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Seismic evidence for an Iceland thermo-chemical plume in the Earth's lowermost mantle

Yumei He [a,*], Lianxing Wen [b,c], Yann Capdeville [d], Liang Zhao [e]

[a] Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, PR China
[b] Department of Geosciences, State University of New York at Stony Brook, Stony Brook, NY 11790, USA
[c] Laboratory of Seismology and Physics of Earth's Interior, University of Science and Technology of China, Hefei, Anhui, 230026, PR China
[d] Institut de Physique du globe de Paris, 4, place Jussieu, Paris, 75005, France
[e] State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, PR China

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ABSTRACT

We constrain the geographic extent, geometry and velocity structure of the seismic anomaly near the Earth's core–mantle boundary (CMB) beneath Iceland, based on travel time and three-dimensional waveform modeling of the seismic data sampling the lowermost mantle beneath Iceland. Our analysis suggests a mushroom-shaped low velocity anomaly situated in the lowermost mantle beneath Iceland surrounded by a high velocity province. The best fitting mushroom-shaped model is 600 km high and has a stem with a radius of 350 km in the lowermost 250 km of the mantle and a cap with increasing radii from 550 km at 250 km above the CMB to 650 km at 600 km above the CMB. The shear velocity structure varies from 0% at the top to −3% at 250 km above the CMB and to −6% at the CMB. These inferred seismic features, in combination with the previous evidence of existence of ultra-low velocity zones at the base of the mantle beneath the region, suggest that Iceland represents a thermo-chemical plume generated by interaction of downwelling and a localized chemical anomaly at the base of the mantle.

1. Introduction

Iceland is characterized by an anomalously thick crust (Foulger et al., 2003), a major, strong, low-wave-speed anomaly in the upper mantle (Tryggvason et al., 1983; Wolfe et al., 1997; Bijwaard and Spakman, 1999; Ritsema et al., 1999; Zhao, 2001; Hung et al., 2004; Montelli et al., 2006), local thinning of the transition zone (Shen et al., 1998), atypical geochemical signatures (Farley and Neroda, 1998; Mukhopadhyay, 2012), and has long been proposed as the manifestation of a mantle plume rising from the core–mantle boundary (CMB) (Morgan, 1971). While there has been accumulated evidence for a mantle plume in the upper mantle and the transition zone, the direct evidence for a seismic anomaly in the lowermost mantle has been limited to just the presence of ultra-low velocity zone in the region (Helmberger et al., 1998). The detailed geometry and velocity structure of the Iceland anomaly near the CMB remain largely unconstrained, fueling the debate of its plume origin from deep mantle (Foulger, 2002; Depaolo and Manga, 2003; Montelli et al., 2006; Mukhopadhyay, 2012; Anderson and Natland, 2014).

In this study, we are able to constrain the detailed seismic features of the lowermost mantle beneath Iceland, based on differential time residuals analysis and three-dimensional (3-D) seismic waveform modeling of the seismic data. The seismic results not only provide evidence to support the hypothesis that the Iceland is a mantle plume erupted from the core–mantle boundary, but also reveal thermo-chemical origin of the plume and likely formation mechanism of the plume. We present seismic data in Section 2, differential time residuals analysis and seismic modeling results in Section 3, and possible origin of the Iceland anomaly in Section 4.

2. Seismic data

Seismic data are collected from the database of the Incorporated Research Institutions for Seismology (IRIS). A Butterworth filter with a frequency range of 0.008–1 Hz is applied to all seismograms in the travel time analysis. We measure ScS–S and sScS–sS differential travel times by the difference of peak-to-peak times of the two phases on the transverse components of seismograms.

* Corresponding author.
E-mail address: ymhe@mail.igcas.ac.cn (Y. He).

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Table 1
Events for travel time analysis.

Origin time	mb	Latitude (°N)	Longitude (°E)	Depth (km)
1999.316.16.57.20	6.3	40.76	31.16	10
2004.149.12.38.44	6.2	36.25	51.62	17
2004.301.20.34.37[a]	5.8	45.79	26.62	96
2006.169.18.28.02	5.5	33.03	−39.70	10
2008.006.05.14.20[a]	6.1	37.22	22.69	75
2009.188.19.11.47	5.9	75.35	−72.45	19
2009.250.22.41.37	5.7	42.66	43.44	15
2010.067.02.32.34	5.9	38.87	39.98	12
2010.101.22.08.13	6.0	36.97	−3.54	610

[a] sScS–sS differential travel time residuals are used.

We further use waveforms of events (2002/03/03 and 2003/12/26) recorded in the United States National Seismic Network, the Canadian National Seismograph Network, the Lamont–Doherty Cooperative Seismographic Network, the Global Seismograph Network (GSN), the Cooperative New Madrid Seismic Network and the GEOFON to constrain the detailed geometric feature and seismic structures of the Iceland anomaly in the lowermost mantle (Fig. 2). The waveforms are deconvolved with their instrumental responses and bandpass-filtered from 0.008 to 0.125 Hz.

3. Geographic boundary and shear-velocity structure of the Iceland anomaly in the lowermost mantle

3.1. Geographic boundary of the Iceland anomaly near the CMB

We first constrain the geographic extent of the Iceland anomaly near the CMB using ScS–S and sScS–sS differential travel-time residuals. We examine broadband tangential displacements of ScSH–SH and sScS–sS phases recorded at a distance range between 45° and 85° for all the events occurring from 1999 to 2010, with a magnitude greater than 5.5 and their ScS and sScS bouncing points at the CMB located between 45°–80°N and −60°–36°E. We choose 9 earthquakes and hand-pick a total of 54 ScS–S and 17 sScS–sS travel-time residuals (Table 1). The seismic data provide good coverage in our study area (Fig. 1(a)). We test six tomographic models: GyPSuM (Simmons et al., 2010), HMSL_S06 (Houser et al., 2008), S362ANI (Kustowski et al., 2008), S40RTS (Ritsema et al., 2011), SAW642ANB (Panning et al., 2010) and TX2011 (Grand, 2002) in the corrections for the effects of the seismic heterogeneities 500 km above the CMB. We choose model S362ANI (Kustowski et al., 2008) for corrections as that model produces the best correction between the corrected ScS travel time residuals and the corrected ScS–S differential travel time residuals, and removes the anti-correlation between the observed S travel time residuals and the observed ScS–S differential travel time residuals at most (Table 2). Average velocity perturbations of lowermost 500 km of the mantle beneath Iceland are estimated based on the corrected ScS–S and sScS–sS differential travel time residuals. The corrected ScS–S and sScS–sS differential travel time residuals exhibit an approximately circular area of positive values (low velocities) with radius of ∼400 km beneath Iceland surrounded by regions with normal or negative values (high velocities) (Fig. 1(b)).

3.2. Geometric feature and velocity structure of the Iceland anomaly

To further constrain the geometric feature and velocity structure of the low-velocity anomaly beneath Iceland, we select seismic data from events 2002/03/03 and 2003/12/26 with their ray paths sampling inside and outside the anomaly for waveform modeling (Fig. 2(a) and Table 3). Event 2002/03/03 occurred in the Hindu Kush region and was recorded in North America. The tangential displacements of the event gradually vary with azimuth,

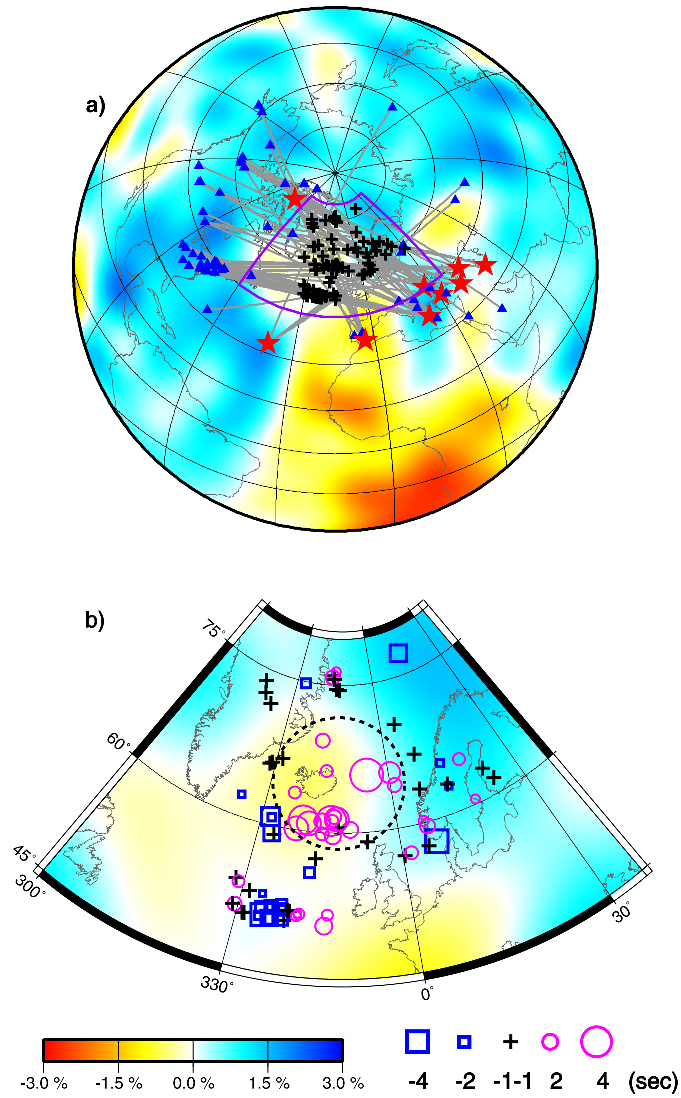

Fig. 1. (a) The study region and ScS, sScS reflected points (black crosses) at the CMB, along with earthquakes (red stars), seismic stations (deep blue triangles) and great-circle paths (gray lines) of the seismic phases used in this study. The background is shear-velocity perturbations from a global shear-velocity tomographic model S362ANI (Kustowski et al., 2008). (b) Observed ScS–S and sScS–sS differential time residuals plotted at the ScS and sScS reflected points at the CMB, after corrected for the effects of the mantle heterogeneities 500 km above the CMB using a shear-velocity model S362ANI (Kustowski et al., 2008). The residuals smaller than −1 s are plotted as blue squares; those ranging from −1 to 1 s as black crosses; and those larger than 1 s as purple circles. The sizes of the symbols are proportional to the magnitudes of the travel-time residuals. The boundary from positive travel-time residuals (low velocities) to zero or negative travel-time residuals (neutral or high velocities) is mapped out approximately by a dashed circle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Correlation Coefficients (CC).

	CC between S and ScS–S	CC between ScS and ScS–S
Raw data	−0.16	0.61
GyPSuM	−0.30	0.53
HMSL_S06	−0.42	0.33
S362ANI	−0.04	0.65
S40RTS	−0.33	0.58
SAW642ANB	−0.20	0.58
TX2011	−0.30	0.51

from sampling the northern portion of the anomaly to outside the anomaly. Event 2003/12/26 occurred in southern Iran and was