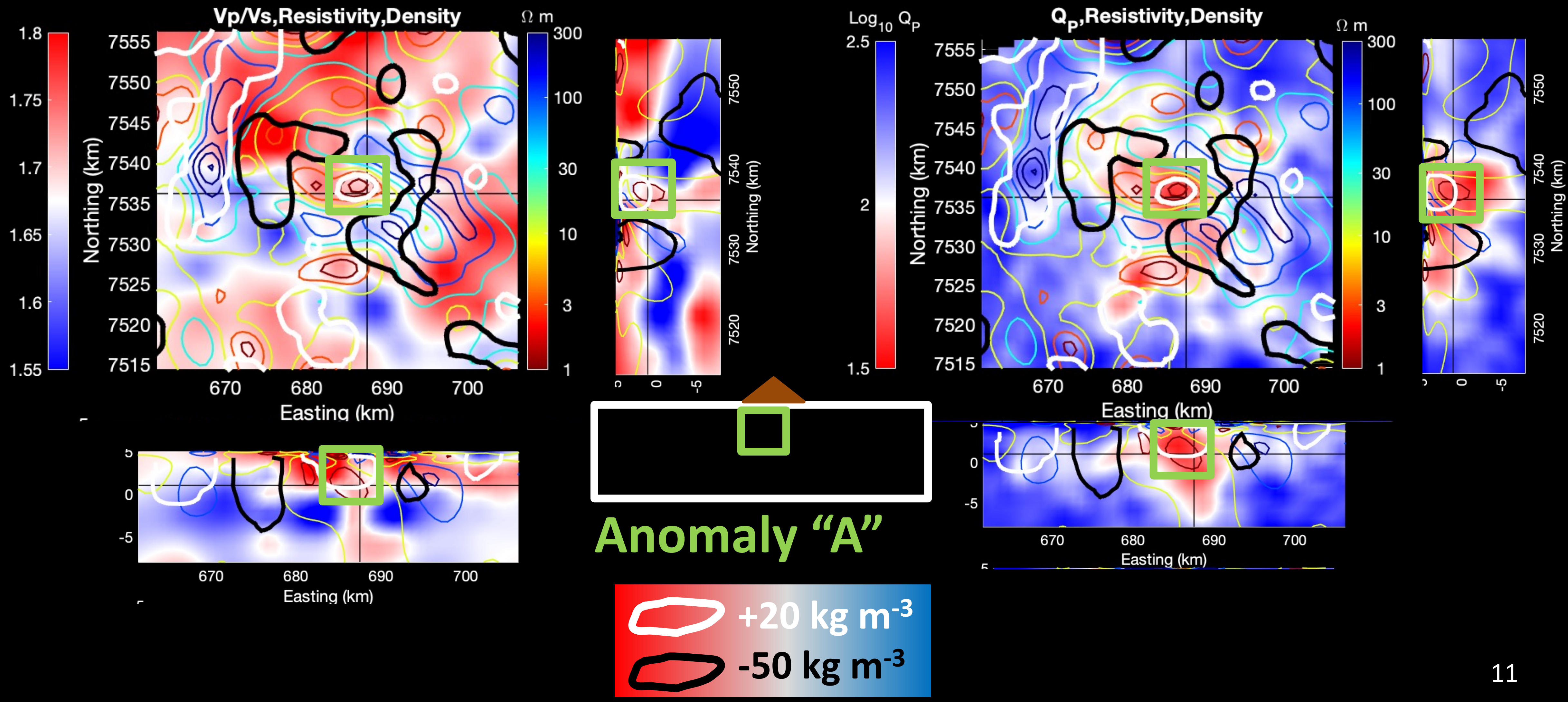
Density contours:

Positive anomalies: +20 kg m^{-3}

Negative anomalies: -50 kg m^{-3}

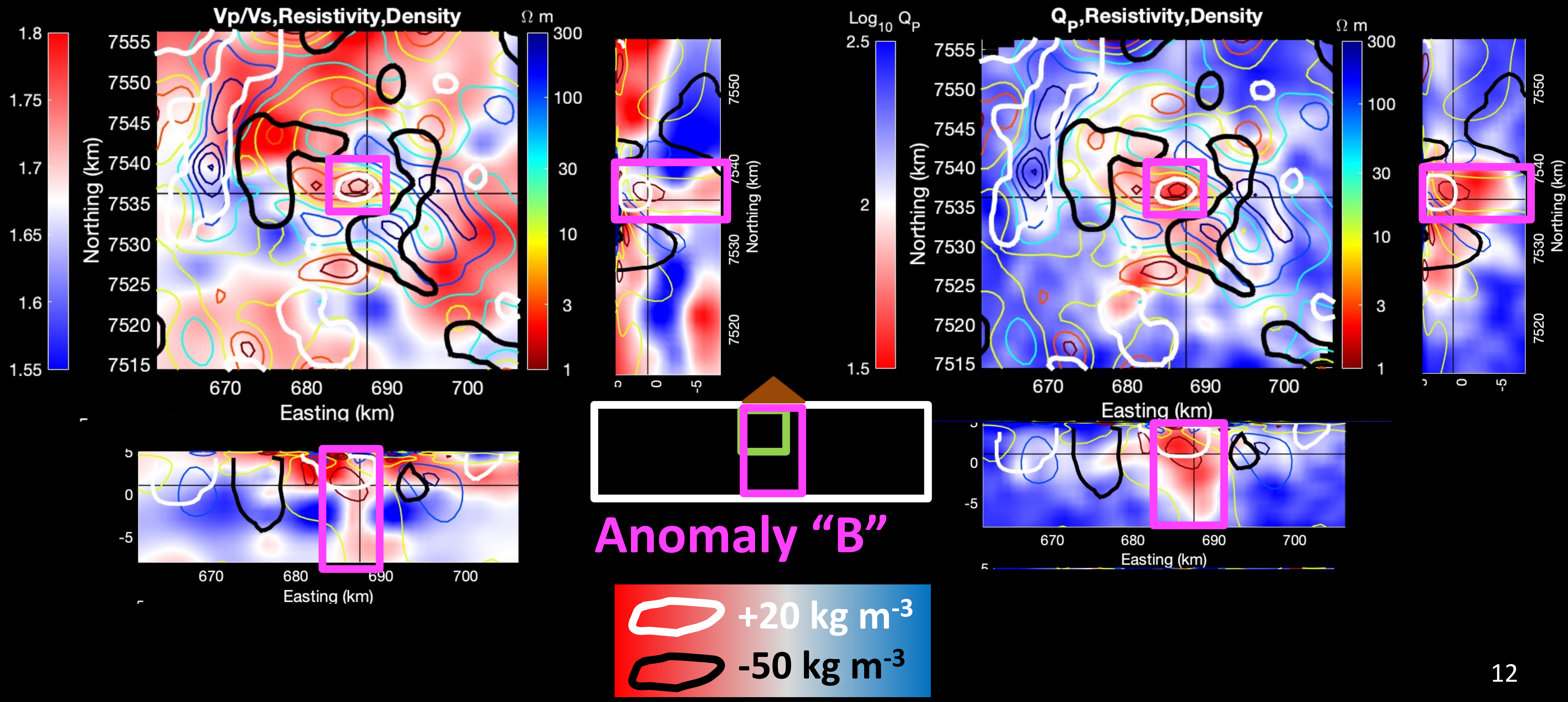
Identifying common anomalies

Slices at 1 km. above sea level



Identifying common anomalies

Slices at 1 km. above sea level



What can we learn from qualitative analysis?

Anomaly A

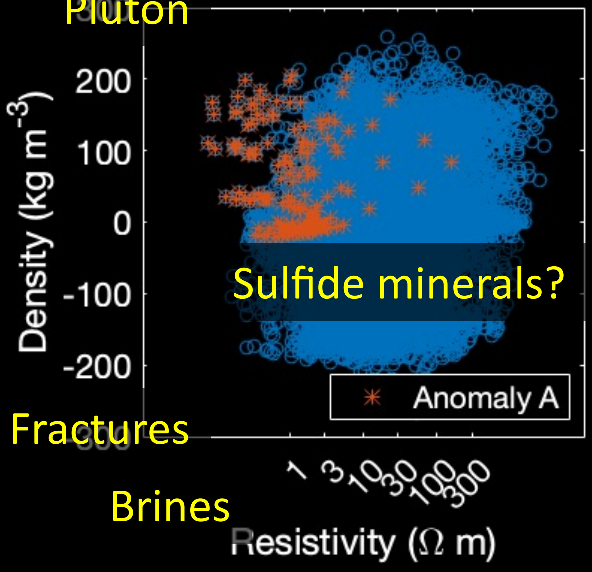
Saturated cracks

Sulfides + (not a lot of) brines

Dry cracks

Brines/Sulfides

Pluton



Sulfide minerals?

Fractures

Brines

Sulfides + brines?

Fractures/fluids

Brines/Sulfides

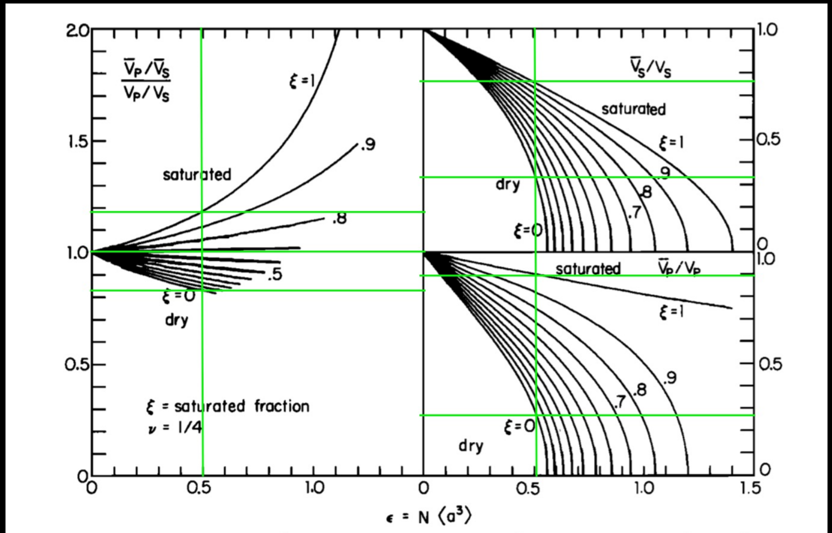
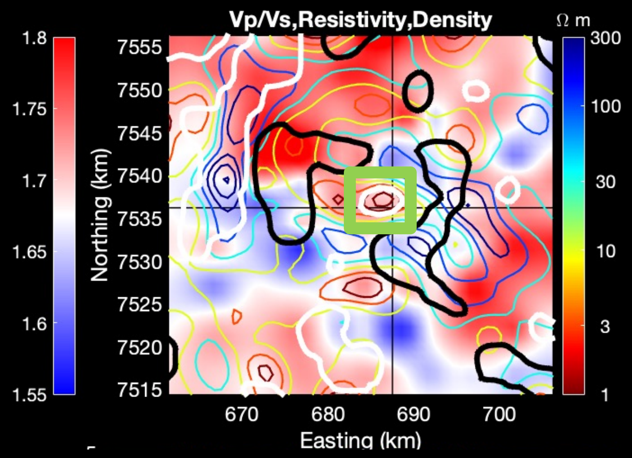
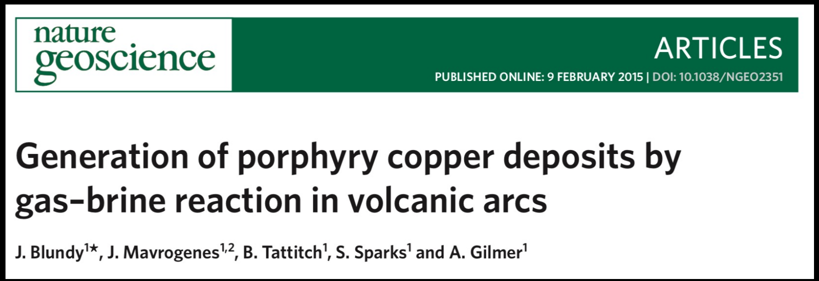


Fig. 6. Effective shear wave velocity $\bar{V}_S/V_S$, compressional wave velocity $\bar{V}_P/V_P$ and velocity ratio $(\bar{V}_P/V_P)/(\bar{V}_S/V_S)$ for a partially saturated cracked solid. The fraction of saturated cracks is ξ. The wave velocities correspond to the moduli shown in Figure 3.

O'Connell and Budiansky (1974)



Slices at 1 km. above sea level



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What can we learn from qualitative analysis?

Anomaly B

Saturated cracks

Sulfides

Brines in fractures?

Brines?
(Not sulfides!)

Brines+gasses in fractures?

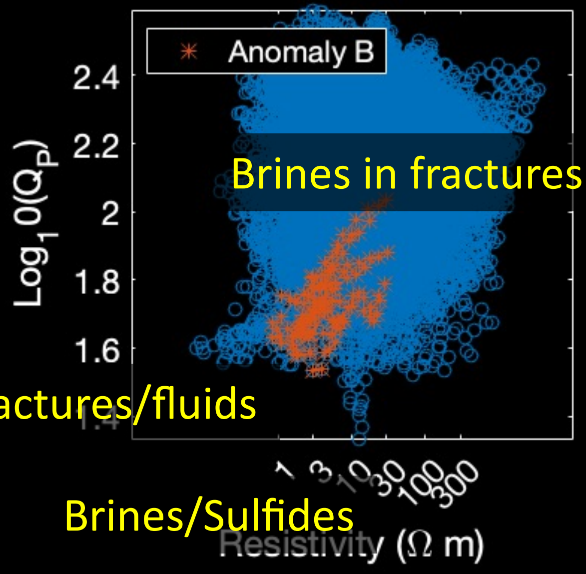
Fractures

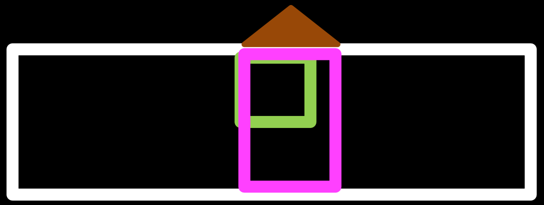
Fractures/fluids

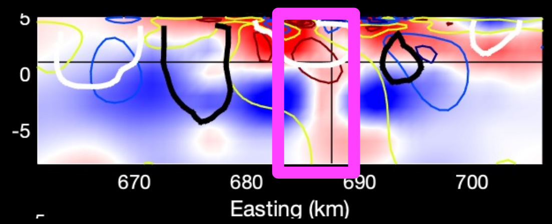
Dry cracks

Brines/Sulfides

Brines/Sulfides







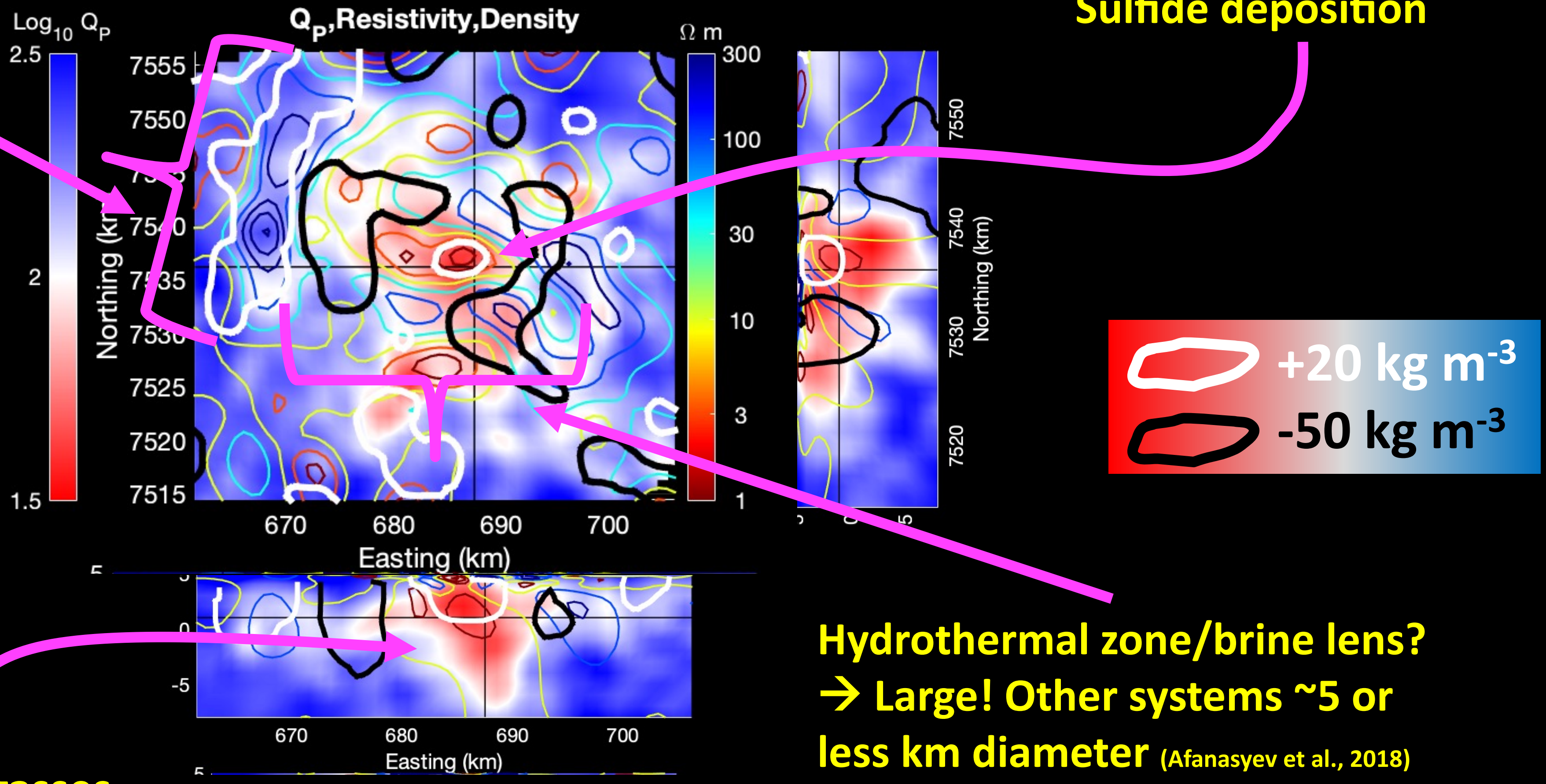
E-W slice at Uturuncu

What did we learn about Uturuncu?

Dry zone of older sulfide deposition

Sulfide deposition

Not a lot to indicate impending eruption!



Hydrothermal zone/brine lens?
→ Large! Other systems ~5 or less km diameter (Afanasyev et al., 2018)

Rising column of brines and gasses

Horizontal slices at 1 km. above sea level

Are there other Uturuncus?

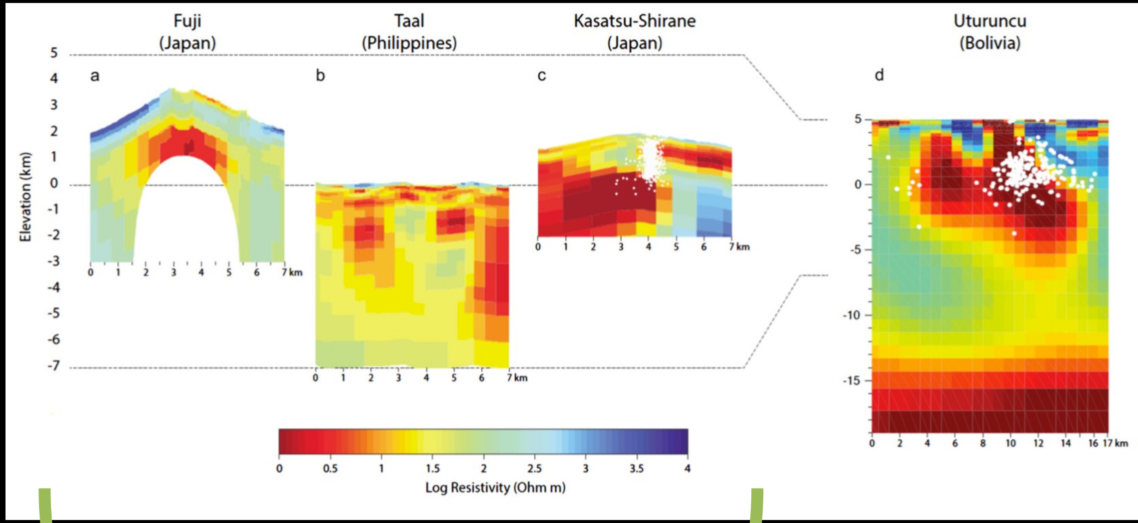
Any other volcanoes with evidence for sulfide deposition?

Ciomadul

- Last eruption ~30 kya
  (Harangi et al., 2015)
- Low resistivity anomaly
  (Harangi et al., 2015)
- Low density anomaly
  (Besutiu et al., 2021)

Volcanoes with brine lenses

(Afanasyev et al., 2018)



- No (recent) gravity data!
- Holocene

Other "zombie" volcanoes!

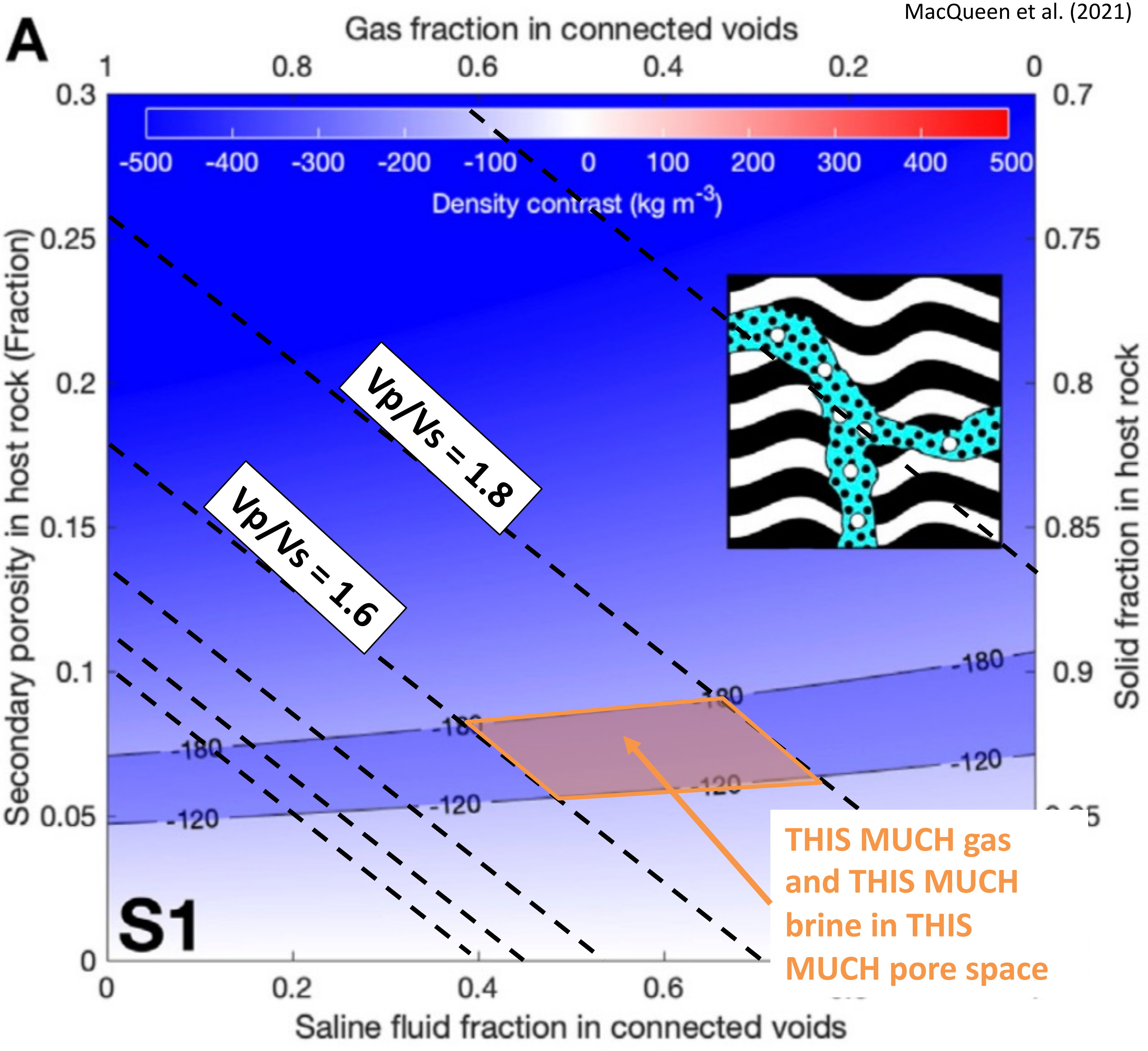
Future work: quantitative calculations

$$\frac{\Delta V_S}{V_S^0} = \left[\Lambda_N - \left(1 - \frac{\rho_L}{\rho_S}\right)\right]\frac{\phi}{2}$$

$$\frac{\Delta V_P}{V_P^0} = \left[\frac{\frac{(\beta - 1)\Lambda_{K_b}}{(\beta - 1) + \Lambda_{K_b}} + \frac{4}{3}\gamma\Lambda_N}{1 + \frac{4}{3}\gamma} - \left(1 - \frac{\rho_L}{\rho_S}\right)\right]\frac{\phi}{2}$$

Iwamori et al. (2021)

MacQueen et al. (2021)



Summary and Conclusions

- Data/models at Uturuncu are consistent with extensive hydrothermal system/brine lens with possible sulfide deposition
- Using multiple data types gives a self consistent picture of the geology and reduces ambiguity
- Strategies such as overlaying models, conceptual cross-plots can help when interpreting multi-dimensional data sets
- Future multiparameter investigations at other zombie volcanoes may reveal similar systems at other volcanoes

@gravity_pat

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Zombie Cartoon: Anton Brand
Wig: Club Penguin Rewritten