Earth and Planetary Science Letters 433 (2016) 159–168

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Depressed mantle discontinuities beneath Iceland: Evidence of a garnet controlled 660 km discontinuity?

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ARTICLE INFO

Article history:
Received 18 August 2015
Received in revised form 29 October 2015
Accepted 30 October 2015
Available online 9 November 2015
Editor: P. Shearer

Keywords:
Iceland
seismology
mantle plume
receiver functions
transition zone
mantle discontinuities

ABSTRACT

The presence of a mantle plume beneath Iceland has long been hypothesised to explain its high volumes of crustal volcanism. Practical constraints in seismic tomography mean that thin, slow velocity anomalies representative of a mantle plume signature are difficult to image. However it is possible to infer the presence of temperature anomalies at depth from the effect they have on phase transitions in surrounding mantle material. Phase changes in the olivine component of mantle rocks are thought to be responsible for global mantle seismic discontinuities at 410 and 660 km depth, though exact depths are dependent on surrounding temperature conditions. This study uses P to S seismic wave conversions at mantle discontinuities to investigate variation in topography allowing inference of temperature anomalies within the transition zone. We employ a large data set from a wide range of seismic stations across the North Atlantic region and a dense network in Iceland, including over 100 stations run by the University of Cambridge. Data are used to create over 6000 receiver functions. These are converted from time to depth including 3D corrections for variations in crustal thickness and upper mantle velocity heterogeneities, and then stacked based on common conversion points. We find that both the 410 and 660 km discontinuities are depressed under Iceland compared to normal depths in the surrounding region. The depression of 30 km observed on the 410 km discontinuity could be artificially deepened by un-modelled slow anomalies in the correcting velocity model. Adding a slow velocity conduit of −1.44% reduces the depression to 18 km; in this scenario both the velocity reduction and discontinuity topography reflect a temperature anomaly of 210 K. We find that much larger velocity reductions would be required to remove all depression on the 660 km discontinuity, and therefore correlated discontinuity depressions appear to be a robust feature of the data. While it is not possible to definitively rule out the possibility of uncorrected velocity anomalies causing the observed correlated topography we show that this is unlikely. Instead our preferred interpretation is that the 660 km discontinuity is controlled by a garnet phase transition described by a positive Clapeyron slope, such that depression of the 660 is representative of a hot anomaly at depth.

1. Introduction

Iceland straddles the mid-Atlantic Ridge spreading centre between the North American and Eurasian tectonic plates. Its high volumes of crustal volcanism, compared to normal spreading ridges, has lead to the hypothesis of the presence of an underlying mantle plume (e.g. White and McKenzie, 1989). Geoid anomalies and surface topographic relief as well as petrological and geochemical evidence support this interpretation (White et al., 1992), though a minority of authors maintain that a mantle plume is not required to explain the observations (Foulger and Anderson, 2005).

A major factor in the continuing debate over the presence of an underlying mantle plume is the inability of seismic tomography to reliably identify a plume tail extending through the whole mantle. Seismic tomography constrains anomalies in seismic wave speed which can be due to regional variations in both temperature and composition. Mineral physics predicts that slow seismic anomalies in the mantle are most likely due to high temperatures, so we expect slow seismic wave speeds to be a signature of mantle plumes. While tomographic studies of Iceland all agree on the presence of a strong low-velocity anomaly in the well-resolved upper mantle to depths of several hundred kilometres, deeper structure continues to be ambiguous with much variation between models. To

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http://dx.doi.org/10.1016/j.epsl.2015.10.053

a certain extent this may be due to practical constraints: local studies are severely restricted in depth resolution (down to only ∼400 km) due to the small aperture of seismic arrays (Keller et al., 2000), while global models which allow for greater depth resolution only use long period seismic data, resolving long-scale features and missing low-velocity anomalies due to wavefront healing (Montelli et al., 2004). While progression in tomographic methodologies, such as finite frequency and full waveform inversion, have produced more studies reporting hints of plume-tail like structures beneath Iceland (Montelli et al., 2006; Rickers et al., 2013; French and Romanowicz, 2015), tomographic results are still unclear as to the existence of deeper low velocity structure extending through the transition zone.

Even if the continuation of the upper mantle slow velocity anomaly to greater depths beneath Iceland is not currently resolvable tomographically, it is still possible to infer the presence of a temperature anomaly at depth from the effect it has on the phase transitions in the mantle transition zone and the corresponding topography of seismic discontinuities. The transition zone between the upper and lower mantle is delineated by global discontinuities at 410 and 660 km depth. These discontinuities are seen on a global scale, in a range of seismic data types including SS precursors (e.g. Shearer, 1993; Flanagan and Shearer, 1998; Deuss and Woodhouse, 2002; Deuss, 2009), receiver functions (e.g. Lawrence and Shearer, 2006; Andrews and Deuss, 2008), triplications and ScS reverberations (e.g. Revenaugh and Jordan, 1991). They are also observed on smaller regional scales, including several receiver function based studies focused on Iceland (Shen et al., 1996, 1998, 2002; Du et al., 2006).

The transition zone discontinuities are generally interpreted as caused by phase changes in the olivine component of mantle rocks. The olivine to wadsleyite (Ol–Wd) transition causes the 410 km discontinuity (e.g. Katsura and Ito, 1989) and the ringwoodite to perovskite and magnesiowustite transition (Rw–Pv) causes the 660 km discontinuity (e.g. Ito and Takahashi, 1989). The Ol–Wd transition has a positive Clapeyron slope, which means that the 410 km discontinuity deepens in hot regions; the Rw–Pv has a negative Clapeyron slope so the 660 km discontinuity shallows in hot regions (Fig. 1a). The opposite signs of the Clapeyron slopes describing the phase transitions thought to cause the 410 and 660 km discontinuities has led to the classic interpretation of a thickened mantle transition zone (TZ) representing a cold anomaly and a thinned TZ representing a hot anomaly (Fig. 1b and c). Ponding of hot plume material below the 660 km discontinuity, which is predicted based on the negative Clapeyron slope and endothermic nature of the Rw–Pv transition (Hirose, 2002), will lead to further complications, causing uplifted topography on the 660 to be observed across a wider area than the corresponding depression on the 410 (Fig. 1d).

However, olivine is thought to make up only 40–60% of mantle composition, with the remainder predominantly comprising garnet and pyroxenes. Recent studies have highlighted the importance of a phase transition in majorite garnet to perovskite (Mj–Pv) also at 660–700 km, which is thought to become dominant at higher temperatures (Hirose, 2002). Since the Mj–Pv transition has the opposite sign Clapeyron slope to the olivine dominant Rw–Pv transition, in a garnet dominant system a hot anomaly would depress the 660 km discontinuity. This would lead to positively correlated depressed topography on both discontinuities and would have little net effect on the thickness of the TZ (Deuss, 2007), (Fig. 1e).

Most studies consider positive correlation of topography on the 410 and 660 km discontinuities to be due to velocity heterogeneities in the upper mantle, and thus only interpret differential TZ thicknesses. With the improvement of tomographic models, we can correct for upper mantle velocity variations, and interpret absolute discontinuity depths. The mineral physical prediction of a garnet transition at high temperatures also provides an indication that a positive discontinuity correlation is not necessarily an artifact. Mapping of absolute discontinuity depths has the potential to shed light on which phase transition is dominant at the base of the mantle transition zone. With the variation in dominant mineral phase transition at 660 km, observations of the TZ thickness are not necessarily always a reliable indicator of temperature variation. Here we use P to S wave seismic conversions at discontinuities (also called receiver functions), to investigate discontinuity topography beneath Iceland in the light of these new ideas.

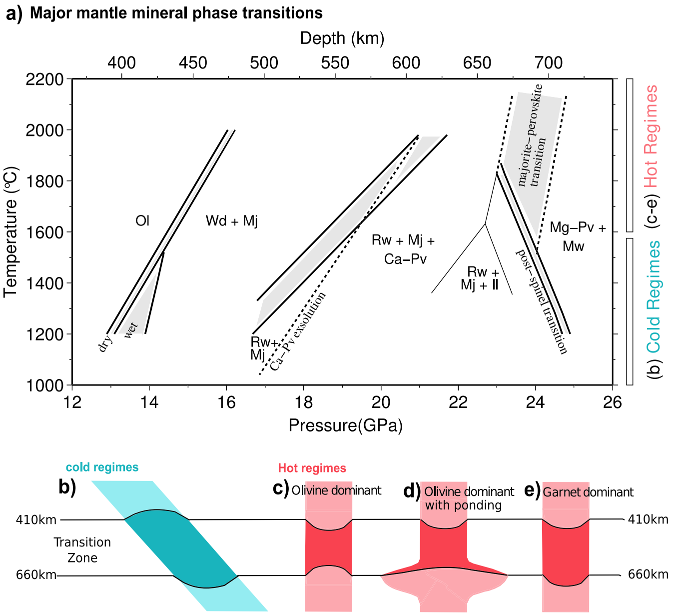

Fig. 1. a) Schematic simplified diagram of pressure–temperature dependence of major mantle mineral phase transitions from Deuss et al. (2013) with abbreviations: Ol—olivine, Wd—wadsleyite, Mj—majorite, Rw—ringwoodite, Mg–Pv—magnesium perovskite (or bridgmanite), Ca–Pv—calcium perovskite, Il—ilmenite and Mw—magnesiowustite. b–e) Cartoons of predicted discontinuity variation with temperature anomalies adapted from Deuss (2007); b) cold uplifted 410, depressed 660, thickened TZ; c) hot—depressed 410, uplifted 660 and thinned TZ regimes in an olivine dominant system; d) as for c) but with ponding of the plume beneath 660 causing uplift across a wider region; e) hot—depressed 410 and depressed 660 with no overall TZ thinning for a garnet dominant regime and no potential for ponding.

2. Data and method

2.1. Seismic data

Seismic data are sourced from a wide spread of stations across the North Atlantic region and a dense network in Iceland itself (Fig. 2a), with the aim of comparing directly the anomalous plume affected area to surrounding reference regions. Outside Iceland we use data from a total of 37 seismic stations located in Greenland, Jan Mayen, the Faroe Islands, the Shetlands, Scotland, England and Northern Ireland. These publicly available data are accessed through IRIS and ORFEUS data centres from a number of contributing national (Danish—DK, Norwegian—NO/NS, British—GB, N. Irish—EI) and temporary networks (North East Atlantic Tomography—NEAT).

Within Iceland we make use of the IRIS station BORG which has been in operation for over 20 yr, two temporary networks (ICEMELT (Bjarnason et al., 1996), 17 instruments between 1993–1996 and HOTSPOT (Foulger et al., 2000), 28 instruments between 1996–1998), as well as data from 26 broadband stations running for varied periods between 1995–2014 supplied by the Icelandic Meteorological office (IMO–SIL network). In addition, we use data from the University of Cambridge run network, mainly distributed