Mantle magma imaged magnetotellurically beneath an active magmatic segment in Afar, Ethiopia

Kathy Whaler

in collaboration with Mohammednur Desissa, Graham Dawes, Shimeles Fisseha, Sophie Hautot, Nick Johnson and other members of the Afar Rift Consortium

Outline

- Introduction
- The MT data sets
- 2D models
- Example joint interpretation
- Chambers versus sills
- Conclusions

Magnetotelluric method

Physical parameter: **electrical resistivity** (ρ in Ωm), or its inverse, **electrical conductivity** (σ in S/m),

Electrical properties of an Earth material governed by:
- Mineralogy
- **Fluid content**

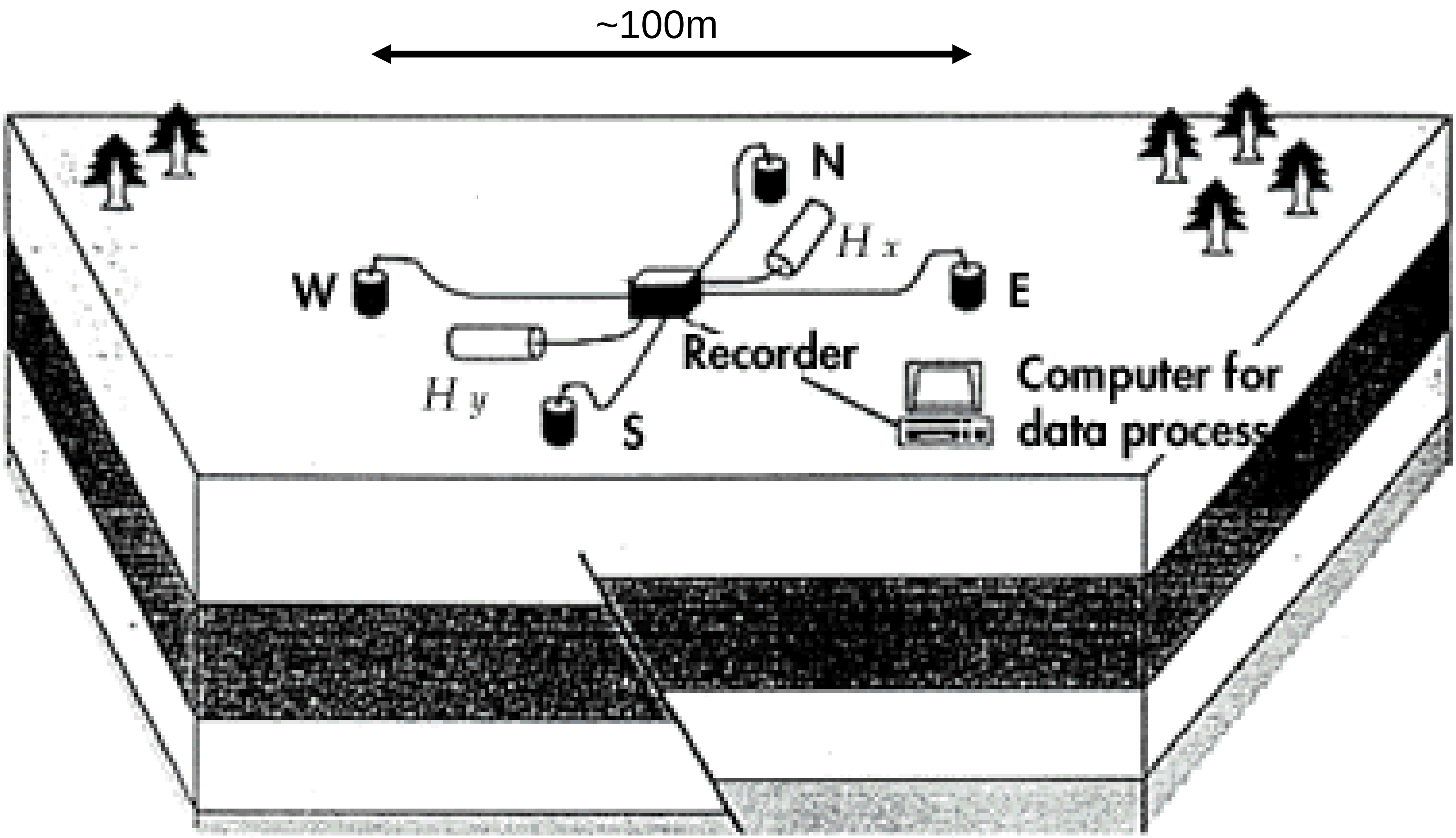
The magnetotelluric method is particularly sensitive to high conductivity (low resistivity) materials – (non-organic) fluids, magma, partial melt

Interest here is to image magma and partial melt in the crust and upper mantle

Magnetotelluric sounding

- Naturally occurring magnetic fields in the magnetosphere and ionosphere induce electrical currents in the sub-surface
- Strength and geometry depend on resistivity distribution
- Measure electrical, **E**, and magnetic, **H**, fields, in North and East directions
- Impedance tensor **Z** = **E**/**H** expressed as amplitude (apparent resistivity) and phase (lag between **E** and **H**) – embodies resistivity information
- Determined as a function of period $\rightarrow$ depth proxy

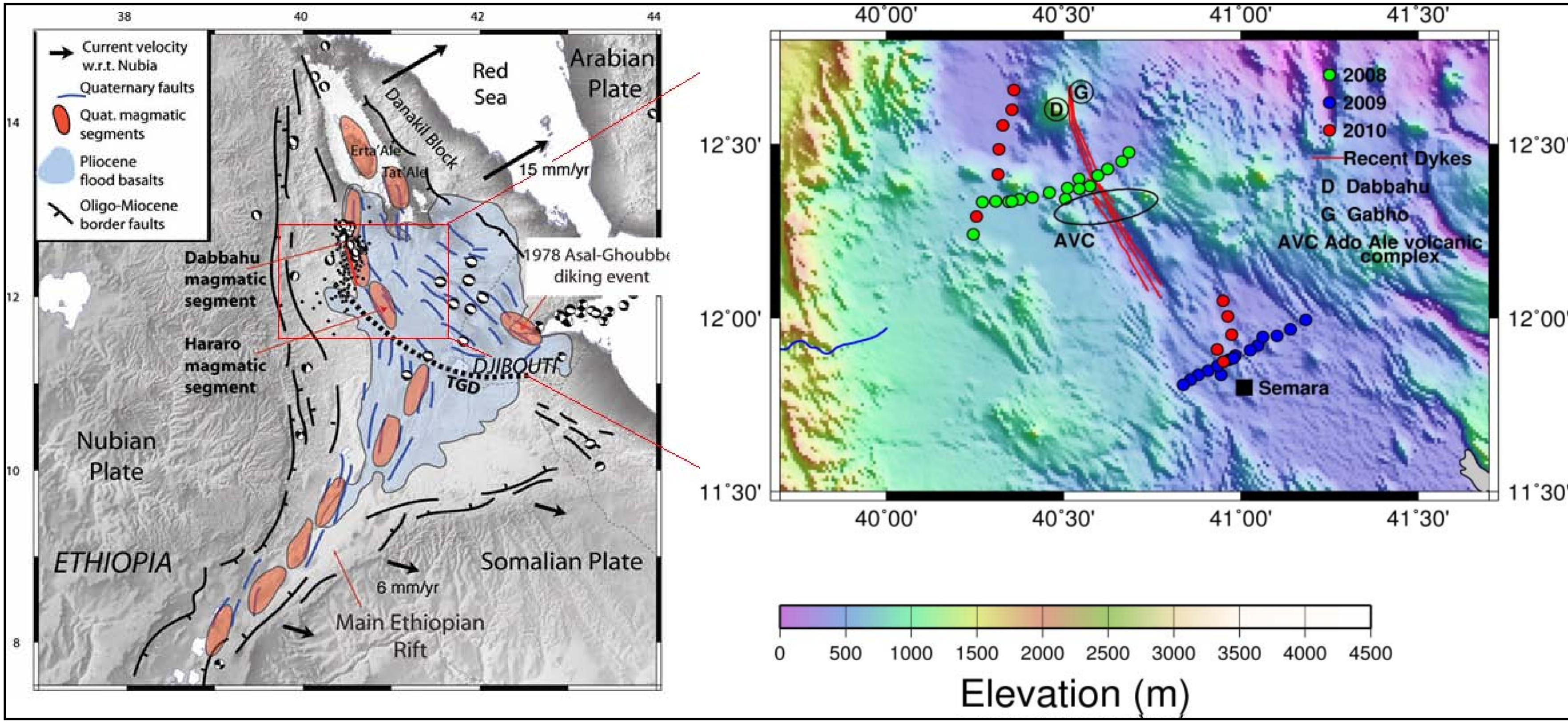
Schematic field layout



2D processing

- At the majority of sites, and for most periods, our data are broadly consistent with a 2D resistivity distribution (but see later talk by Sophie Hautot)
- In this case, only two of the four possible Z ratios are non-zero …
- … if rotated such that the axes are along and perpendicular to geoelectrical strike
- Process data to find the strike direction and correct for shallow 3D distortion effects

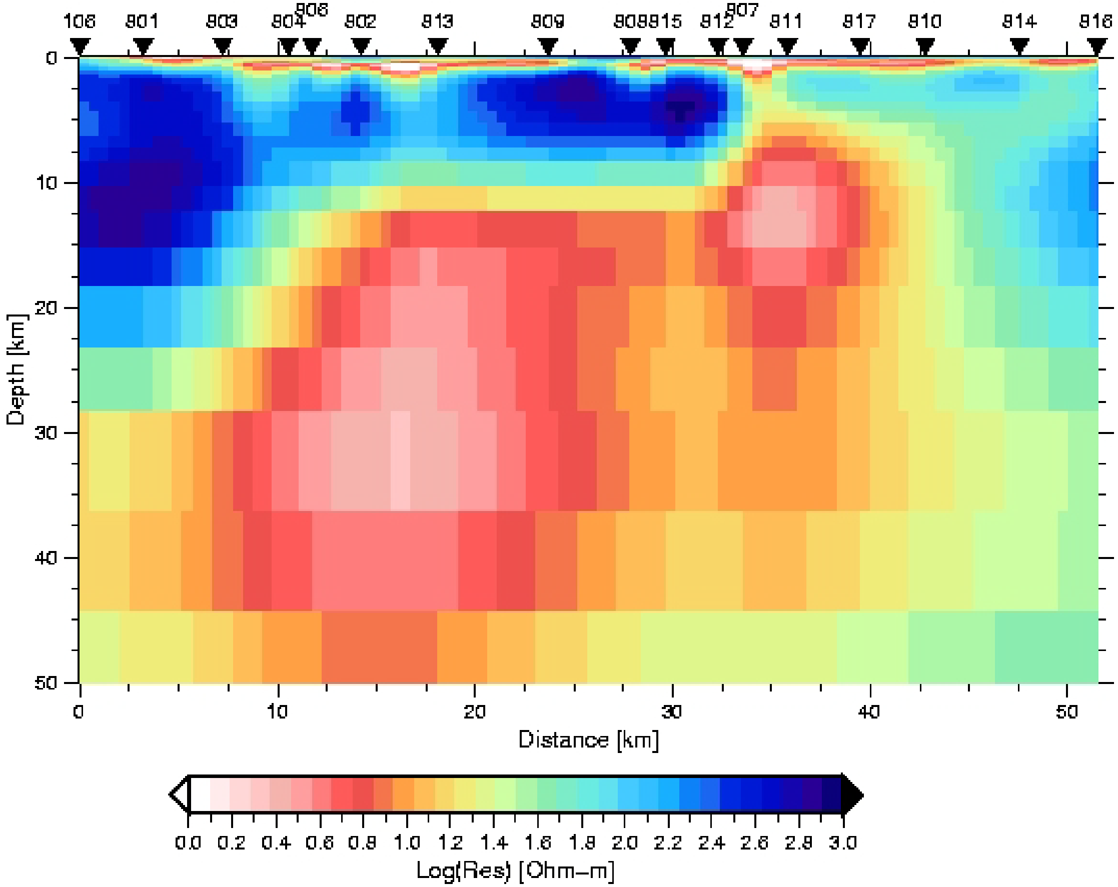
Site distribution

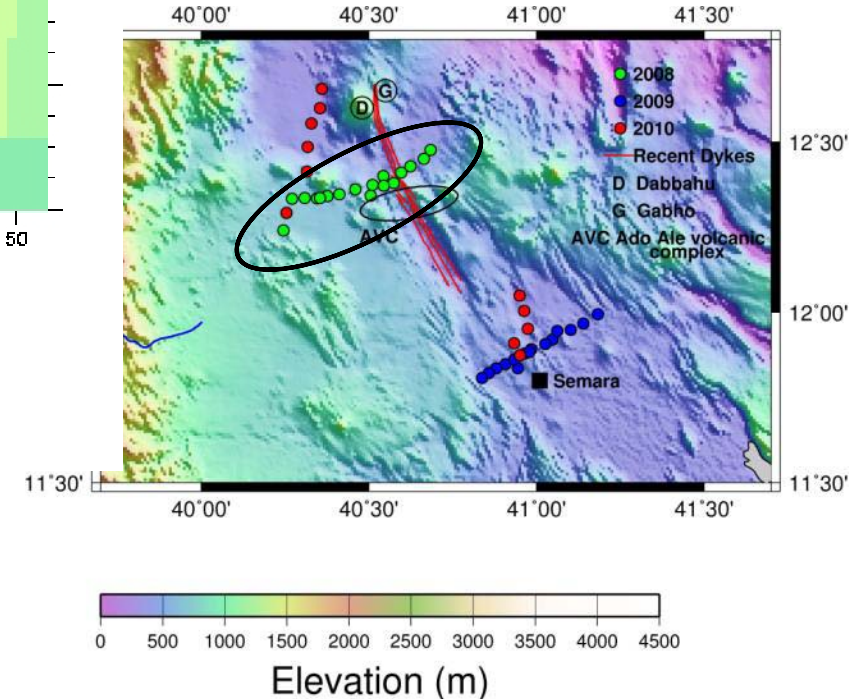


2D modelling

- Extend area to be modelled well beyond that covered by the data to match boundary conditions
  - only area below profiles shown here
- Parameterise the sub-surface into blocks of constant resistivity
- Block size increases with depth to reflect data resolution
- Invert for smoothest model fitting the data
- But can test other resistivity distributions by forward modelling

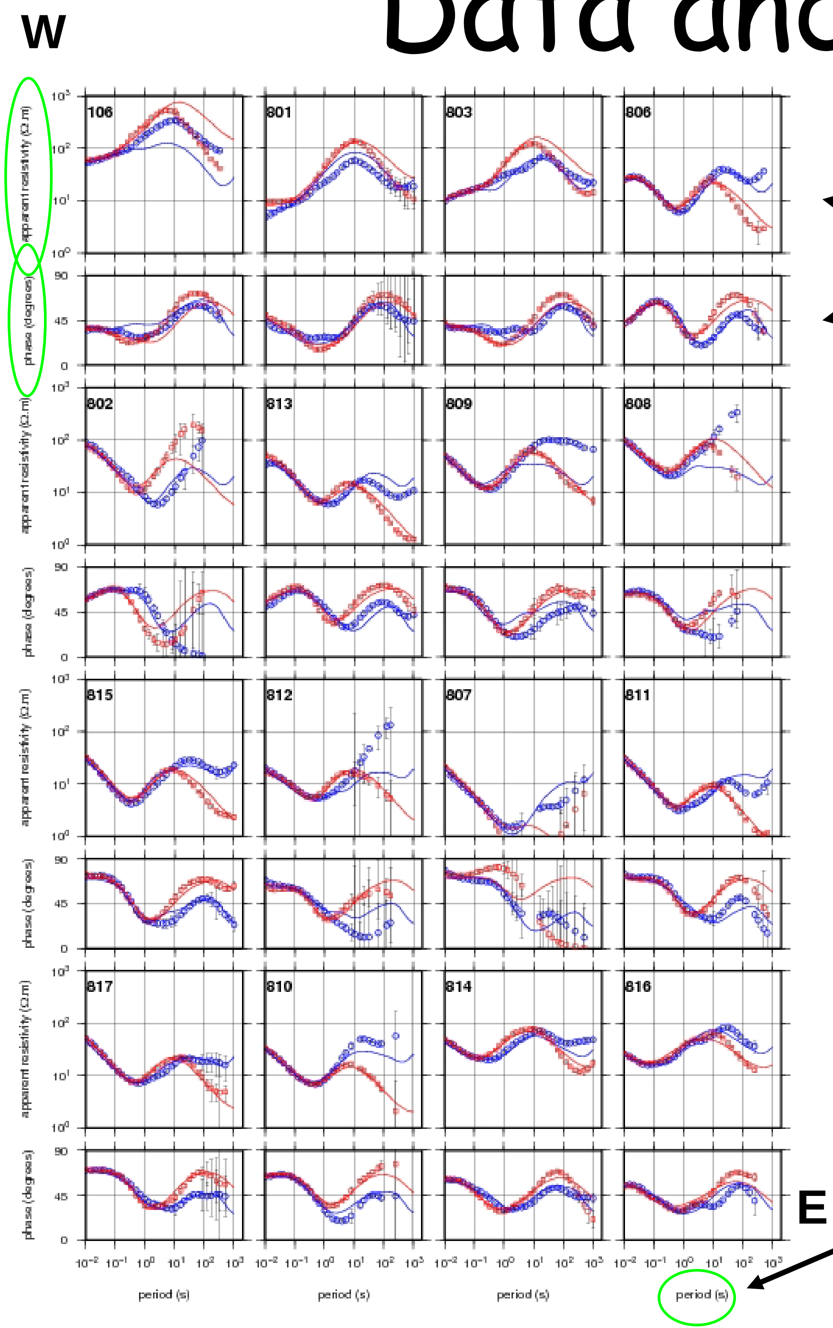
Profile across active segment





Best-fitting smooth 2D model of resistivity parameterised in blocks

Data and model fits



2D processed apparent resistivity (top) and phase (bottom) components, for currents flowing along and perpendicular to geoelectrical strike (plotted red and blue)

Points are data, solid curves model predictions

Data plotted horizontally as a function of period – depth proxy

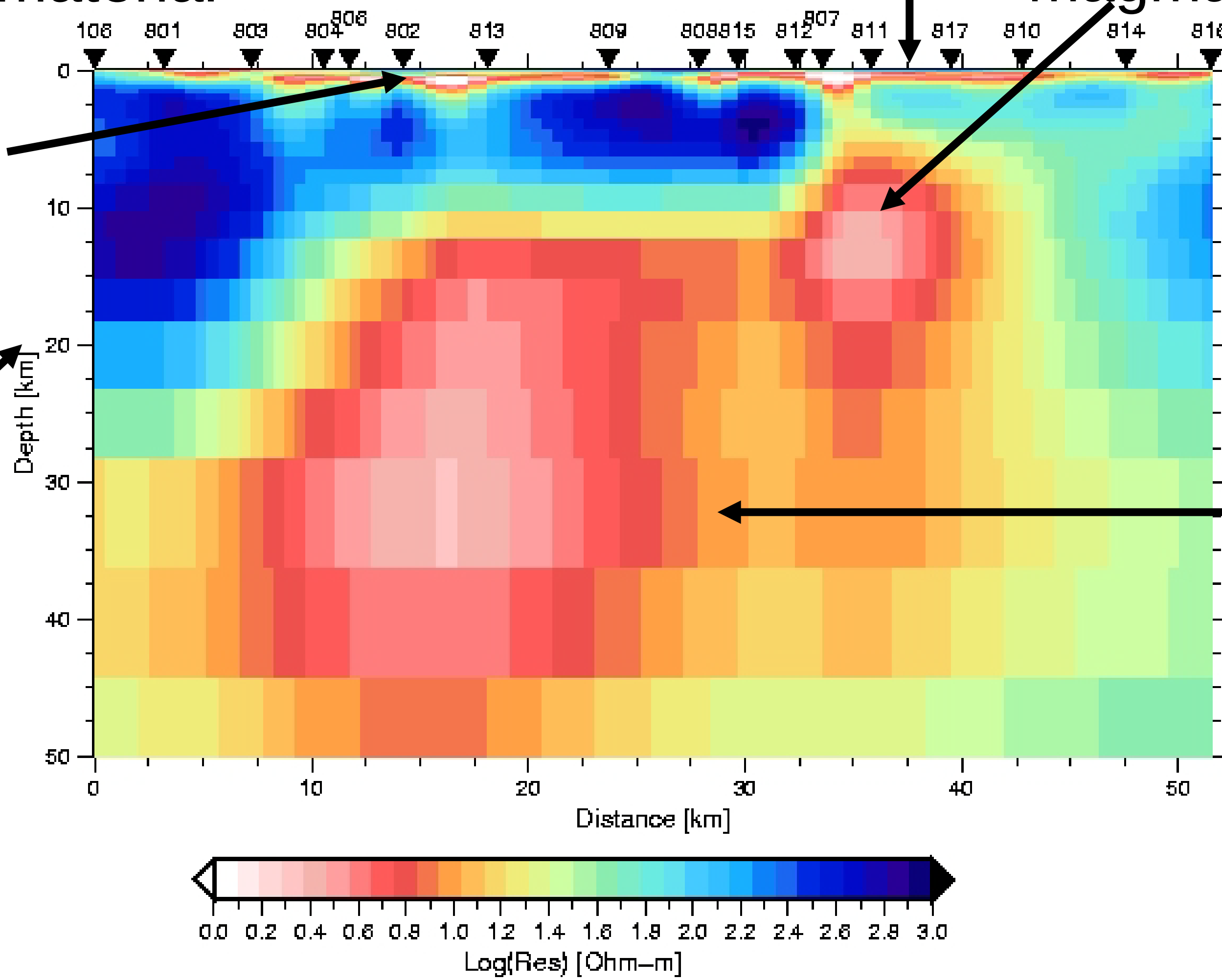
Cross-rift model and interpretation

Warm colours: low resistivity, hot/molten material

Rift axis

Known shallow magma chamber

Hot, saline-rich fluids (see poster by James Lindsay)



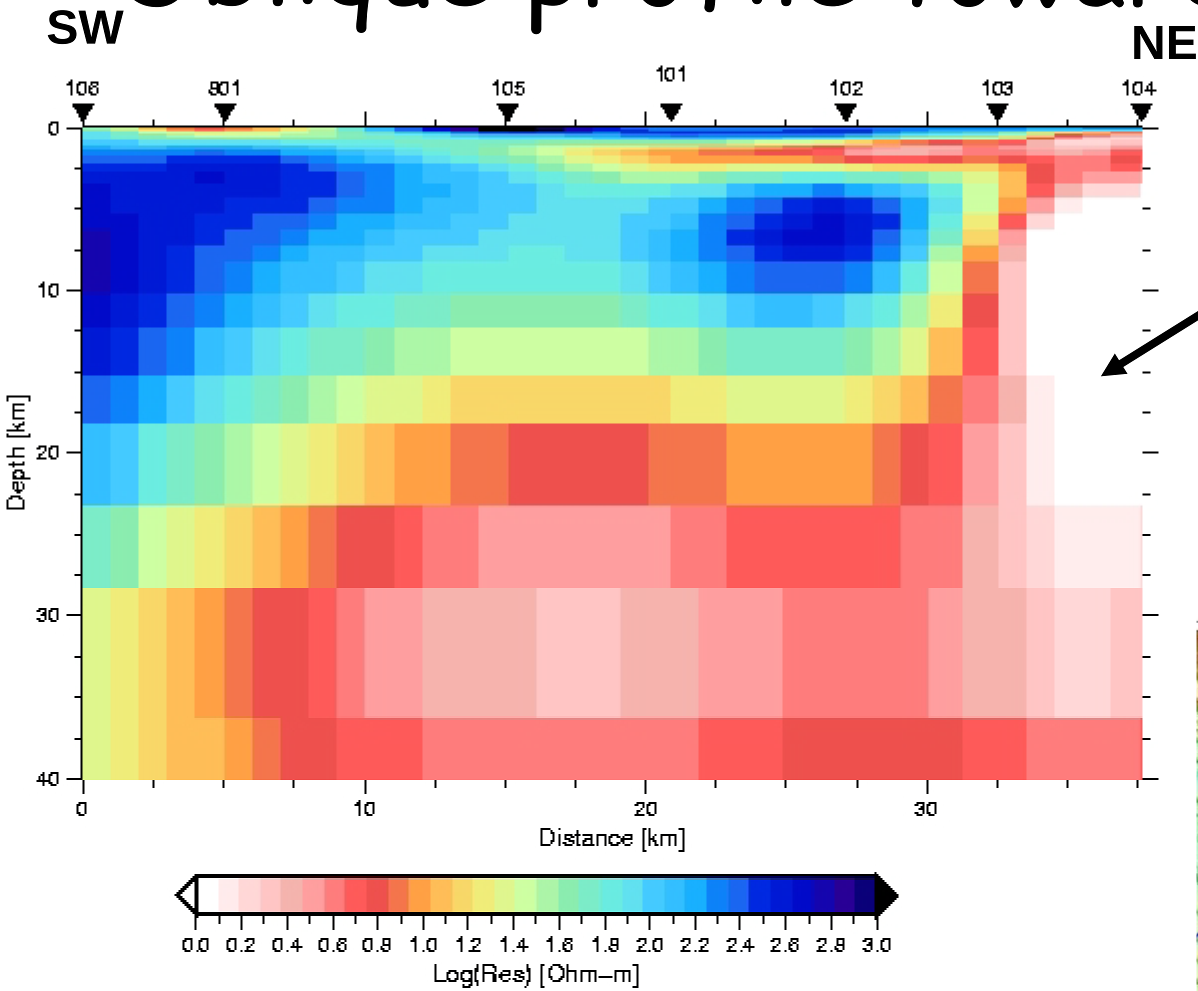
Deep magma chamber feeding dykes?

Base of the crust about here

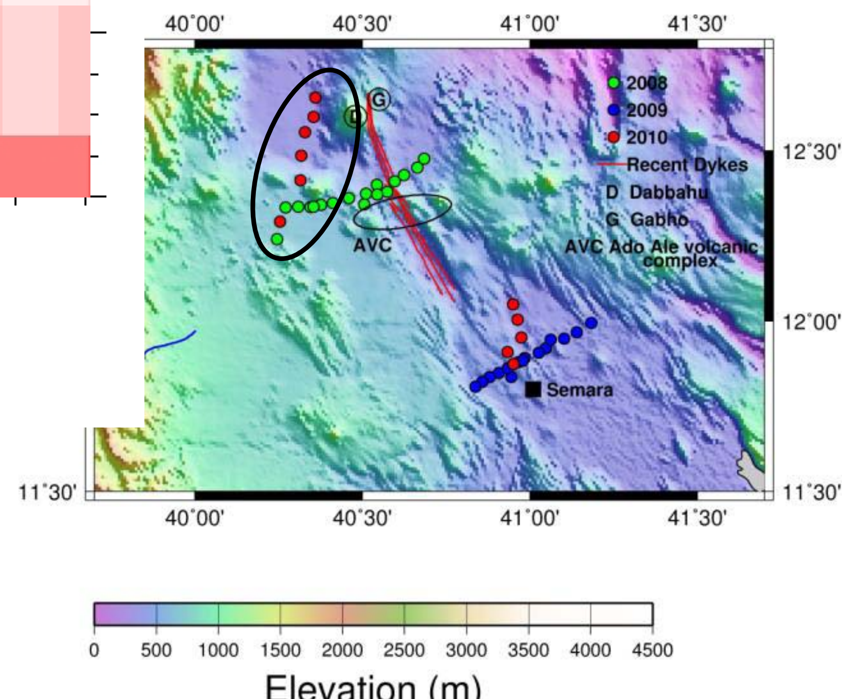
Model testing

- Conductor top surface depth well constrained
- Base affected by model regularisation (smoothness constraint – vertical smearing of structure)
- Base definitely sensed by data
- Tests show no shallower than 30 km
- Vertically integrated conductivity (conductance) equivalent to at least 4 km of seawater – exceptionally high

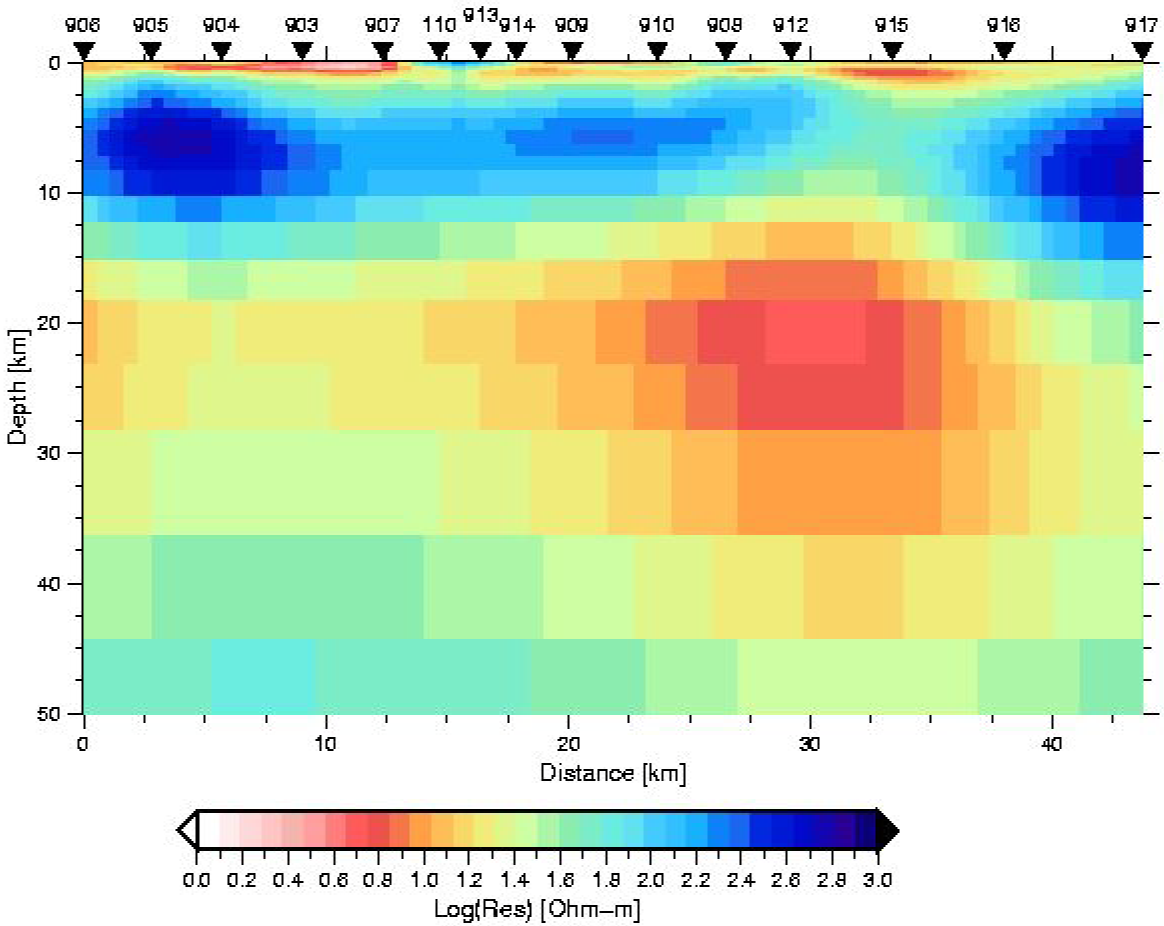
Oblique profile towards Dabbahu

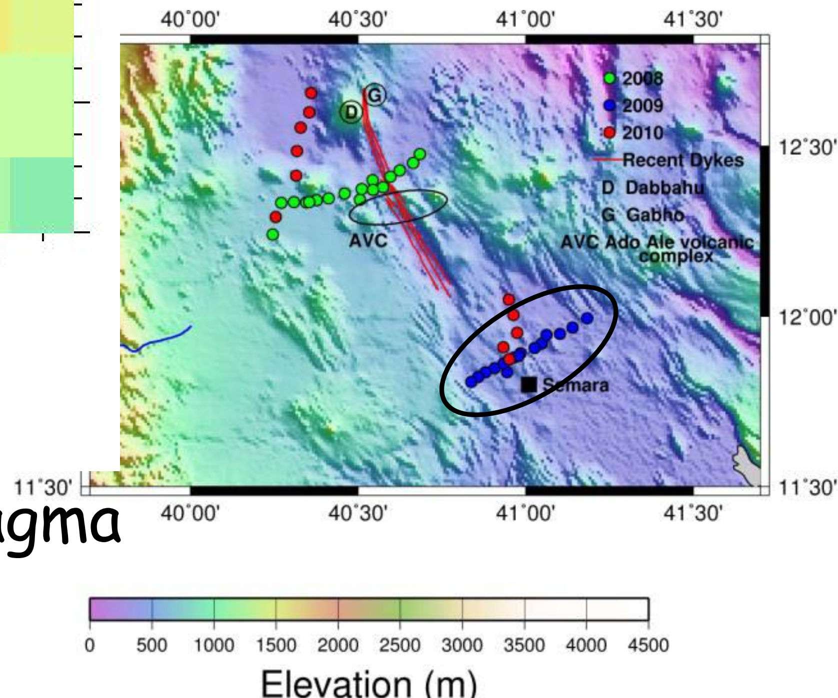


Enormous volumes of melt in crust and mantle



Comparison with inactive segment



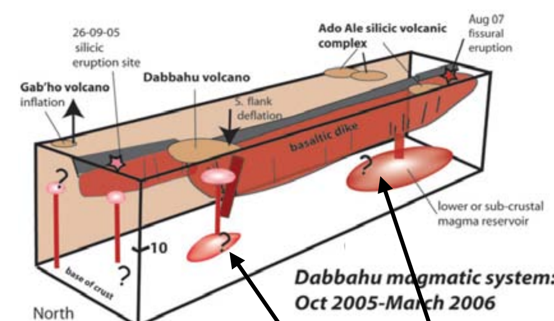


Higher resistivities ⇒ much less magma

No evidence for sub-crustal magma chamber

Summary

- Lots of magma beneath the active segment, and especially up around Dabbahu volcano
- Deep magma chamber beneath mid-segment profile centred close to Badi volcano
- Magma at depth
  - imaged for the first time
  - definitely at least partly in the mantle
- Much less magma beneath inactive segment, particularly in the mantle

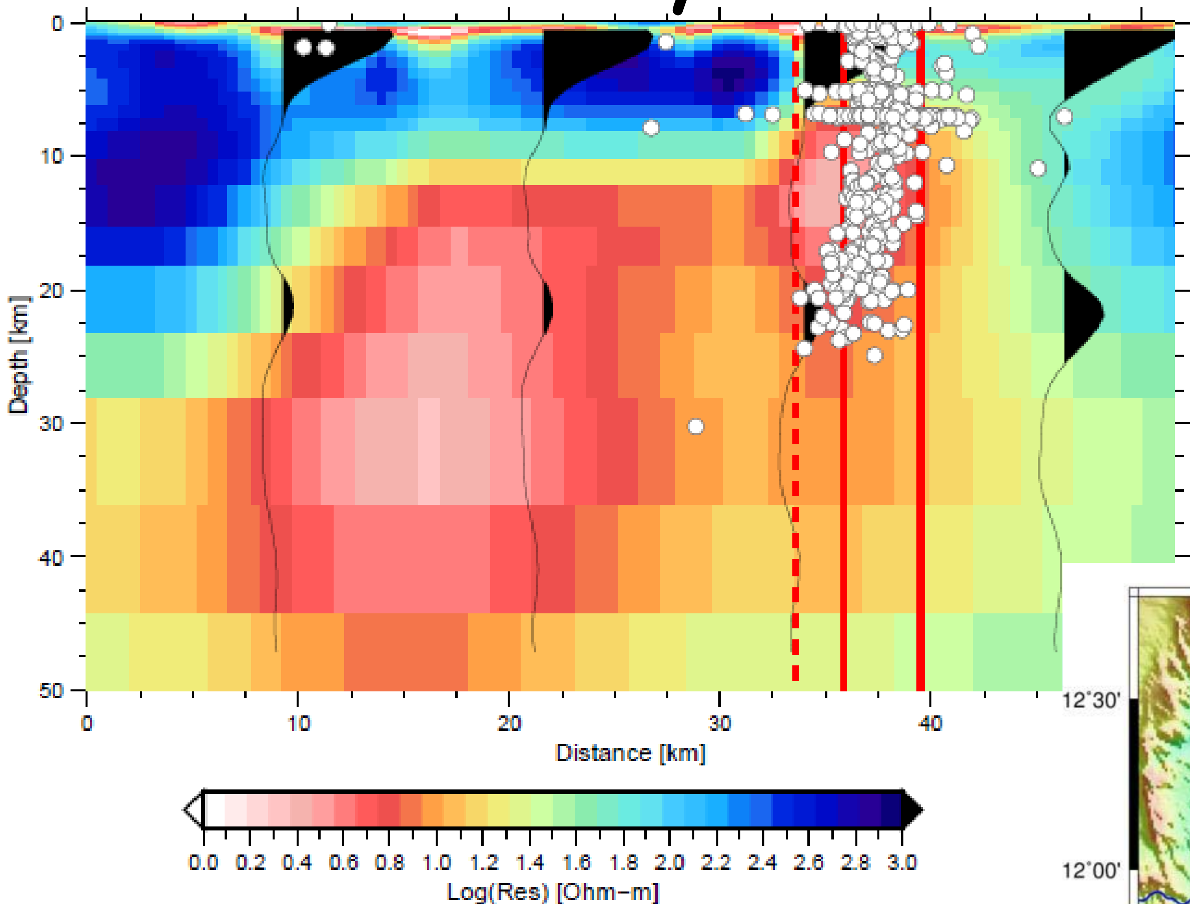


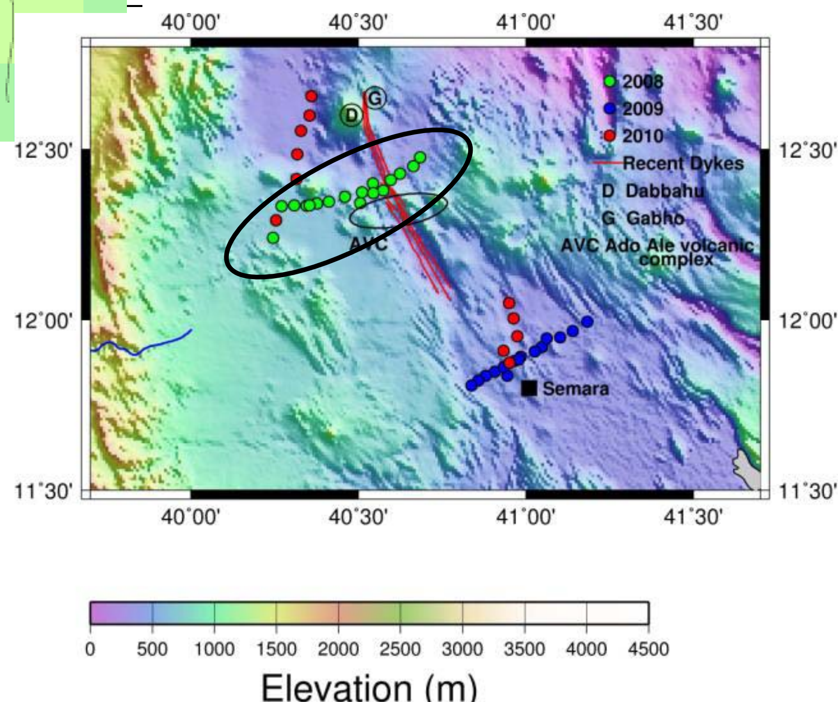
Take these question marks away

Supporting evidence for deep crustal magma

- Receiver function $v_P/v_S \sim 2.1$ (high) $\Rightarrow$ low $v_S \Rightarrow$ lots of melt
- Since upper crustal ratio is 1.8, lower crust even more molten to get 2.1 as average value
- Viscoelastic relaxation model of GPS data has 10-12 km effective elastic thickness crust (dry crust?) over low viscosity layer (partially molten crust?)

Add seismicity and receiver functions

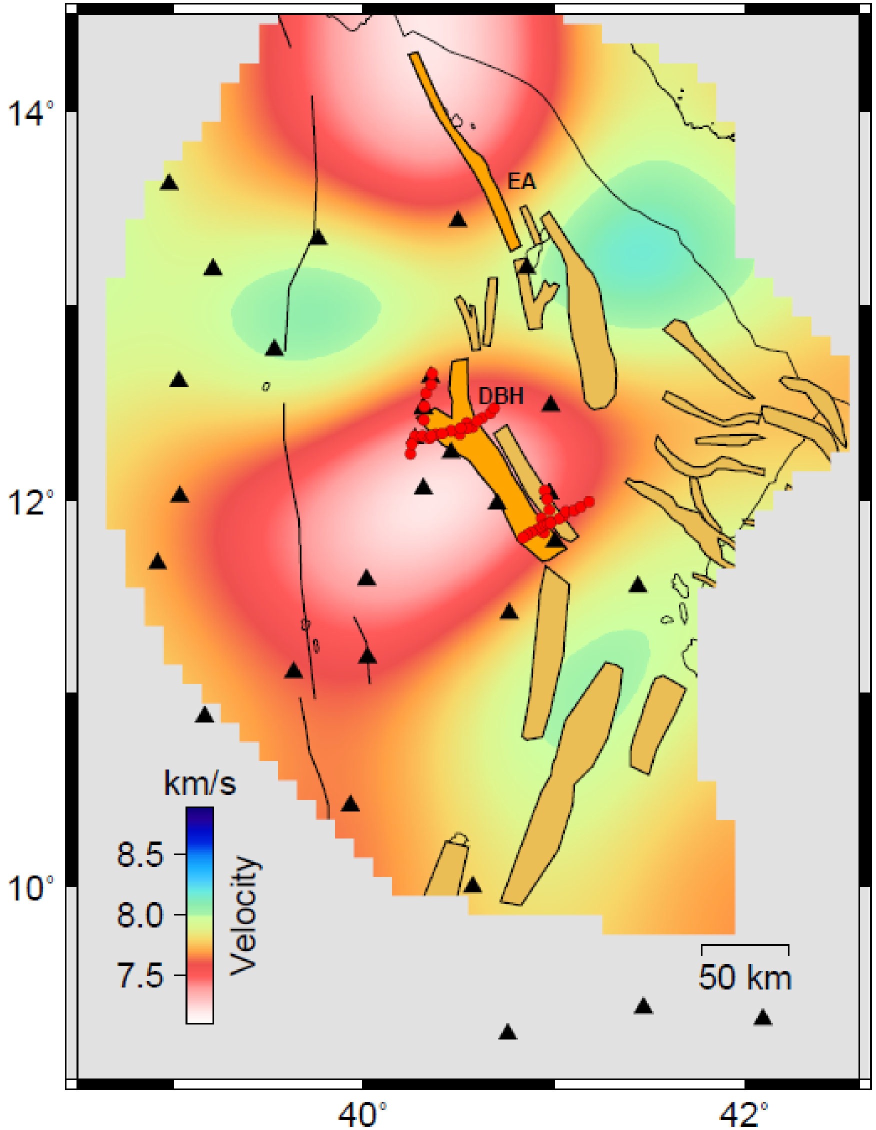




Seismicity over shallow conductor beneath rifted region

Migrated Moho receiver function signal weak in conductor

Supporting evidence for upper mantle magma



Pn velocity – samples around the Moho

Grey areas have uncertainties > 0.5 km/s

Typical velocities 8-8.1 km/s; here, substantially lower, indicating extensive melt in the upper mantle

Dabbahu profile has lower values than Hararo segment, in agreement with MT results

From Stork, Stuart & Henderson, submitted

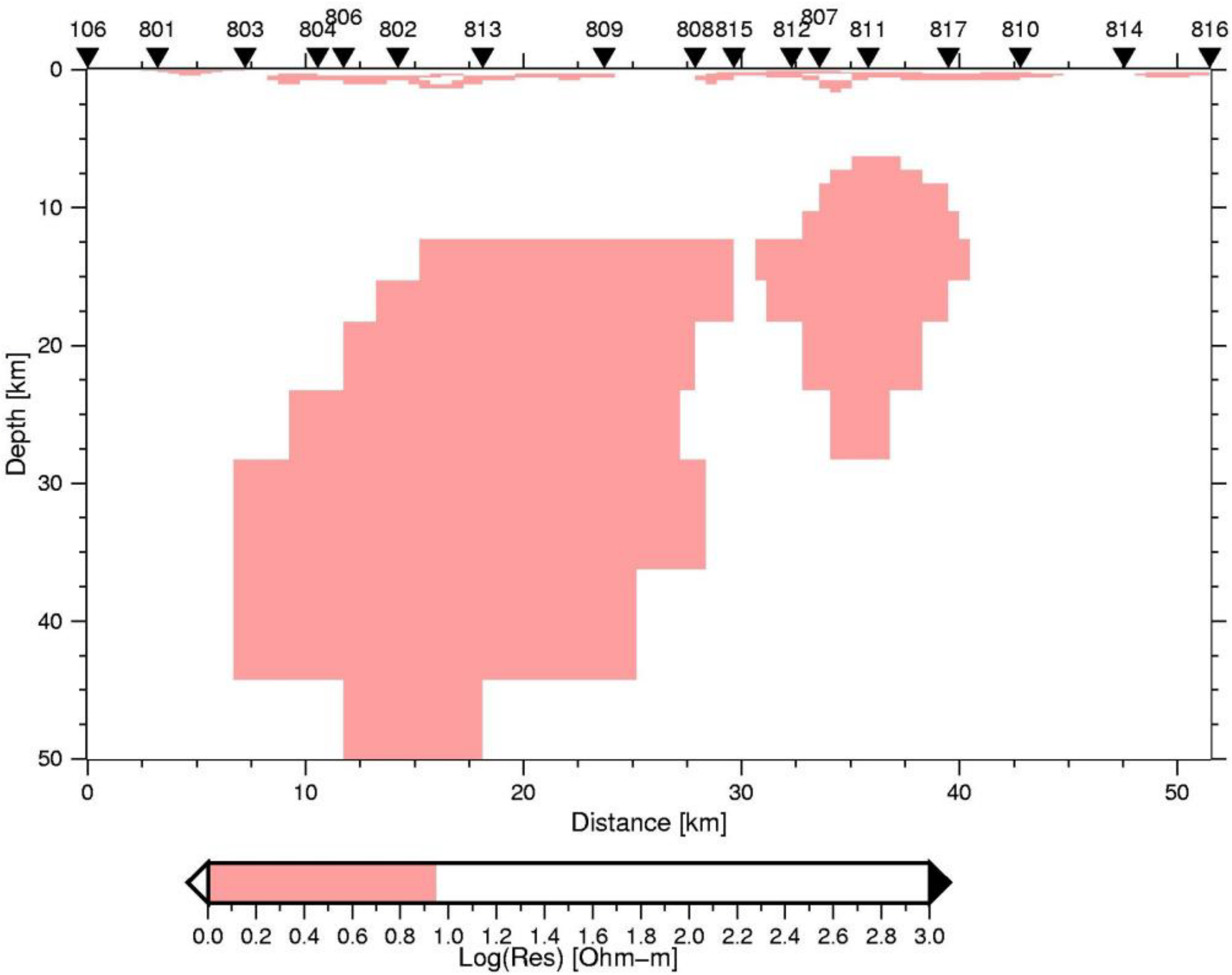
Example joint interpretation

- Seismic data are anisotropic – in crust/upper mantle, caused by oriented melt pockets
- Electric current flows more easily in the direction aligned with the melt pockets – lower resistivity for the same melt fraction
- $\Rightarrow$ Use parallel bound rather than Hashin-Shtrikman upper bound to infer amount of melt from bulk conductivity
- Gives minimum ~20%

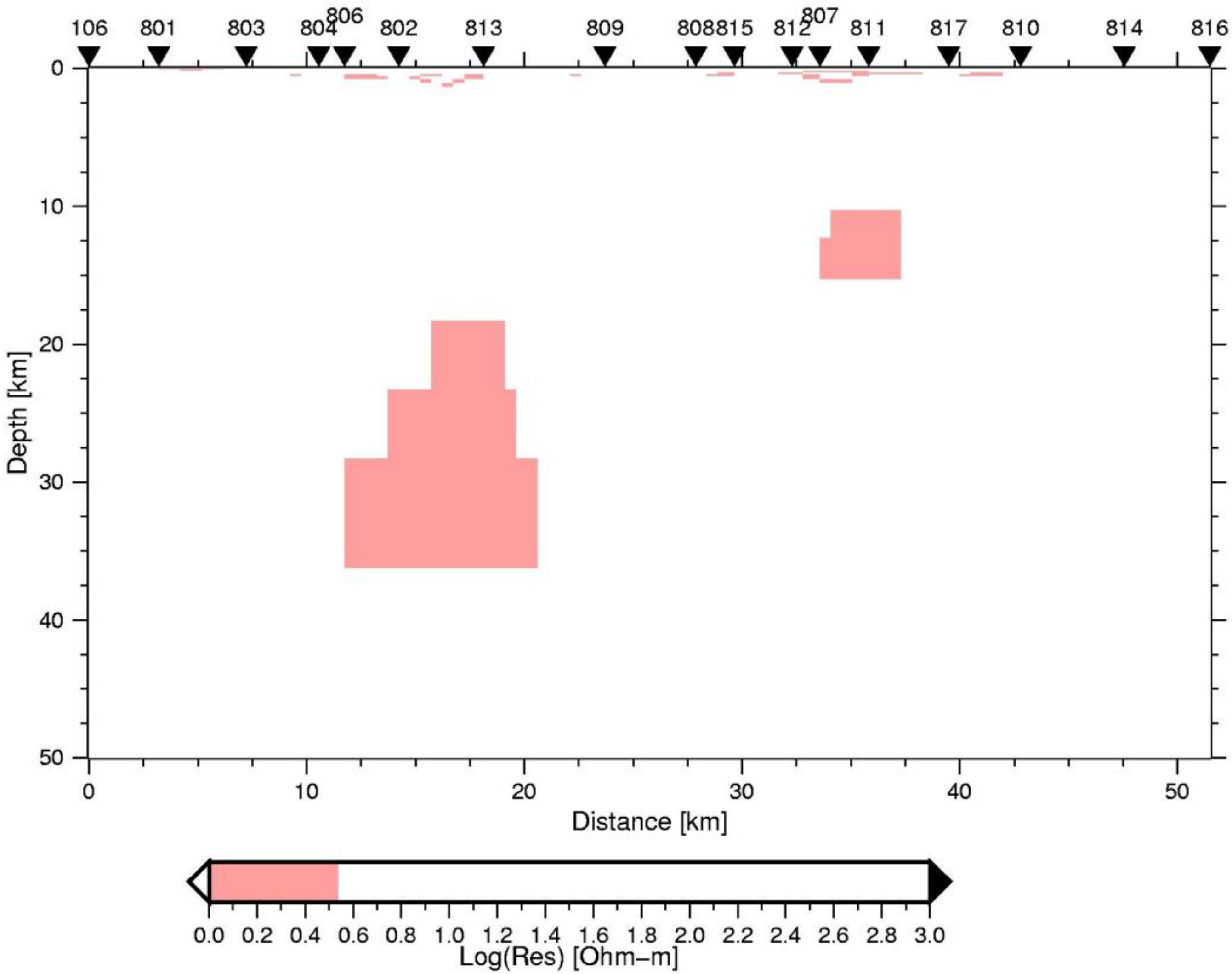
Joint interpretation (cont.)

- Use melt fractions inferred to bound (lower) volume of melt in the deeper chamber

4% melt outline



10% melt outline



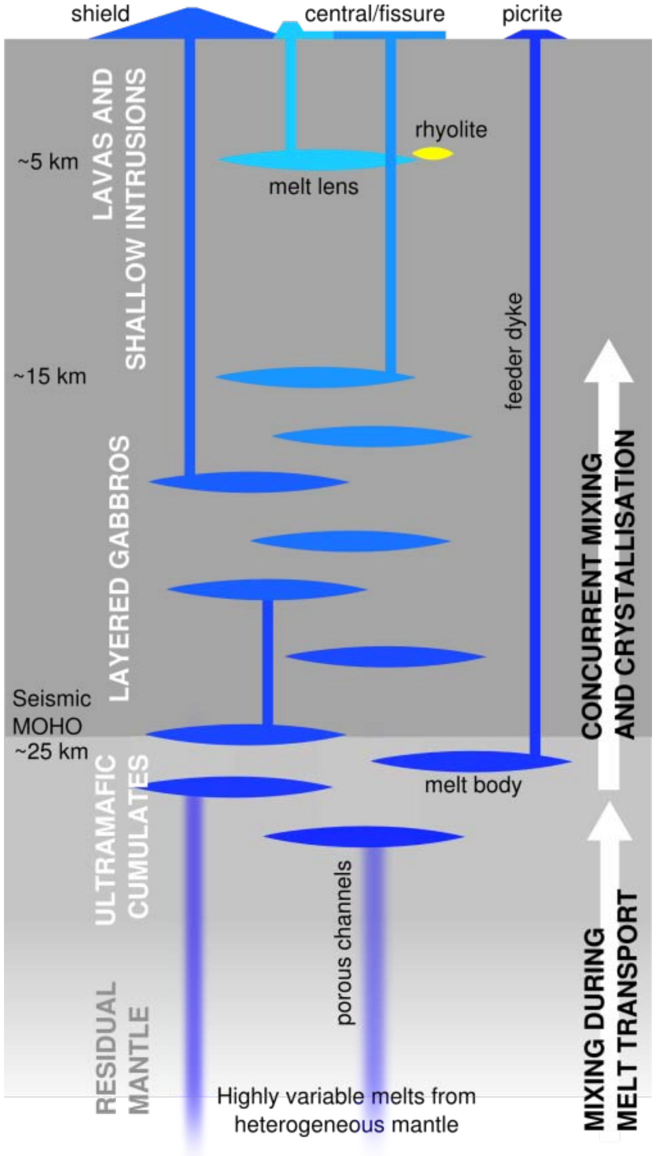
Joint interpretation (cont.)

- Assume surfaces spherical (2D modelling assumes structures continue along axis perpendicular to profile)
- Sphere of 10% melt nested inside annulus of 4% melt – conservative volume
- Gives > 3000 km^3 melt
- Enough to feed activity at current rate for 5000 years (2.5 km^3 in 5 years)

Joint interpretation (cont.)

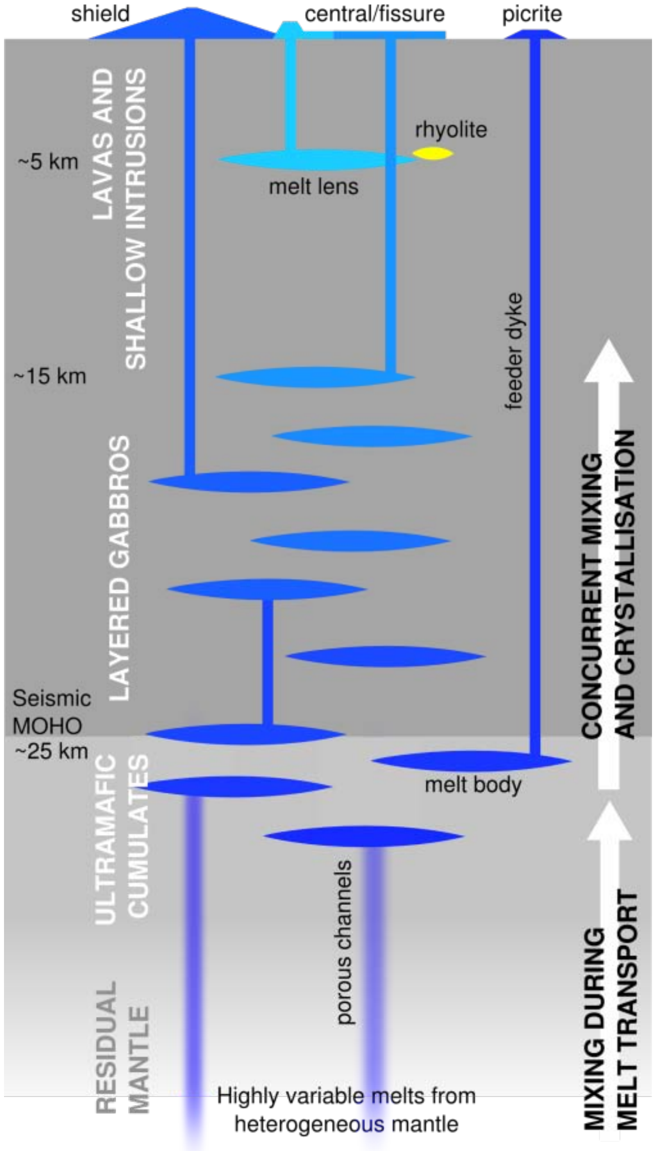
- But current events only every 400 years or so?
- 20 mm/yr far-field spreading rate, building crust 20 km thick
- Hence enough for 150,000 years
- Calculations dependent on value assumed for melt resistivity; taking highest published value gives ~ 750 km^3 melt (factor 4 smaller)

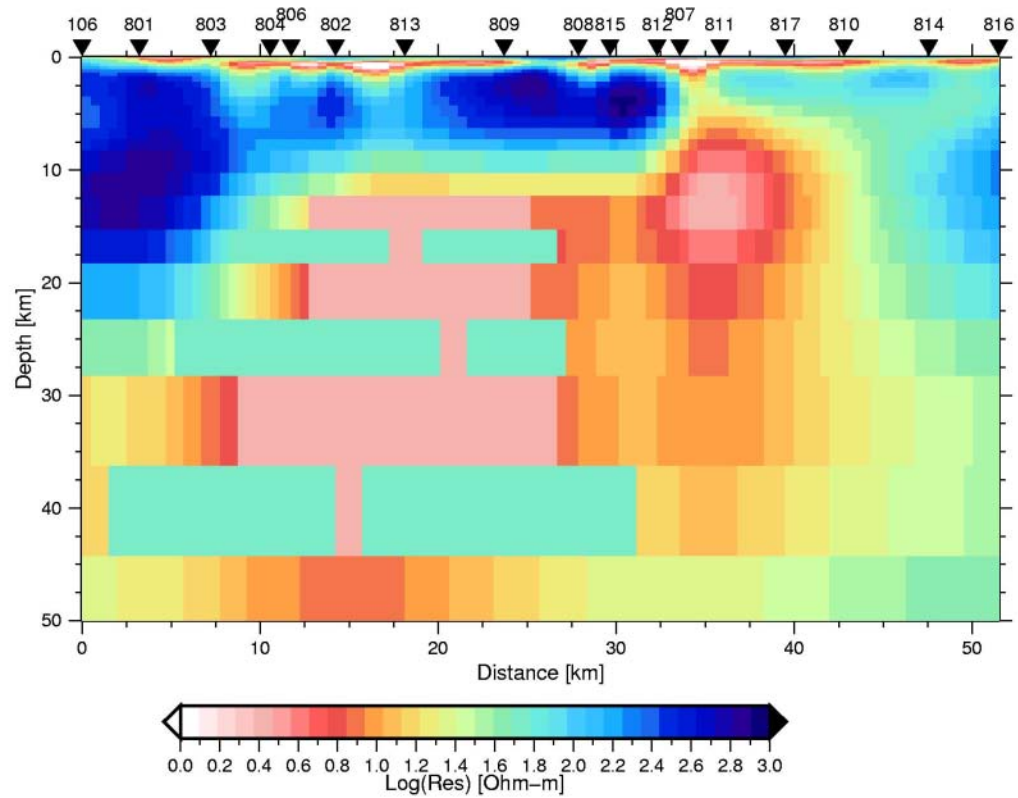
Sills or a magma chamber?



Schematic from John Maclennan based on data from Iceland

Sills or a magma chamber?





Replace single conducting volume by a series of stacked conductors (≡ sills) and resistors

Sills more conductive than single chamber

Fits data equally well

Sills or a magma chamber?

- Melt volumes and integrated conductance inferred from the two models very similar
- Sill conductivity increases with depth – probably melt conductivity increasing with temperature
- Future work: sub-divide the layers to allow thinner sills

Conclusions

- There is a substantial magma volume in the mantle beneath the Dabbahu mid-segment
- The region around the Dabbahu volcano has the most melt – very high % melt values
- Along the mid-segment profile, the main chamber is displaced from the rift axis, to beneath the Badi volcano