

Wide-scale detection of earthquake waveform doublets and further evidence for inner core super-rotation

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SUMMARY

We report on more than 100 earthquake waveform doublets in five subduction zones, including an earthquake nest in Bucaramanga, Colombia. Each doublet is presumed to be a pair of earthquakes that repeat at essentially the same location. These doublets are important for studying earthquake physics, as well as temporal changes of the inner core. Particularly, our observation from one South Sandwich Islands (SSI) doublet recorded at station INK in Canada shows an inner core traveltime change of ~ 0.1 s over ~ 6 yr, confirming the inner-core differential motion occurring beneath Central America. Observations from one Aleutian Islands doublet, recorded at station BOSA in South Africa, and from one Kuril Islands doublet, recorded at station BDFB in Brazil, show an apparent inner core traveltime change of ~ 0.1 s over ~ 7 yr and ~ 6 yr, respectively, providing evidence for the temporal change of inner core properties beneath Central Asia and Canada, respectively. On the other hand, observations from one Tonga–Fiji–Solomon Islands doublet, recorded at station PTGA in Brazil, and from one Bucaramanga doublet, recorded at station WRAB in Australia and station CHTO in Thailand, show no/little temporal change (no more than 0.005 yr^{-1} , if any) of inner core traveltimes for the three corresponding ray paths for which the path in the inner core is nearly parallel to the equatorial plane. Such a pattern of observations showing both presence and possible absence of inner-core traveltime change can be explained by the geometry and relative directions of ray path, lateral velocity gradient and inner-core particle motion due to an eastward super-rotation of a few tenths of a degree per year.

Key words: Geomechanics.

1 INTRODUCTION

Earthquakes can repeat naturally, as indicated by their nearly identical seismograms at common stations, providing evidence that the events must have essentially the same hypocentre location and focal mechanism. Pairs of such repeating events are known as waveform doublets, or often, simply as doublets. For three or more repeating events, we refer to as triplets or multiplets. For repeating earthquakes whose waveforms are highly similar across sufficiently large time windows and frequency bands, we presume that the space–time distribution of slip was very similar on the fault plane or planes associated with the repeating events.

Many studies have recognized and analysed small repeating earthquakes, using local or regional records (for example, Geller & Mueller 1980; Poupinet *et al.* 1984; Vidale *et al.* 1994; Ellsworth 1995; Marone *et al.* 1995; Nadeau *et al.* 1995; Schaff *et al.* 1998;

Nadeau & McEvilly 1999; Rubin *et al.* 1999; Tullis 1999; Dimitrief & McCloskey 2000; Matsuzawa *et al.* 2002; Rubin 2002; Schaff *et al.* 2002; Igarashi *et al.* 2003; Waldhauser *et al.* 2004; Schaff & Waldhauser 2005). Moderate-size repeating earthquakes ($m_b = 4$ to 6) have also been found in a few studies. Wiens & Snider (2001) have found repeating deep earthquakes with $M_w \sim 5$, using regional broad-band waveforms, and found that repeating deep earthquakes show a strong preference for short recurrence intervals. Schaff & Richards (2004a) discovered that 10 percent or more of earthquakes in and near China occurred as repeating events that have similar waveforms, even for highly scattered *Lg* wave and coda (Schaff & Richards 2004b).

More discoveries of moderate-size repeating earthquakes have come from recent efforts on the study of inner core rotation, using earthquake doublets. The first observational evidence of inner core rotation was based on changes in the traveltime of seismic waves that pass through the inner core (Song & Richards 1996). However, claims of an inner-core traveltime change have been challenged as artefacts of event mislocation and contamination from heterogeneities (Poupinet *et al.* 2000). A straightforward method

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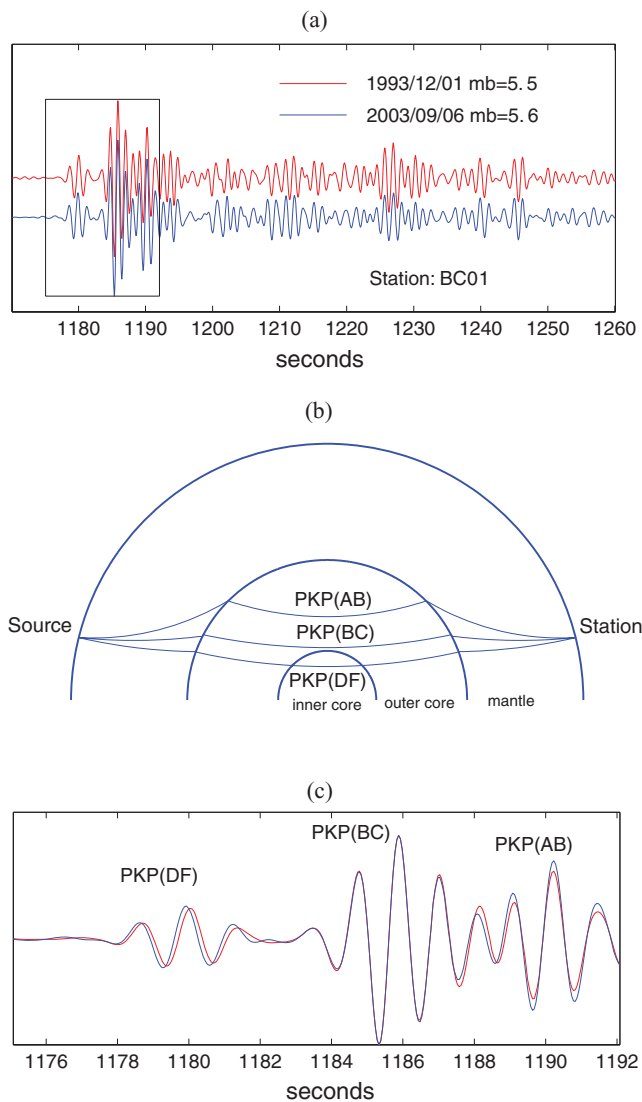


Figure 1. An example of earthquake waveform doublets and illustration of how doublets are used to detect inner-core traveltime change (from Zhang *et al.* 2005). (a) Highly similar and clear *PKP* arrivals at station BC01 (in Alaska), for two SSI events separated by ~ 10 yr (1993/12/01 $m_b = 5.5$ and 2003/09/06 $m_b = 5.6$); (b) Ray paths of *PKP* waves turning in the solid inner core (*DF*), the bottom of the fluid outer core (*BC*) and the mid-outer core (*AB*); (c) Superimposed and enlarged *PKP* waveforms from the box in (a). Doublets are ideal for detecting the inner core rotation. For the doublet shown in (a), the high similarity of *PKP(BC)* and *PKP(AB)* signals is due to propagation paths outside the inner core that sample the same structures. Observed traveltime difference in *PKP(DF)* is due to changes in the inner core.

of avoiding possible artefacts is to use ideal waveform doublets (Fig. 1a), namely pairs of events occurring essentially at the same location, as evidenced by their highly similar waveforms, and large enough to generate clear *PKP* signals [including three branches turning in the solid inner core (*DF*, also known as *PKIKP*), the bottom of the fluid outer core (*BC*) and the mid-outer core (*AB*), see Fig. 1b]. For the two doublet events, their ray paths are nearly identical. The high similarity of *PKP(BC)* and *PKP(AB)* signals is due to propagation paths outside the inner core that sample the same structures. Observed difference in *PKP(DF)* indicates changes in the inner core (Fig. 1c). To have high waveform similarity, the

source separation between the two doublet events should be less than a quarter of the corresponding wavelength (~ 2 km in our studies, using short period waveforms), which is also confirmed by the earthquake relocation (for example, Zhang *et al.* 2005). If the inner core is not in differential motion, at least 8 km difference in epicentral distance for the two events would be needed to cause the observed 0.1 s change of the *PKP(DF)* traveltime (Zhang *et al.* 2005; Fig. S8). Li & Richards (2003a) reported 17 pairs of $m_b \sim 5$ doublets found in the South Sandwich Islands (SSI) region. One of these doublets provided direct evidence at one station for an inner-core traveltime change over 8 yr. More recently, Zhang *et al.* (2005) reported 18 additional waveform doublets in the SSI region, some of them with very high signal-to-noise ratios at numerous stations in Alaska. These ideal doublets—with clear and strong *PKP(DF)* phases at up to 57 stations—show a consistent temporal change of inner core traveltimes, providing strong evidence of inner-core differential motion, though based only on seismic ray paths from SSI to Alaska.

Moderate-size repeating earthquakes, separated by several years or more, turn out to be the key to detecting inner core motion with high confidence. They allow traveltime measurements of teleseismic signals to attain precision at the level of ~ 10 ms, which in turn can lead to high precision estimates of location. Moreover, repeating earthquakes are of great interest in earthquake physics. Motivated by the discovery of high-quality repeating earthquakes in the SSI region using teleseismic data and the evidence of inner core motion that they provide, in this work, we extended our search for moderate-size repeating earthquakes to a much wider scale—to document available observations of any temporal changes or absence of change—for seismic waves passing through the inner core along a variety of ray paths. We chose the SSI region, the Aleutian Islands (AI) region, the Kuril Islands (KI) region (including parts of Kamchatka and Japan), the Tonga—Fiji—Solomon Islands (TFSI) region and an earthquake nest in Bucaramanga of Colombia as our targets. The repeating earthquakes discovered in these regions and their available *PKP(DF)* records were then used to examine inner-core differential motion with a range of data much wider than the SSI-to-Alaska paths of previous studies.

2 DOUBLET SEARCH

For each of five study regions, we selected events from the Preliminary Determinations of Epicenters (PDE) catalogue, which met criteria on proximity and magnitude—criteria that differed slightly from region to region. Thus, for a small subduction region in South America (the Bucaramanga nest), we worked with $m_b \geq 4$ events, but for the vast TFSI region, we selected events with $m_b \geq 5$. The selected time periods for each study region are also different. This is due to the different operation time of digital archives at stations we used. Then, for the selected events, we acquired vertical component broad-band waveform data at a few stations from the Data Management Center (DMC) of the Incorporated Research Institutions for Seismology (IRIS). We prefer stations that have continued operation for many years and have low noise level at short-period band, and thus, clear *P* or *PKP* phases. Note that at the stage of doublet search, it is not necessary to restrict stations to those that show core phases. Once we obtained the waveform data, we applied efficient time-domain waveform cross-correlation techniques (Schaff *et al.* 2002) to quantify waveform similarity for the selected event pairs. Through this process, we have documented more than 100 waveform doublets/triplets, which are described below.

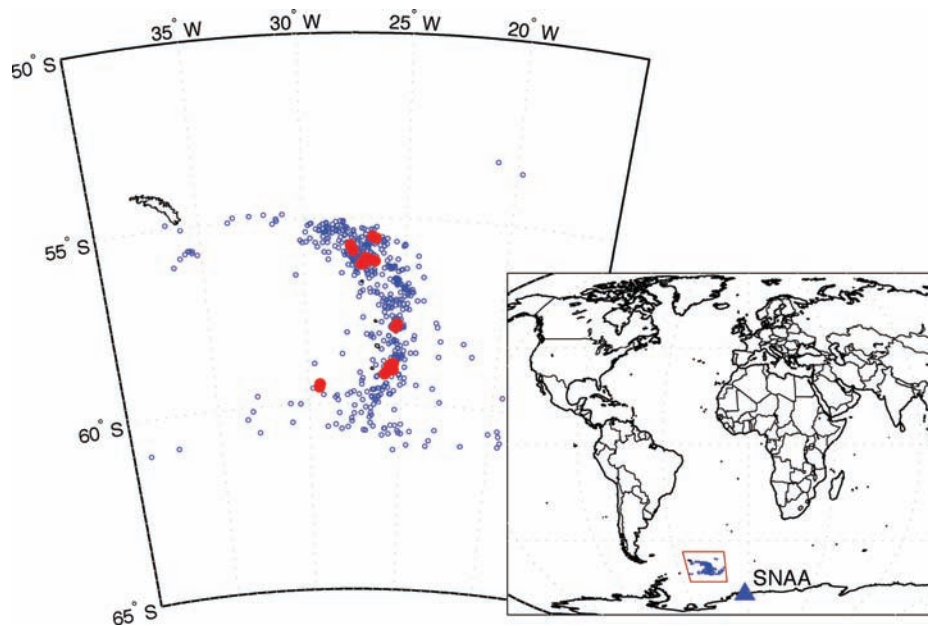


Figure 2. Map view of the South Sandwich Islands earthquakes and high-quality repeating earthquakes. Blue circles represent all the selected events. Red dots represent high-quality repeating events found in this study. The insert shows the global location of the studied region (brown box). Triangle represents station SNAA from which the waveform data are used for finding repeating earthquakes.

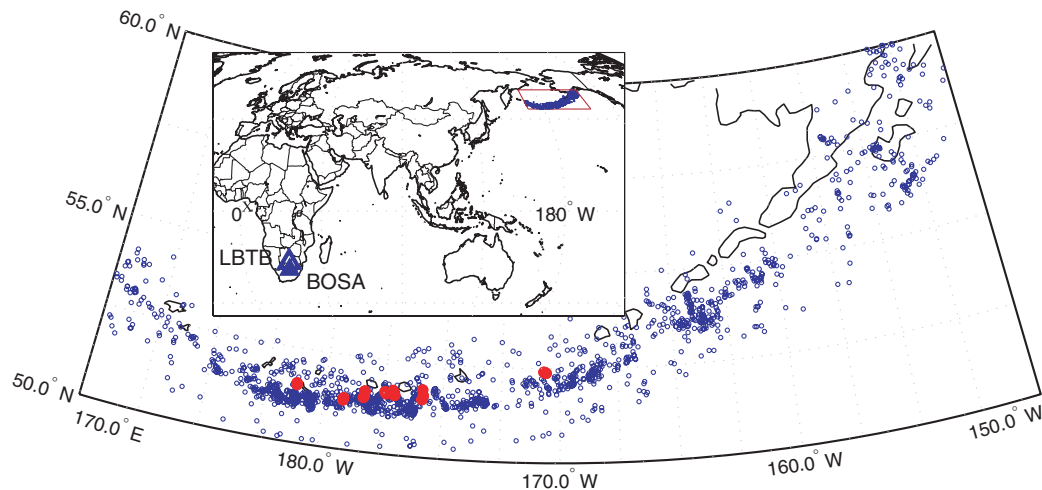


Figure 3. Map view of the Aleutian Islands earthquakes and high-quality repeating earthquakes. Blue circles represent all the selected events. Red dots represent high-quality repeating events found in this study. The insert shows the global location of the studied region (brown box). Triangles represent station BOSA and LBTB from which the waveform data are used for finding repeating earthquakes.

2.1 South Sandwich Islands (SSI) region

In this work, we report on an additional search for waveform doublets in the SSI region that included events in more recent years (2003–2005). Within the region from 50°S to 60°S and from 15°W to 40°W, we selected 602 $m_b \geq 4.5$ events (blue circles in Fig. 2) from the PDE catalogue, which occurred from 1997 March to 2005 June and were recorded at station SNAA. SNAA is located in Antarctica and has been operating since 1997 March. SSI events with $m_b \geq 4.5$ recorded at SNAA have clear P -wave arrivals and generally good signal-to-noise ratios for the P waveform. For selected events, we bandpassed the waveform data with corner frequencies at 0.8 and

1.5 Hz to increase the signal-to-noise ratio. For each event pair, in a time window from 5 s before the IASP91 predicted P arrival and lasting 30 s, we calculated cross-correlation coefficients for each event pair and used a value of 0.9 as the criterion of waveform similarity. We then checked the waveforms of these potential repeating event pairs by eye to see whether they are truly highly similar, namely waveform doublets.

By this means, we found 11 high-quality waveform doublets in the SSI region, additional to those reported by Zhang *et al.* (2005). In other words, at least 22 (~4 per cent) of 602 SSI earthquakes between 1997 and 2005 are found to be repeating earthquakes in the sense that each of these events has seismograms like at least

one other event. The event origin times, locations and magnitudes are listed in Table A1 (see the Appendix S1 in the Supplementary Material). The time separation for individual doublet ranges from ~ 1 (SSI03) to ~ 7 yr (SSI11). Note that the depth values of 10 and 33 km are the default depth assigned by the PDE catalogue. The locations of these doublets are shown as red dots along the subduction zone in Fig. 2, indicating that repeating earthquakes may occur at a number of independent patches. Each of these doublets shows highly similar P waveforms at station SNAA. Their waveform comparisons are shown in Figs A1(a–d) (see Appendix S1). Among these doublets, SSI01 is unusual in terms of both waveform and magnitude difference of the two events, in that they have a relatively simple impulsive vertical P waveform for which the first arrival has the strongest signal that reduces greatly in a few seconds, whereas the signals of the other 10 doublets are of significant amplitude for tens of seconds and are more complicated. Besides, SSI01 has m_b difference of 0.5, which is the largest among all these doublets. Note that doublet SSI04 and the doublet 93&01 presented in Zhang *et al.* (2005) share event 2001 January 29. These two doublets constitute a triplet.

2.2 Aleutian Islands (AI) region

We performed a search for waveform doublets in the AI region among 1622 $m_b \geq 4.5$ events within the area from 50°N to 60°N and from 170°E to 150°W and occurring from 1993 February to 2005 June (blue circles in Fig. 3). The waveform records were acquired for stations BOSA and LBTB (two stations near each other in southern Africa). The signal-to-noise of PKP waves from the selected events and recorded at these two stations are strong, even for events with m_b less than 5. After a bandpass of 1.0–2.0 Hz, we computed cross-correlation for each event pair in a 30 s time window (beginning 10 s before the predicted PKP). Event pairs with cross-correlation value above 0.9 were then picked and checked by eye.

We found six high-quality waveform doublets and two high-quality waveform triplets through this process. Thus, at least 18 (~ 1 per cent) of 1622 AI earthquakes between 1993 and 2005 are repeating earthquakes. The event origin times, locations and magnitudes are listed in Table A2 (see Appendix S1). These repeating events are shown as red dots in Fig. 3. The recurrence intervals of AI doublets range from days (first two events of AI02) to ~ 12 yr (the first and the third events of AI01). The waveform comparisons of each doublet/triplet are shown in Figs A2(a)–(c) (see Appendix S1). Each event pair has highly similar waveforms.

2.3 Kuril Islands (KI) region (including parts of Kamchatka and Japan)

In the KI region, we searched for waveform doublets among 2222 m_b 5–6 events, within the region from 30°N to 60°N and from 135°E to 170°E and between 1990 January and 2005 November. All the selected events are shown as blue circles in Fig. 4. We acquired waveform data recorded at station MAJO (in Japan), which has a high noise level. However, it is suitable in our study since it is close to the selected events and has clear P -wave signals. We then performed a bandpass of 0.8–2.0 Hz and cross-correlation in a 30 s time window for the nearby event pairs to obtain event pairs with cross-correlation values over 0.9. There are two points to note here. First, we performed waveform cross-correlation only for events located within 200 km from each other. Such a criterion

reduces computing time in the case of a large number of events, being examined over a broad area. Second, we chose a 30 s time window to begin 5 s *after* the first P arrival (according to IASP91). The reason for choosing such a window is that many events may generate an impulsive P wave at MAJO, namely the major strong signals occur within the first several seconds after the first arrival. In this case, many event pairs with high cross-correlation values (mostly contributed by the first few seconds of strong signals) turn out not to be waveform doublets when assessed overall for similarity over a long window. A time window beginning a few seconds later can avoid such problems.

Our search resulted in 24 high-quality waveform doublets and 3 high-quality waveform triplets. At least 57 (~ 3 per cent) of 2222 KI events between 1990 and 2005 are repeating earthquakes. We show the information on event origin time, location and magnitude in Table A3 (see Appendix S1). All the repeating events are shown as red dots in Fig. 4. The recurrence intervals of KI repeating earthquakes range from ~ 6 months (KI022) to ~ 13 yr (the first and the third events of KI02). The highly similar waveforms of each doublet/triplet are shown in Figs A3(a)–(d) (see Appendix S1).

2.4 Tonga–Fiji–Solomon Islands (TFSI) region

The TFSI region is the most active and complicated subduction zone on our planet. It is also the largest search area in our work. We searched an area from 0° to 50°S and from 140°E to 170°W , including 4681 m_b 5–6 events between 1991 January and 2005 January (blue circles in Fig. 5). Station CTAO in Australia is the best for our search since it has a long operation of high-quality signals and appropriate P distances to all the selected events. Similarly as for the KI region, we used a bandpass of 0.8–2.0 Hz and cross-correlation in a 30 s time window for the nearby event pairs. Again, we cut a time window that begins 5 s after the first P arrival.

By selecting event pairs with cross-correlation values over 0.9 and checking waveform similarity by eye, we obtained 28 high-quality waveform doublets and 4 high-quality waveform triplets and found that at least 68 (~ 1.5 per cent) of 4681 events in the TFSI region are repeating earthquakes. The information on event origin time, location and magnitude are listed in Table A4 (see Appendix S1). The repeating events are shown as red dots in Fig. 5. Most doublets have time separation of several years. Doublet TFSI04 has a recurrence interval of ~ 35 hr. The second and third events of triplet TFSI03 have recurrence interval of ~ 4 months. Among all these TFSI repeating earthquakes, only one pair, TFSI019, is a waveform doublet of deep events. The highly similar waveforms of each doublet/triplet are shown in Figs A4(a)–(d) (see Appendix S1).

2.5 Bucaramanga earthquake nest (B-nest)

The type of seismicity known as an earthquake nest is another candidate for finding doublets since they also have very high seismicity and earthquake density. We studied one of the most active examples, namely the Bucaramanga earthquake nest in Colombia. The nest is situated at a depth of about 160 km beneath Colombia at 6.8°N and 73°W , and produces about eight $m_b \geq 4.7$ earthquakes each year from a source region only about 10 km across (Frohlich *et al.* 1995).

To search for repeating earthquakes, we selected 379 $m_b \geq 4$ events between 1994 January and 2005 July and within an area

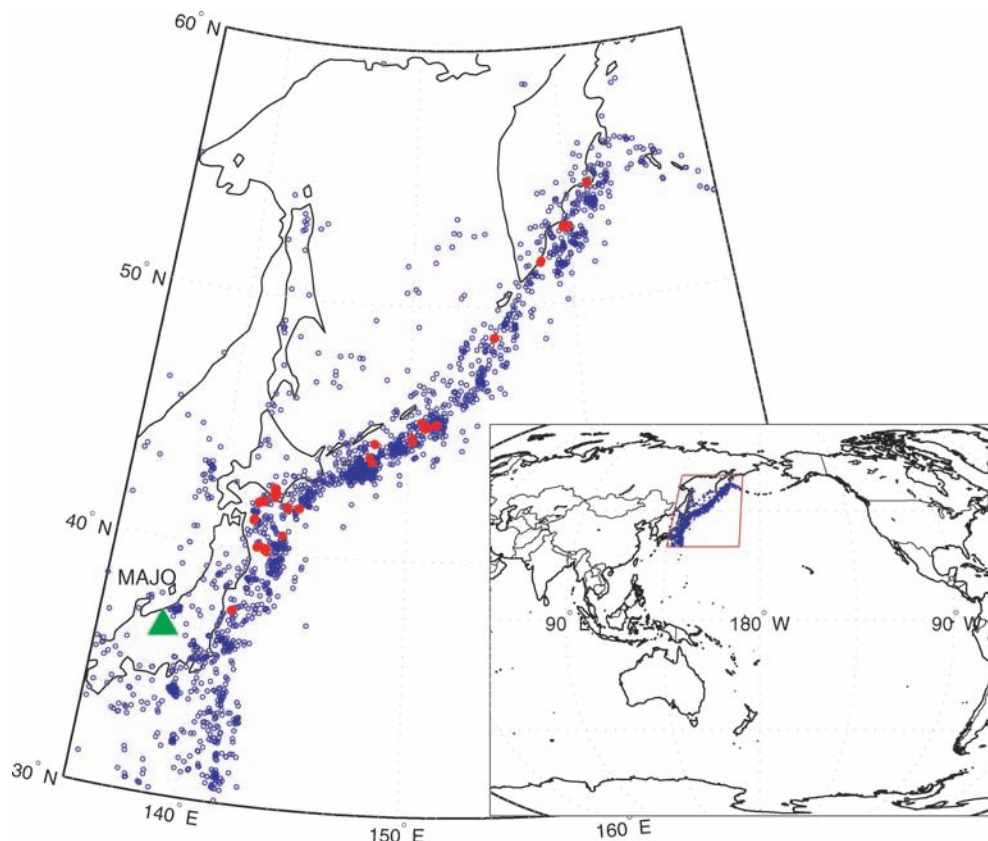


Figure 4. Map view of the Kuril Islands (including parts of Kamchatka and Japan) earthquakes and high-quality repeating earthquakes. Blue circles represent all the selected events. Red dots represent high-quality repeating events found in this study. Triangle represents station MAJO from which the waveform data are used for finding repeating earthquakes. The insert shows the global location of the studied region (brown box).

from 6.5°N to 7.2°N and from 73.4°W to 72.7°W (blue circles in Fig. 6). We chose station CHTO in Thailand since it has a long operation and clear *PKP* records, suitable for an inner core study. We used a bandpass of 0.9–2.5 Hz as the filter this time. And once again, we calculated cross-correlation in a 30 s time window including *PKP* arrivals and took a value of 0.9 as the similarity criterion.

In this way, we found 19 repeating earthquakes (red dots in Fig. 6), which amounted to ~ 5 per cent of total 379 B-nest events between 1994 and 2005. It turned out that all these 19 earthquakes combine to be an earthquake multiplet. The information of event origin time, location and magnitude are listed in Table A5 (see Appendix S1). The waveforms of all 19 events are shown in Fig. A5 (see Appendix S1).

3 DETECTION OF INNER-CORE DIFFERENTIAL MOTION

Our documentation of high-quality earthquake waveform doublets in different regions allows us to look for evidence of inner core motion on paths different from those of previous studies, which emphasized events in the SSI region and recorded at stations in Alaska.

Among the new SSI doublets that we have found in this work, doublet SSI09 recorded at station INK in Canada provided a new observation, showing an apparent change of inner core traveltimes over a period of 6 yr. Fig. 7 shows the ray path from SSI09 to INK

and a misalignment of *PKP(DF)* phases of the two events: 1998 April 12 m_b 4.7 and 2004 March 23 m_b 4.9. After 6 yr, the wave travelling through the inner core from the latter event arrived at INK ~ 0.1 s faster than that of the earlier colocated event. This new direct observation reconfirmed the conclusion of Zhang *et al.* (2005) that there is a temporal change of inner core properties, occurring along the inner core region sampled by SSI–Alaska/INK ray paths (the path to INK in Canada being slightly different from paths to Alaska).

As an example of a traveltimes change associated with a very different path through the inner core, one important observation came from an AI doublet—the first and second events of AI02: 1993 April 21 m_b 4.9 and 2000 August 08 m_b 4.6. The records of the two events at station BOSA in South Africa show both an apparent change of inner core traveltimes and a change of *PKP(DF)* coda. Fig. 8 shows the map view of the ray path and a misalignment of *PKP(DF)* phases and coda for the two events. It can be seen that the later signal arrived at BOSA ~ 0.1 s faster than the one ~ 7 yr earlier. Note that the ray path travels through the inner core beneath Central Asia. This new observation provides strong evidence of inner-core differential motion inferred from the part of the inner core sampled by AI–BOSA ray paths.

Another new ray path on which we observed an apparent temporal change of inner core traveltimes is that from a KI doublet (KI10: 1996 January 22 m_b 5.3 and 2001 November 18 m_b 5.4) to station BDFB in Brazil. The ray path and the waveform records are shown in Fig. 9. On the same ray path, seismic waves of the later event travelled through the inner core ~ 0.1 s faster than that of the event

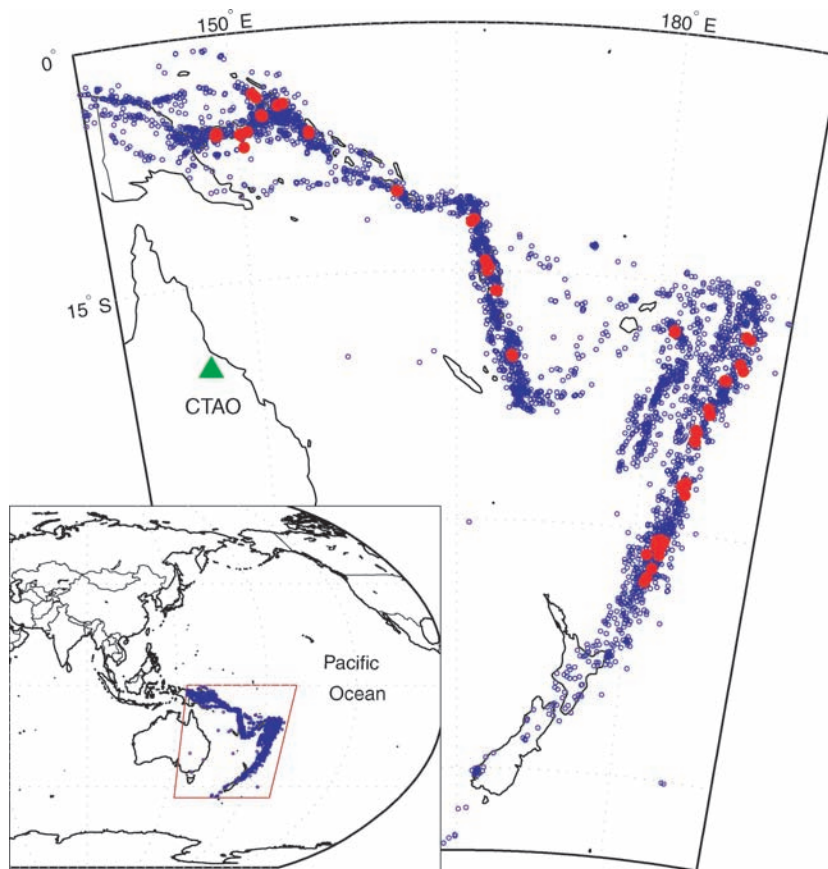


Figure 5. Map view of the Tonga–Fiji–Solomon Islands earthquakes and high-quality repeating earthquakes. Blue circles represent all the selected events. Red dots represent high-quality repeating events found in this study. Triangle represents station CTAO from which the waveform data are used for finding repeating earthquakes. The insert shows the global location of the studied region (brown box).

~ 6 yr earlier, indicating a temporal change of inner core properties along the KI–BDFB ray path beneath Canada.

There are three other important observations provided by two waveform doublets recorded at three stations. They are: a 4-yr TFSI doublet (1997 July 10 m_b 5.1 and 2001 June 30 m_b 5.0) recorded at station PTGA in Brazil (Fig. 10a) and a 10-yr B-nest doublet (1994 December 10 m_b 5.0 and 2005 July 09 m_b 4.7) recorded at station WRAB (in Australia) and station CHTO (in Thailand), respectively (Fig. 11a). A common feature of these three observations is that there are no differential inner core traveltimes, amounting to more than 0.05 s—the sampling interval of the data, which is a reasonable upper bound to define a possible absence of inner-core traveltime change (Figs 10b, 11b and c). However, it may be noted that relative phase arrival times can be obtained with subsample precision, for highly similar waveforms (Poupinet *et al.* 1984). Thus, such small differential inner core traveltimes for these three ray paths (about 0.01 s in 4 yr, 0.02 s in 10 yr and 0.05 s in 10 yr), though not apparent, might still be the real amount of inner-core traveltime changes and place an upper limit of about 0.005 yr^{-1} on any change. Another common feature is that most part of each of these three ray paths within the inner core is nearly parallel to the equatorial plane, sampling the inner core beneath the South Pacific and Iceland Sea.

To summarize, (1) the observation of a new SSI doublet recorded at INK confirmed inner-core differential motion from data for a path beneath Central America; (2) one new observation of an AI dou-

blet recorded at BOSA provided evidence of inner-core differential motion from data for a path beneath Central Asia; (3) another new observation of a KI doublet recorded at BDFB provided evidence of inner-core differential motion from data for a path beneath Canada and (4) no/little temporal change of inner core traveltimes is observed for three other ray paths where most of the path is nearly parallel to the equatorial plane. By using the high-quality waveform doublets we found, we now observe a pattern of temporal changes of inner core traveltimes for six different ray paths.

4 DISCUSSIONS

4.1 Repeating earthquakes

In our work, the documentation of repeating earthquakes is based on the similarity of waveforms in a specified frequency band of short-period signals. It may be noted that there are many more event pairs with waveforms that are highly similar in a lower passband but that are dissimilar in a higher passband. Thus, our decision of whether or not a pair of events is a high-quality doublet must be interpreted in terms of the bandwidth we used. In practice, we chose event pairs with highly similar waveforms (with cross-correlation value above 0.9) not only in lower frequency passband (e.g. 0.5–1 Hz), but also in higher frequency passband (e.g. 1–3 Hz), as *high-quality* waveform doublets. In addition, we calculated cross-correlation values for fairly long time windows (30 s). Only if waveforms are similar for

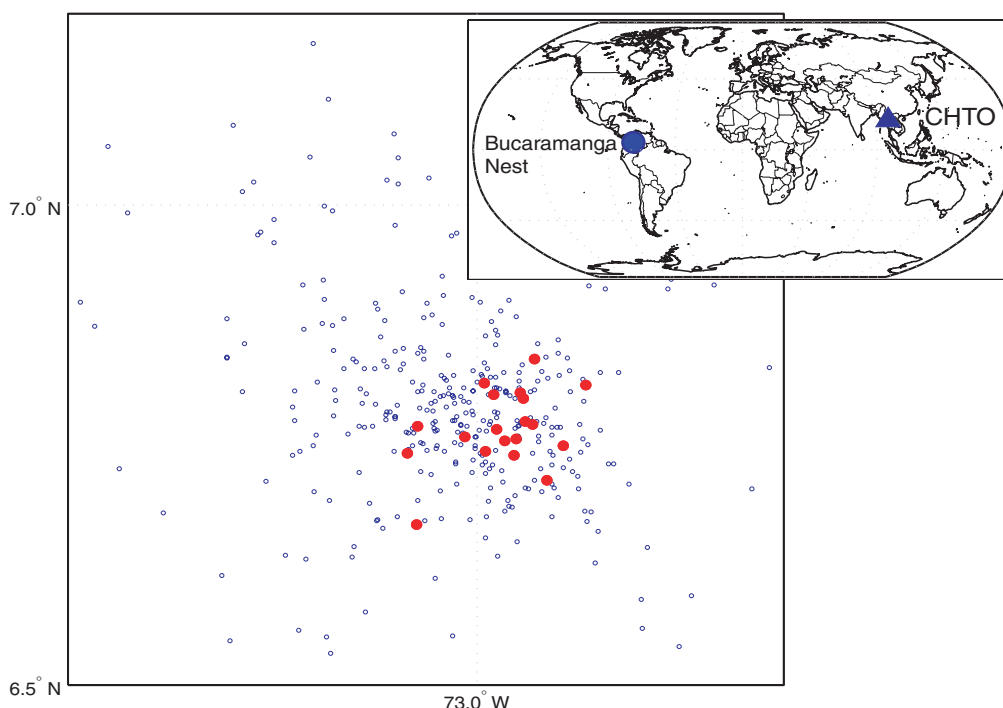


Figure 6. Map view of the Bucaramanga earthquakes and a multiplet of 19 repeating earthquakes. Blue circles represent all the selected events. Red dots represent a multiplet of 19 repeating events found in this study. The insert shows the global location of the studied region (blue dot). Triangle represents station CHTO from which the waveform data are used for finding repeating earthquakes.

significant bands of frequency and time, we can claim the events are within about a quarter wavelength (as discussed further by Schaff & Richards 2004a,b). We are interested only in high-quality repeating earthquakes in this work, basically because our major objective is to detect inner core motion using earthquake doublets occurring at essentially the same spatial point. However, we note that many other event pairs of slightly lower quality could still represent repeating ruptures of at least part of the same slip region and could be studied in terms of earthquake physics and be used for better estimates of relative location.

Another important feature of the moderate-size repeating earthquakes we found is that the recurrence intervals of repeating event pairs range from hours (SSI03, TFSId04, for example) to years (triplets AIt02 and TFSIt03, for example). Observations of short repeat times of doublets have been reported by other studies. For example, Wiens & Snider (2001) makes the same observation for Tonga–Fiji and suggests a thermal mechanism for the deep events. Short repeat times have also been observed elsewhere in the crust. In Schaff & Richards (2004a; Table 1), 23 per cent of the 950 doublets discovered in China occurred within a day or less of each other. The simplest explanation for these is that the second one is basically an aftershock caused by triggering of some mechanism such as static and/or dynamic stress transfer or pore fluid effects. Another possibility is that the two doublet events simply occurred on two separated subfaults, although these two fault planes must be close by to each other. A point to note is that our documentation is restricted to those repeats with recurrence period less than two decades, due to the limitation of the availability of digital data. The recurrence period of moderate-size earthquakes may range up to and/or peak at a few decades, which we are not able to examine yet. Continued accumulation of repeating earthquakes is necessary.

Any new earthquake may be a repeat of an old one. Thus, we expect that more doublets will be found as long as earthquake archives keep growing, and that possibly the percentage of all moderate-size events that are doublets will increase significantly for archives that cover several decades.

4.2 Inner core super-rotation

The strongest evidence for temporal change of inner core travel-times comes from observations of high-quality earthquake doublets (Zhang *et al.* 2005). Our results in this work not only re-confirm the temporal change of inner core traveltimes for the ray path from SSI region to Alaska region but also provide new observations for several other ray paths. Inner core super-rotation, predicted by geodynamo models, is still the simplest and perhaps the strongest candidate for interpreting both the presence and possible absence of the temporal change of inner core traveltimes.

The original explanation of a change in inner core traveltimes was given by Song & Richards (1996) as a change in orientation (due to super-rotation) of the fast axis of the inner core anisotropy. However, although this may be a contributing factor for some paths, it has been shown by Creager (1997) and Song (2000) that lateral velocity gradients in the inner core (i.e. lateral to the ray path) can be substantial. Such gradients are now the preferred feature of inner core, rather than a fast axis of anisotropy, that can serve as a marker; and that, as this marker moves, can explain the observed traveltimes changes. Then the geometry and relative directions of ray path, lateral velocity gradient and motion of inner core particles due to any inner core rotation will play an important role.

Assuming that inner core super-rotation is occurring about the same axis as that of the Earth's rotation, both the presence and

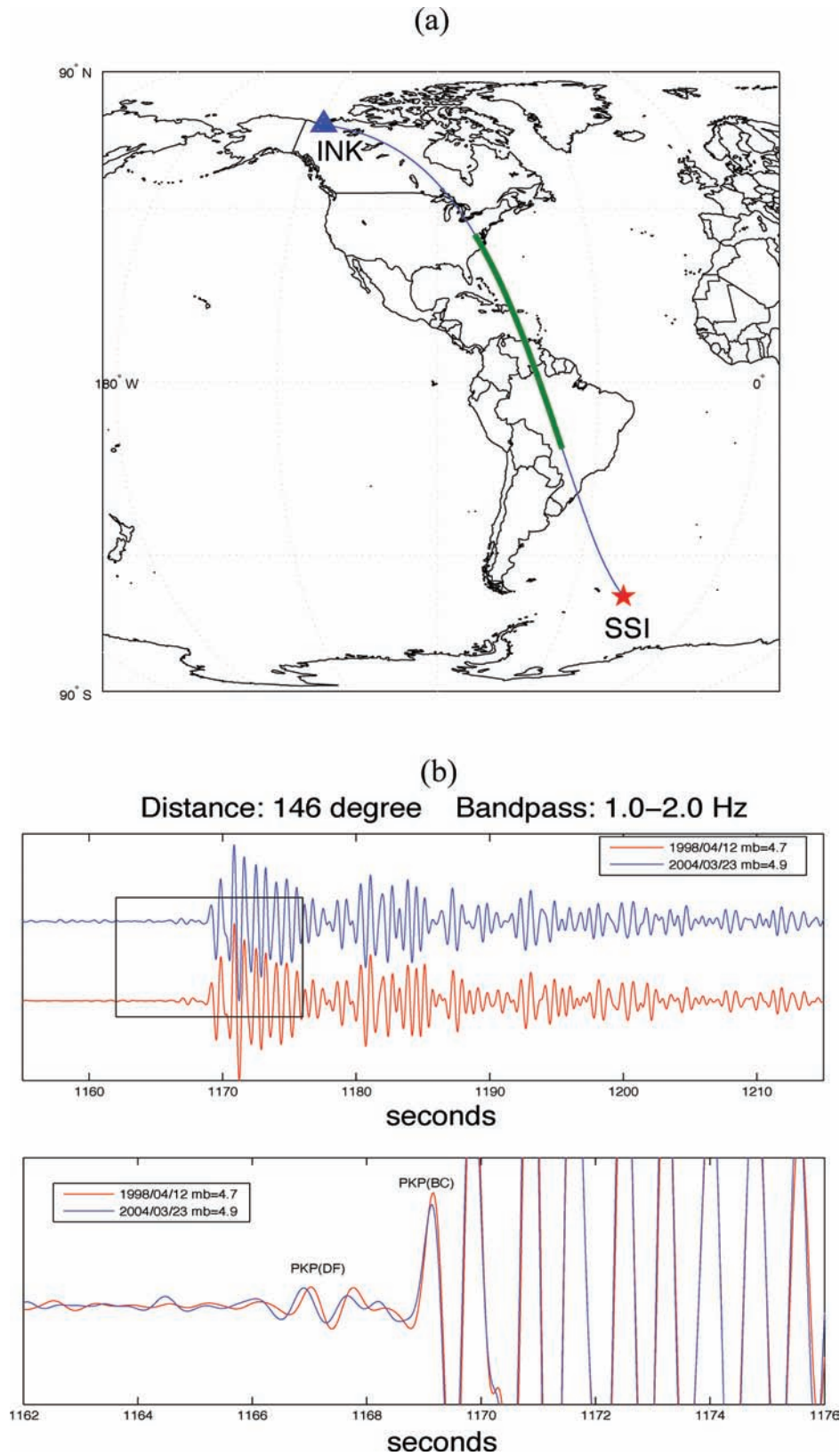


Figure 7. An apparent temporal change (~ 0.1 s) of inner core traveltimes observed from a SSI doublet (~ 6 yr apart in time) recorded at station INK. (a) Map view of the ray path projected on the Earth's surface. Star represents a SSI doublet. Triangle represents station INK. Blue curve represents the ray path projected on the Earth's surface. The green part of the curve represents the projected part of the ray path within the inner core. (b) Comparison of the highly similar waveforms of a SSI doublet recorded at INK. *PKP* signals within the box in the *upper* panel are superimposed and enlarged in the *lower* panel, showing an apparent change of inner core traveltimes.

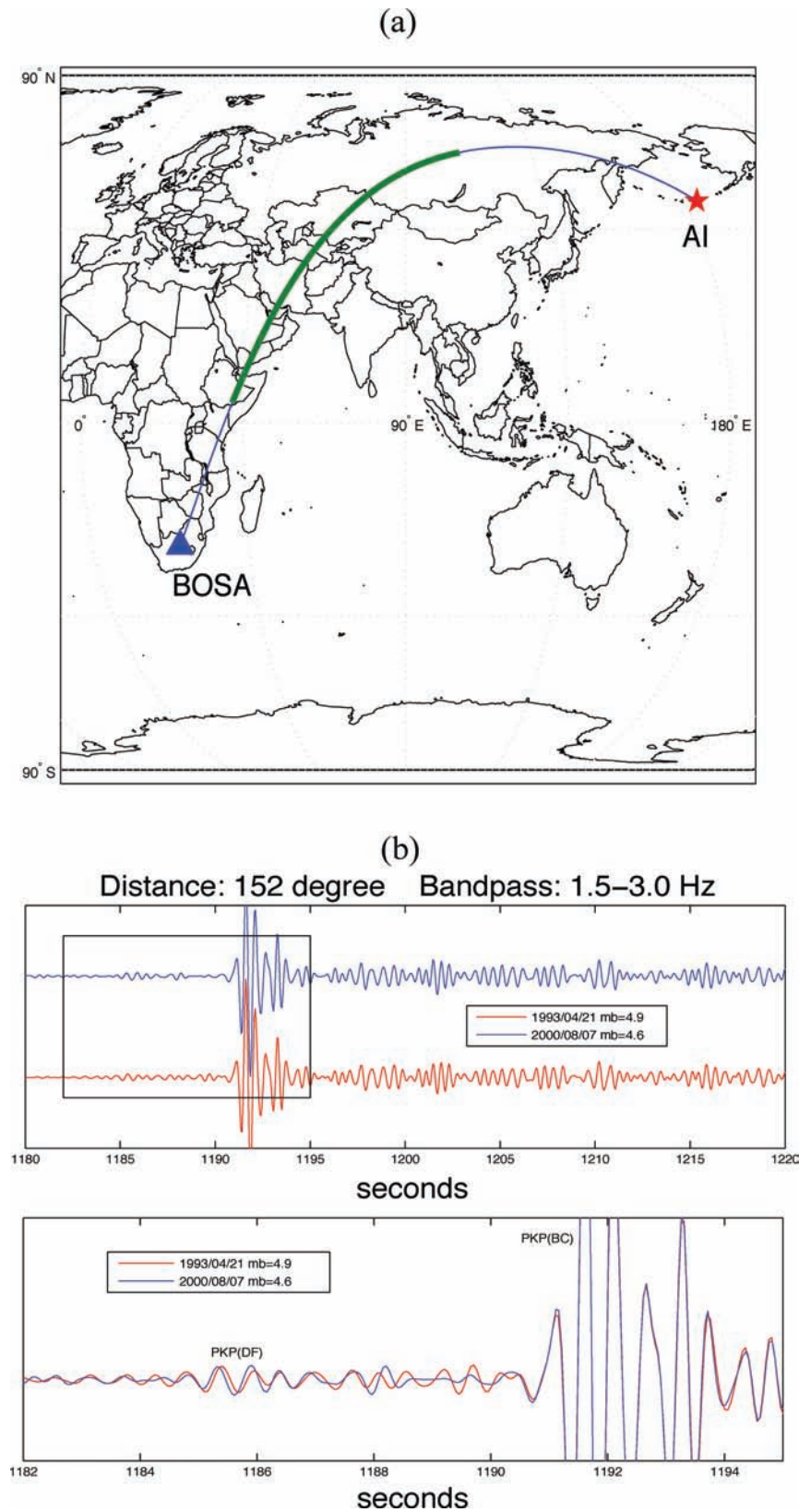


Figure 8. An apparent temporal change (~ 0.1 s) of inner core traveltimes observed from an AI doublet (~ 7 yr apart in time) recorded at station BOSA. (a) Map view of the ray path projected on the Earth's surface. Star represents an AI doublet. Triangle represents station BOSA. Blue curve represents the ray path projected on the Earth's surface. The green part of the curve represents the projected part of the ray path within the inner core. (b) Comparison of the highly similar waveforms of an AI doublet recorded at BOSA. *PKP* signals within the box in the upper panel are superimposed and enlarged in the lower panel, showing an apparent change of both inner core traveltimes and *PKP(DF)* coda.

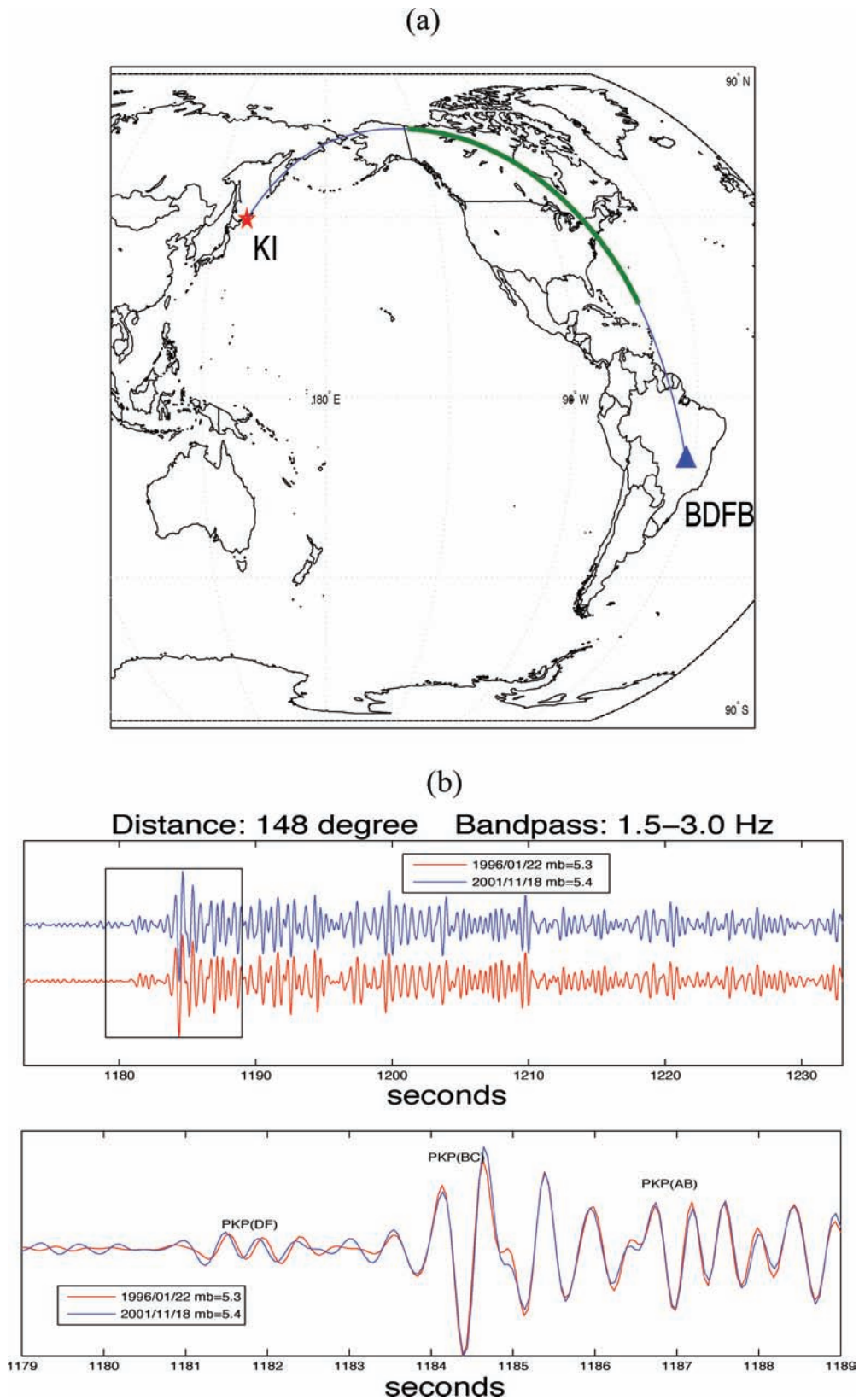


Figure 9. An apparent temporal change (~ 0.1 s) of inner core traveltimes observed from a KI doublet (~ 6 yr apart in time) recorded at station BDFB. (a) Map view of the ray path projected on the Earth's surface. Star represents a KI doublet. Triangle represents station BDFB. Blue curve represents the ray path projected on the Earth's surface. The green part of the curve represents the projected part of the ray path within the inner core. (b) Comparison of the highly similar waveforms of a KI doublet recorded at BDFB. *PKP* signals within the box in the *upper* panel are superimposed and enlarged in the *lower* panel, showing an apparent change of inner core traveltimes.

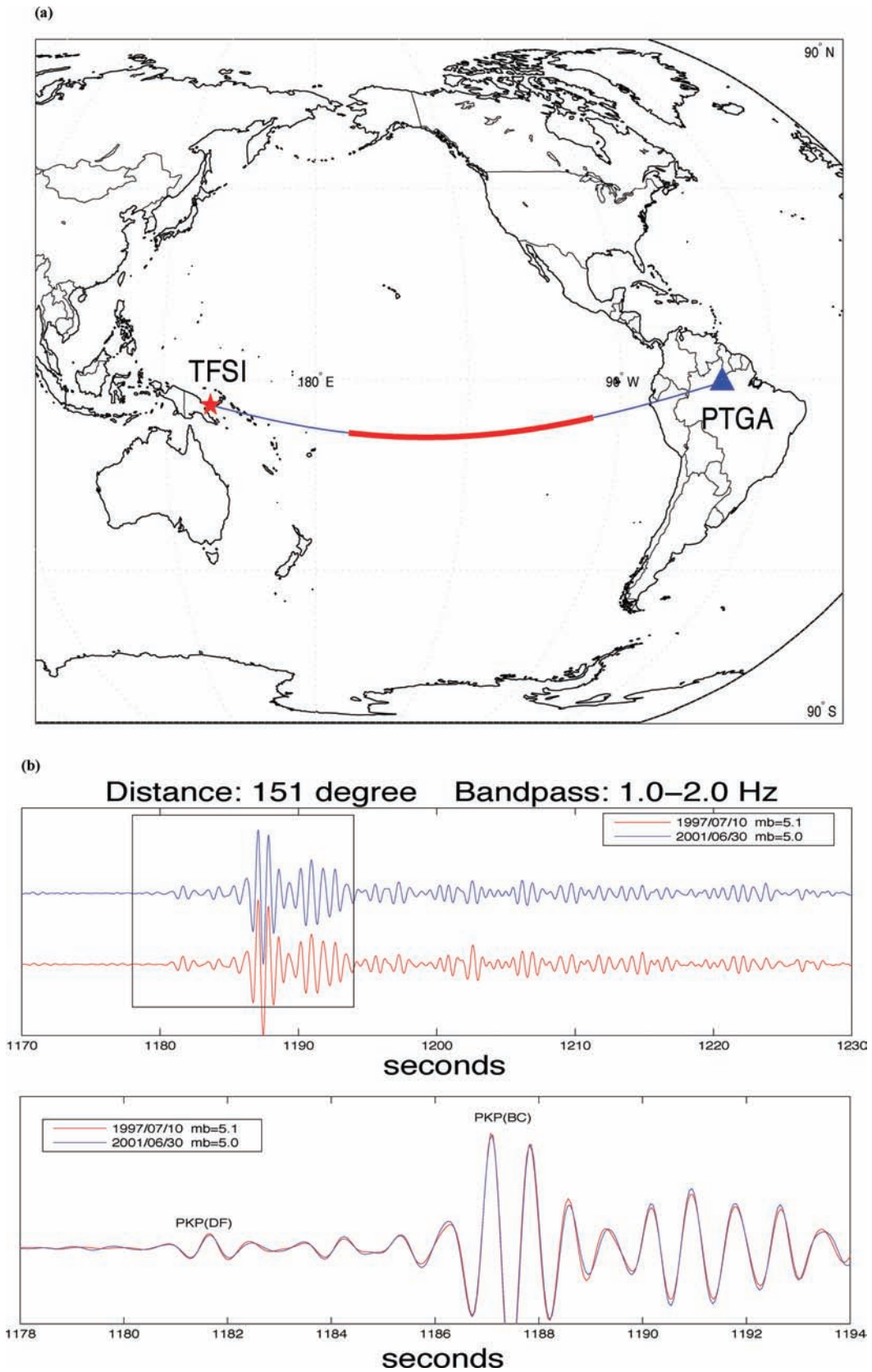


Figure 10. No temporal change of inner core traveltimes, amounting to more than 0.01 s, is observed from a TFSI doublet (~4 yr apart in time) recorded at station PTGA. (a) Map view of the ray path projected on the Earth's surface. Star represents a TFSI doublet. Triangle represents station PTGA. Blue curve represents the ray path projected on the Earth's surface. The red part of the curve represents the projected part of the ray path within the inner core. (b) Comparison of the highly similar waveforms of a TFSI doublet recorded at PTGA. PKP signals within the box in the upper panel are superimposed and enlarged in the lower panel, showing a possible absence of inner-core traveltime change.

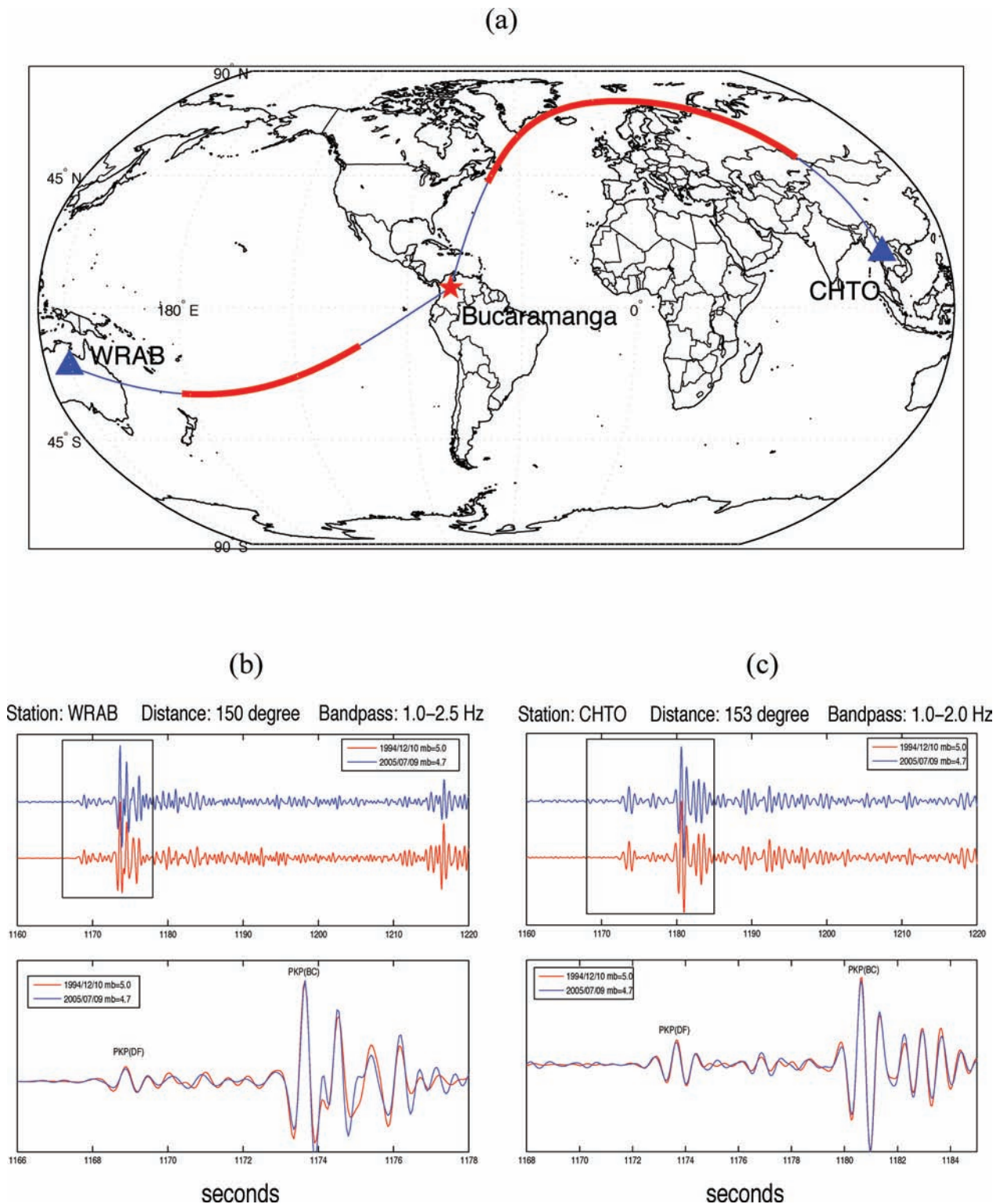


Figure 11. No temporal change of inner core traveltimes, amounting to more than 0.05 s, is observed from a Bucaramanga doublet (~10 yr apart in time) recorded at stations WRAB and CHTO. (a) Map view of the ray paths projected on the Earth's surface. Star represents a Bucaramanga doublet. Triangles represent station WRAB and station CHTO. Blue curves represent the ray paths projected on the Earth's surface. The red parts of the curves represent the projected part of the ray paths within the inner core. (b) Comparison of the highly similar waveforms of a Bucaramanga doublet recorded at WRAB. *PKP* signals within the box in the 'upper' panel are superimposed and enlarged in the 'lower' panel, showing a possible absence of inner-core travelttime change (or no more than 0.02 s if any). (c) Comparison of the highly similar waveforms of a Bucaramanga doublet recorded at CHTO. *PKP* signals within the box in the upper panel are superimposed and enlarged in the lower panel, showing only a possible absence of inner-core travelttime change (or no more than 0.05 s if any).

possible absence of the change of inner core traveltimes we observed can be explained. For a ray path oblique to the direction of particle motion associated with inner core rotation (Figs 7–9), the inner core structure along the ray path changes in time; hence, a temporal change of inner core traveltimes would be observed if the new material moved into the ray path has a different velocity (e.g. a lateral velocity gradient). On the other hand, for a ray path that for the most part in the inner core is more nearly parallel to the direction of particle motion due to inner core rotation (Figs 10 and 11), the inner core structure around the ray path changes little in time. Say, in 10 yr, a shift (nearly parallel to the ray path in this case) of the inner core structure along the ray path would be less than about 90 km, given a rotation rate of $\sim 0.5^\circ \text{yr}^{-1}$ (Zhang *et al.* 2005), whereas the length of the part of typical ray paths within the inner core is more than 1000 km. Note that this can explain possible absence of inner-core traveltime change even if there is a lateral velocity gradient. Such gradients can change the traveltime, if super-rotation occurs, only to the extent that the particle motion moves enough new material into the ray path and this does not occur for ray paths subparallel to the equatorial plane.

A change in *PKP(DF)* coda, which is presumably caused by scattering within a complex anisotropic heterogeneous structure, is an independent indicator of any temporal change of the inner core structure. Thus, there could be a slight change in *PKP(DF)* coda in the case that no/little temporal change of inner core traveltimes can be observed since the focusing and interference patterns for scattered waves would change. For example in Figs 11(b) and (c), although there is no apparent change in differential *PKP(DF)* traveltimes, we see a slight change in *PKP(DF)* coda, and this might reflect the effect of inhomogeneities moving to new positions along the ray path.

Assuming the temporal change of inner core traveltimes is the result of a shift of the lateral velocity gradient in the inner core due to the inner core super-rotation, imaging lateral changes of velocity within the inner core (Creager 1997; Song 2000) is necessary to determine the inner-core rotation rate. For the two ray paths AI-BOSA and KI-BDFB, we tried selecting events equidistant to the station, close in time, large enough to generate *PKP(DF)* signals and sampling a range of azimuths to examine any lateral variation within the inner core. Unfortunately our efforts failed simply due to the lack of events that can be used. Over time, as more doublets accumulate, we can expect that it will become possible to estimate the size and extent of such lateral heterogeneities.

Another feature of our observations is that all three ray paths (SSI–INK, AI–BOSA and KI–BDFB), showing a temporal change of inner core traveltimes, have the same sign, namely the seismic wave generated from the latter event of a doublet travelled through the inner core and arrived at the common station faster than that from the earlier event. However, this may be just a coincidence. The sign of a temporal change of inner core traveltimes does not have to be same, considering the presumed lateral velocity gradient could be locally variable. In fact, Li & Richards (2003b) have studied the signals from nuclear explosions at Novaya Zemlya, as recorded at three stations in Antarctica (NVL, DRV, SBA), indicating slightly slower paths as time increased.

Lastly, we suggest that an inner core super-rotation is the simplest type of inner-core differential motion that may cause the observed temporal changes of inner core traveltimes, although other examples such as temporal changes of inner core topography (Wen 2006; Cao *et al.* 2007) cannot be ruled out, with our observations. The pattern we have found, for the rate at which traveltimes change for six different paths through the inner core, is compatible with an

overall inner core rotation. In terms of temporal changes in inner core topography, it could only be explained by *ad hoc* changes in some locations and not others and raises questions about how the slowly cooling boundary between fluid and solid iron could suddenly move.

5 CONCLUSIONS

In this paper, we reported our search for high-quality moderate-size repeating earthquakes in several high-seismicity regions around the world. Thus, 11 additional doublets were found in the SSI region; 6 doublets and 2 triplets were found in the AI region; 24 doublets and 3 triplets were found in the KI region; 28 doublets and 4 triplets were found in the TFSI region and a multiplet of 19 earthquakes was found in the Bucaramanga earthquake nest in Colombia.

Among the above high-quality repeating earthquakes, some allow us to examine the differential motion of the inner core sampled by several ray paths. A SSI doublet SSI09, recorded at station INK in Canada, provided additional evidence for a temporal change of inner core properties occurring along the inner core region sampled by SSI–Alaska/INK ray paths. An AI doublet: 1993 April 21 m_b 4.9 and 2000 August 08 m_b 4.6, recorded at station BOSA in South Africa, shows that the inner core wave arrived at BOSA ~ 0.1 s faster than did ~ 7 yr earlier, providing additional evidence of inner core differential motion from data for a path beneath Central Asia. A KI doublet KI10 recorded at station BDFB in Brazil shows that the inner core wave arrived at BDFB ~ 0.1 s faster than did ~ 6 yr earlier, providing additional evidence of inner core differential motion from data for a path beneath Canada. We also found that a 4-yr TFSI doublet (1997 July 10 m_b 5.1 and 2001 June 30 m_b 5.0) recorded at station PTGA in Brazil and a 10-yr B-nest doublet (1994 December 10 m_b 5.0 and 2005 July 09 m_b 4.7) recorded at station WRAB in Australia and station CHTO in Thailand, places an upper limit of about 0.005 yr^{-1} on any change in inner core traveltimes that can be observed for the three ray paths where most of the path within the inner core is almost parallel to the equatorial plane.

Assuming that the inner core super-rotation occurs and shares the same axis as of the Earth's rotation, both the presence and possible absence of the change of inner core traveltimes that we observed can be explained by the geometry and relative directions of ray path, lateral velocity gradient and motion of inner core particles due to any inner core rotation.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of the article.

Appendix S1. This appendix contains 5 tables listing repeating earthquakes and 5 figures showing comparisons of waveform records (PDF format).

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