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

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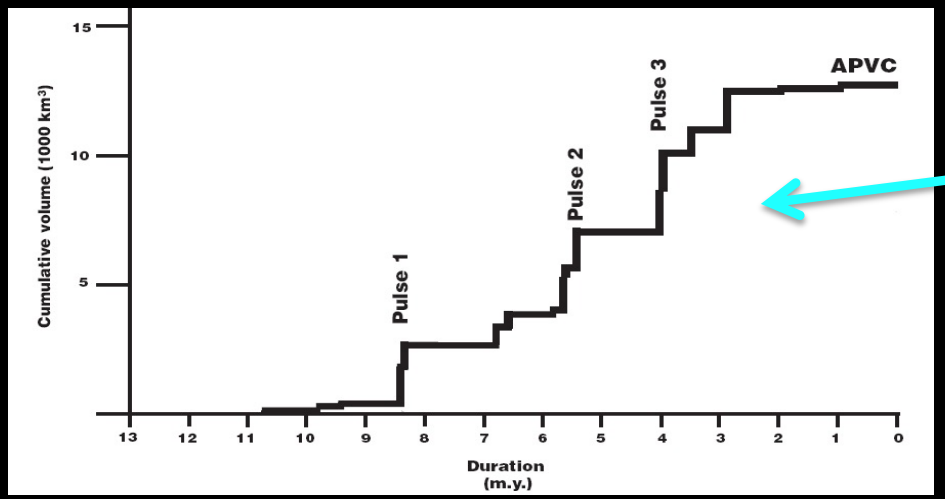
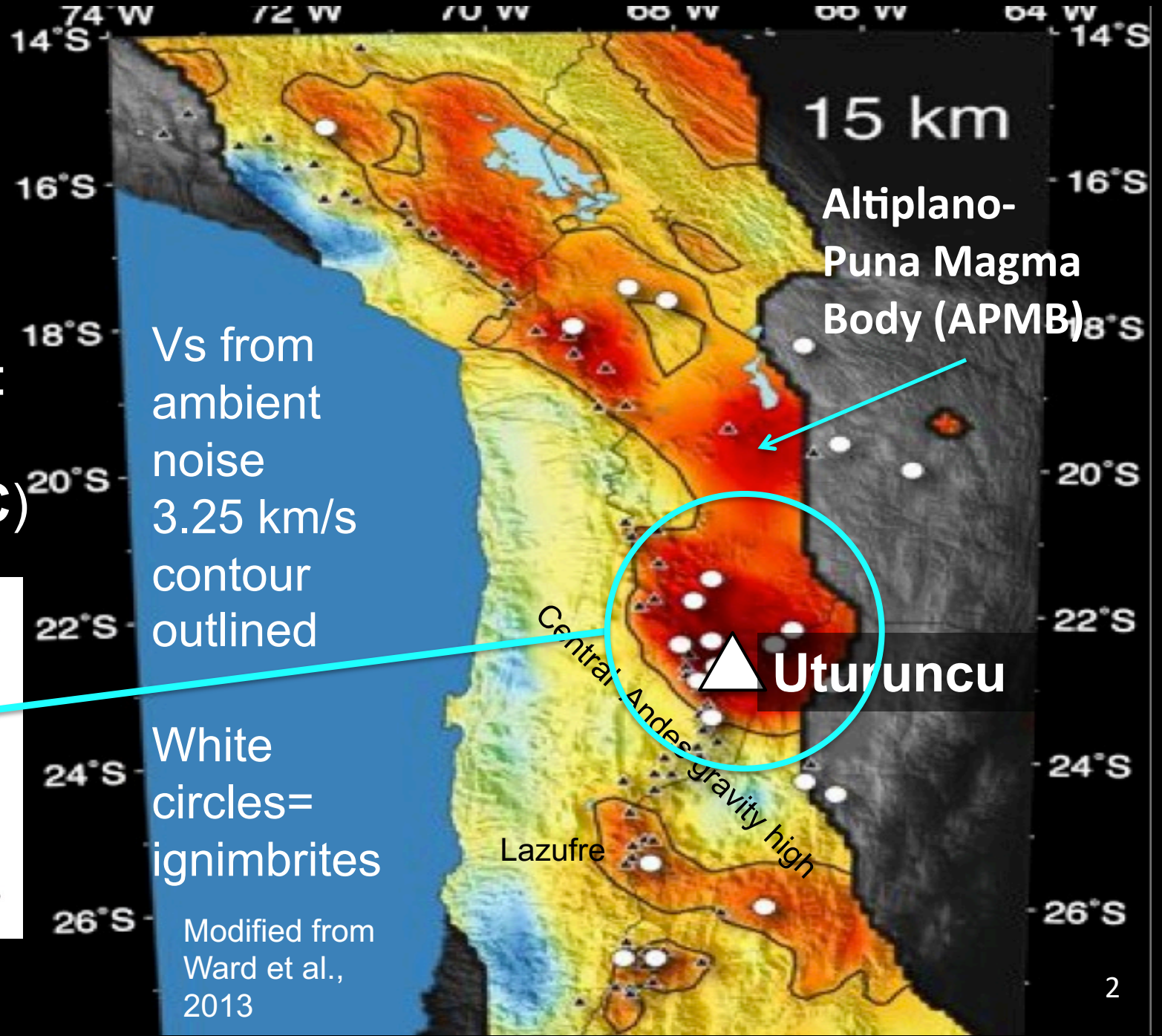
Zombie Cartoon: Anton Brand
Wig: Club Penguin Rewritten

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

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



From: Salisbury et al., 2010

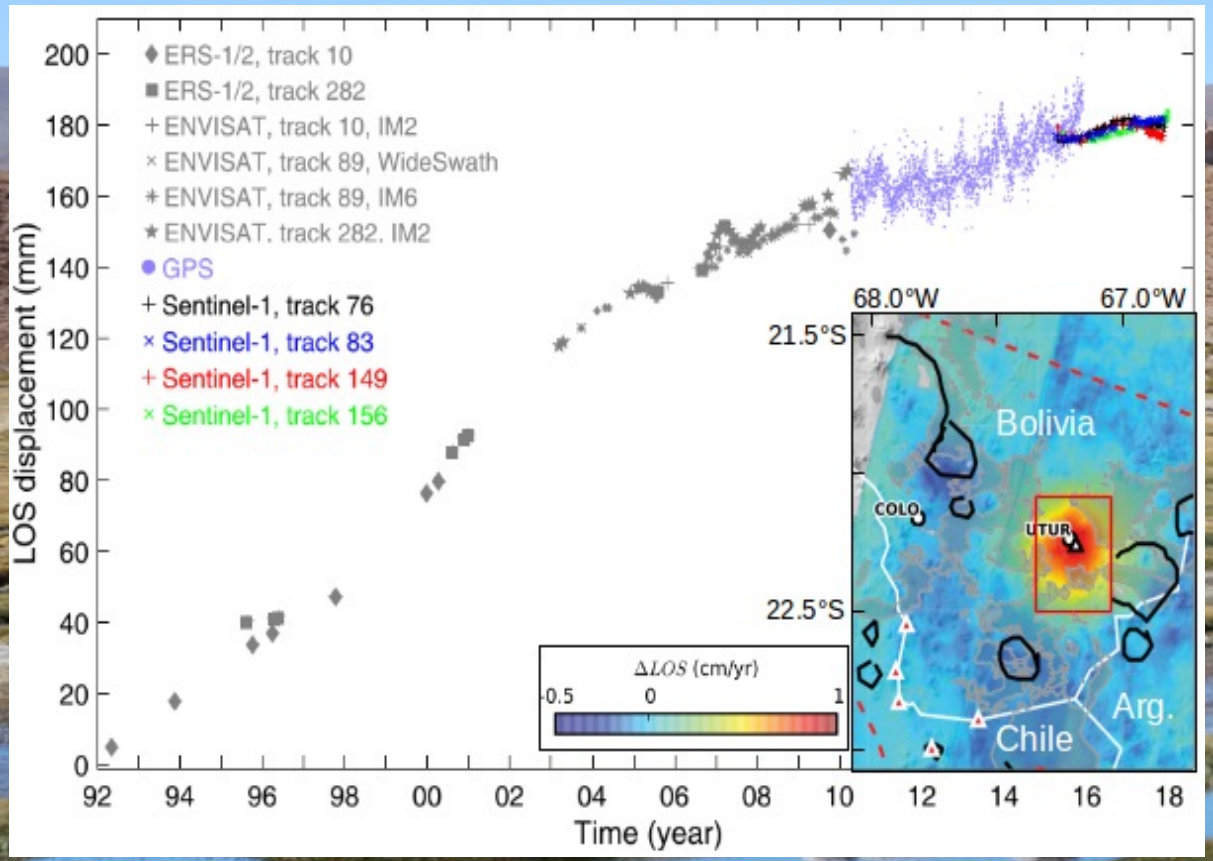


Modified from Ward et al., 2013

Uturuncu, Bolivia

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

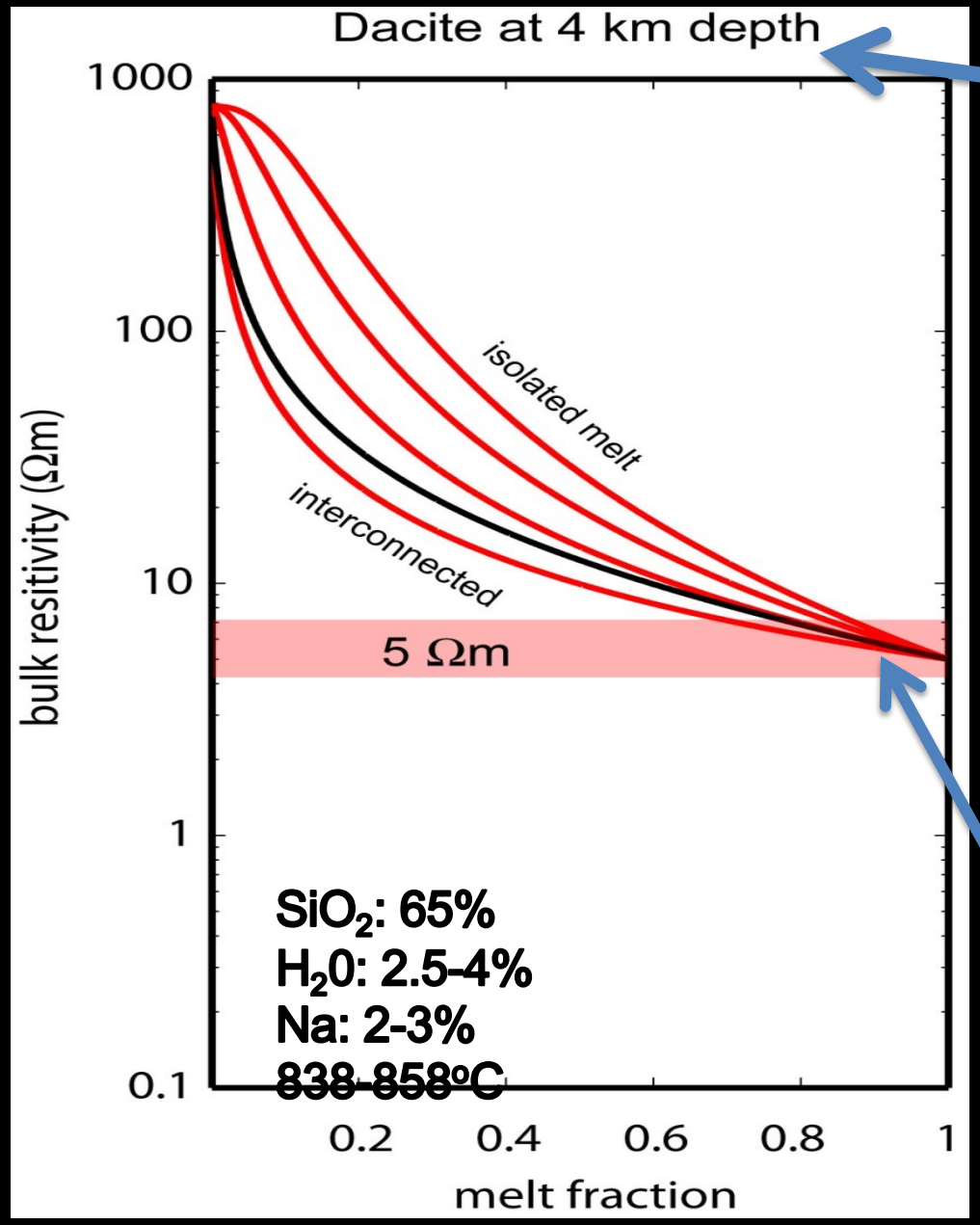
Deforming for ~50 years! (Gottsmann et al., 2018)



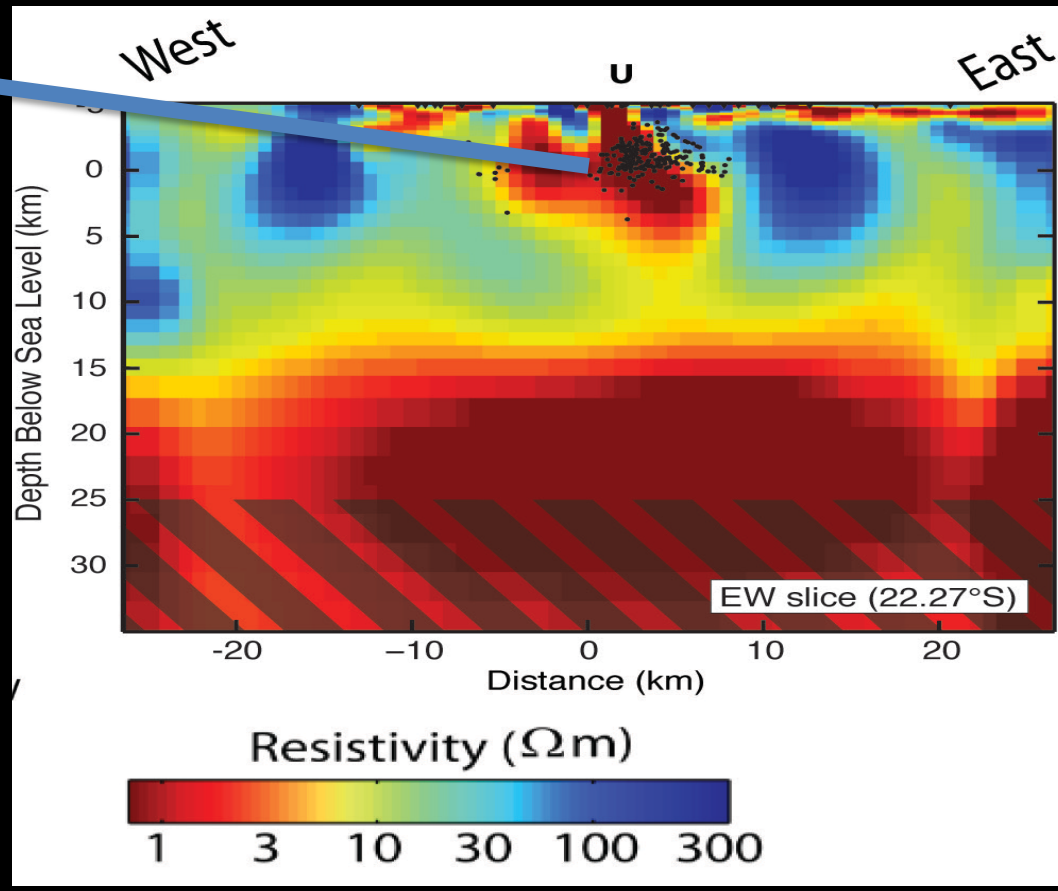
(Lau et al., 2017; Henderson and Pritchard, 2013, 2017)

Photo by Tom Fournier

Melt and Brines Beneath Uturuncu



SiO_2: 65%
H_20: 2.5-4%
Na: 2-3%
~~838-858°C~~



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

Contents lists available at ScienceDirect

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Formation of magmatic brine lenses via focussed fluid-flow beneath volcanoes

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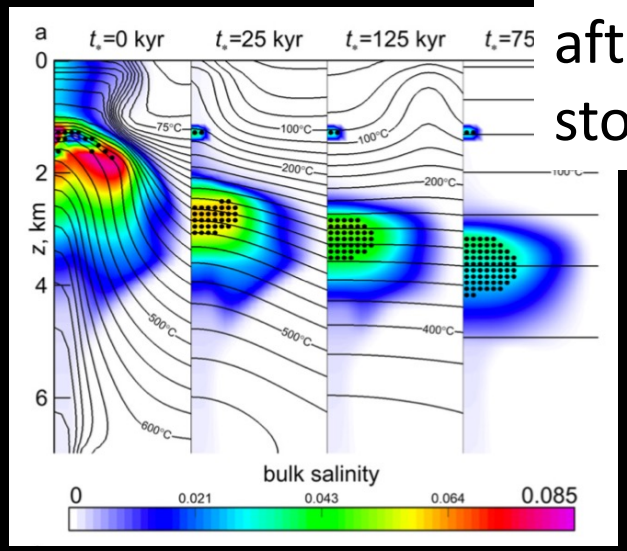
Brine lenses can persist long after degassing stops



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ARTICLES

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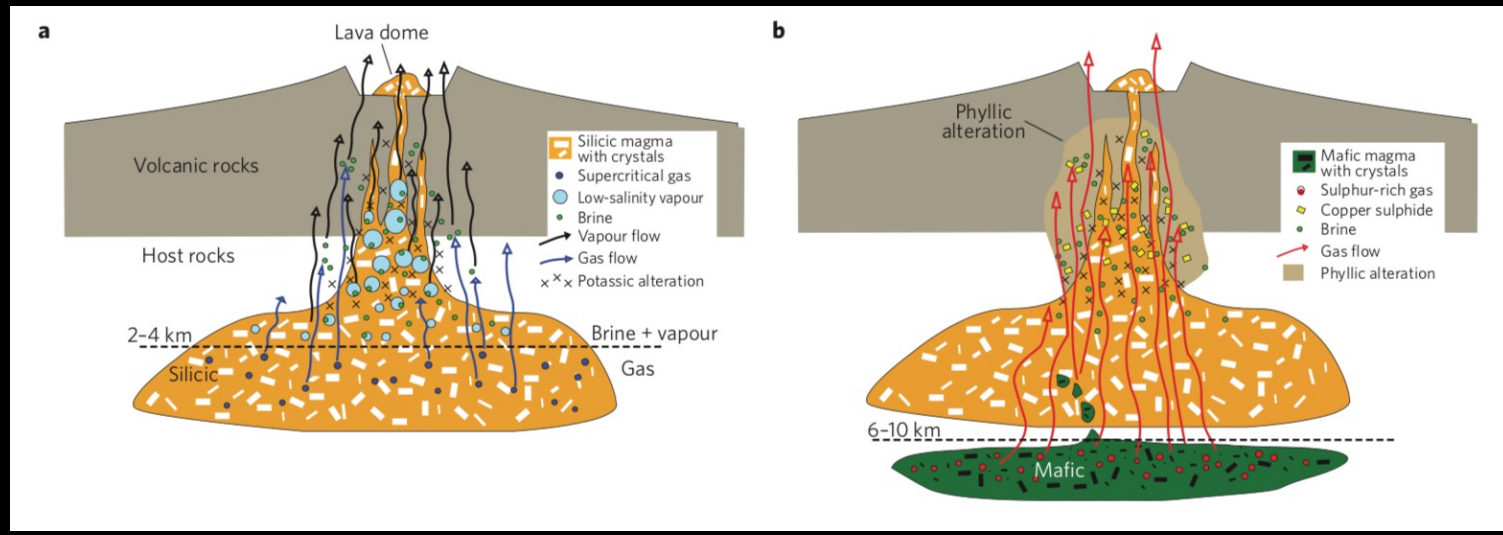
Generation of porphyry copper deposits by gas–brine reaction in volcanic arcs

J. Blundy[1]*, J. Mavrogenes[1,2], B. Tattitch[1], S. Sparks[1] and A. Gilmer[1]

Pulses of brines and gasses could create ore deposits



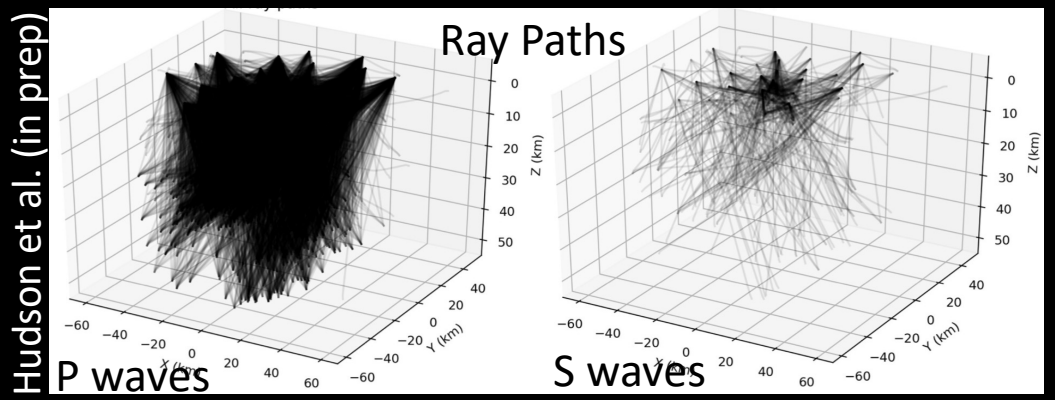
The geology problem

- 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

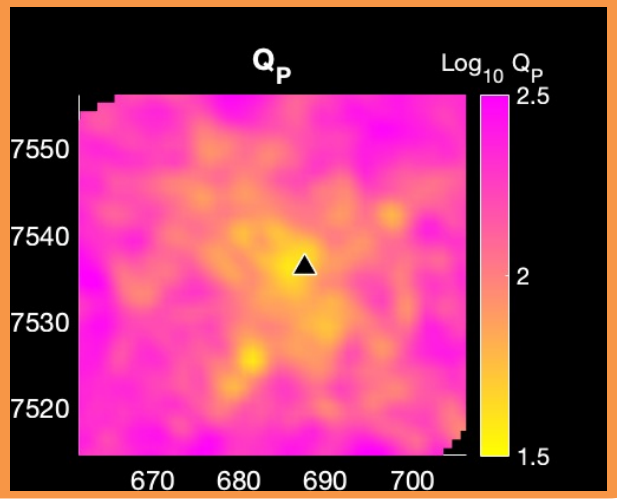
- Resistivity model (Comeau et al., 2016)
- Density model (MacQueen et al., 2021)
- NEW seismic tomography models (Liu et al., in prep)
- NEW seismic attenuation model (Hudson et al., in prep)
- InSAR - Uplift currently waning, subsidence moat gone (**See poster V15H-0144**; Eiden et al. 2022, in prep)
- 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

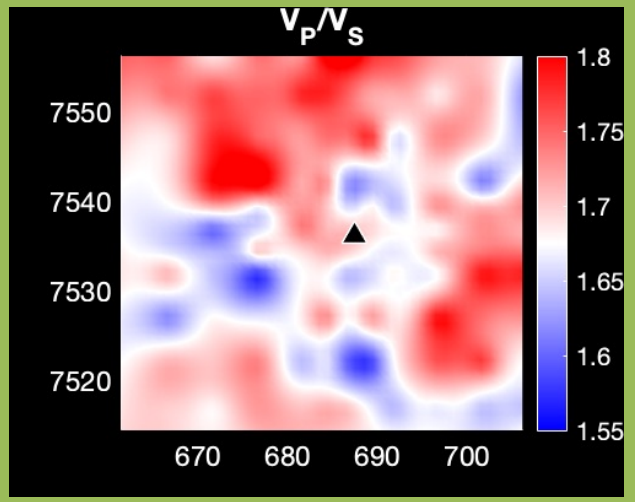


- Using updated seismic catalog from Hudson et al. (2022)
  - Two deployments 2009-2012, 42 stations
  - ~2000 local earthquakes (Mw 0 to 3.5)

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)

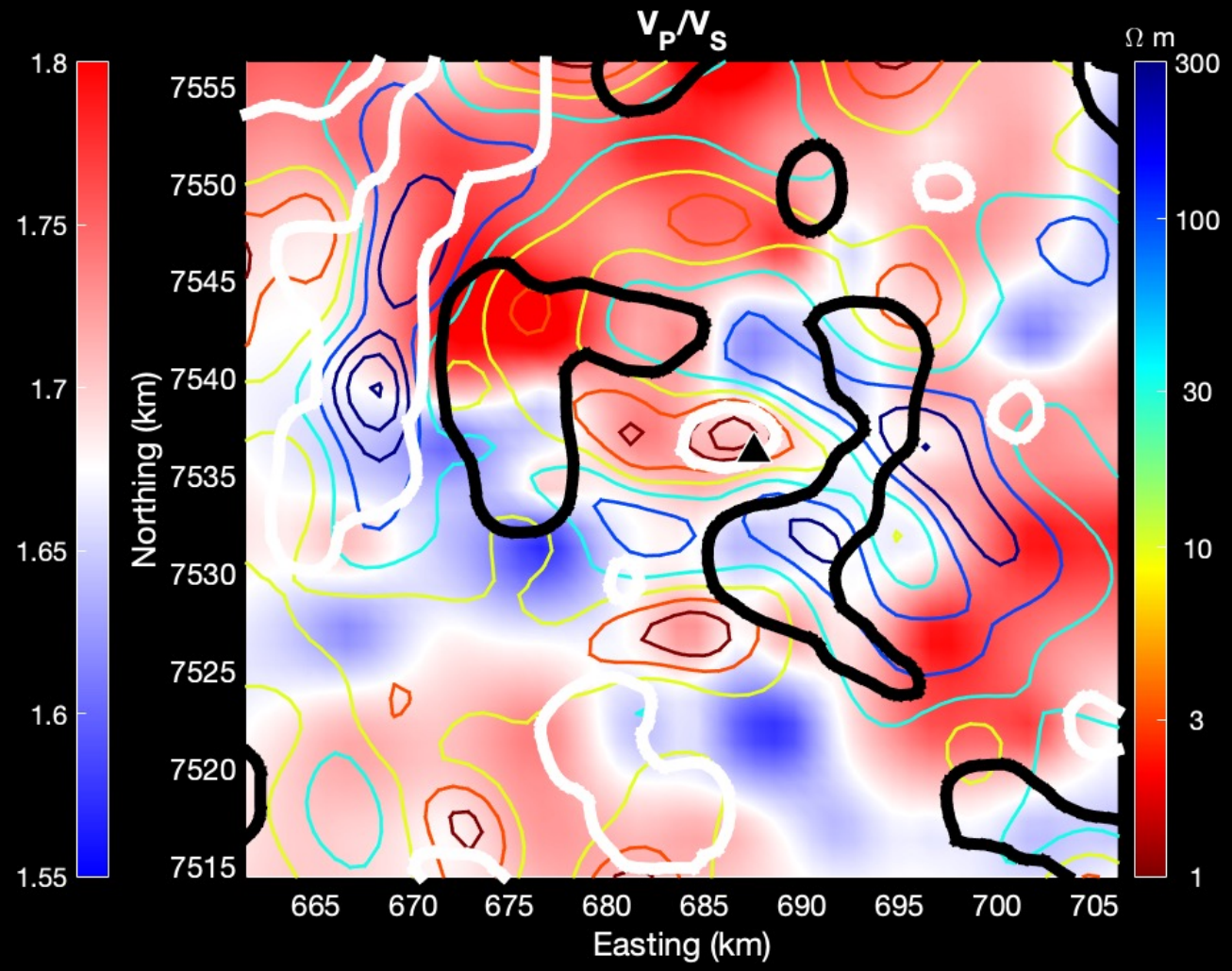
Slices at 1 km. above sea level

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



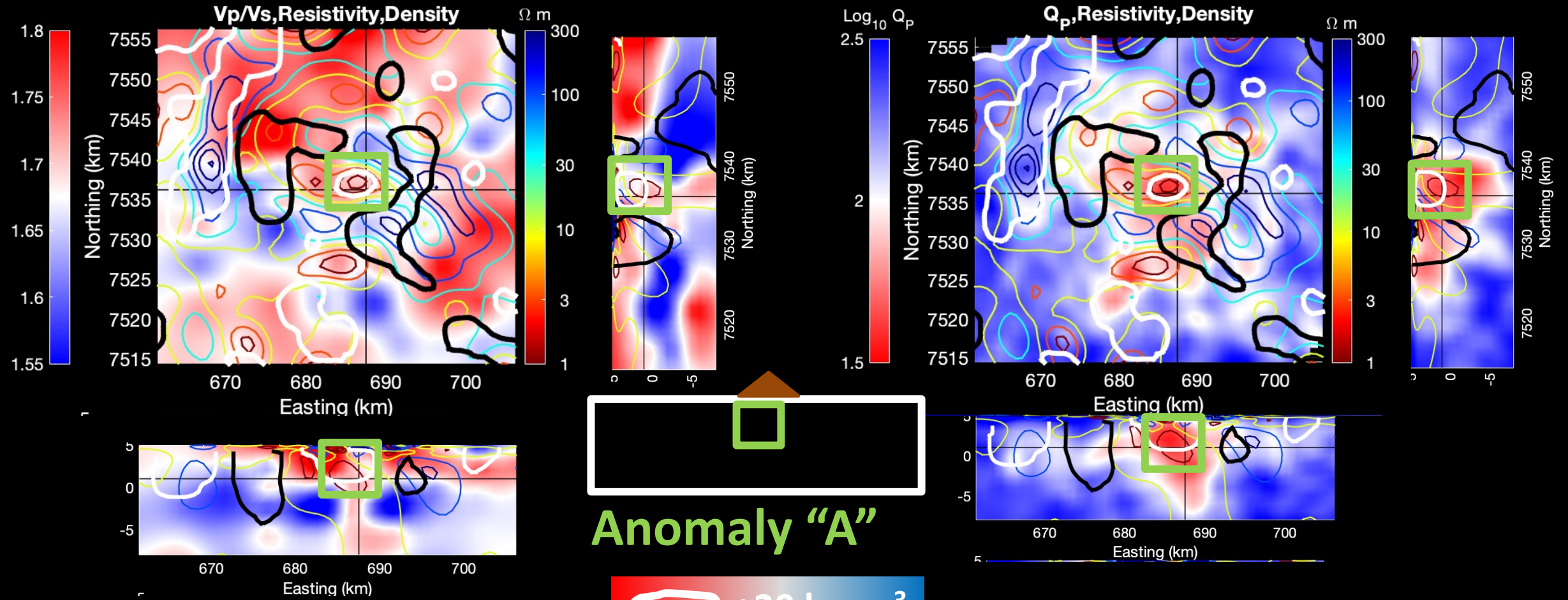
Density contours:

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

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

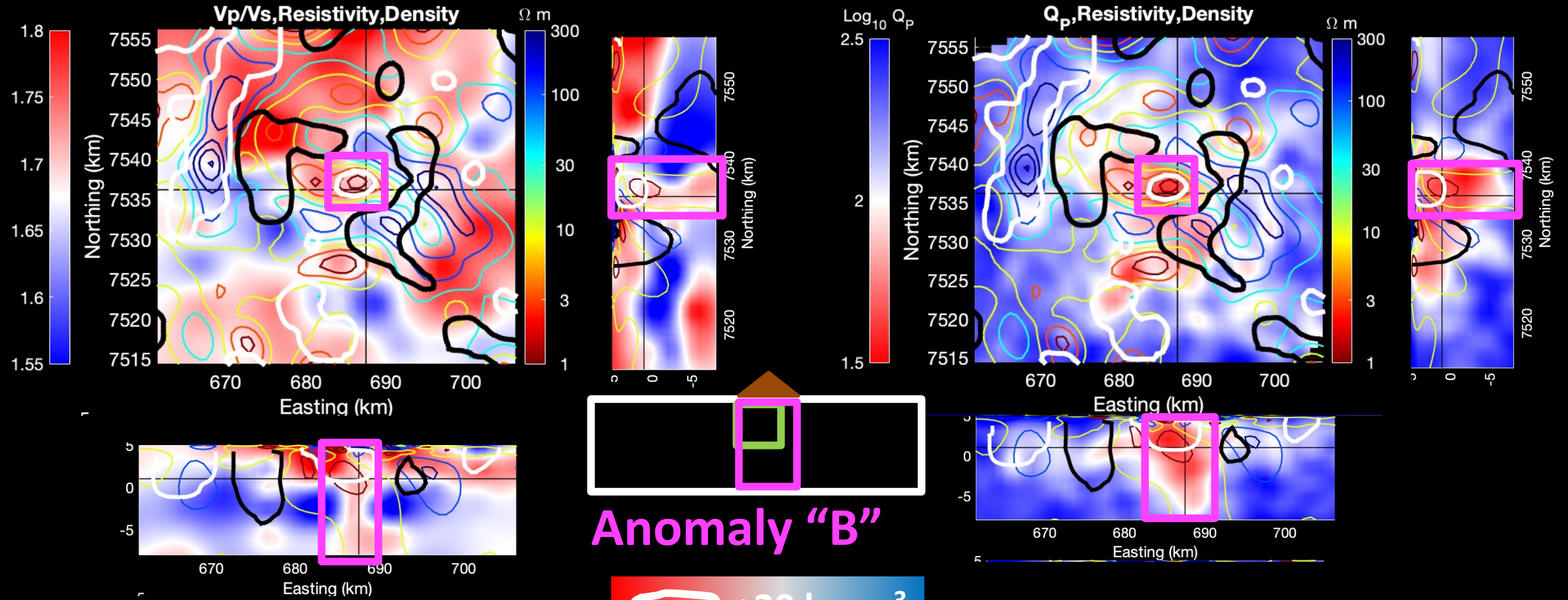
Identifying common anomalies

Slices at 1 km. above sea level



Identifying common anomalies

Slices at 1 km. above sea level



What can we learn from qualitative analysis?

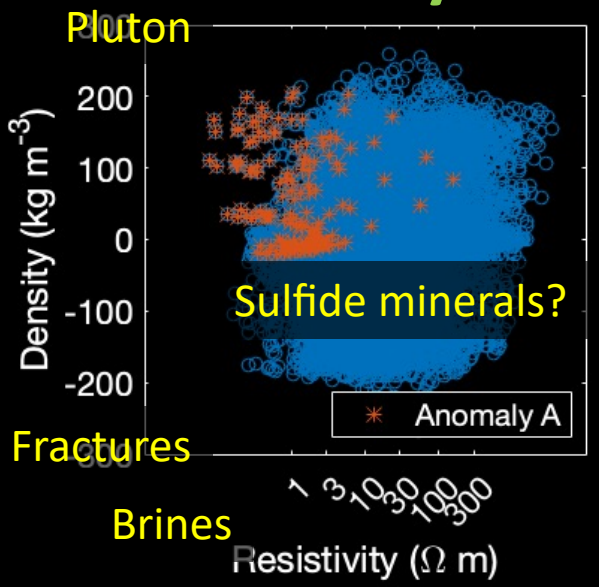
Anomaly A

Saturated cracks

Sulfides + (not a lot of) brines

Dry cracks

Brines/Sulfides



Sulfides + brines?

Fractures/fluids

Brines/Sulfides

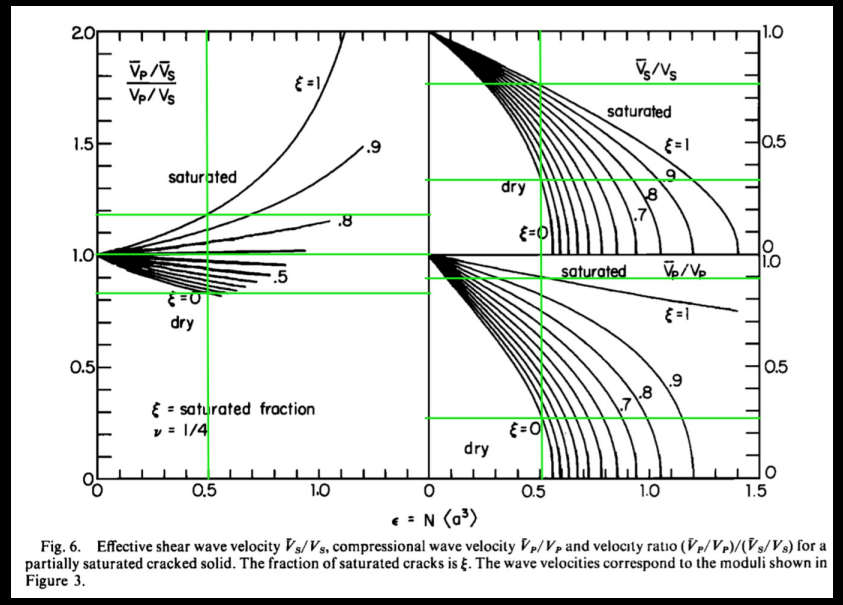
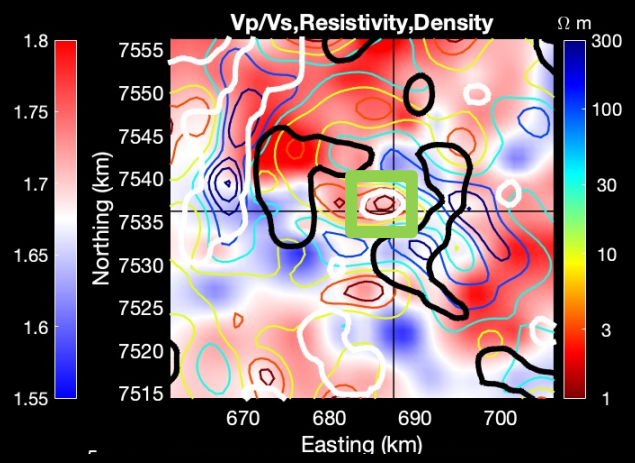
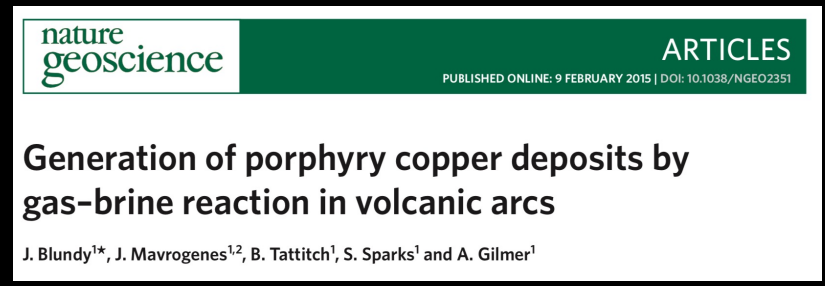


Fig. 6. Effective shear wave velocity $\bar{V}_S/V_S$, compressional wave velocity $\bar{V}_P/V_P$ and velocity ratio $(\bar{V}_P/V_P)/(\bar{V}_S/V_S)$ for a partially saturated cracked solid. The fraction of saturated cracks is ξ. The wave velocities correspond to the moduli shown in Figure 3.



Slices at 1 km. above sea level



O'Connell and Budiansky (1974)

What can we learn from qualitative analysis?

Anomaly B

Saturated cracks

Sulfides

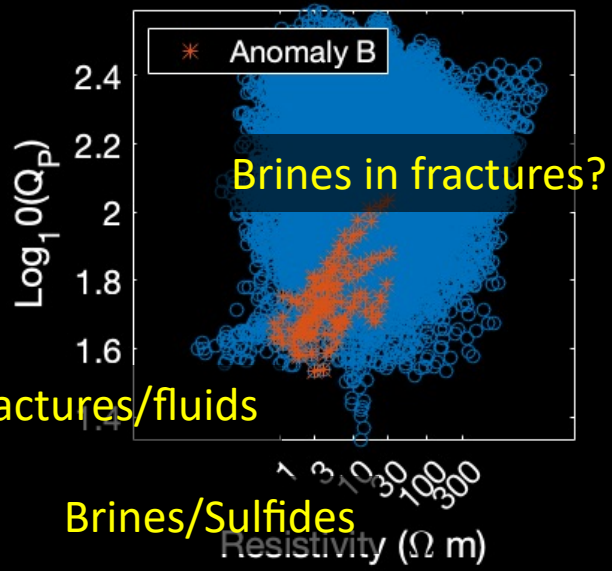
Brines?
(Not sulfides!)

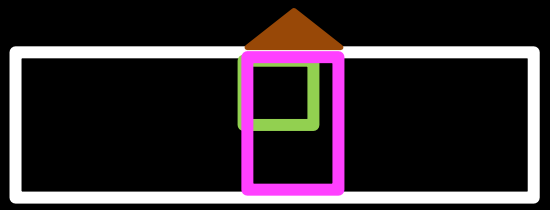
Brines+gasses in fractures?

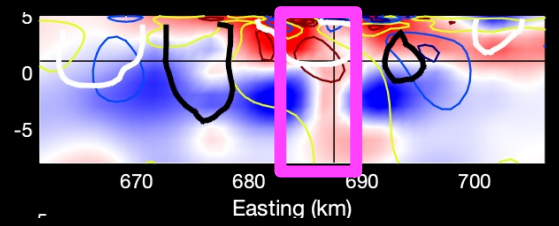
Fractures

Dry cracks

Brines/Sulfides





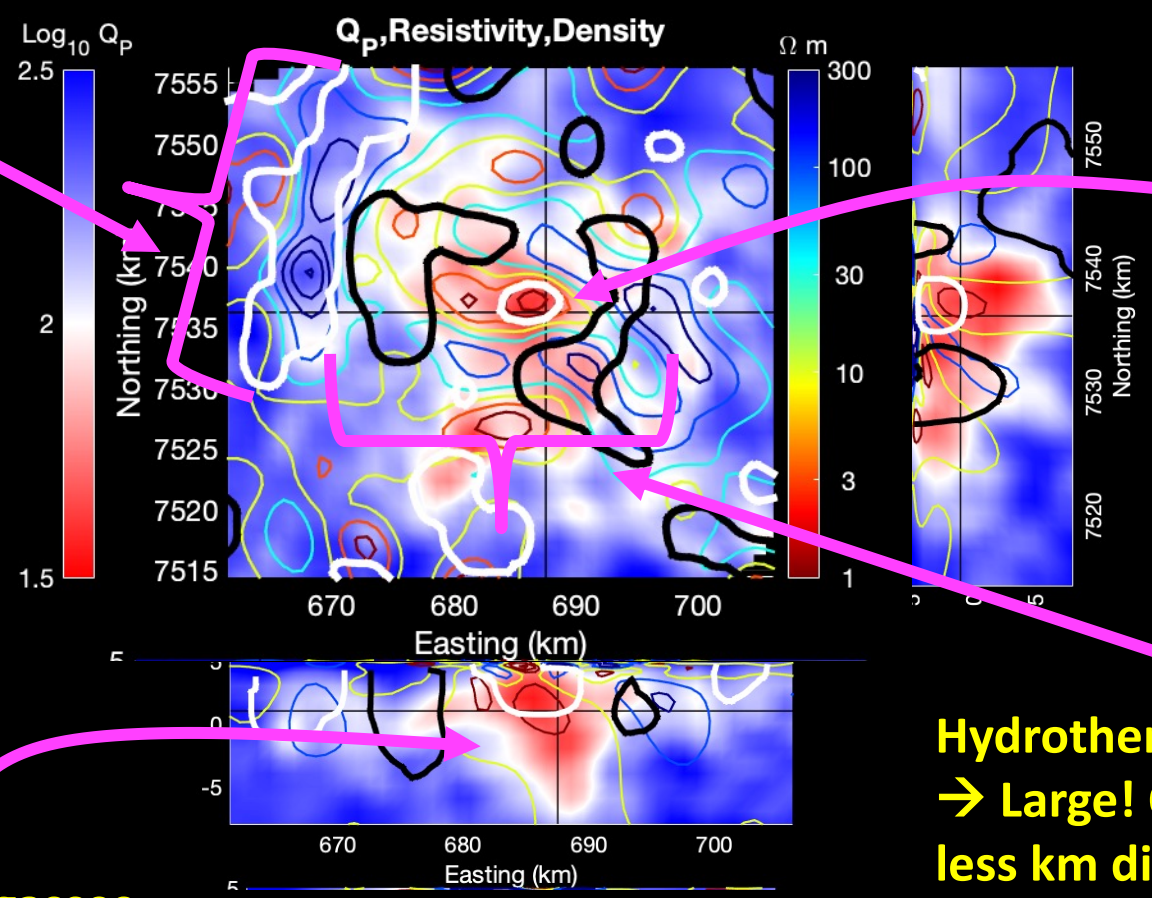


E-W slice at Uturuncu

What did we learn about Uturuncu?

Dry zone of older sulfide deposition

Sulfide deposition



Not a lot to indicate impending eruption!

+20 kg m^{-3}

-50 kg m^{-3}

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?

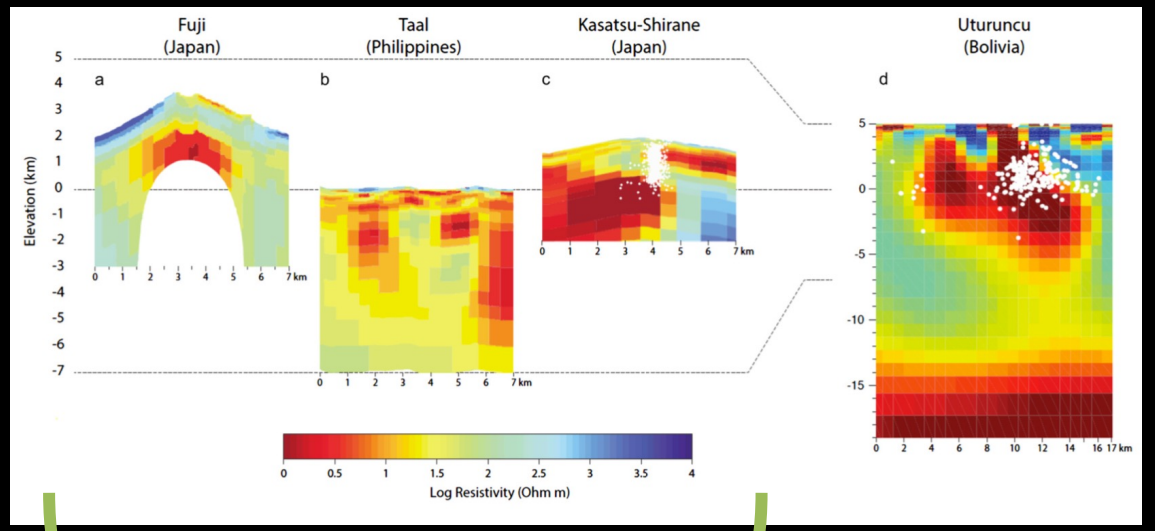
Ciomadul

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

Other "zombie" volcanoes!

Volcanoes with brine lenses

(Afanasyev et al., 2018)



- No (recent) gravity data!
- Holocene

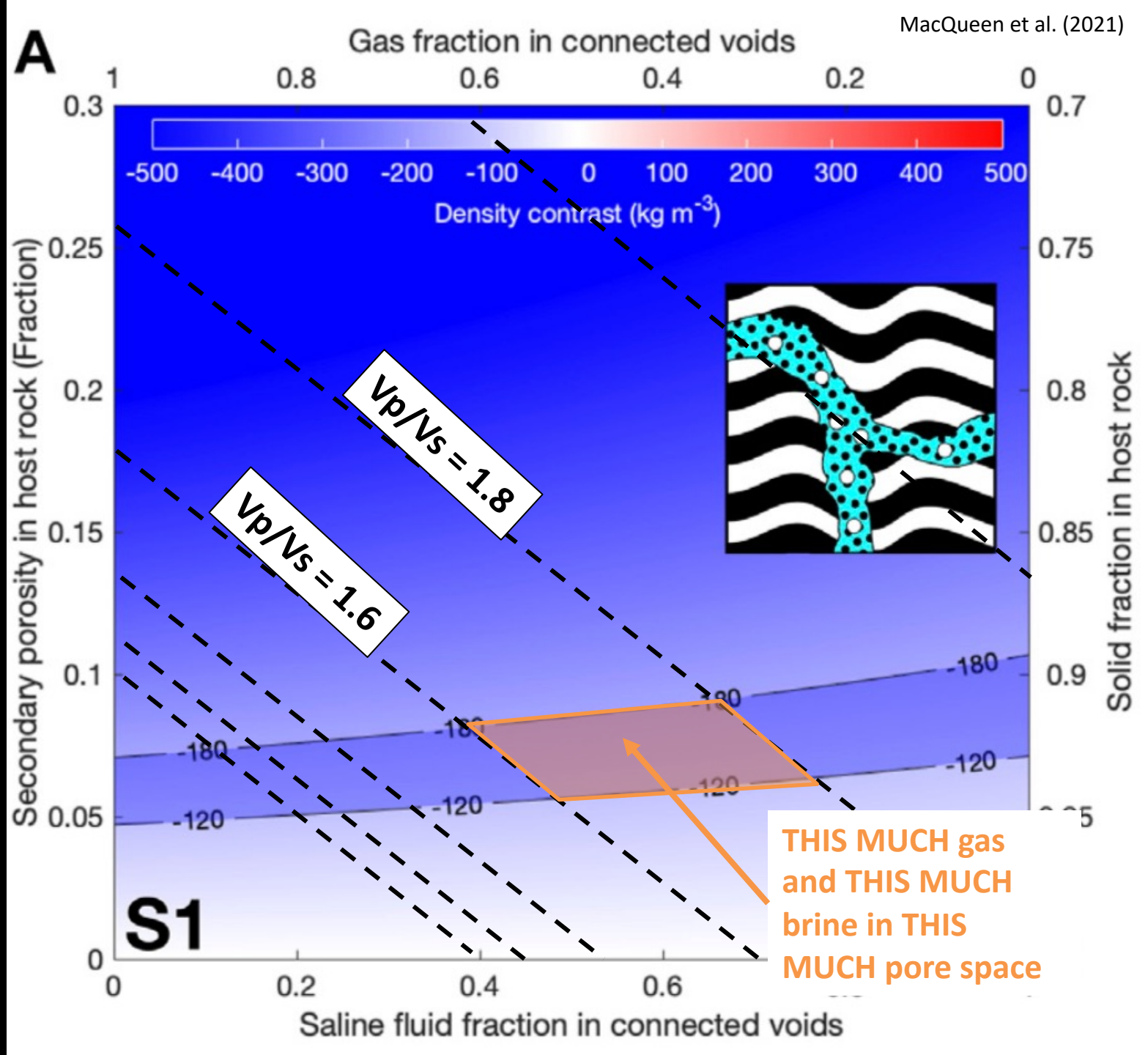
Future work: quantitative calculations

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

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

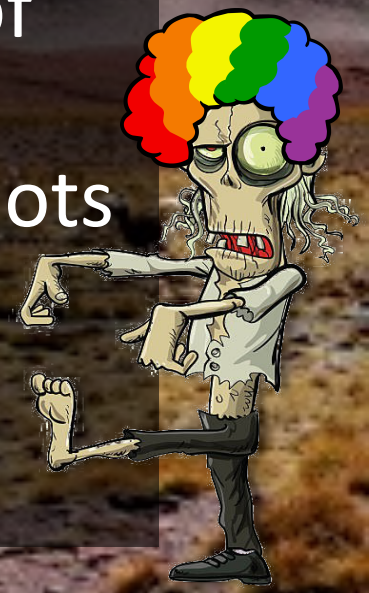
Iwamori et al. (2021)

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



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Zombie Cartoon: Anton Brand
Wig: Club Penguin Rewritten