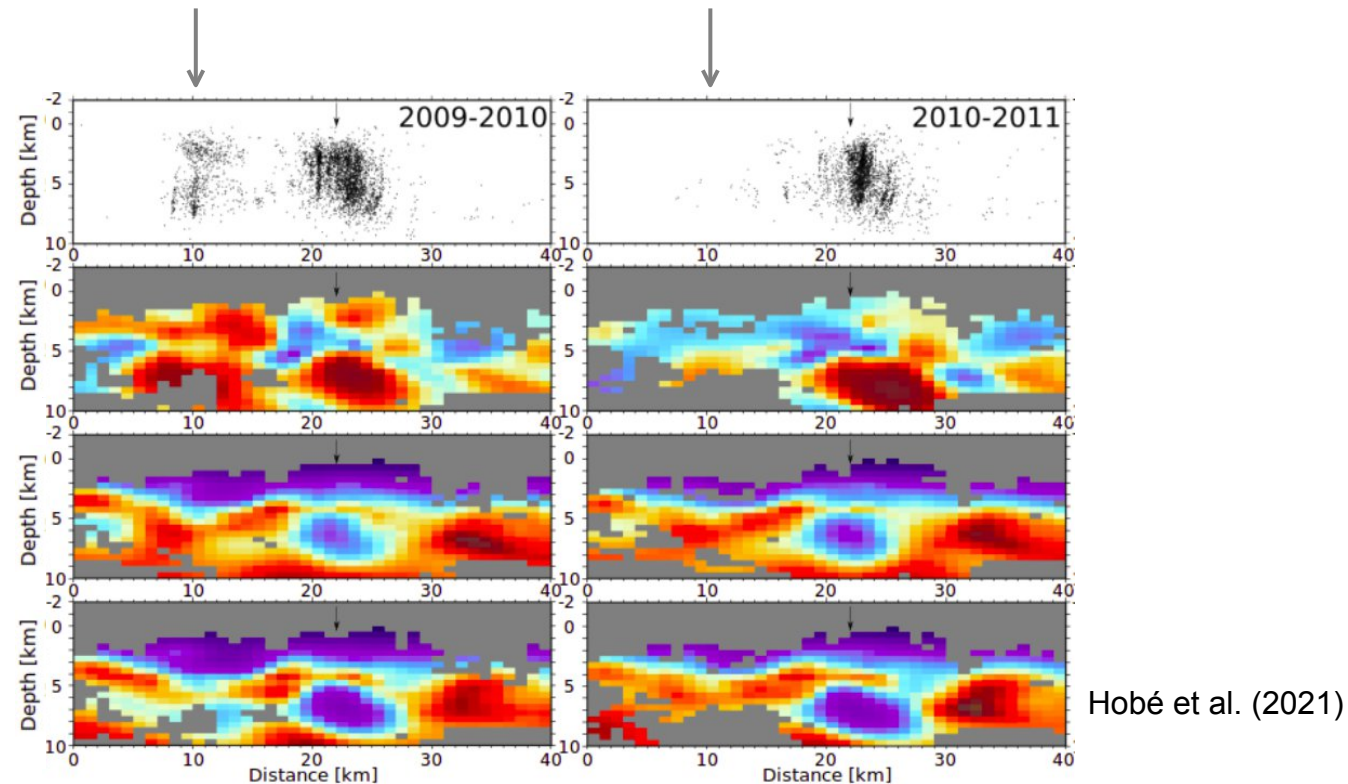


Interpreting Time-Varying Processes Using Empirical Data



Alex Hobé, A. Tryggvason, B. Almqvist, O. Gudmundsson
Department of Earth Science, Uppsala University



UPPSALA
UNIVERSITET

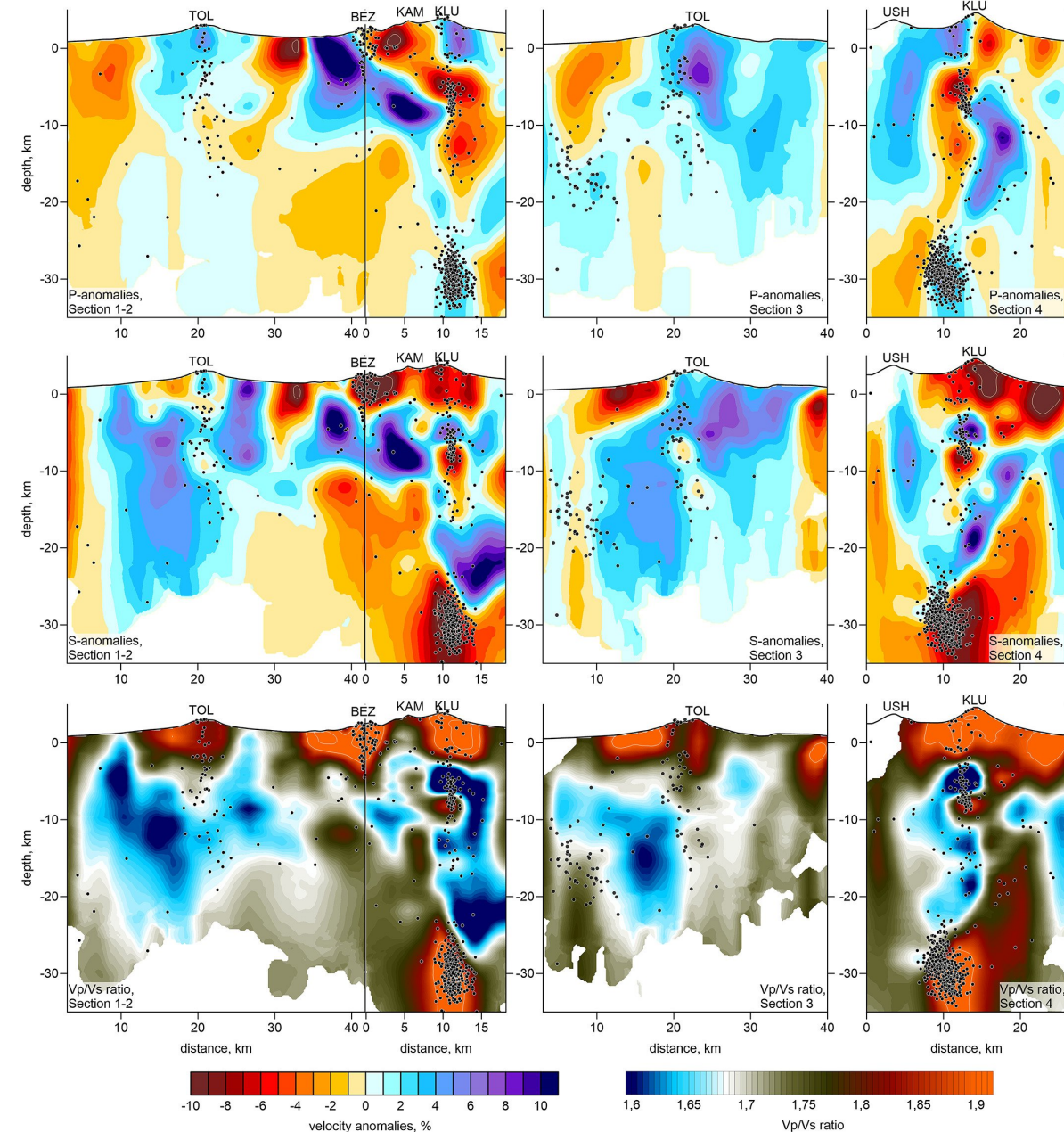
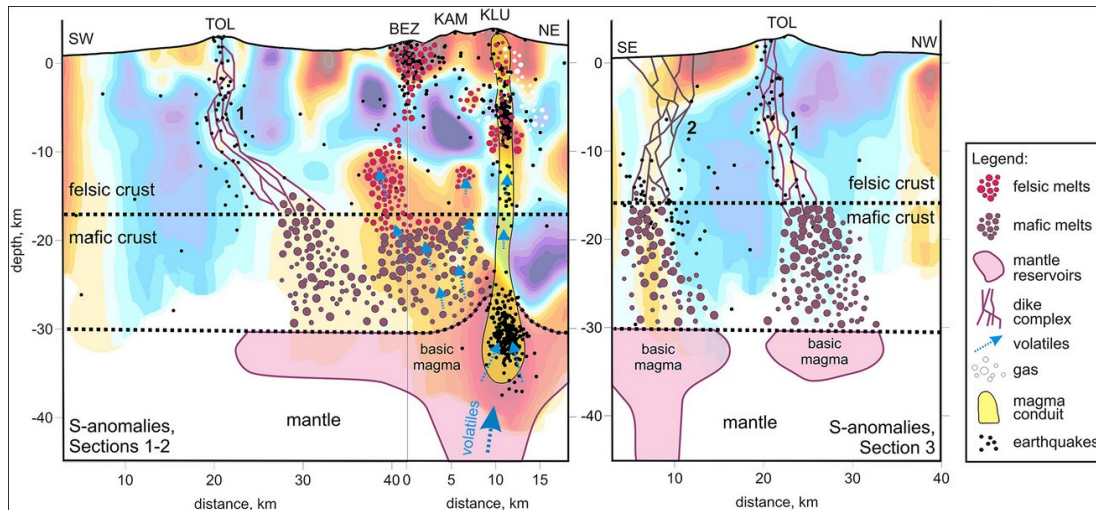
Interpreting geophysical results

Non-uniqueness:

- Observables: a function of many variables

Solutions:

- Integrate other methods/information
- Time-varying processes



Concept

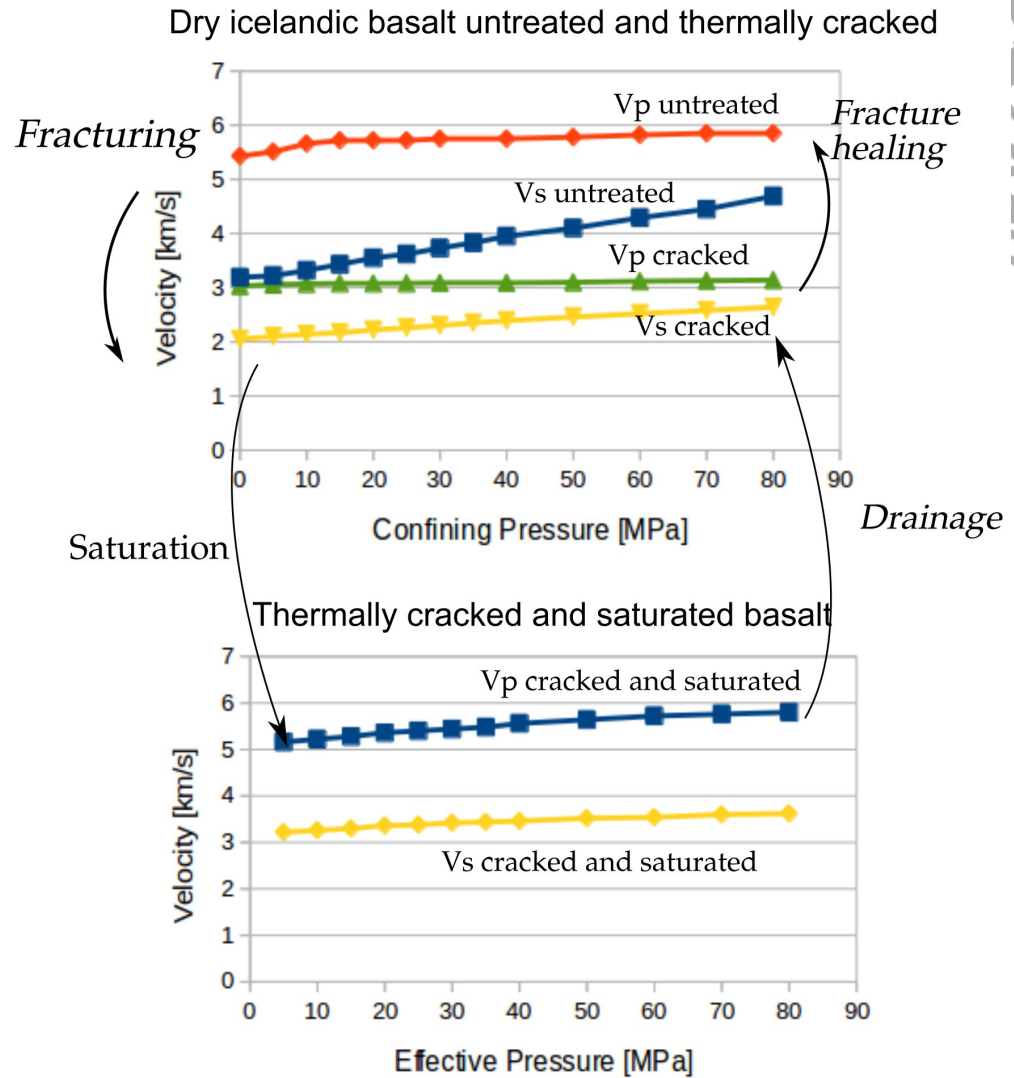
Different states affect geophysical properties, e.g.:

- Intact rock
- Fracturing
- Fluid content
- Fluid phase

The effect of these is measured in the lab at different temperatures and pressures.

Although other geophysical properties (e.g. permeability, gravity and resistivity) are similarly affected by these states, we will mainly focus on seismic velocities in this presentation.

Time-varying processes have specific signals that differentiate them. Thus, reducing the non-uniqueness in interpretation.



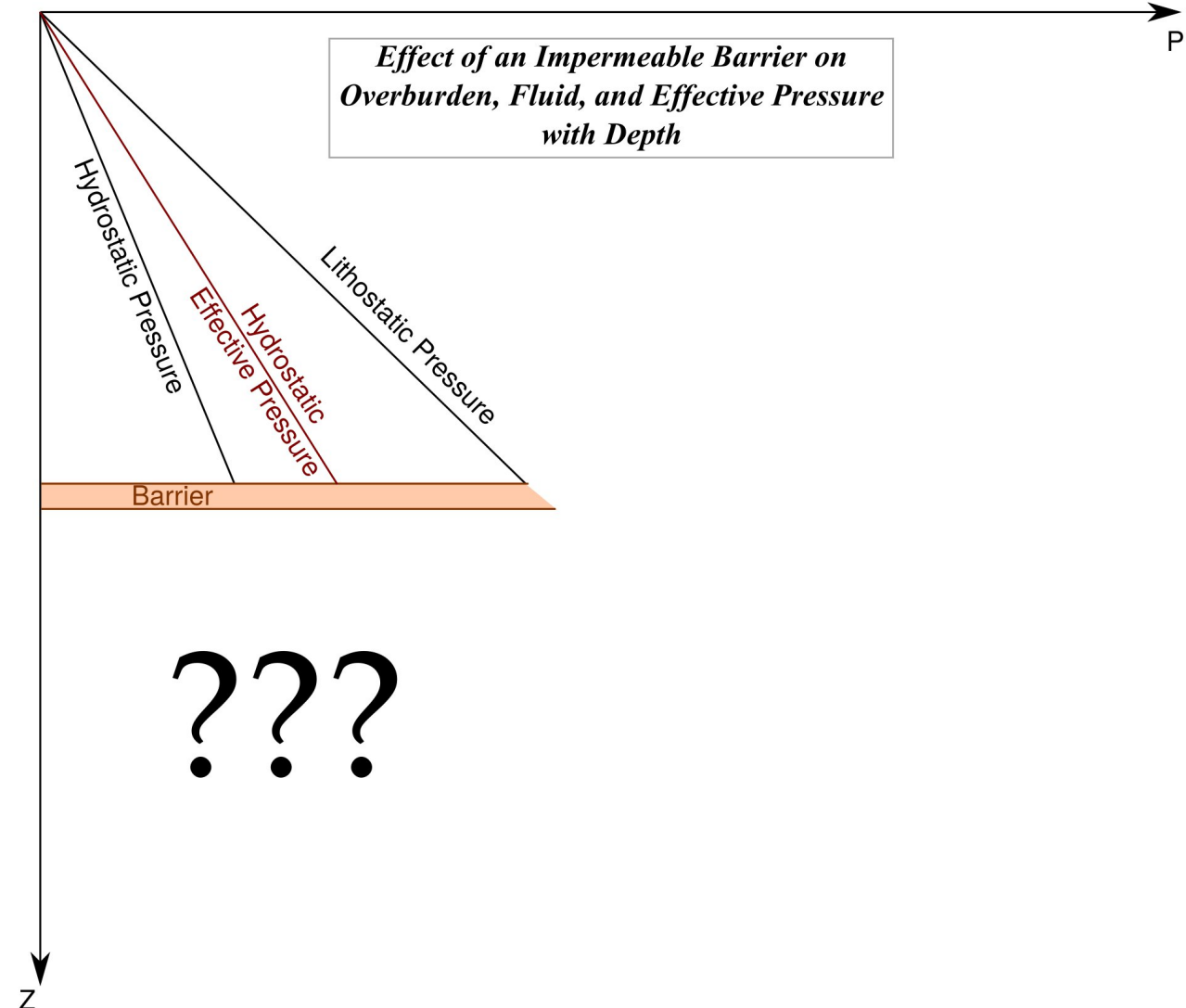
Modified from Vinciguerra et al. (2005)





Overview

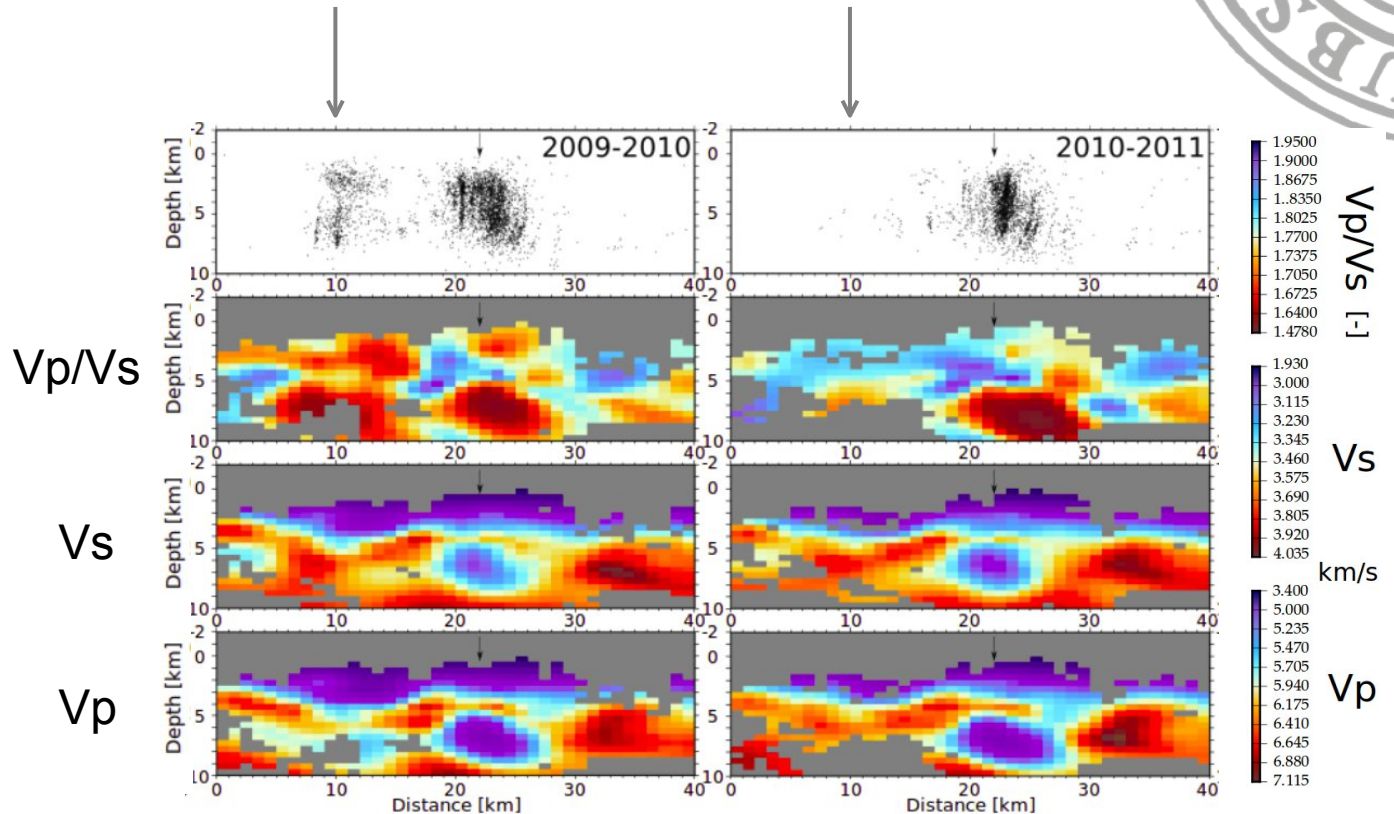
- Direct usage examples
- Effective pressure
 - Static variation with depth
 - Dynamic changes
- Complex interactions
 - Decompression boiling
 - Comparing Campi Flegrei, Italy & Krysuvik, Iceland



Direct usage

Fracturing & fracture healing

- Clear temporal signals
- Fracturing:
 - Seismicity
 - Low V_p
 - Low V_s
 - Low V_p/V_s
- Fracture Healing:
 - No seismicity
 - V_p , V_s , V_p/V_s return to average



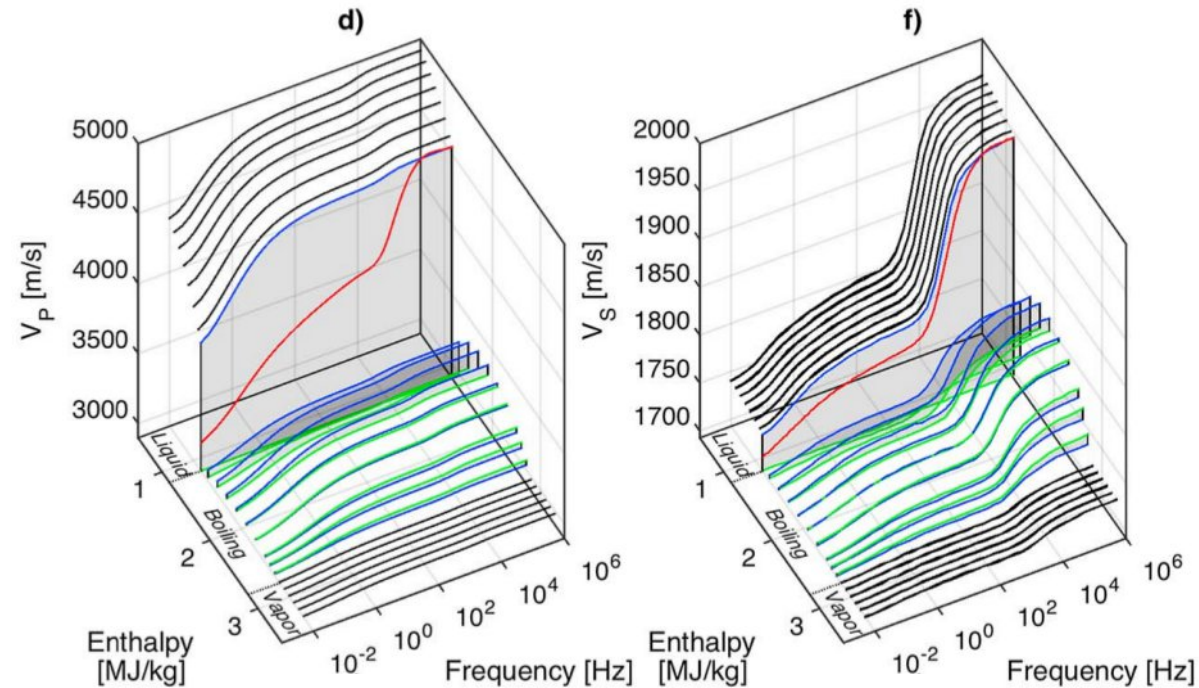
Local Earthquake Tomography profile of Krysuvik, Iceland (Hobé et al. 2021)



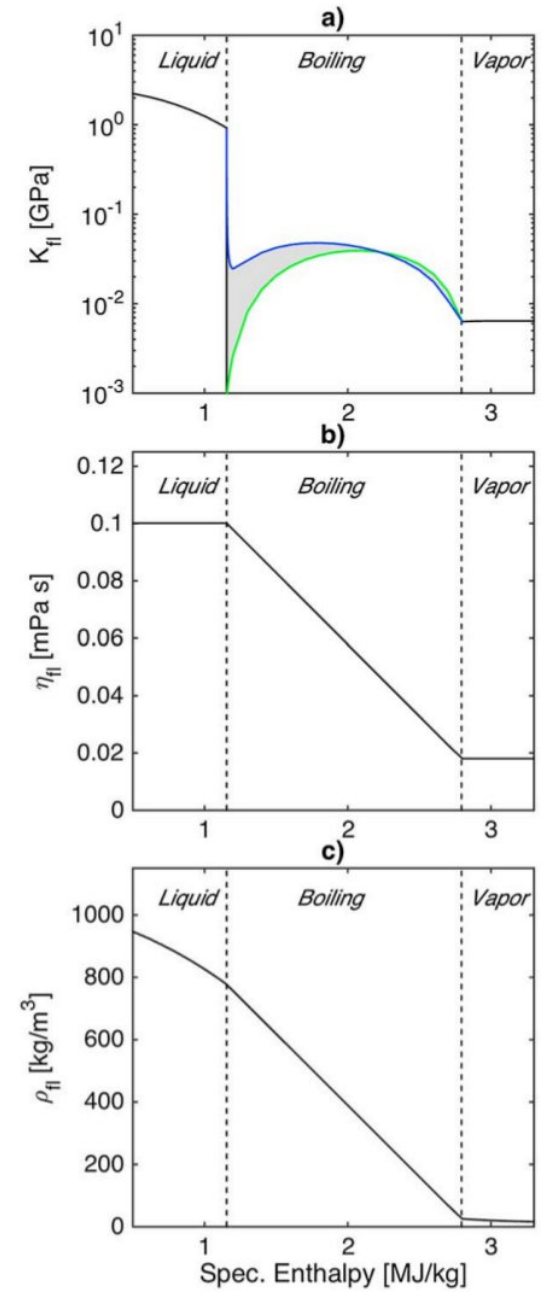
Direct usage

Liquid vs. compressible fluid

- Clear temporal signals
- Liquid water:
 - Seismicity
 - Increased V_p
 - Average V_s
 - Increased V_p/V_s
- Compressible fluid:
 - Seismicity
 - Low V_p
 - Average V_s
 - Low V_p/V_s



Grab et al. (2017)

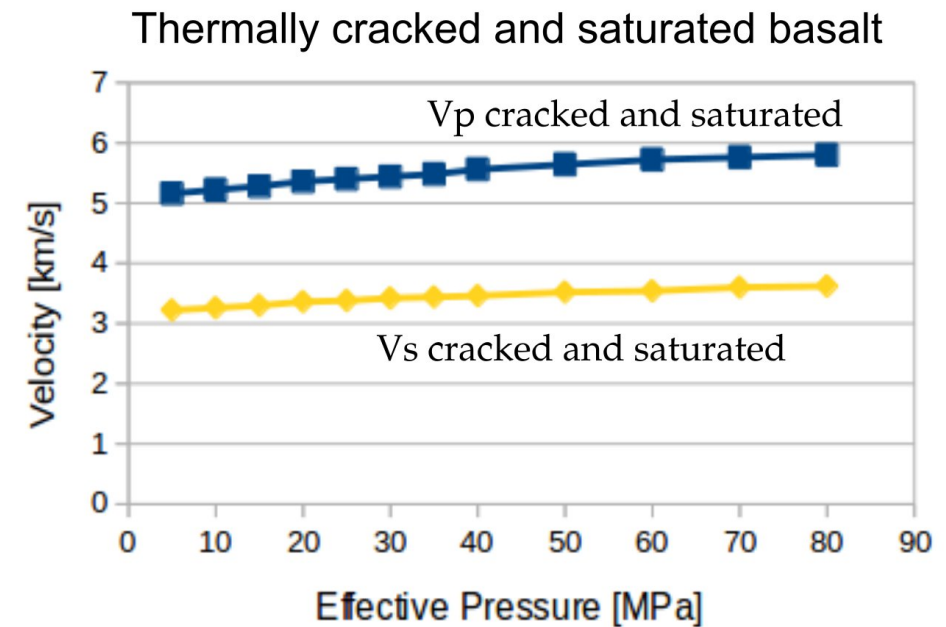




Effective Pressures (rare in interpretation)

Time-varying processes can change P_{eff}

- Temporal signal combines with previous
- Effect depends on state and state change
- Saturated fractured rock
 - Changing P_{eff} affects both V_p and V_s
 - Up to 12.4 % difference in V_p and V_s shown here



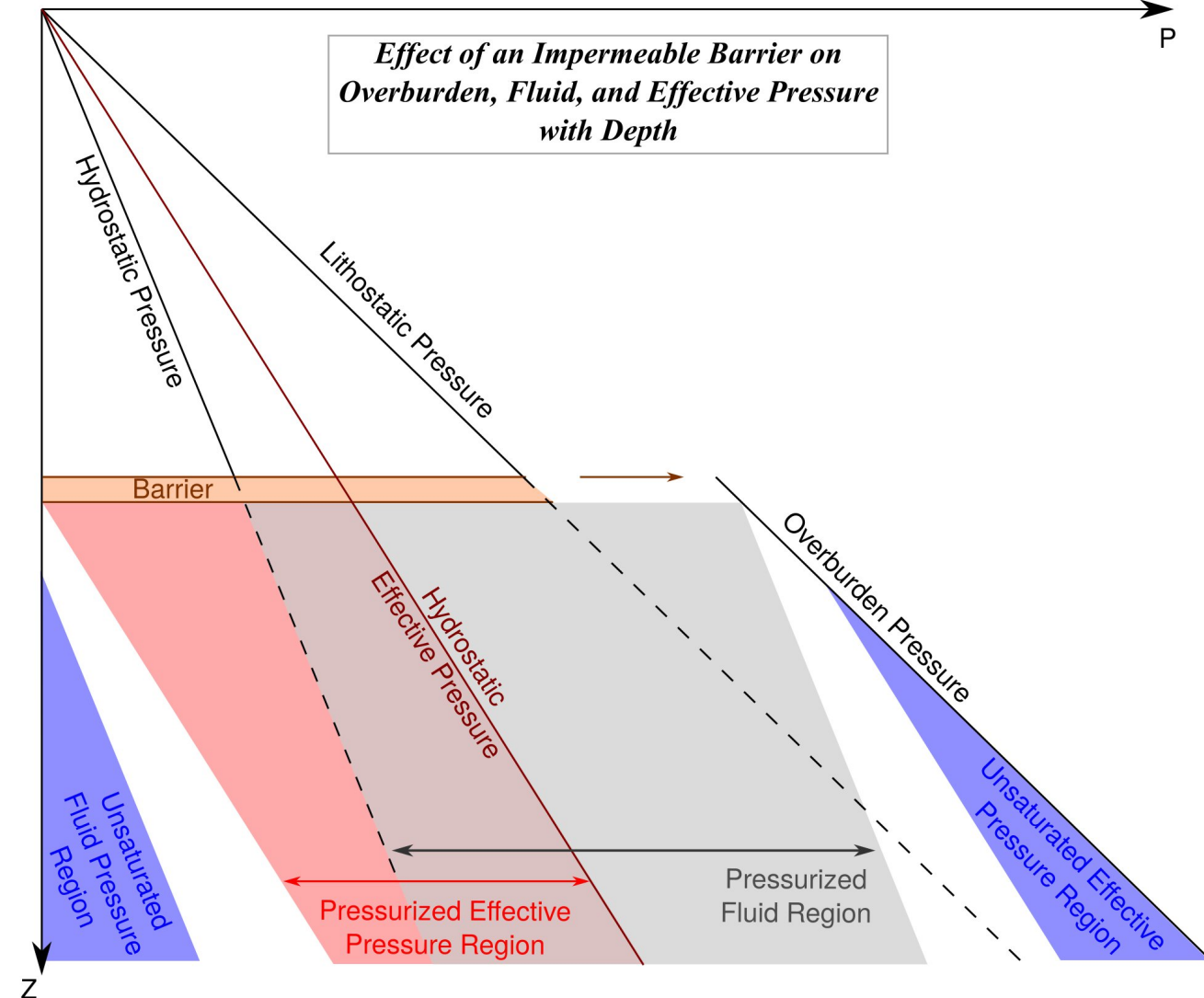
Modified from Vinciguerra et al., 2005





How does P_{eff} vary with depth?

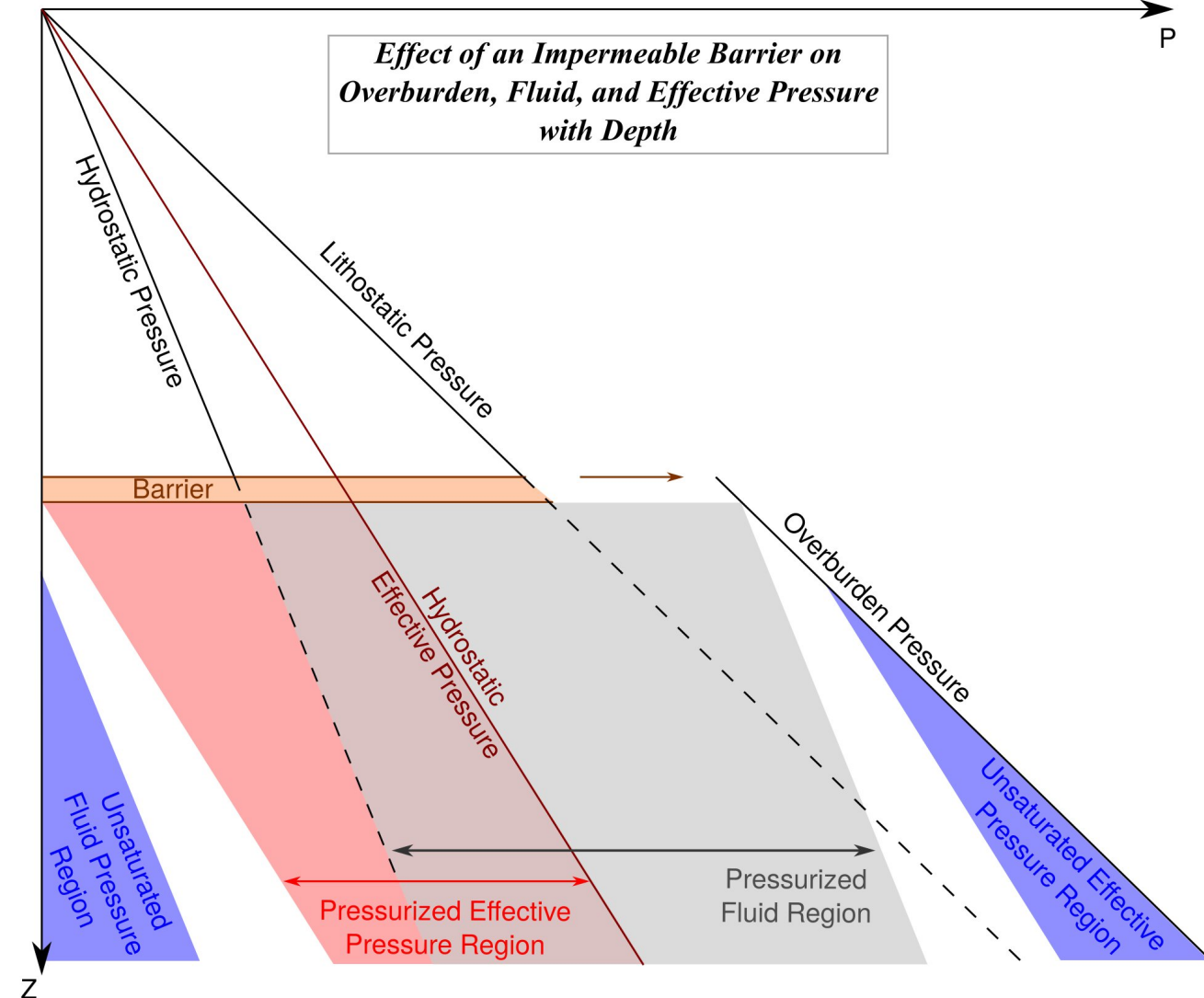
- Continuous fluid column (above barrier)
 - $P_{eff} \approx P_{lithostatic} - P_{hydrostatic}$
- At/below an impermeable barrier
 - $P_{overburden} \approx P_{lithostatic} + P_{hydrostatic}(Z_{barrier})$
 - $P_{eff} \approx P_{overburden} - P_{fluid}$
- Incomplete fluid column below barrier
 - Lowered P_{fluid}
 - Higher P_{eff}
 - P_{eff} jump below barrier
- Pressurize fluid column below barrier
 - $P_{fluid} \geq P_{hydrostatic}$
 - Lowered P_{eff}
 - (small) P_{eff} jump below barrier





Which processes change P_{eff} ?

- Introducing a barrier into a fluid column
 - Can increase/decrease P_{eff} depending on fluid column below the barrier
- Breaking a barrier
 - Pushes P_{eff} back to hydrostatic case
 - Can drain/inflate fluid column above the barrier
 - Affects entire depth range of the newly connected column
- Creating a path elsewhere (barrier intact)
 - Can drain lower reservoir > increases P_{eff}
 - Can pressurize lower reservoir > decreases P_{eff}
 - Only affects depth range of column below the barrier
 - Production/injection produce similar effects

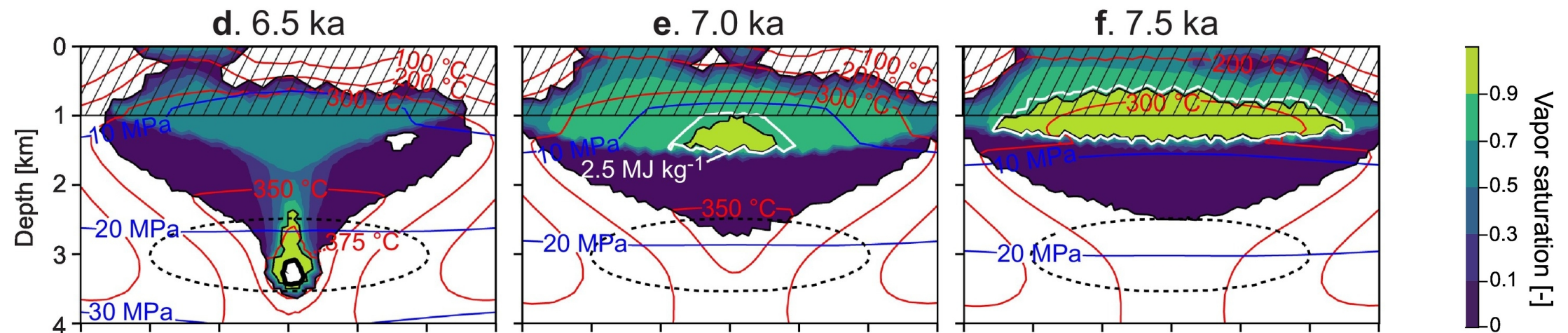




Decompression boiling

Complex interconnection

- Lowering P_{fluid} in broad region
 > causes phase change in specific region
- Geophysical properties affected in both cases
 - Doubly affected in compressible fluid region

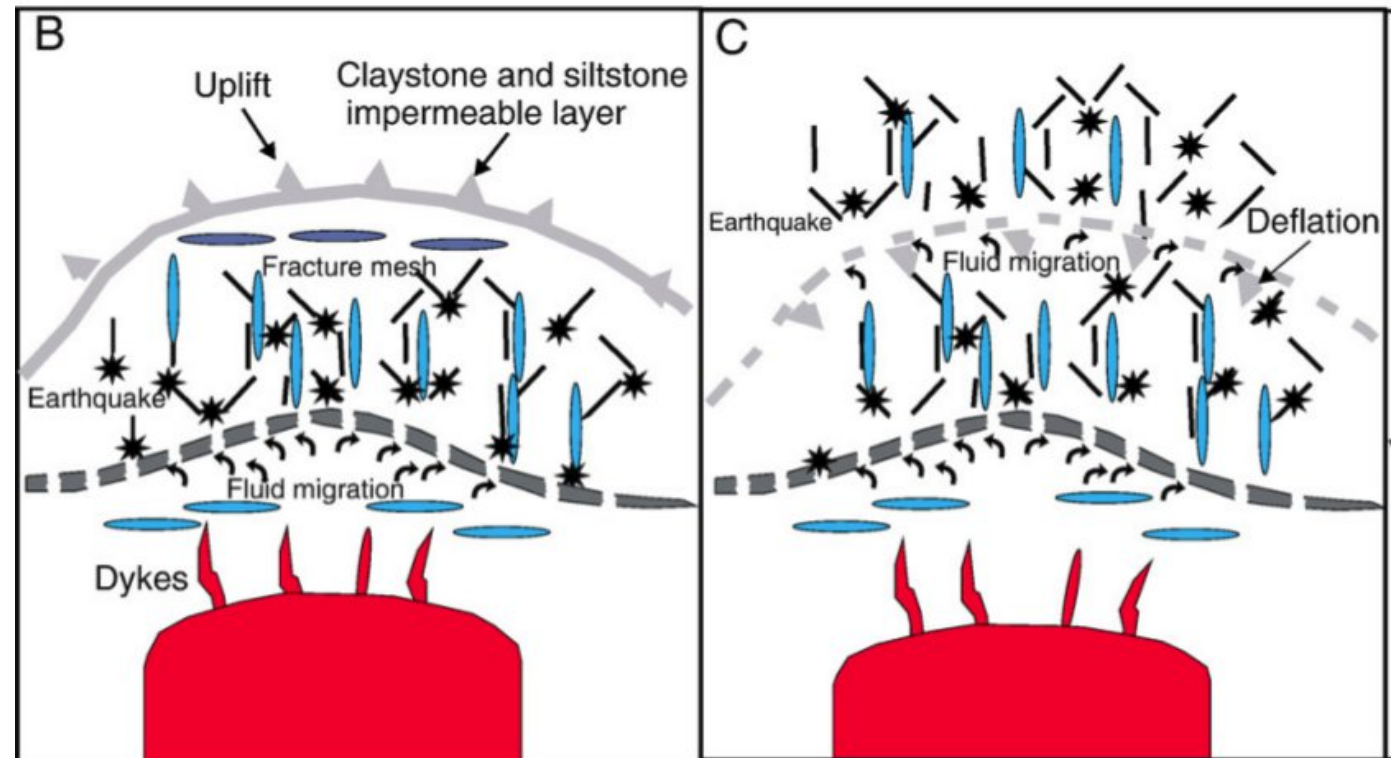




Campi Flegrei, Italy (theoretical)

Bending and subsequent fracturing of an impermeable barrier by expanding fluids

- While bending the barrier
 - Increased P_{fluid} below barrier
 - > decreased P_{eff} below barrier
 - + fracturing below barrier
- After fracturing the barrier
 - Shallower fracture signal
 - Decreasing P_{fluid} below barrier
 - > increased P_{eff} below barrier
 - Increasing P_{fluid} above barrier
 - > decreased P_{eff} above barrier
 - Compressible fluid signal above barrier



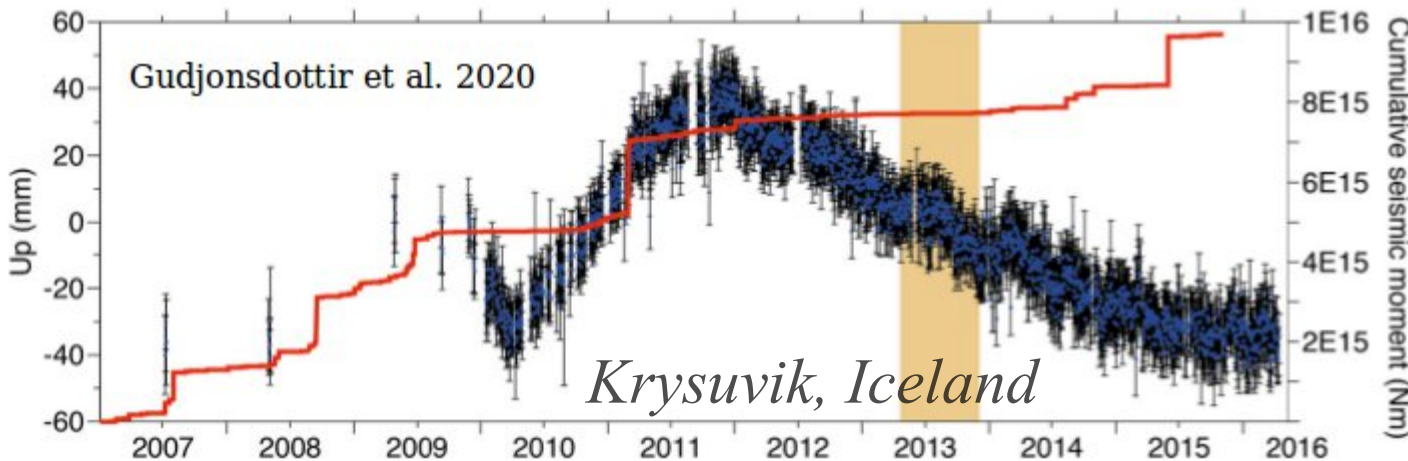
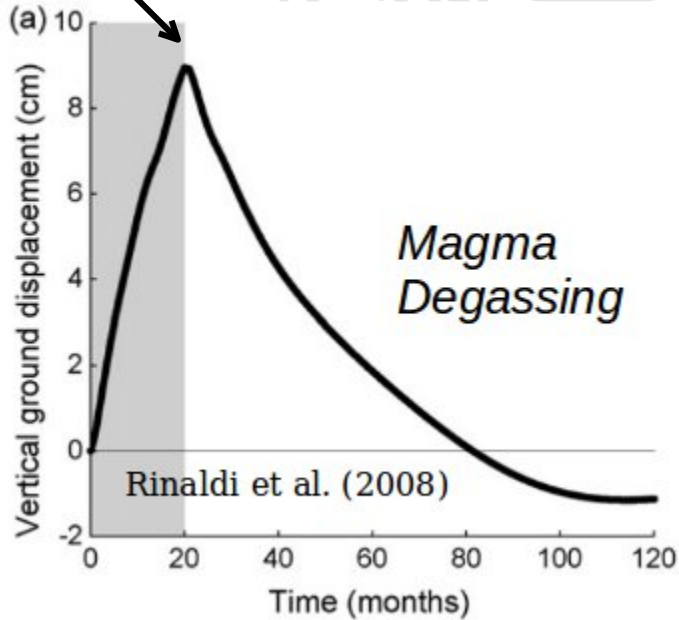
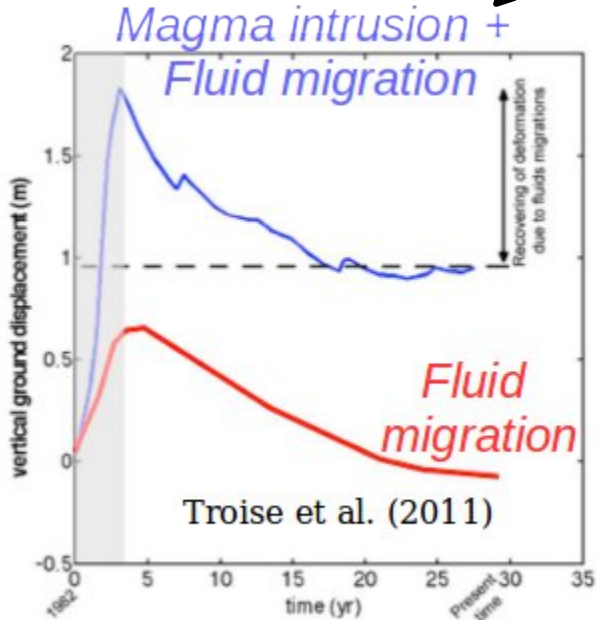


Campi Flegrei, Italy

Deformation signal comparison

Campi Flegrei, Italy & Krysuvik, Iceland

- Krysuvik signal similar to non-permanent component of Campi Flegrei
 - Sharp rise
 - Prolonged decay
- Bending and fracturing boundary applicable in Krysuvik?
 - Time-Dependent Vp/Vs tomography



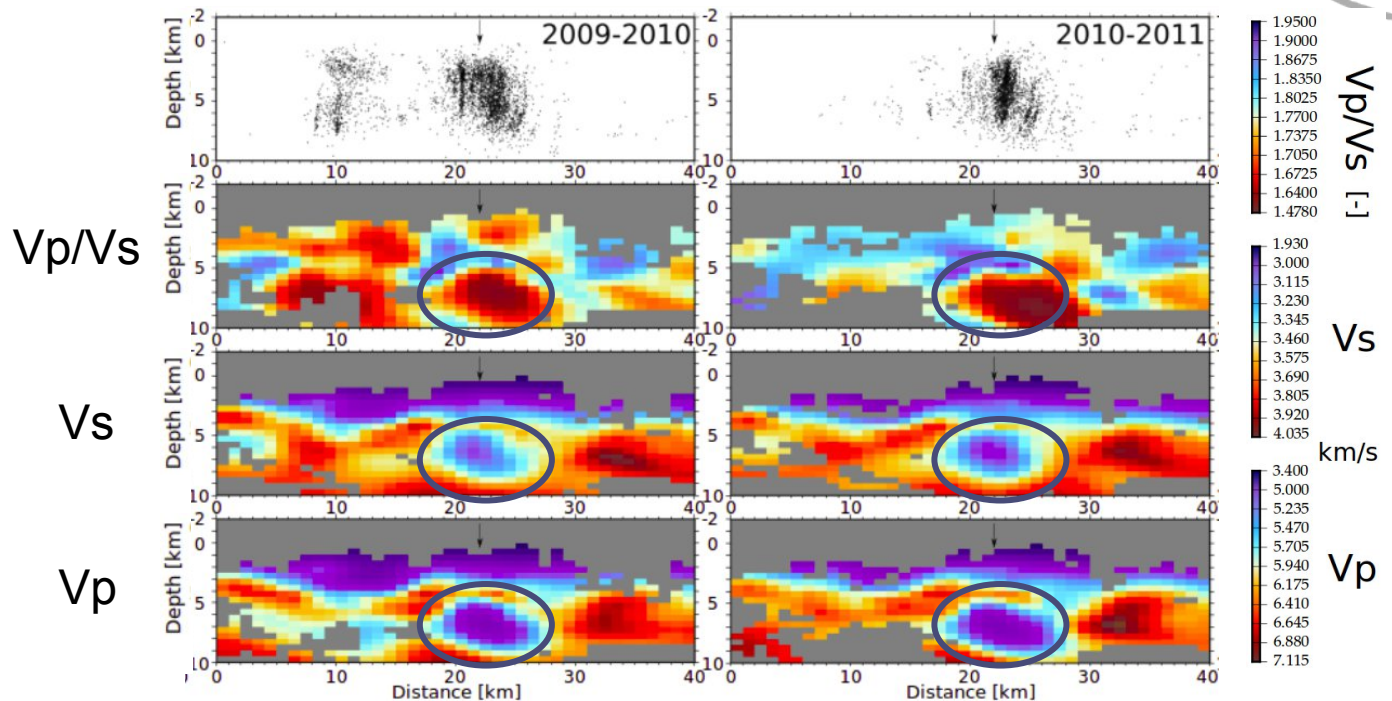
Krysuvik, Iceland



Krysuvik, Iceland

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 - > decreased P_{eff} above barrier



Local Earthquake Tomography profile of Krysuvik, Iceland (Hobé et al. 2021)

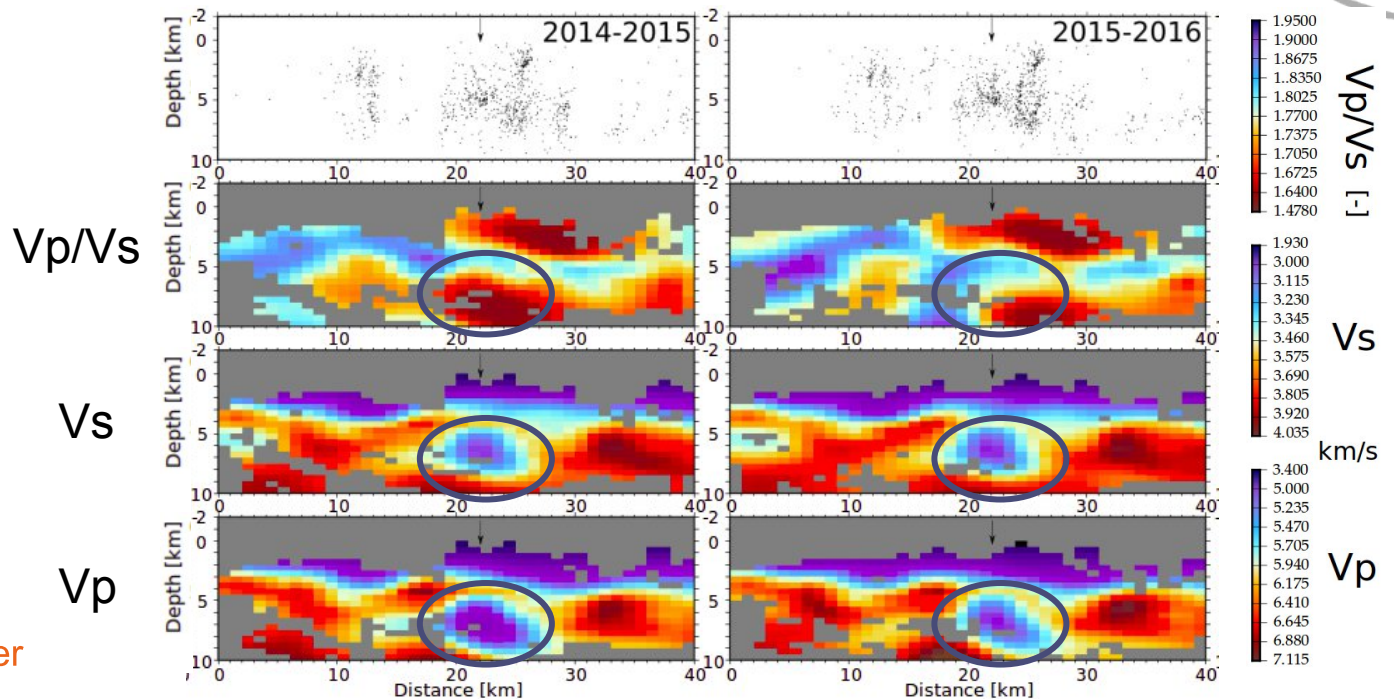




Krysuvik, Iceland

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Local Earthquake Tomography profile of Krysuvik, Iceland (Hobé et al. 2021)

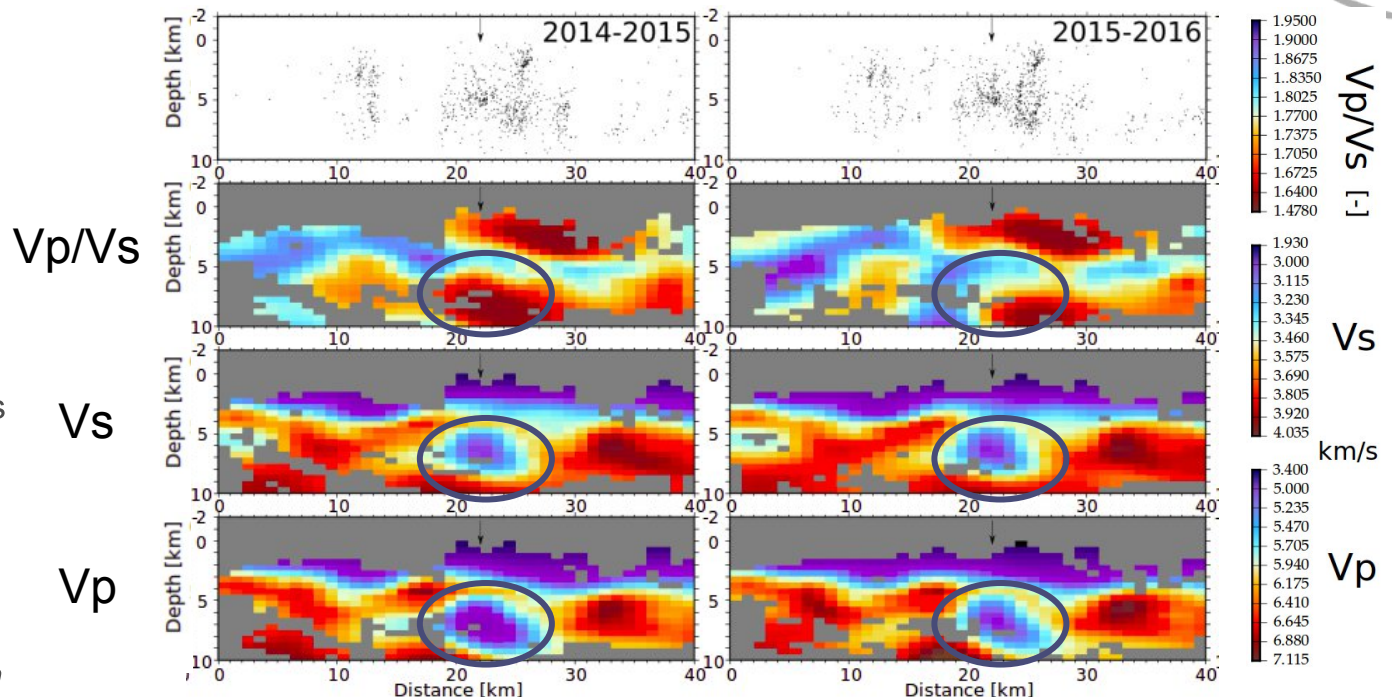




Conclusions

Time-varying processes reduce the non-uniqueness in interpretation of geophysical inverse models.

- By changing properties directly
 - Fracturing & fracture healing
 - Liquid $\leftrightarrow$ Compressible fluid
 - Through changing fluid content
- By changing P_{eff}
 - Changing fluid column length
 - Draining/pressurizing confined reservoirs
 - Breaking an impermeable barrier
- Comparable complex interactions in Campi Flegrei & Krysuvik
 - *Bending and subsequent fracturing of an impermeable barrier by expanding fluids*



Local Earthquake Tomography profile of Krysuvik, Iceland (Hobé et al. 2021)



And now with magma!



Seismicity Patterns Due to Magma Intrusions Underneath Geothermal Power Plants

Hobé et al. 2021b

*Alex Hobé, H. Geirsson, A. Tryggvason
O. Gudmundsson, SIL seismological group*

