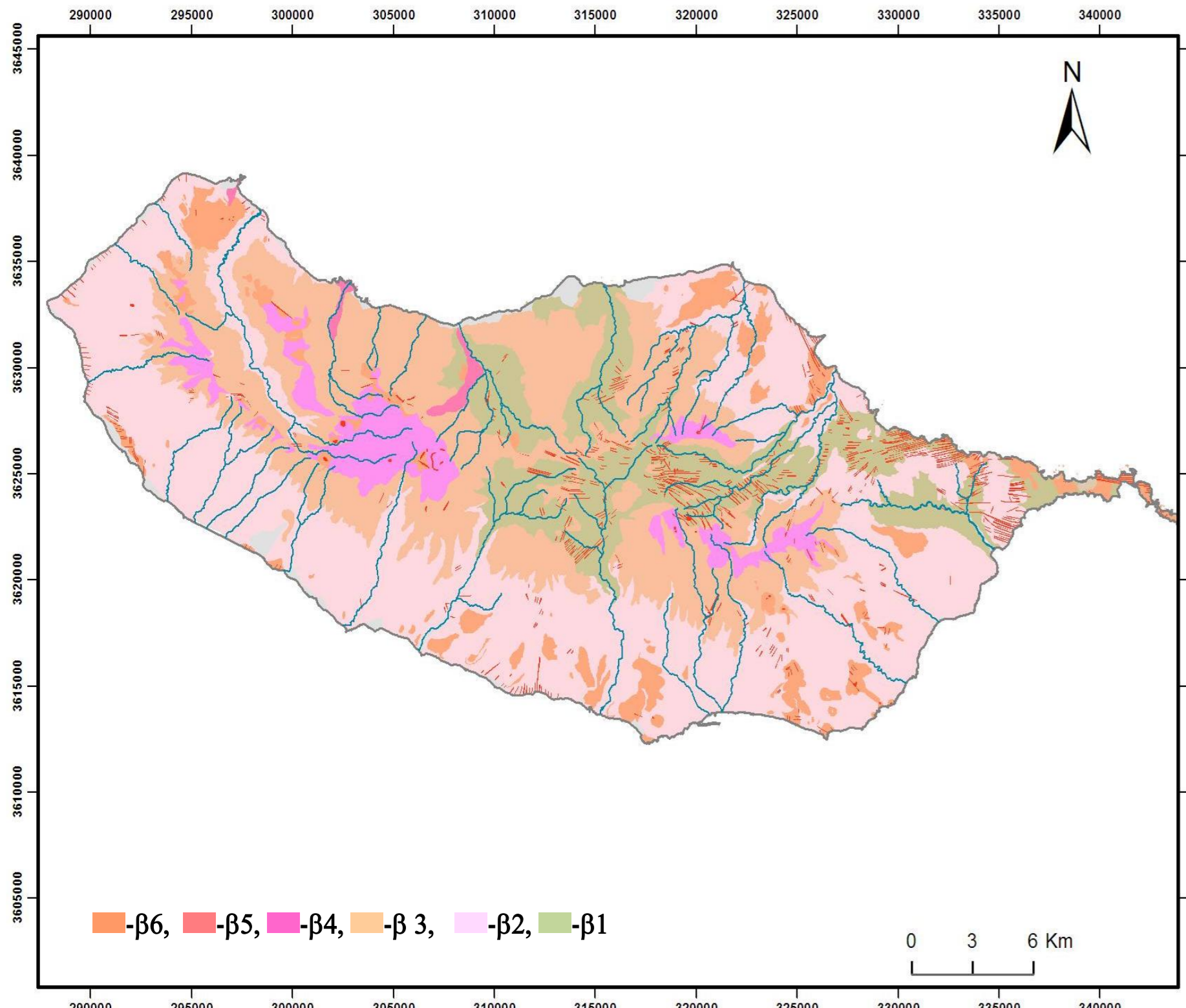


Geochemical and Short-Period Rayleigh Wave Dispersion Measurements as evaluation tools to estimate Madeira Island magma chambers depths

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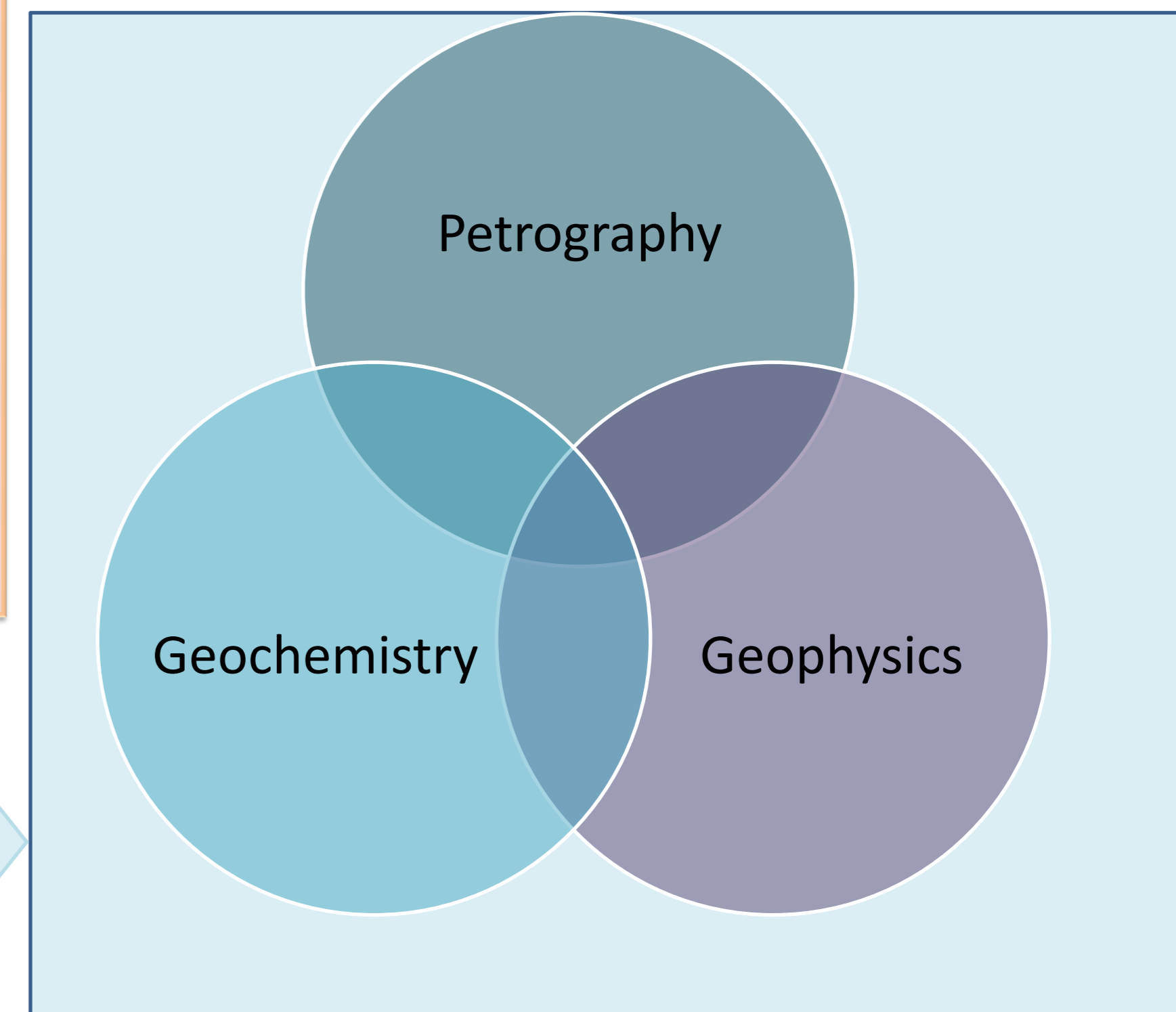


Geological sketch of Madeira Island

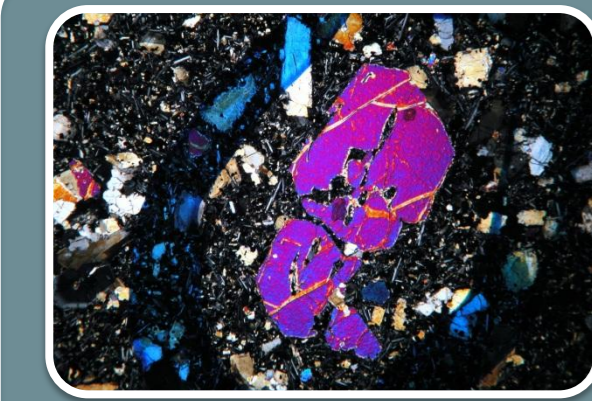
Madeira is an intraplate volcanic island, located at the eastern North Atlantic Ocean, that shows evidences of recent volcanism. This is suggestive of a heat source enough to induce rocks/water with significant temperatures at depths likely to be exploitable for economic generation of electricity, given the Island favourable fracture framework. This setting makes of Madeira an intermediate and innovative case study between classical volcanic geothermal systems and enhanced geothermal systems. In a volcanic geothermal system the heat source comes from magma emplacement at relatively shallow levels, thus knowledge of magma chamber(s) depth(s) is one of the keys to geothermal reservoir assessment.

Generally three major volcanic stages and six volcanic complexes ($\beta 1$ to $\beta 6$) are attributed to Madeira (e.g. Zbyszewski *et al.* 1976, 1975; Geldmacher, 2000; Mata *et al.* 1989; Ribeiro, 2009).

The integration of geochemical and geophysical methods are being applied, to the determination of the characteristics of the magma body(s) emplaced beneath Madeira Island, as part of the methodology for the evaluation of Madeira island geothermal potential.



Petrography

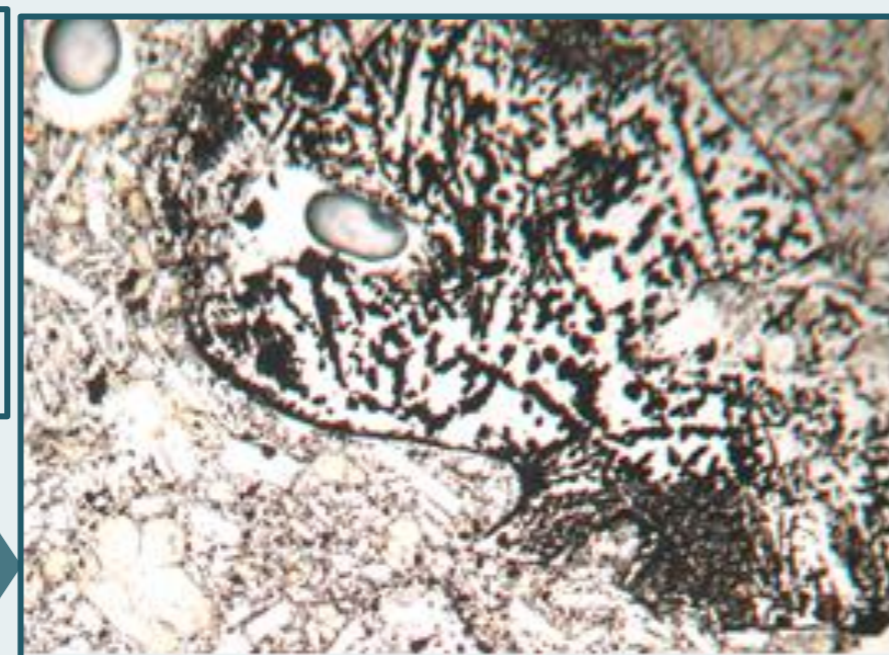


- determine the crystallization history
- detect aspects suggestive of hydrothermal fluids circulation
- select suitable crystals to perform geothermobarometric calculations.

Basaltic rocks; phenocrysts of olivine, clinopyroxene and sometimes plagioclase in a matrix composed of plagioclase microliths, clinopyroxene, oxides and often small olivine crystals, confirms a polibarc crystallization.

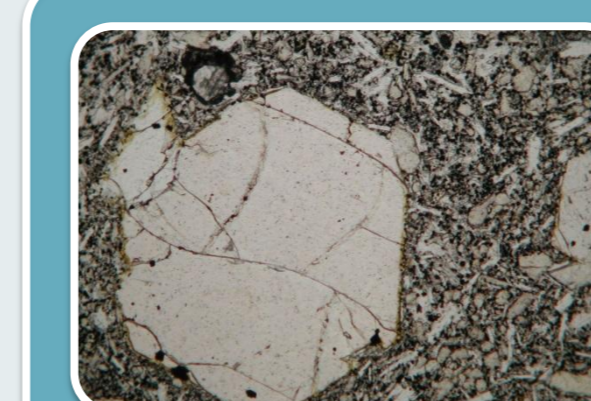
Some clinopyroxene phenocrysts centers are replaced by matrix which may correspond to a filling of pre-existing cavities in the crystals, caused by crystallization under conditions of supercooling or by partial dissolution

Inclusions in the growing crystals are oxides probably generated by hydrothermal alteration within the crystals internal fractures.



Absence of xenoliths and xenocrysts in the more recent complexes, favoring the hypothesis of the existence of superficial crustal magma chambers, since these can act as filters to the xenoliths when transported by the magmas, preventing their ascent to the surface

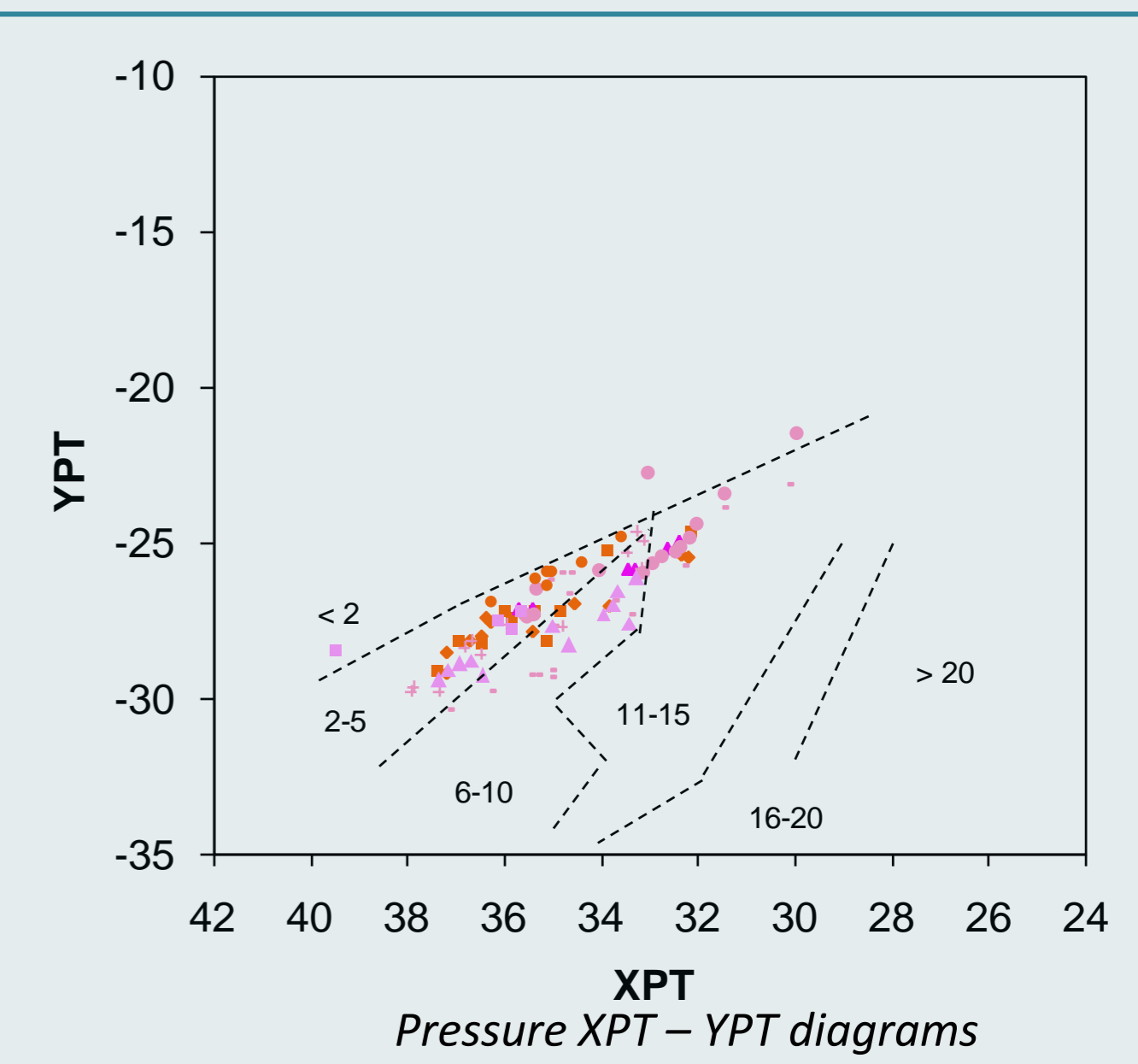
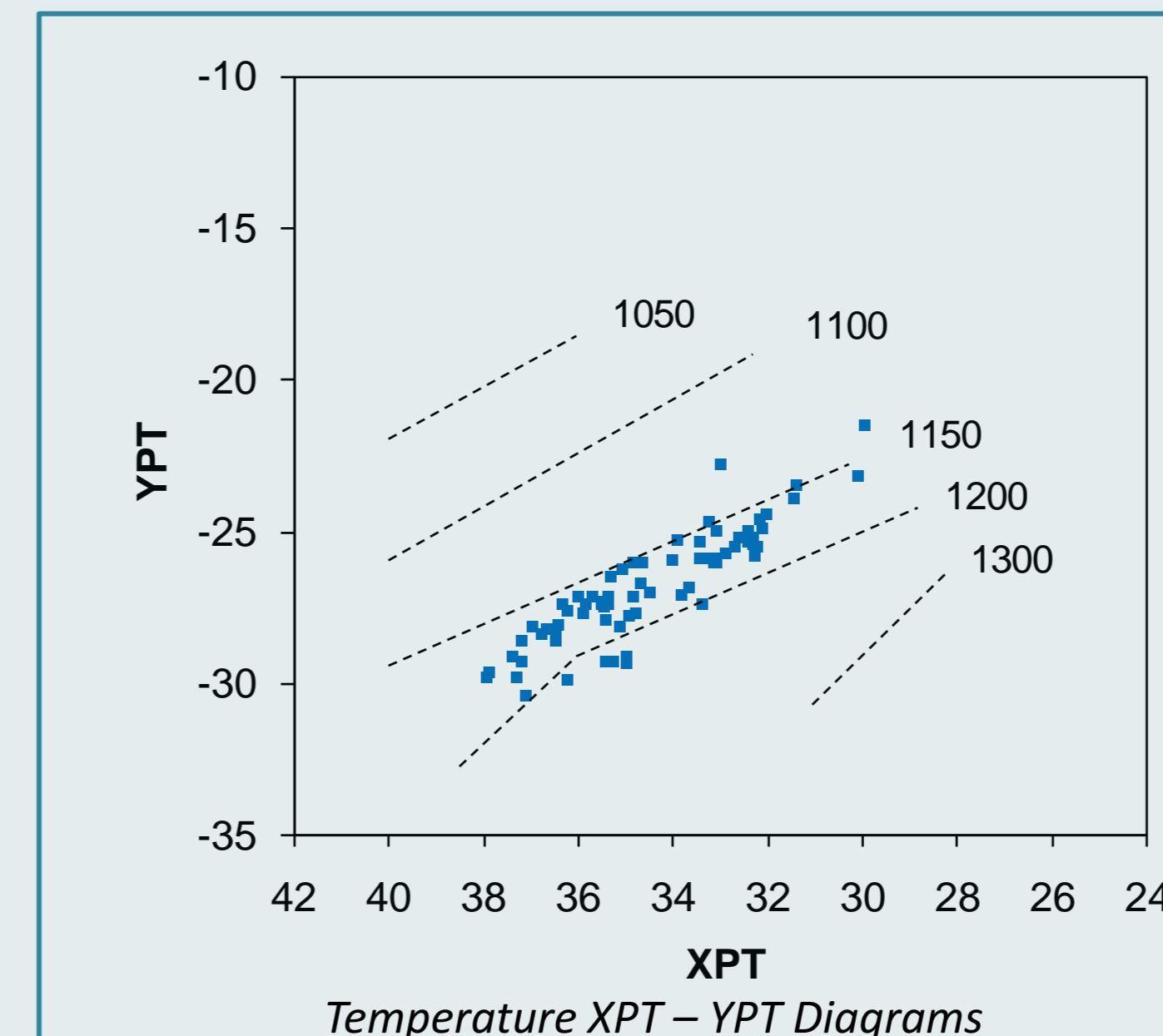
Geochemistry – Mineral Chemistry



- determine crystallization temperatures and pressures/depths of magmas
- constrain depths of possible levels of magma storage (magma chambers)

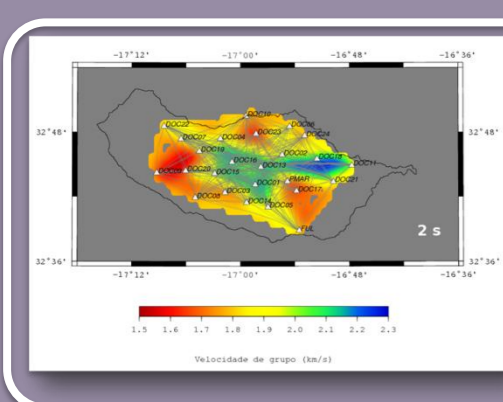
The application of the empiric geothermobarometer of Soesoo (1997), based on clinopyroxene composition, indicated the following:

- crystallization temperatures vary between 1150 °C and 1200 °C
- crystallization pressures calculated for $\beta 6$, the most recent complex, fall in the 2-5 kb field
- pressure of crystallization for $\beta 4$ and $\beta 5$ phenocrysts is more variable, with values from < 2 kb to 11-12 kb

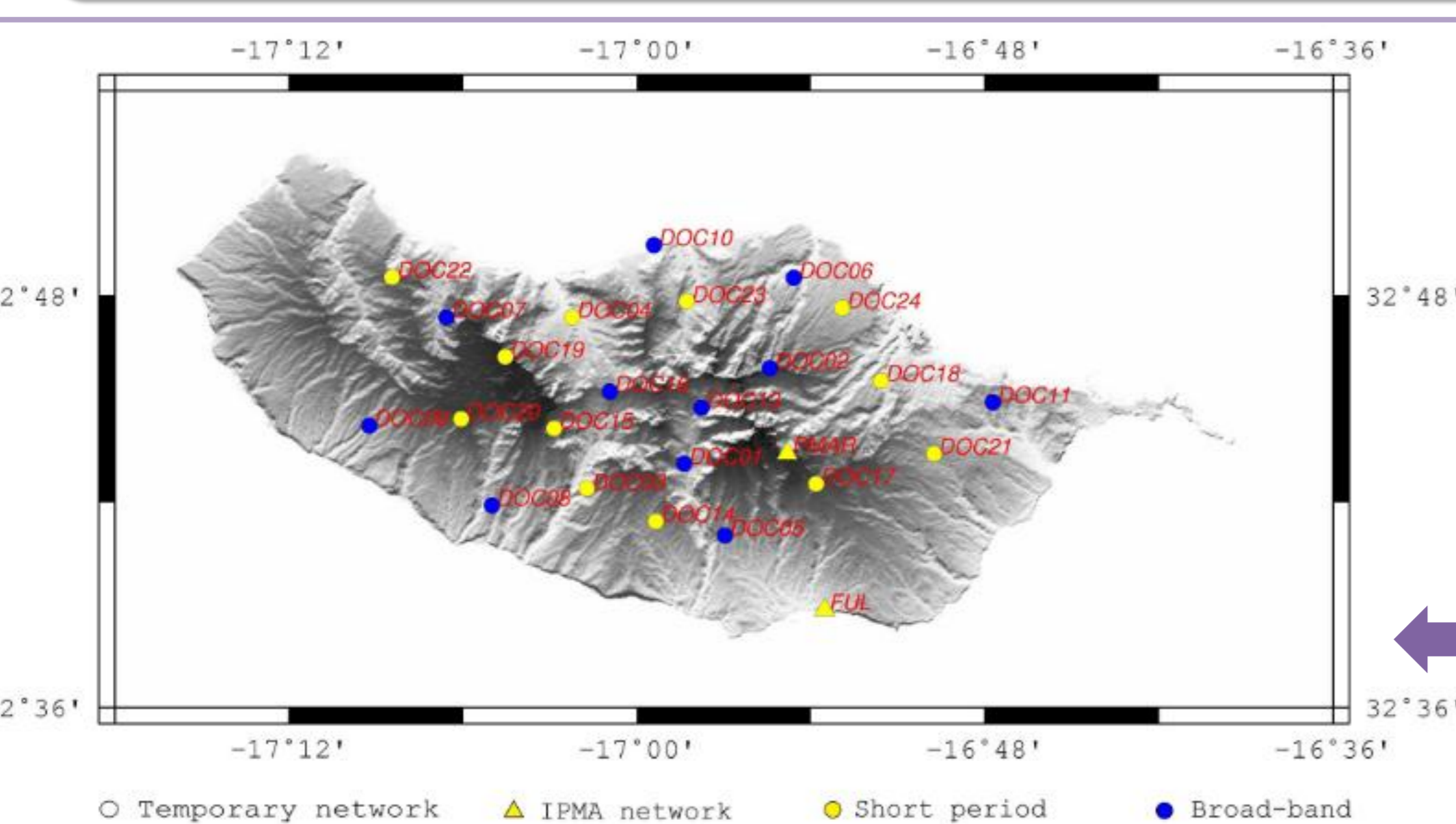


These results suggest fractional crystallization at various depths and can be interpreted as a consequence of the existence of at least two magma chambers. One, 20 to 40 km depth (6-12 kb) in the lithospheric mantle, and another between 7 and 16 km (2 a 5 kb) in the oceanic crust. The application of other geothermobarometers based on olivine-liquid and clinopyroxene-liquid equilibrium Putirka (1999) and Putirka *et al.* (2003) will allow validating or otherwise constraining the crystallization levels already obtained, so that these parameters, important to the geothermal assessment, will be as accurate as possible.

Geophysics - Surface-Wave Tomography



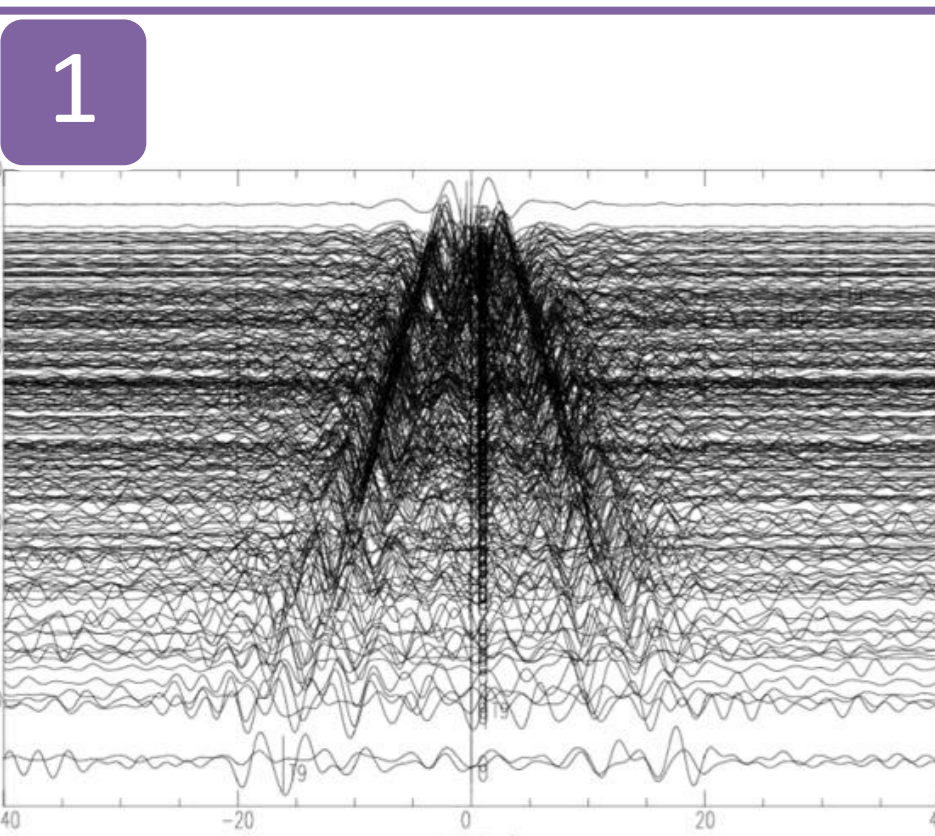
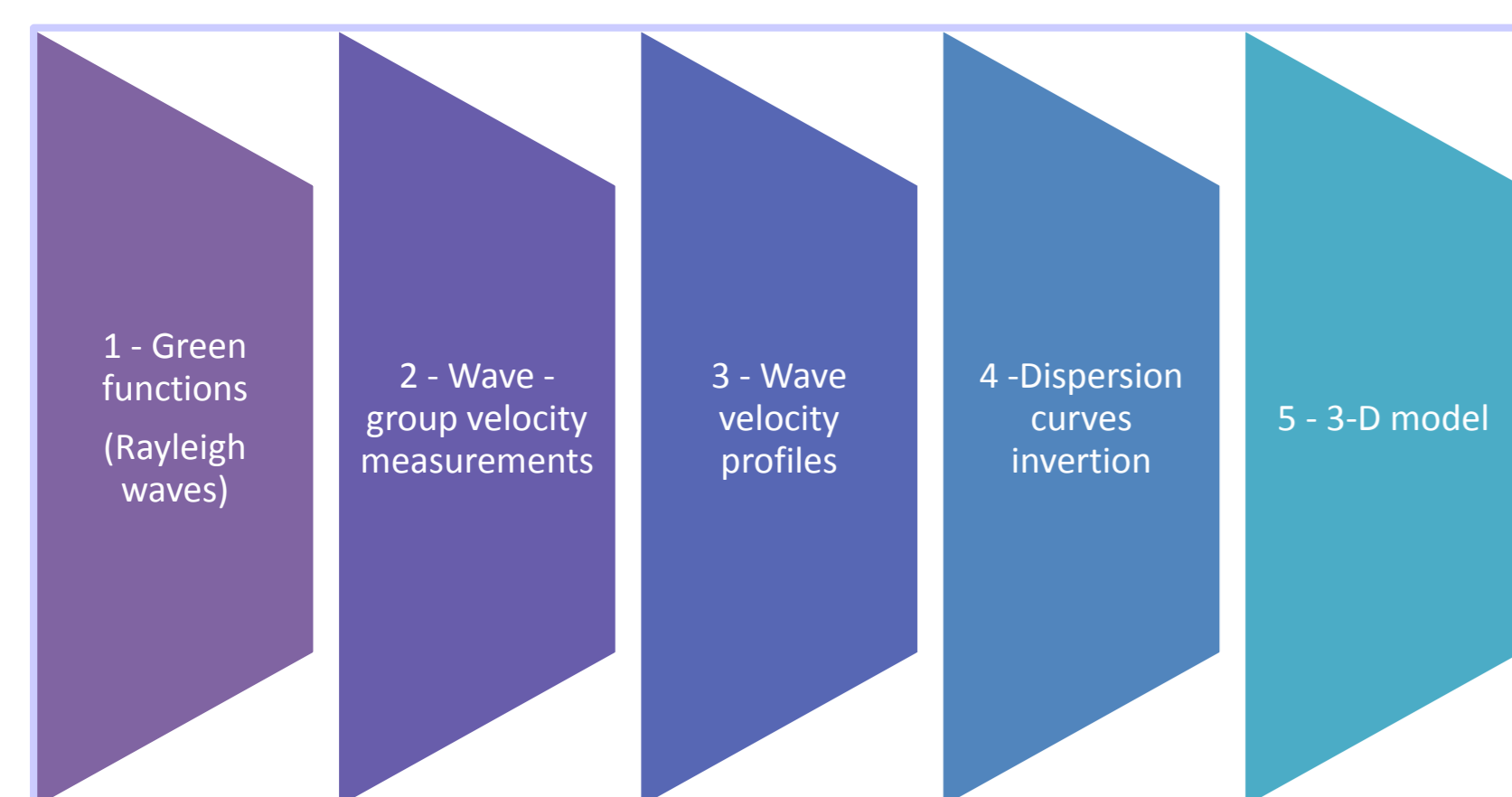
- map crustal structure in areas of low or practically no seismicity, which is the Madeira island situation.
- enable to image the shallower structures.



23 seismic stations have been deployed from May 2011 to September 2012. This temporary network was composed of 11 broad-band seismic stations and 14 short-period stations

Topographic map of Madeira and location of seismographic-stations. Symbols: Short period - yellow, broad-band - blue. IPMA stations are represented with a triangle and temporary stations with a circle

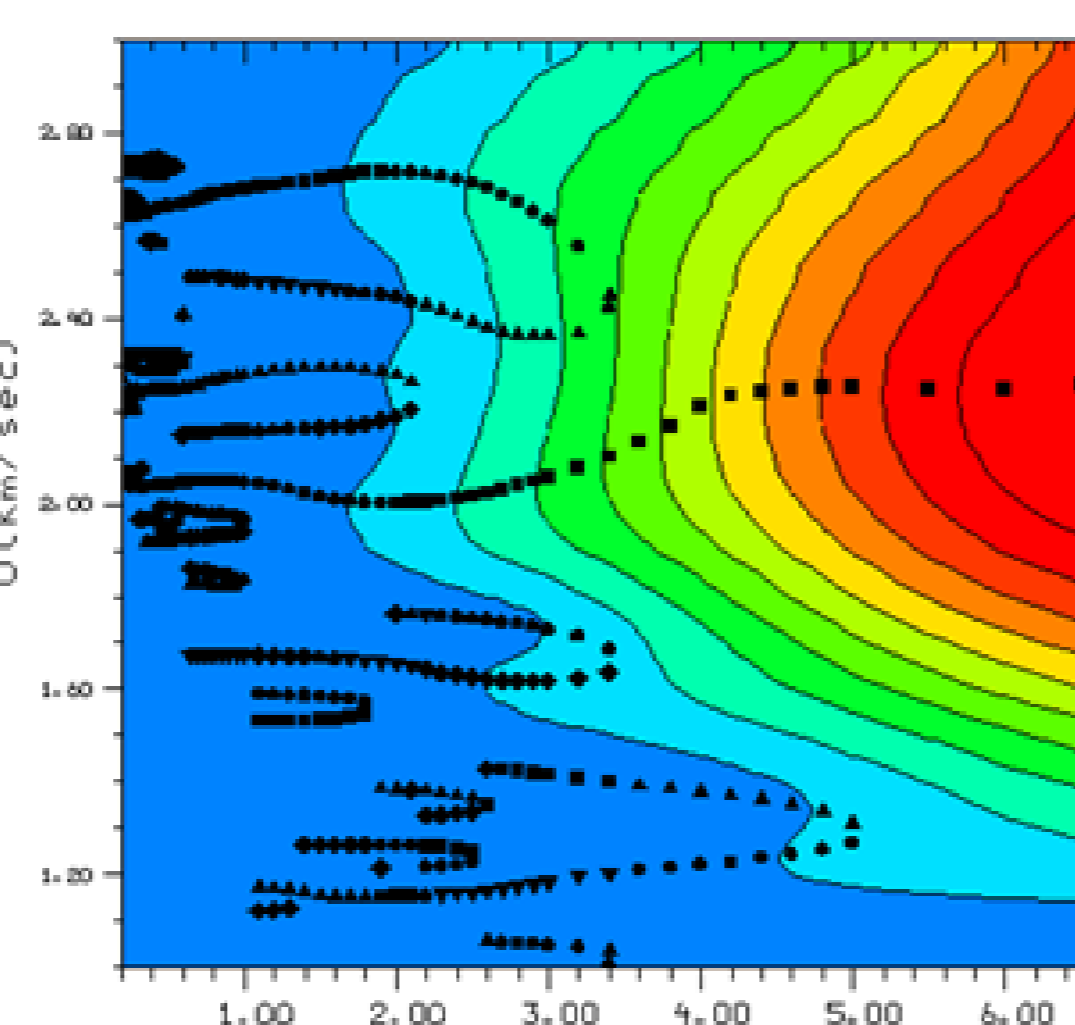
Methodology



To obtain Green's functions, one-hour segments of the data set were cross-correlated and stacked for the entire recording period to improve signal-to-noise ratio. Final Green functions for each pair were obtained by summing both causal and acausal parts of the crosscorrelograms.

Short period record section (0.5 - 5 s) of the correlations computed between 300 stations pairs.

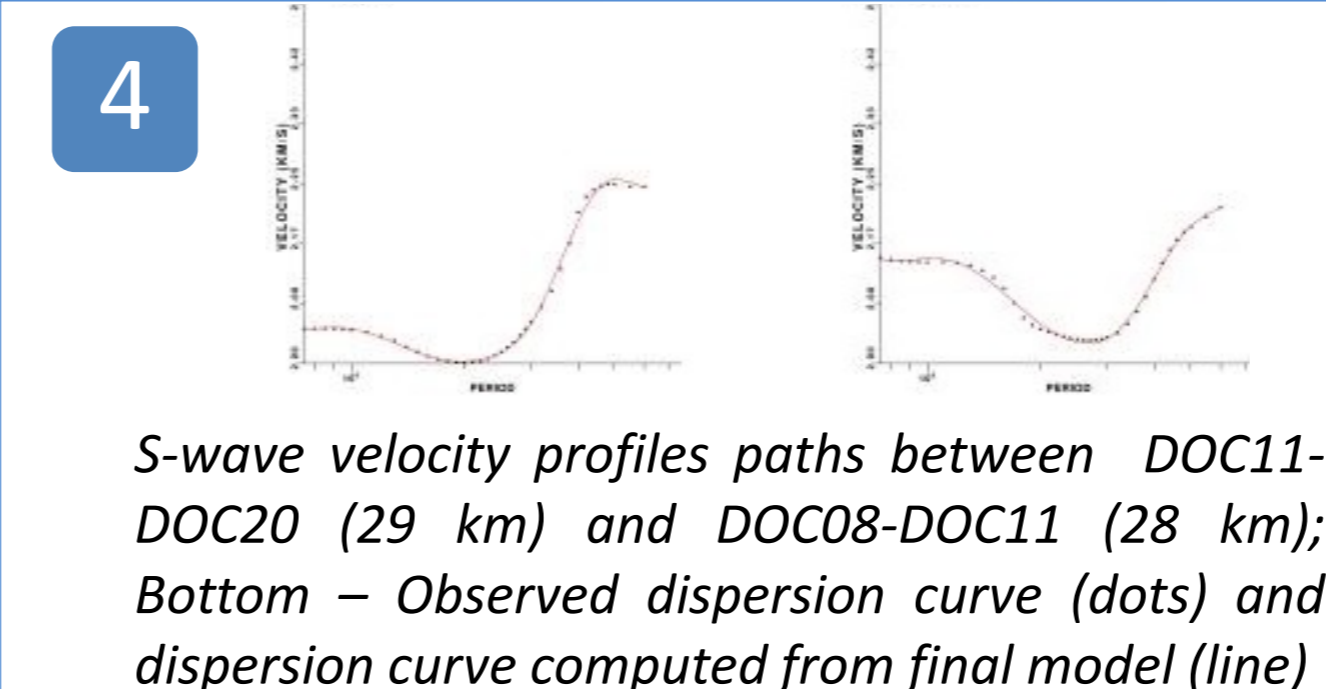
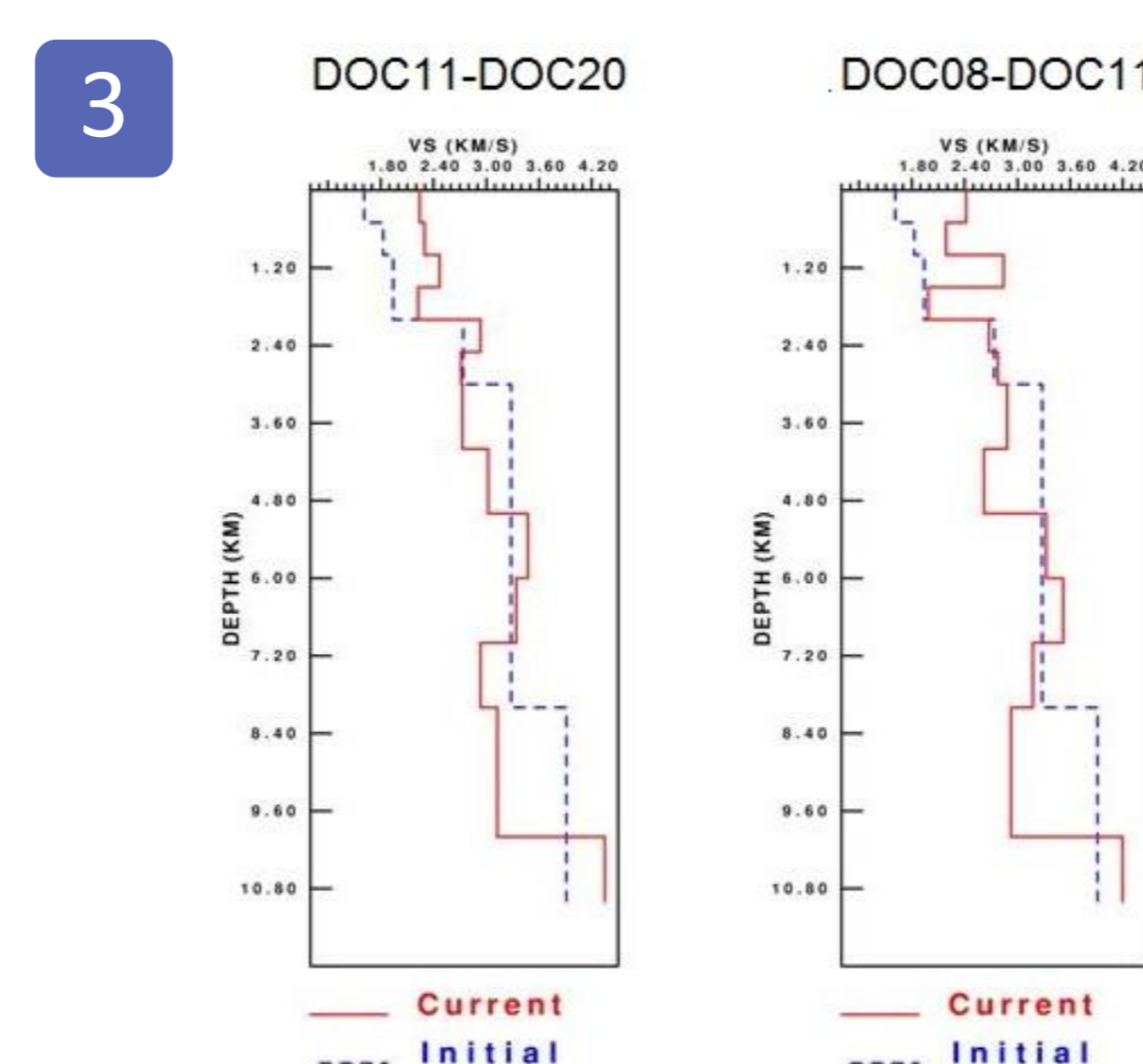
Group velocity dispersion on the Green's functions was measured using the time-frequency analysis developed by Herrmann and Ammon (2002).



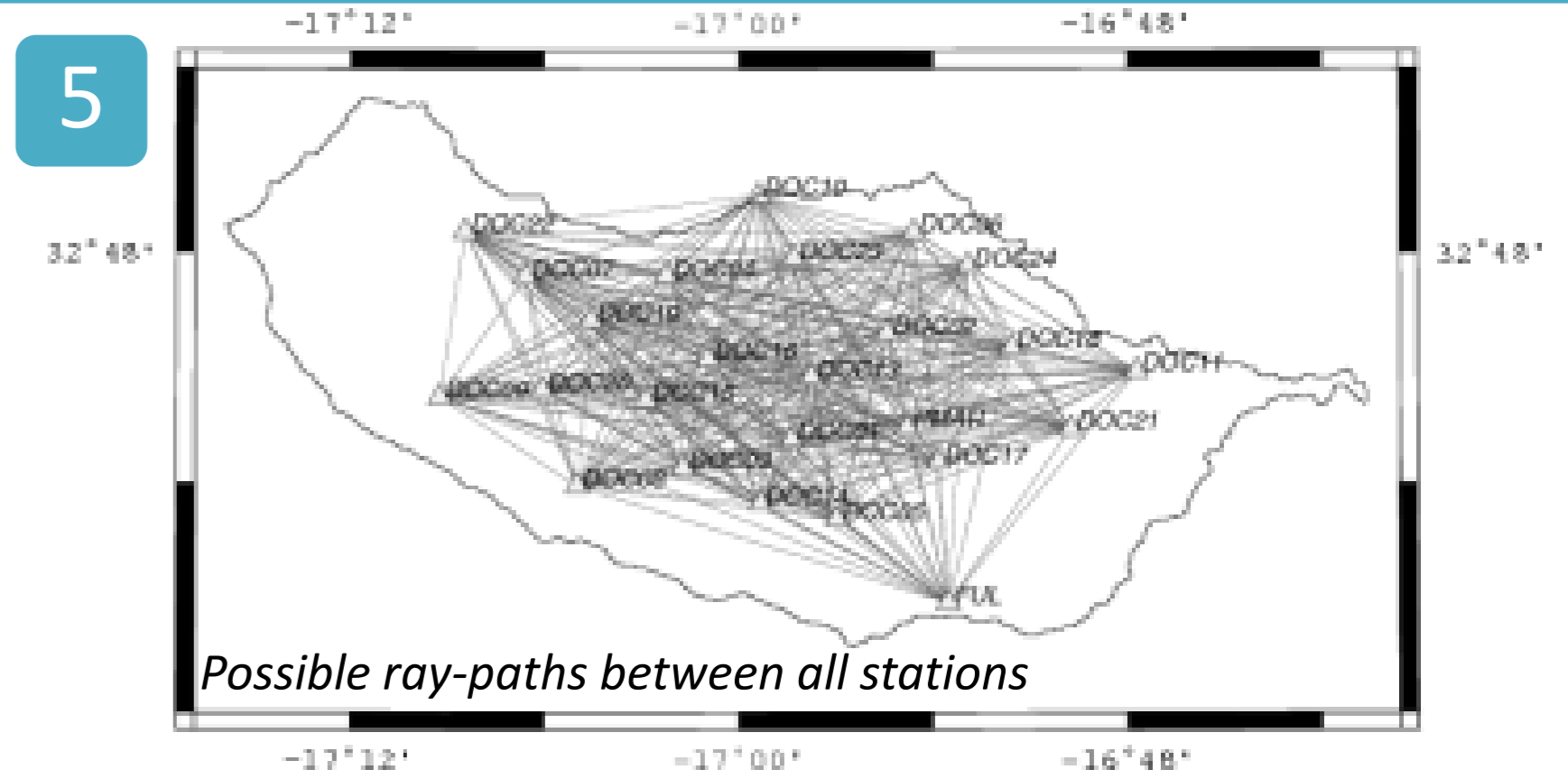
Energy diagram computed for DOC11-DOC20 station pair. Dispersion can be measure by picking the maximum for each period (frequency)

Taking into account the azimuthal coverage of the area, a 2D group velocity inversion to obtain maps with velocity lateral variations as a function of the period is underway. This will enable to produce 1D S-wave velocity profiles in each grid node, as a function of depth, towards a quasi-3D model.

Group velocity curves for selected paths have then been inverted to obtain a S-wave velocity profile as a function of depth.



S-wave velocity profiles paths between DOC11-DOC20 (29 km) and DOC08-DOC11 (28 km); Bottom - Observed dispersion curve (dots) and dispersion curve computed from final model (line)



Conclusions

The methodologies described above are being applied to the Madeira Island in order to locate a magma body that might be considered as a geothermal system heat source. Some of the depths indicated by geobarometric calculations are partially within the limits of the application of short-period Rayleigh wave dispersion measurements to the Madeira Island (up to 10 km). The combination of these two methods will be essential to geographically constrain the location of the heat source.

Acknowledgements

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References

Bensen, G.D. *et al.* (2007) - *Geophys. J. Int.* 169, 1239-1260.
Geldmacher J. *et al.* (2000) - *Geochemistry, Geophysics, Geosystems*, vol 1, paper 1999GC000018.
Herrmann, R. B. *et al.* (2002) - Computer Programs in Seismology version 3.20: Surface Waves, Receiver Functions, and Crustal Structure, St. Louis University, Missouri.
Mata, J. *et al.* (1989) - *Comun. Serv. Geol. Portugal*, 75, 73-87.
Putirka, K. (1999) - *Contrib. Mineral. Petrol.*, 135, 151-163.
Putirka, K. *et al.* (2003) - *American Mineralogist*, 88, 1542-1554.
Ribeiro, M. L. (2009).: Carta Geológica Simplificada das ilhas da Madeira e Porto Santo à esc.1/80 000. Ed. da Direcção Regional do Comércio, Indústria e Energia da Região Autónoma da Madeira e LNEG.
Soesoo, A. (1997) - *GFF*, 119, 55-60.
Zbyszewski, G. *et al.* (1975). - Notícia explicativa das Folhas A e B da Ilha da Madeira da Carta Geológica de na escala 1:50 000. *Serviços Geológicos de Portugal*.