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High temperature in the upper mantle beneath Cape Verde as a possible cause for the oceanic lithosphere rejuvenation inferred from Rayleigh-wave phase-velocity measurements.

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Geological setting

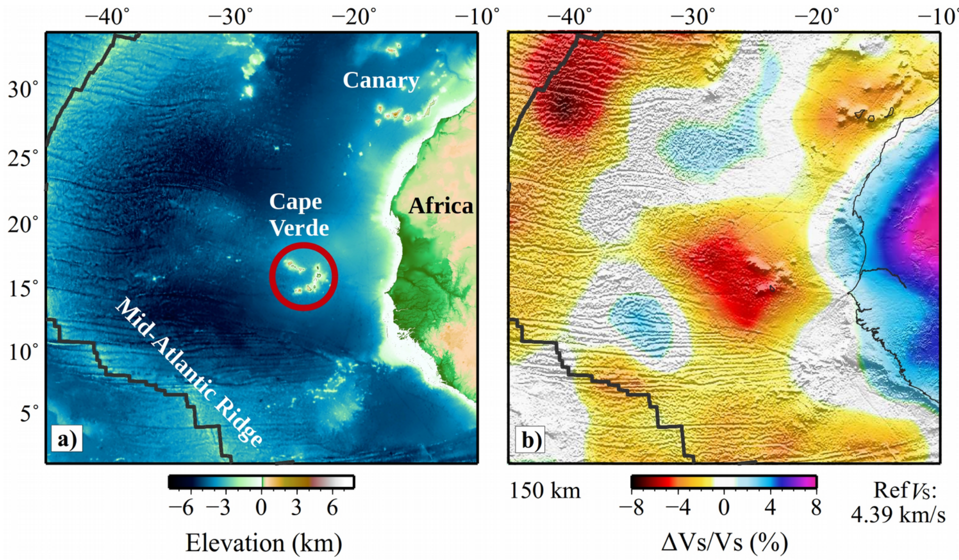

Figure 1: *(a) Topographic map of the Central Atlantic region. A red circle marks the location of Cape Verde, 560 km west of Africa. (b) Shear wave speed anomalies at 150 km depth beneath the region, according to the waveform tomography of Celli et al. (2019). A strong low velocity (Vs) anomaly can be observed beneath the Cape Verde region.*

- Part of the Macaronesia, together with Canary, Azores, Madeira and Selvagens.
- Located at ~560 km from the African coast, on the eastern Central Atlantic Ocean, where the oceanic crust age range between 115 to 140 Ma.
- Intraplate active volcanic archipelago, consisting in 9 inhabited islands and some minor islets.
- Presents a particular distribution of the islands in an horse-shoe shape, with a peculiar age progression.
- It has been included in several hotspot catalogues.
- Tomographic studies have shown low-velocity anomalies beneath Cape Verde (e.g. Fig. 1b).
- The magmatism origin has been debated: Some attributed it to mantle plumes models and others to edge-drive convection.

Seismic data

7 broadband Guralp 3Ts (120s) stations, recording from 2002-2004 (yellow triangles) plus **38 stations** equipped with Earth Data PR6-24 data loggers and Guralp CMG-3ESP (60s) seismometers recording from 2007-2008 (red triangles).

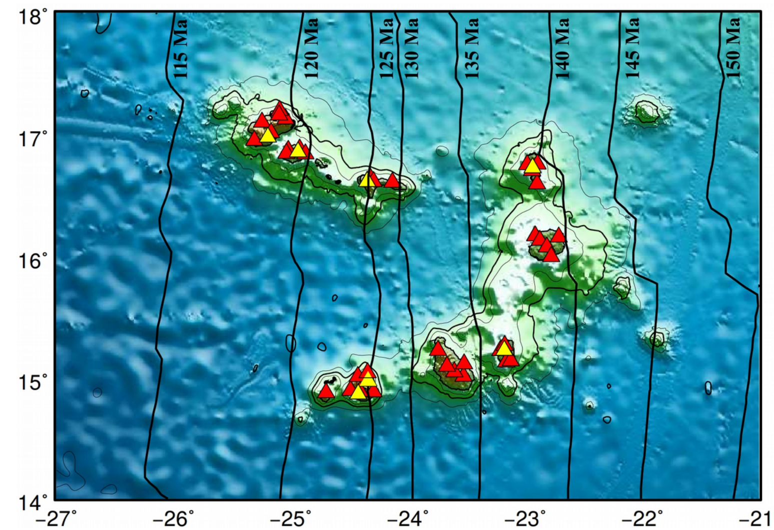

Figure 3: *Seismic network and seafloor age isochrons (Müller et al., 2008).*

Data challenge

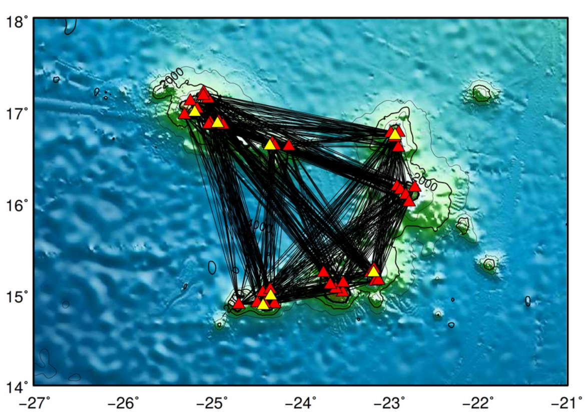

Figure 4: *Seismic network and station-to-station path coverage (black lines).*

- The high level of ambient noise, limiting the number of successful measurements;
- Remoteness of Cape Verde from the seismically active areas;
- The unevenness of the station-to-station path coverage, due to the distribution of the islands and the absence of OBS.

Methodology

Two-station method

- **Cross-correlation** of the teleseismic events of each pair of stations;
- Dispersion curves were calculated from the **phase of the cross-correlation functions**;
- To **reduce the effect other signals**, the cross-correlation was **filtered** with a frequency-dependent **Gaussian band-pass filter** and **windowed in the time domain**, enhancing the SNR.

Phase-velocity measurements

- Manual selection based on the smoothness, length and deviation from a reference curve;
- Minimum of two measurements for each frequency (not achieved for some stations)
- Gather all the stations per island, to avoid losing good measurements;
- Compute an average curve, per each frequency, for all the selected measurements.

Phase-velocity measurements

- To overcome the 2π ambiguity arctangent function a reference curve is required. At first, we used the AK135, but a a more regional model was necessary. We also plotted the PREM and PA5 phase-velocity curves, for comparison but not for the measurements selection.
- To determine a more suitable curve for Cape Verde we selected automatically all the possible measurements, rejecting only the signals dominated by noise. By gathering these measurements a density plot was computed, from which an average dispersion curve was calculated.

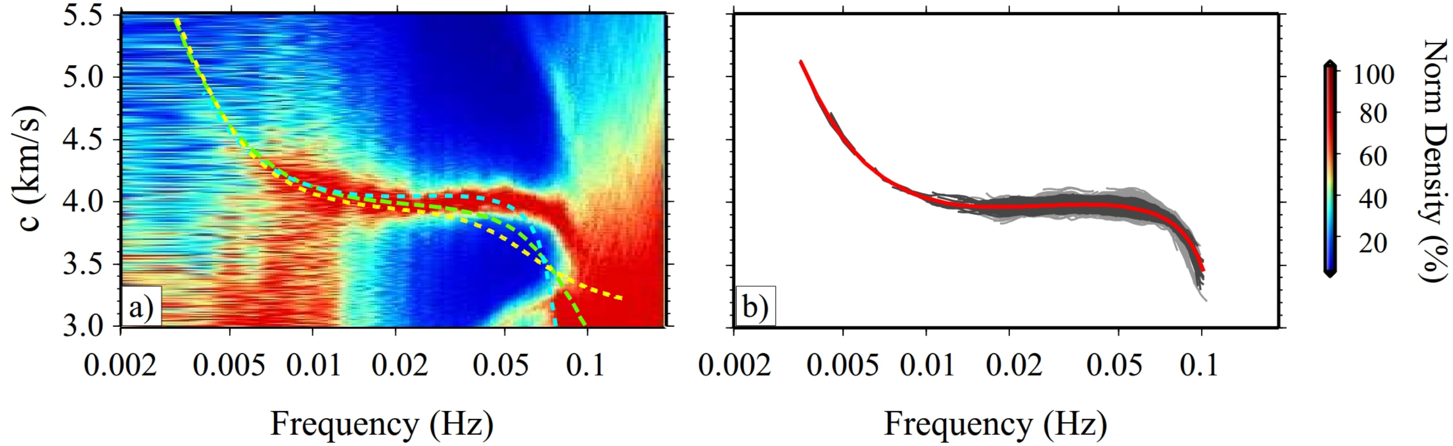

Figure 5: *a) Density distribution plot for the stack of automated preliminary measurements, normalized to the maximum at each period. The regional reference curve is substantially different from the global reference curves AK135 (yellow dashed line) (Kennett et al. 1995), PREM (green dashed line) (Dziewonski and Anderson, 1981), and also from the PA5 model for the Pacific (blue dashed line) (Gaherty et al. 1996). b) Average phase-velocity curve (red line) obtained from the smoother dispersion curves (dark grey), used for the 1D inversion for Vs profile in depth.*

Cape Verde versus Atlantic

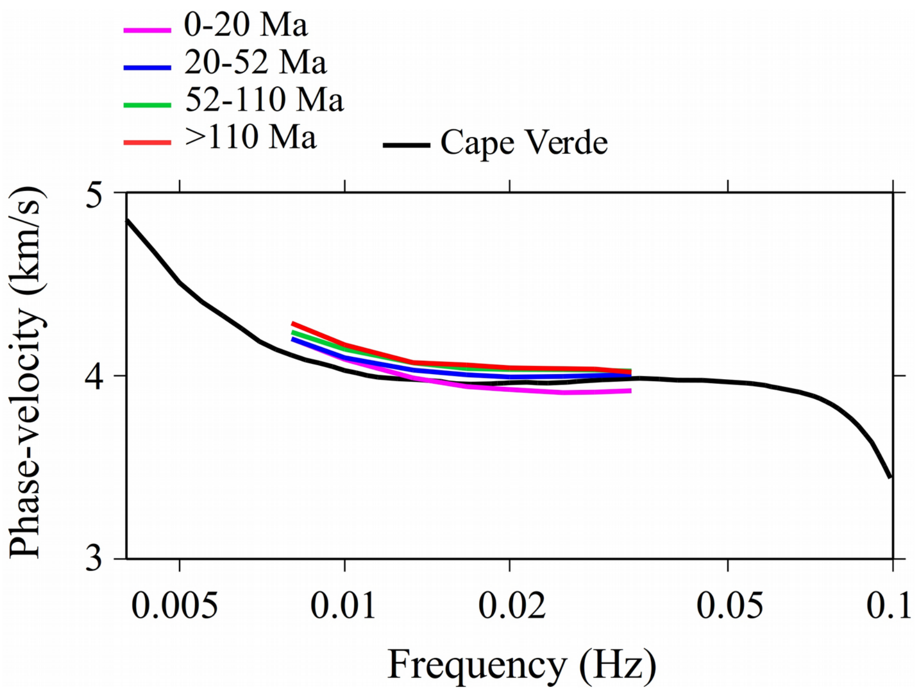

Figure 6: *Comparison of Cape Verde-region average dispersion curve (black line) with the Atlantic Rayleigh-wave phase velocities averaged for different lithospheric ages (James et al. 2014).*

We compared our average dispersion curve with the Atlantic Rayleigh-wave phase-velocity dispersion curves for different lithospheric ages.

↓

Cape Verde exhibits lower velocities, for frequencies < 0.025 Hz, than any of the Atlantic average curves, and lower for the entire frequency band for any curve representing an age higher than 20 Ma.

↓

This suggests that Cape Verde lithosphere was reset to an younger age and the asthenosphere is hotter than the average for the Atlantic.

Average shear-wave velocity structure

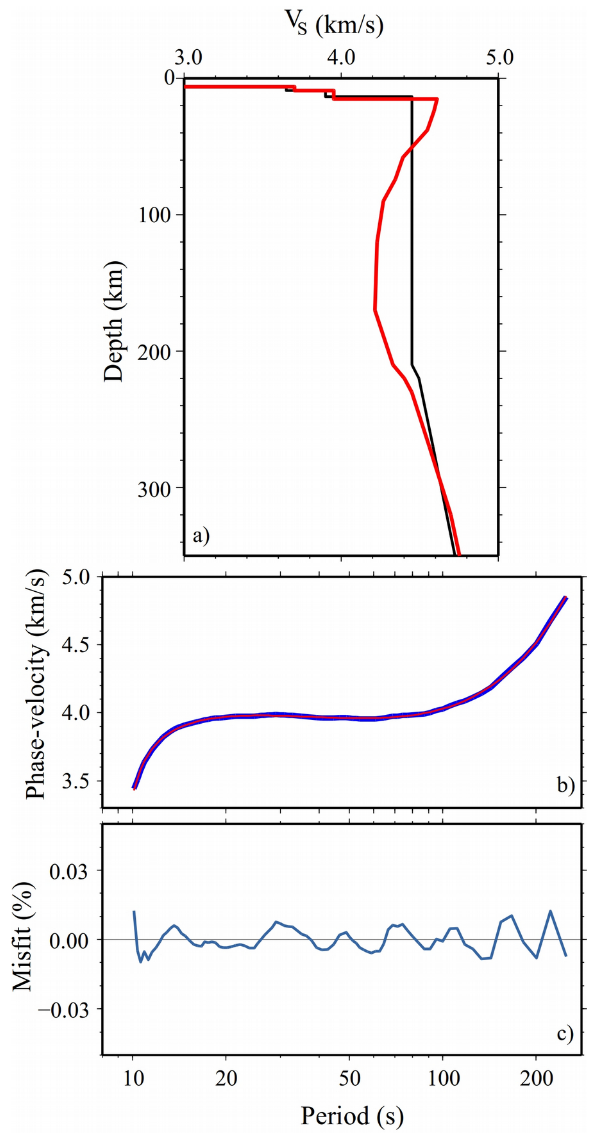

Figure 7: *Results of the inversion. (a) Inversion result (red line) and the modified AK135 (black line) as a reference model (Kennett et al. 1995). (b) Measured dispersion curve (blue line) and the synthetic phase-velocities (red line). (c) The relative data-synthetic misfit.*

The **average dispersion curve** was inverted using a non-linear, Levenberg-Marquart gradient search algorithm.

Initial model:

- 4 layer model for the crust (from CRUST 2.0)
- AK135 modified to the mantle

Constant shear-wave velocities (4.45 km/s) until 220 km depth, linearly increasing below that depth.

Parametrization:

- Boxcar functions for the crustal layers;
- Triangle basis functions for the mantle;
- Moho discontinuity also taken in consideration.

Striking feature: a pronounced **low-velocity zone** (∼60 to ∼210 km depth) with a velocity of ~4.2 km/s. At 280–350 km the models are indistinguishable.

Evidence for a rejuvenated lithosphere

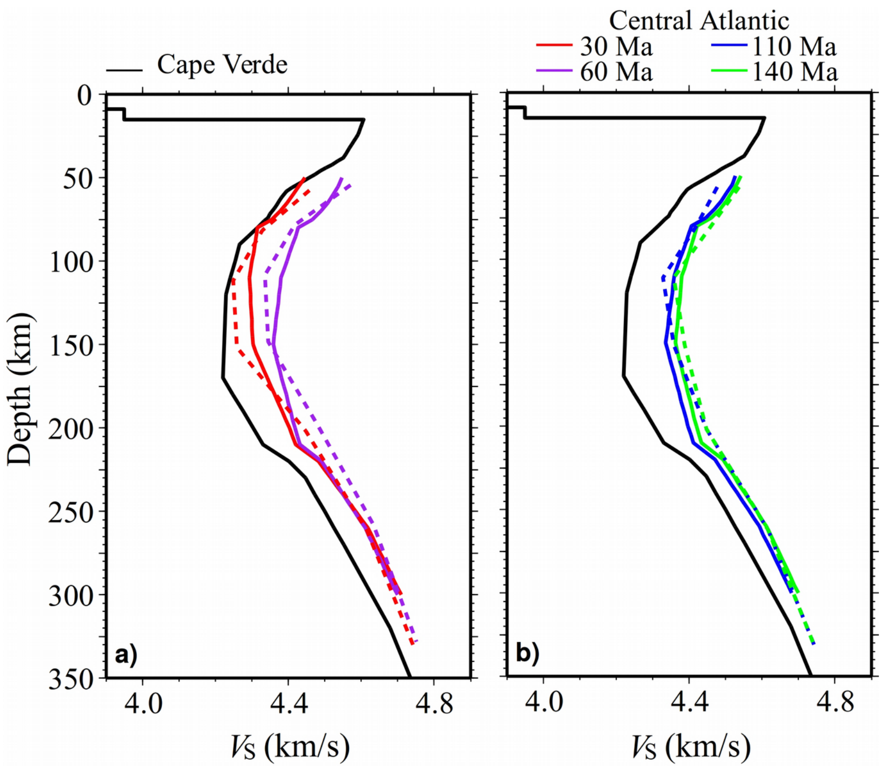

Figure 8: *Comparison of Cape Verde average profile (black line) with different lithospheric ages profiles for the Central Atlantic Ocean from waveform tomography. Dashed lines correspond to the same lithospheric ages calculated from the SL2013sv model (Schaeffer and Lebedev, 2015).*

Cape Verde presents clearly lower velocities than it would be expected for an oceanic lithosphere age of 115 – 140 Ma.

Anomalous hot mantle

Lithosphere thermal age match with **~30 Ma, but the asthenosphere** still presents **lower velocities**.

The plate is re-heated and acquire a geotherm characteristic of a younger lithospheric age = thermal rejuvenation

Rejuvenated lithosphere by an **hotspot**

Petrological arguments confirm our results, pointing to an **excess of temperature** beneath Cape Verde:

T_p (**Cape Verde**) ≈ 1430-1470ºC

> T_p (**Average mantle**) ≈ 1337±35º

> T_p (**MORB**) ≈ 1440ºC

On the origin of Cape Verde hotspot

Lithospheric, age-dependent profiles for the Central Atlantic show that S-wave velocities for different ages tend to converge at a depth of ∼200 km **BUT** the Vs profile of the Cape Verde region is distinctly different: down to 300 km it shows Vs values lower than typical for the Central Atlantic.

consistent with a deep (> 300 km) origin for the hotspot

mantle plume

mantle upwelling caused by edge-driven convection

Our study does not allow the distinction between these two hypotheses

BUT if Cape Verde is originated from a mantle plume anchored in the lower mantle, the mantle transition zone beneath it should be anomalously hot.

The thickness of the MTZ responds to temperature variation by thickening when cooled or by thinning in the presence of an ascending hot mantle plume.

On the origin of Cape Verde hotspot

Seismic studies in Cape Verde

Deuss (2007) → SS precursors → no MTZ thinning

Gu et al. (2009) → SS precursors → significant MTZ thinning, as much as beneath Hawaii

Saki et al. (2015) → Precursor arrivals to PP and SS seismic phases → anomalously thin MTZ

Helffrich et al. (2010) → arrival times of the Ps converted waves at 410 and 660 km discontinuities → standard, global-average MTZ thickness

Vinnik et al. (2012) → PS and SP receiver functions → pronounced thinning of the MTZ

Geochemistry in Cape Verde

Noble gas isotopic geochemistry is considered an important tool to assess the nature of contributions of distinct mantle reservoirs to magma sources.

Douceland et al. (2003) → $^{3}He/^{4}He$ ratios up to 15.7 Ra for silicate rocks

Mata et al. (2010) → $^{3}He/^{4}He$ ratios up to 15.5 Ra for carbonatites

Unradiogenic signatures preserved in the lower mantle could have contributed to the Cape Verde origin.

Hoernle et al. (2002) → $^{206}Pb/^{204}Pb$ ratios up to 20.238 for carbonatites

Mourão et al. (2012) → $^{206}Pb/^{204}Pb$ ratios up to 20.251 for silicate rocks

Indirect evidence for an origin related to a deep rooted plume

Jackson et al. (2018) showed that hotspots with a strong contribution of high time-integrated U/Pb mantle component, as is the case of Cape Verde, are more likely to be associated with deeply anchored mantle plumes.

Geochemical arguments strongly suggest an origin of the Cape Verde hotspot related with a mantle plume rooted in the lowest levels of the mantle, whereas in what concerns the **seismic studies** there is no agreement.

Comparison with other hotspots

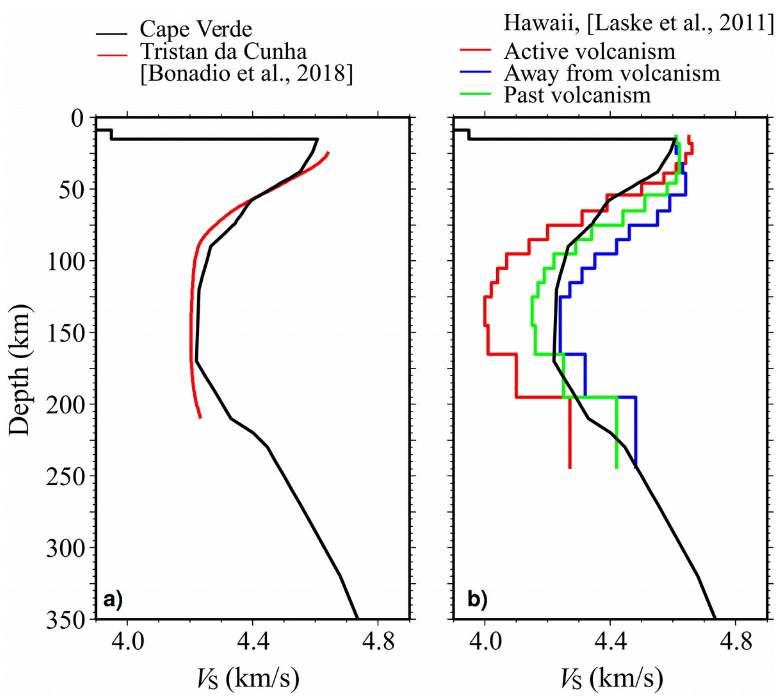

Figure 9: *(a) Vs profiles for Tristan da Cunha (red line) (Bonadio et al., 2018) and Cape Verde (black line). (b) Cape Verde (black line) and Vs profiles for three different regions in Hawaii.*

- **Similar** to Tristan da Cunha with slightly lower velocities.
- **Hawaii active volcanism** zone **similar** within the **lithosphere**.
- > 75 km Hawaii evinces lower velocities, which means warmer asthenosphere, as expected.

The comparison with hotspots located on, or close to, the Mid Atlantic Ridge showed, at depths down to 150 km, higher velocities beneath Cape Verde, suggesting a **thicker lithosphere beneath Cape Verde** when compared with the "near-ridge" archipelagos.

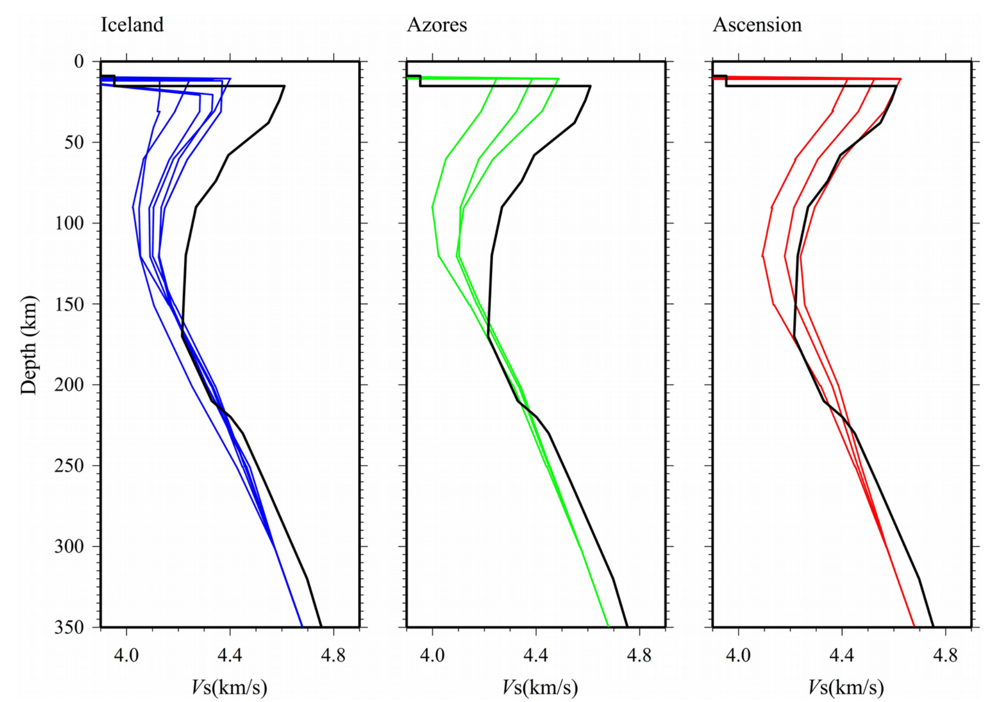

Figure 10: *Vs profiles for Iceland (blue lines), Azores (green lines) and Ascension (red lines) hotspots (Gaherty and Dunn, 2007). Cape Verde Vs profile is represented by a black line. The several lines of the same color for each hotspot represent different oceanic lithosphere ages.*

Conclusions

We measured fundamental-mode Rayleigh-wave dispersion curves in a broad period range, yielding an accurate and definitive local Vs profile than available previously;

Our data reveals a low-velocity zone reaching a minimum Vs of ~ 4.2 km/s at 170 km depth, suggestive of a temperature anomaly, likely to have been the cause for a significant thermal rejuvenation of the oceanic lithosphere beneath Cape Verde to an apparent age of approximately 30 Ma;

The determined apparent age is much lower than the previously proposed value of 59 Ma (Sleep, 1990) reducing the need to invoke a significant role of dynamic support of the Cape Verde swell;

The minimum value of Vs at the Cape Verde asthenosphere is higher than the one reported for under the active volcanoes of Hawaii but similar to that for Tristan da Cunha, consistent with higher potential temperatures for Hawaii compared to Cape Verde and Tristan da Cunha;

Our results, interpreted together with the evidence on the relatively He-unradiogenic signatures and low-seismic-velocity anomalies in the lower mantle, strongly suggest an origin of the Cape Verde hotspot related to a deeply anchored mantle plume.

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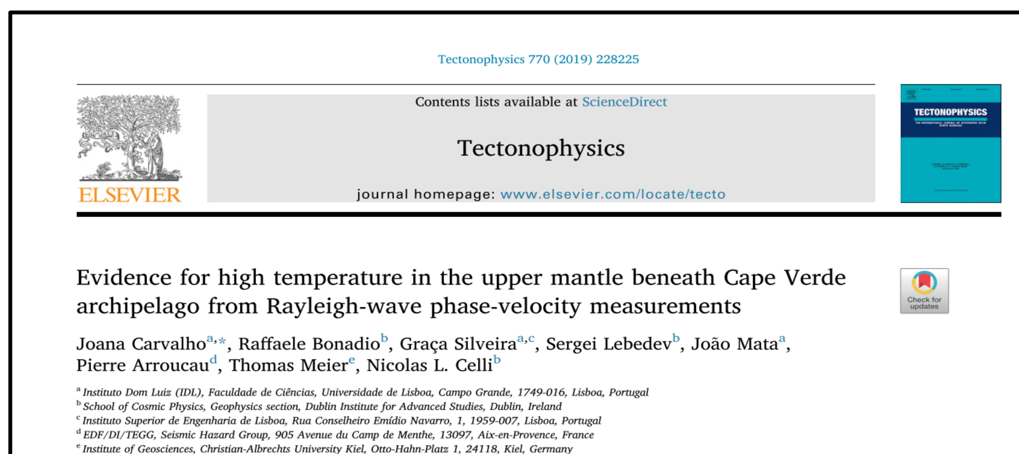
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Evidence for high temperature in the upper mantle beneath Cape Verde archipelago from Rayleigh-wave phase-velocity measurements

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All figures presented are from Carvalho et al. (2019)

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