www.sciencemag.org/cgi/content/full/1131692/DC1

Supporting Online Material for

Localized Temporal Change of the Earth's Inner Core Boundary

Lianxing Wen

E-mail: wen@earth.geo.sunysb.edu

Published 28 September 2006 on *Science* Express
DOI: 10.1126/science.1131692

This PDF file includes:

Materials and Methods
Figs. S1 to S3
Table S1
References

Supporting Online Materials for:

Localized Temporal Change of the Earth's Inner Core Boundary

by Lianxing Wen

Materials and Methods

Seismic data

Seismic data are collected from the Global Seismographic Network, the Canadian National Seismographic Network, the Global Telemetered Seismograpic Network, The Berkeley Network, the Pacific Northwest Regional Seismic Network, the GEOSCOPE, the University of Utah Regional Seismic Network and the Trinet (Terrascope) in southern California for both events. The observed vertical components of the seismic data are used and are bandpass filtered with the WWSSN short period response. The non-IC phases used in the relocation analysis are compressional waves that include the direct wave in the mantle (P), the two branches of the seismic phases traveling in the outer core (PKPbc and PKPab), the wave reflected once off the bottom side of the core-mantle boundary (PKKPbc) and the wave scattered near the core-mantle boundary (PKP precursor). The availability of these non-IC phases provides good azimuthal coverage for relocation analysis (Fig. S1). The travel time differences of all the phases between the two events are obtained by cross-correlating the waveforms between the two events. An error of ± 0.01 s exists in such measurements. The values reported in the text took this uncertainty into account. The data time series were time interpolated to an evenly spaced time series with a time sampling rate of 0.0025 s based on the Wiggins interpolation method *(S1)* before the cross-correlations were performed. The data interpolations are performed using the standard software package Seismic Analysis Code (SAC). PKIKP and PKiKP phases (Fig. 1a) are not used in the relocation analysis. Their arrival times and waveforms are independently checked and presented in the main text based on the relocated event parameters.

Relocation procedure

I used event 93 as the master event (i.e., fix its origin time and location to those reported in the PDE catalog, Table S1) and derive relative event location and origin time of event 03 with respect to those of event 93. For events 93 and 03, there exist these relationships:

$$T_{03,k,p} = O_{03} + t_{03,k,p} \qquad (1)$$

$$T_{93,k,p} = O_{93} + t_{93,k,p} \qquad (2)$$

where, *T* is the absolute arrival time of the seismic phase, *O* is event origin time and *t* is the time it takes the seismic phase to travel from the hypocenter to the station, *k* denotes station index, *p* seismic phase, *03* for event 03 and *93* for event 93. Subtracting equation (2) from (1) yields:

$$\Delta T_{03-93,k,p} = \Delta O_{03-93} + \Delta t_{03-93,k,p} \qquad (3)$$

where, $\Delta T_{03-93,k,p} = T_{03,k,p} - T_{93,k,p}$, $\Delta O_{03-93} = O_{03} - O_{93}$, $\Delta t_{03-93,k,p} = t_{03,k,p} - t_{93,k,p}$.

The above equation simply states that the difference in arrival time of seismic phase *p* recorded at station *k* between the doublet ($\Delta T_{03-93,k,p}$) equals to the difference between the origin times of the two events (ΔO_{03-93}) plus the travel time difference of the seismic phase caused by a difference in relative hypocenter locations of the doublet ($\Delta t_{03-93,k,p}$).

$\Delta t_{03-93,k,p}$ is sensitive only to the relative location between the two events and can be expressed as:

$$\Delta t_{03-93,k,p} = dD_k * \frac{dt}{dD}(k,p,D,h) + dh * \frac{dt}{dh}(k,p,D,h) \qquad (4)$$

dD_k is the difference in epicentral distance at station k due to the relative difference in event location between the two events, $\frac{dt}{dD}(k,p,D,h)$ is the derivative of travel time of the seismic phase with respect to epicentral distance D, $\frac{dt}{dh}(k,p,D,h)$ is the derivative of travel time of the seismic phase with respect to event depth h, and dh is relative change of event depth between the two events. $\frac{dt}{dD}(k,p,D,h)$ and $\frac{dt}{dh}(k,p,D,h)$ can be calculated for each station and its associated seismic phase using a reference Earth's model. They would depend on epicentral distance D, event depth h, seismic phase p and slightly the reference model used, but exhibit little change with the absolute location and depth we assume for event 93 within their plausible error bars.

For a relative hypocenter location and a relative origin time of event 03, the predicted relative arrival time for seismic phase p recorded at station k between the doublet is defined as:

$$T^{pre}_{03-93,k,p} = \Delta O_{03-93} + \Delta t_{03-93,k,p} \qquad (5)$$

with ΔO_{03-93} being the time difference between the relative origin time of event 03 and the origin time of event 93 (fixed to the reported origin time in the PDE catalog, Table S1), and $\Delta t_{03-93,k,p}$ being the difference in travel time caused by the difference in hypocenter location between the two events. $\Delta t_{03-93,k,p}$ is calculated based on equation (4) using the relative hypocenter location of event 03 for seismic phase *p* at station *k*.

Let $T^{obs}_{03-93,k,p}$ be the arrival time difference of seismic phase *p* recorded at station *k* and measured by cross-correlating their waveforms of the two events. For a relative location and an origin time of event 03, the travel time residual of the doublet for seismic phase *p* recorded at station *k* is defined as:

$$\Delta T^{res}_{03-93,k,p} = T^{obs}_{03-93,k,p} - T^{pre}_{03-93,k,p} \qquad (6)$$

with $T^{pre}_{03-93,k,p}$ calculated based on equation (5). Positive travel time residuals mean that, if event 03 occurs in the relative location and at the relative origin time as assumed, the seismic phase *p* at station *k* arrives later in event 03 than in event 93 even after corrected for the effects of relative hypocenter location between the two events. The negative travel time residuals indicate the opposite.

Relative location and depth for event 03 are grid-searched around the reported location and depth of event 93. The best fitting relative location, depth and origin time of event 03 are the one that generates the smallest RMS travel time residual variation defined as:

$$\sqrt{\sum_{k=1}^{N} [\Delta T^{res}_{03-93,k,p}]^2 / N} \qquad (7)$$

N is the total number of observations used in the relocation.

The above relocation technique is similar to those used to determine the relative event locations in the master event approach (e.g., *S2-S7*). The relative origin times of the events are also jointly inverted in the above procedures. The absolute origin times and event locations of the both events are subject to the traditional errors such as those caused by our imperfect knowledge of three-dimensional seismic structure of the Earth, but the relative timing and event location between the doublet are not. Neither are the predictions based on equations (4), (5) and (6).

The measured $T^{obs}_{03-93,k,p}$, seismic phases, and seismic stations used in the relocation analysis are shown in Fig. S1a. The search region for the relative hypocenter location of event 03 is a 10 km (N-S direction) ×10 km (E-W direction) × 2 km (vertical) box centered at the reported location and depth of event 93. The search grid intervals are 0.002 km in N-S and E-W directions and 0.002 km in depth.

The above relocation analysis places the best-fitting relative event horizontal locations of the doublet within 0.37 km and event depths within 0.7 km (Fig. S2a). Using the Preliminary Reference Earth Model (PREM) *(S8)* and AK135 *(S9)* essentially yields same results. The best-fitting origin time for event 03 (with respect to the reported PDE origin time of event 93 in Table S1) is 2003/09/06 15:47:00.205. The relocation procedures reduce the RMS travel time residual to 0.016 s (using PREM) or 0.015 s (using AK135) for the best-fitting relative locations and origin times. The best-fitting relative location and origin time of the events also reduce the travel time residuals at each individual station between the two events (Fig. S1b). The travel time residuals of the non-IC phases in the individual stations for the best-fitting relative location and origin time range from -0.029 s (SNZO) to 0.031 s (DAWY) in the individual stations (Fig. S1b).

My relocation epicentral locations are slightly different from those obtained by Zhang et al. *(S10)*, who used a double-difference method developed by Waldhauser and Ellsworth *(S11)*. The difference is probably due to the fact that different datasets are used in the relocation analyses. The difference is small and insignificant.

RMS travel time residuals for explaining the PKiKP arrival times at ARU

While the difference in absolute PKIKP travel time observed at ARU between the doublet is just slightly above the relocation error bar, the differences in the PKiKP travel time observed at ARU, AAK and OBN between the doublet cannot be explained by a difference in event location or origin time between the doublet. I present here more analyses to show that the travel time residual of 0.11 s of the PKiKP phases between the doublet observed at station ARU cannot be explained by a difference in event location or origin time between the doublet. Same arguments can be made for the travel time shifts of the PKiKP phases observed at stations AAK and OBN.

A difference in event depth between the doublet cannot explain the data, because placing event 03 deeper to reduce the positive 0.11 s residual of the PKiKP phase at ARU would generate a similar amount of negative travel time residuals of the PKiKP and PKIKP phases at other stations. The effect of the difference in event depth is not explored further. I calculate the RMS travel time residuals and travel time residuals of the non-IC phases at each station for all possible relative event epicentral locations of event 03, by forcing the PKiKP arrival times between the doublet to fit within 0.031 s, the maximal relocation error at station DAWY in Fig. S1b. For each assumed event location of event 03, a relative origin time of event 03 is found so that the PKiKP travel time residual at ARU between the doublet (calculated based on equation (6)) is within 0.031 s. All relative event positions result in unacceptable RMS travel time residuals (Fig. S2b) and travel time residuals at many stations between the doublet (see two examples in Fig. S3). The above analysis indicates that the arrival time difference of the PKiKP phases recorded at ARU of the two events cannot be explained by a difference in event location.

Sensitivity of change of differential PKiKP-PKIKP travel time to relative event location between the doublet

The observed smaller differential PKiKP-PKIKP travel times of about 0.07 s at stations ARU and AAK in event 03 further confirm that the PKiKP travel time residuals are not caused by relative event location or origin time of the doublet. The PKiKP-PKIKP differential travel time is not affected by the earthquake origin times and is insensitive to the uncertainties of the relative location between the two events. To generate a difference of 0.07 s in PKiKP-PKIKP differential travel time, a difference of 65 km (based on PREM) or 59 km (based on AK135) in epicentral distance between the doublet is needed and a difference in PKIKP absolute travel time of 1.12 s (based on PREM) or 1.01 s (based on AK135) would result for that difference in epicentral distance. The PKiKP-PKIKP differential travel time is even less sensitive to the event depth. A change of event depth from 33 km to 0 km would only yield a difference of 0.004 s (PREM and AK135) in PKiKP-PKIKP differential travel time. All these scenarios can be excluded based on the measured arrival time differences of the two events and the relocation analysis (Figs. S1, S2a).

Effects of noise or other energy perturbation on PKiKP phase

The observed PKiKP travel time residuals at stations, ARU, AAK and OBN are not caused by noise or possible temporal changes of seismic energy proceeding the PKiKP phases. A slight ground motion unrelated to the earthquakes at a recording station, occurring at either one of the PKiKP arrival times of the doublet, may perturb the PKiKP signal. But it is highly unlikely that this would occur for all three stations with ground motions happening to occur at the PKiKP arrival times at those stations. The PKIKP phases may generate coda waves and the coda waves may experience temporal changes (e.g., *S12, S10*). Such temporal changes of coda waves may affect the PKiKP waveforms and thus produce the apparent time shifts of the PKiKP phases at stations ARU and AAK. It is, however, a very unlikely explanation for the observed time shifts of the PKiKP phases. Note that, such PKiKP time shift is also observed at station OBN. Synthetics for all available inner core models indicate that, at an epicenter distance of stations OBN (about 123.069^{o}), the energy of the PKIKP phase is less than 4% of the PKiKP energy. The coda waves of the PKIKP phases would presumably have even less energy. The temporal changes of the PKIKP coda waves, even if they exist, would unlikely alter the PKiKP arrival times. The PKnIKP (n = 2, 3, 4 …) phases, which propagate through the inner core and are reflected off the downside of the inner core boundary $n-1$ times, would arrive between the PKIKP and PKiKP phases and their possible temporal change could potentially be another source that may affect the PKiKP arrivals. But the PKnIKP phases do not appear until the epicentral distances larger than the recording distances of these stations.

Effects of temporal change of seismic properties near the hypocenters or in the mantle on PKiKP-PKIKP differential travel time

The temporal changes of travel time for the PKiKP phases recorded at stations ARU, AAK and OBN between the doublet are unlikely caused by temporal change of seismic properties near the hypocenters or in the mantle. Local temporal changes of seismic properties near the hypocenters (for example, some velocity changes due to the first event) may occur, but it would not generate the smaller PKiKP-PKIKP differential travel time in event 03, as these two phases have almost identical take-off angles from the earthquakes (Fig. 1a). Temporal change of the seismic properties elsewhere in the mantle is unlikely. But even if it exists, the PKiKP-PKIKP differential travel times are not sensitive to the seismic structures in the mantle as they have almost identical ray paths there (Fig. 1a) *(S13, S14)*. The observed temporal changes of the PKiKP travel time recorded at ARU and AAK between the doublet are thus associated with some temporal change of the properties of the inner core boundary.

Effects of a shift of entire inner core on the change of PKiKP travel time

The localized change of inner core radius cannot be caused by a slight shift of the entire inner core toward middle Africa (the reflected points of the PKiKP phases recorded at ARU, AAK and OBN) by 0.98 - 1.75 km. A slight shift of the entire inner core would change the position of the inner core boundary elsewhere and generate PKiKP travel time difference at other stations, which is different from the observations. The PKiKP and PKiKP-PKIKP observations do not exhibit temporal change at other stations (Figs. 2, 3). A slight shift of the entire inner core would also produce similar changes of the inner core boundary position in the entry and exit points for the PKIKP phases recorded at ARU and AAK, and would generate similar amount of the travel time differences for the PKIKP phases at these two stations, and thus similar PKiKP-PKIKP differential travel times between the two events. That is also different from the observations (Figs. 1c, 1d). Thus, a localized change of inner core radius cannot be explained by a shift of the inner core.

Fresnel zone of the PKiKP waves and separation of PKiKP and PKIKP phases near the inner core boundary

For the dominant frequency of the seismic signals, the width of the Fresnel zone of PKiKP is about 150 km in the inner core boundary. This is smaller than the separation of the PKiKP and PKIKP phases at the inner core boundary, so PKiKP and PKIKP phases could respond differently to localized temporal change of inner core boundary. However, if one considers the PKIKP travel time residual of 0.04 s at ARU to be significant (which is just slightly above the relocation error bar), it is possible that the PKIKP phase at ARU is also affected by temporal change of the inner core boundary.

Temporal change of PKiKP and PKIKP coda

There is another large time shift of phase at about 4 s after the first arrivals, or about 3 s after the PKiKP phases, in the superimposed ARU waveforms (Figs. 1b,1c). This may be caused by scattering of the time-shifted PKiKP main phases by the seismic structure beneath ARU or possible temporal change of PKiKP coda waves.

The dissimilarity of the PKiKP coda waves observed at OBN, if it is attributed to the same cause for the misalignment of the PKiKP main phases, would suggest that the temporal change of topography is spatially varying to small scales. Small length scales of temporal change of inner core topography would also affect PKIKP coda waves, and may be considered as another candidate for explaining the observed temporal change of PKIKP coda waves in other studies. Different time widows of the PKiKP coda wave change are sensitive to temporal changes of different part of the inner core boundary, so the dissimilarities of the coda waves could be used to study temporal change of the inner core boundary in a large area.

Supplementary Figure Legends

Figure S1. a) Measured difference in absolute arrival time (circles and squares) of various non-IC phases used in the relocation analysis between the doublet plotted at the location of each station, along with the great circle paths (gray traces) from the doublet (star) to the stations. The arrival time differences are plotted with respect to a ΔO_{03-93} that generates a zero mean of the arrival time differences for all the stations. The circles indicate that the non-IC phases in event 03 arrive relatively earlier than their counterparts in event 93, while the squares show the opposite. Seismic stations and phases are labeled in the Figure. b) Travel time residuals $\Delta T^{res}_{03-93,k,p}$ between the doublet calculated from the measurements in a) and equations (6) and (5) using the best-fitting relative location (Fig. S2a) and origin time (2003/09/06 15:47:00.205) for event 03.

Figure S2. a) Best-fitting location of event 03 (dot labeled as 2003/09/06) relative to the location of event 93 (0,0) (star labeled as 1993/12/01) that minimizes the RMS travel time residual of the non-IC phases between the doublet, along with the RMS travel time residuals as a function of relative location of event 03. b) RMS travel time residuals of the non-IC phases as a function of relative location of event 03 by forcing the travel time residual of the PKiKP phases observed at ARU between the doublet to be within 0.031 s. Two relative locations are labeled with one that generates the minimal RMS travel time residual (dot labeled as A) and the other that produces a minimal RMS travel time residual among those that also generate a zero mean of the travel time residuals of the non-IC phases between the doublet. The travel time residuals in individual stations between the doublet in these two cases are shown in Fig. S3a and Fig. S3b, respectively.

Only the relative locations with a RMS travel time residual less than 190 ms are plotted in the figures.

Figure S3. a) Travel time residuals of the non-IC phases between the doublet for two example locations shown in Fig. S2b. Panels a and b are for the locations labeled as A and B in Fig. S2b, respectively.

Fig. S1

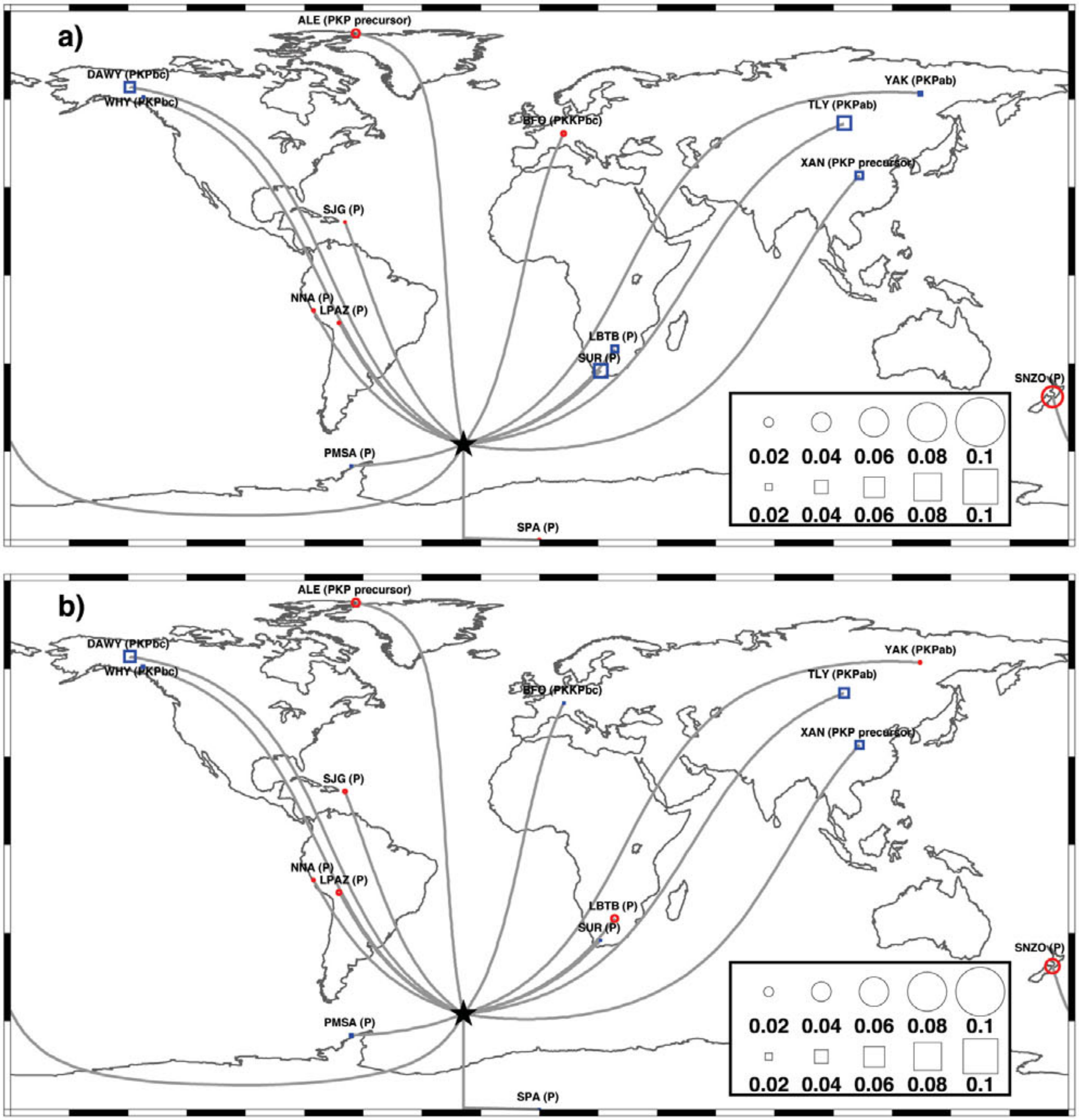
a)
ALE (PKP precursor)
DAWY (PKPbc)
WHY (PKPbc)
BFO (PKKPbc)
YAK (PKPab)
TLY (PKPab)
XAN (PKP precursor)
SJG (P)
NNA (P)
LPAZ (P)
LBTB (P)
SUR (P)
SNZO (P)
PMSA (P)
SPA (P)
0.02 0.04 0.06 0.08 0.1
0.02 0.04 0.06 0.08 0.1
b)
ALE (PKP precursor)
DAWY (PKPbc)
WHY (PKPbc)
BFO (PKKPbc)
YAK (PKPab)
TLY (PKPab)
XAN (PKP precursor)
SJG (P)
NNA (P)
LPAZ (P)
LBTB (P)
SUR (P)
SNZO (P)
PMSA (P)
SPA (P)
0.02 0.04 0.06 0.08 0.1
0.02 0.04 0.06 0.08 0.1

Fig. S2

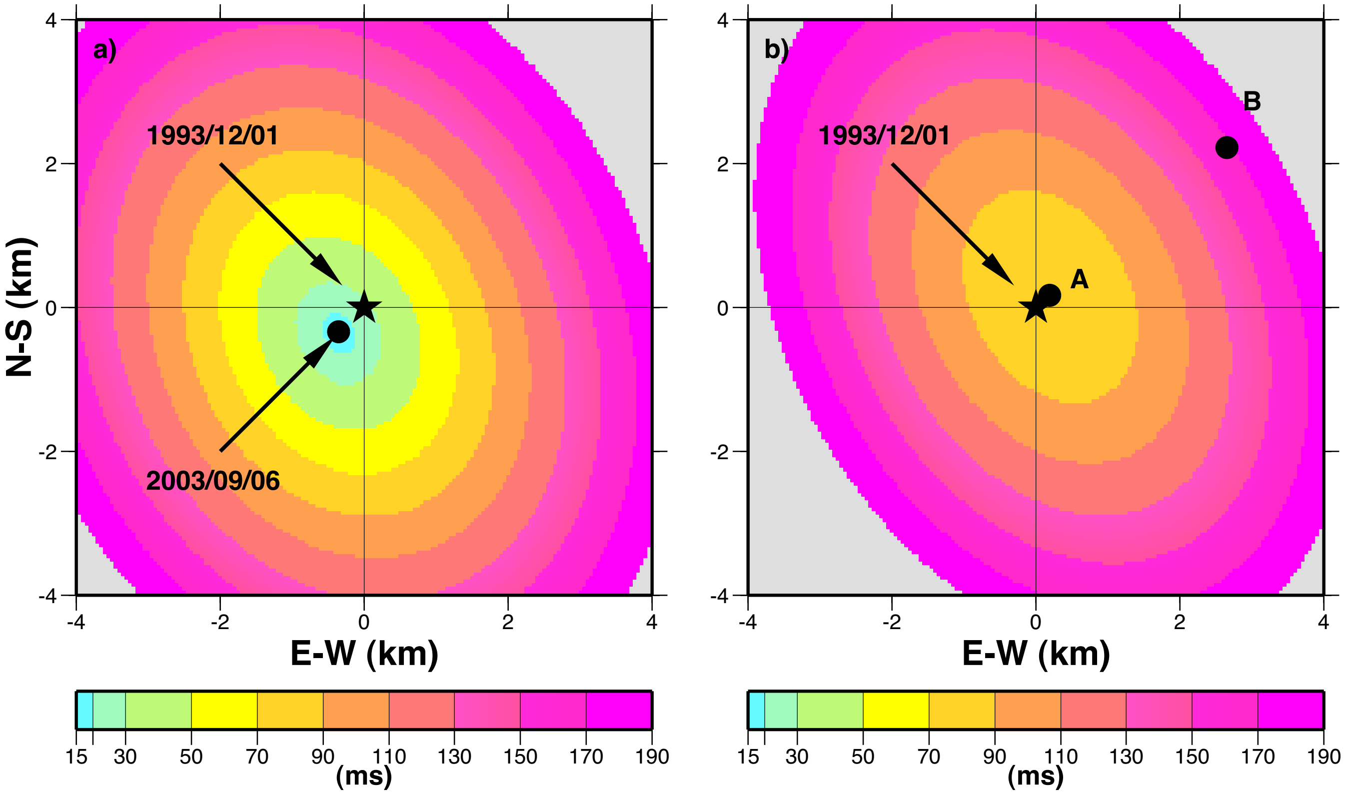
a)
1993/12/01
2003/09/06
b)
1993/12/01
A
B
N-S (km)
E-W (km)
E-W (km)
4
2
0
-2
-4
-4
-2
0
2
4
15
30
50
70
90
110
130
150
170
190
(ms)
(ms)

Fig. S3

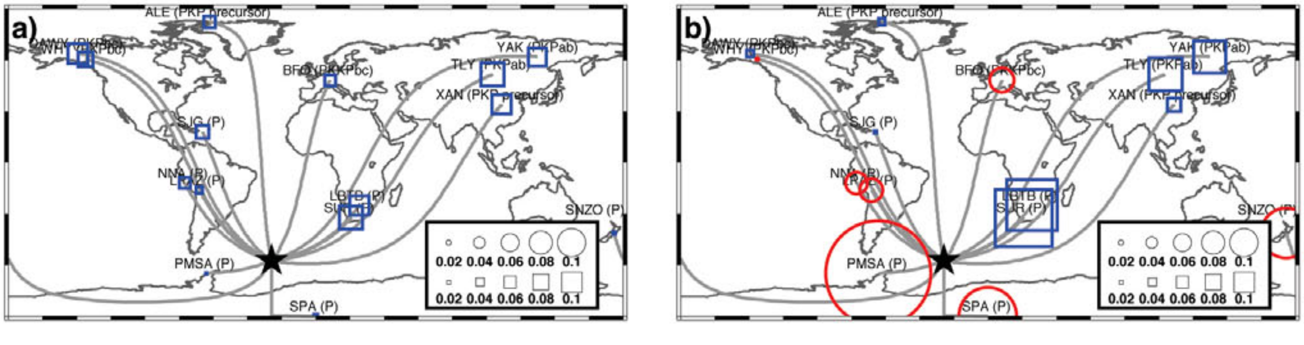
a)
ALE (PKP precursor)
DAWY (PKPbc)
WHY (PKPbc)
BFO (PKPbc)
YAK (PKPab)
TLY (PKPab)
XAN (PKP precursor)
SJG (P)
NNA (P)
LPAZ (P)
LBTB (P)
SUR (P)
SNZO (P)
PMSA (P)
SPA (P)
0.02 0.04 0.06 0.08 0.1
0.02 0.04 0.06 0.08 0.1
b)
ALE (PKP precursor)
DAWY (PKPbc)
WHY (PKPbc)
BFO (PKPbc)
YAK (PKPab)
TLY (PKPab)
XAN (PKP precursor)
SJG (P)
NNA (P)
LPAZ (P)
LBTB (P)
SUR (P)
SNZO (P)
PMSA (P)
SPA (P)
0.02 0.04 0.06 0.08 0.1
0.02 0.04 0.06 0.08 0.1

Table S1. Event Location and Origin Time of the Doublet (PDE)

Event	Date (year/mm/dd)	Origin time (hh:mm:ss)	Latitude (°N)	Longitude (°E)	Depth (km)	m_b
93	1993/12/01	00:59:01.500	-57.475	-25.685	33	5.5
03	2003/09/06	15:46:59.900	-57.419	-25.639	33	5.6

References for Supporting Online Materials:

S1. R. A. Wiggins, *Bull. Seism. Soc. Am.* **76**, 2077 (1976).

S2. A. Ito, *J. Phys. Earth* **33,** 279 (1985).

S3. F. Scheberbaum, J. Wendler, *J. Geophys.* **60**, 157 (1986).

S4. M.-J. Fremont, S. D. Malone, *J. Geophys. Res.* **92,** 10223 (1987).

S5. J. C. VanDecar, R. S. Crosson, *Bull. Seism. Soc. Am.* **80**, 150 (1990).

S6. N. Deichmann, M. Garcia-Fernandez, *Geophys. J. Int.* **110**, 501 (1992).

S7. J. M. Lees, *Bull. Seism. Soc. Am.* **88**, 1127 (1998).

S8. A. M. Dziewonski, D. L. Anderson, *Phys. Earth Planet. Inter.* **25**, 297 (1981).

S9. B. L. N. Kennett, E. R. Engdahl, R. Buland, *Geophys. J. Int.* **122**, 108 (1995).

S10. J. Zhang, X. Song, Y. Li, P. G. Richards, X. Sun, F. Waldhauser, *Science* **309**, 1357 (2005).

S11. F. Waldhauser, W. L. Ellsworth, *Bull. Seism. Soc. Am.* **90**, 1353 (2000).

S12. J. E. Vidale, P. S. Earle, *Geophys. Res. Lett.* **32**, L01309, doi:10.1029/2004GL021240 (2005).

S13. F. Niu, L. Wen, *Nature* **410,** 1081 (2001).

S14. L. Wen, F. Niu, *J. Geophys. Res.* **107**, 2273, doi:10.1029/2001JB000170 (2002).