Geochemistry
Geophysics
Geosystems
G³
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society

Article
Volume 4, Number 9
9 September 2003
1072, doi:10.1029/2002GC000379
ISSN: 1525-2027

Using earthquake doublets to study inner core rotation and seismicity catalog precision

Anyi Li and Paul G. Richards

Lamont-Doherty Earth Observatory, and Department of Earth and Environmental Sciences, Columbia University, Palisades, NY 10964, USA (anyili@ldeo.columbia.edu; richards@ldeo.columbia.edu)

[1] We report our search for doublets in the South Sandwich Islands (SSI) region among 906 earthquakes from January 1982 to December 1998. Event pairs with source separation less than 40 km, which was calculated using PDE locations, were checked using vertical component short period and broadband digital records. Cross correlation coefficients of P (or PKP) waveforms were computed for similarity comparison. Whole waveforms of those event pairs with correlation coefficients larger than 0.8 were checked by eye. By this process, 17 doublets were found, some of which form multiplets. However, only one doublet event pair (14 August 1995 and 28 March 1987) has clear PKP(DF) phases on both records at College, Alaska (COL). The PKP(DF) travel time change measured by cross correlation is a decrease by 0.15 s, with standard deviation 0.02 s, over a time period of about 8 years. This result strongly supports differential rotation of the Earth's inner core relative to the mantle and the crust. The estimated rotation rate ranges from 0.4° to 1° per year eastward. The special case of a locked inner core can then be ruled out. We also checked the precision of PDE and ISC locations using the 17 doublets. Results show that both catalogs have relatively high location precision. Standard deviations in latitude, longitude and depth are less than 4 km, 6 km, and 10 km respectively, supporting prior claims of detection of inner core rotation [*Song and Richards*, 1996].

Components: 9159 words, 7 figures, 3 tables.

Keywords: Doublet; inner core rotation; inner core phase; PKP(DF).

Index Terms: 8115 Tectonophysics: Core processes (1507); 1734 History of Geophysics: Seismology; 7207 Seismology: Core and mantle.

Received 13 May 2002; **Revised** 26 April 2003; **Accepted** 23 June 2003; **Published** 9 September 2003.

Li, A., and P. G. Richards, Using earthquake doublets to study inner core rotation and seismicity catalog precision, *Geochem. Geophys. Geosyst.*, *4*(9), 1072, doi:10.1029/2002GC000379, 2003.

1. Introduction

[2] Since the discovery of the Earth's solid inner core [*Lehmann*, 1936], scientists have endeavored to explore its relationship to the outer parts of the Earth and to the generation and evolution of the geomagnetic field. The inner core is believed to be formed by solidification of liquid iron from the outer core into hexagonal close-packed (hcp) crystals [*Takahashi and Bassett*, 1964; *Stixrude and Cohen*, 1995]. Because of cooling, its radius continues to grow (about 1220 km at present). The inner core is positioned at the center of the liquid outer core, which is mostly iron and has a radius about 3480 km. The growth process entails iron solidification at the inner core boundary (ICB) and fractionation of light elements into the outer core. This process releases latent heat and gravitational

potential and continuously supplies energy by thermal and compositional buoyancy for geodynamo motion within the liquid outer core to generate and sustain the geomagnetic field [*Jacobs*, 1953; *Buffett*, 2000a]. Because the inner core, almost purely iron, has high electrical conductivity [*Hollerbach and Jones*, 1993a], it must be part of the electro-magnetic geodynamo system and play roles within it. The inner core works to stabilize the magnetic field and to reduce the frequency of polarity reversal [*Hollerbach and Jones*, 1993b, 1995; *Glatzmaier and Roberts*, 1995a].

[3] Because the outer core has low viscosity [*Gans*, 1972; *Poirier*, 1988; *de Wijs et al.*, 1998], the inner core may rotate freely within it, so the inner core is mechanically decoupled from the daily rotation of the mantle and the crust. However, the presence of mass anomalies in the mantle causes aspherical gravitational perturbations that distort surfaces of constant potential throughout the Earth, including the inner core boundary. Gravitational coupling between the surface topography of the inner core and the mass anomalies in the mantle supplies a mechanism to resist the inner core differential rotation relative to the mantle [*Buffett*, 1997]. If the inner core rotates, it may adjust its shape to accommodate to the static equilibrium by viscous deformation because of its finite viscosity (about 10^{17} Pa·s) [*Buffett*, 1997; *Creager*, 1997] or by other mechanisms [*Buffett*, 2000b]. Therefore inner core rotation may not be a rigid body movement.

[4] A decoupled inner core with its own rotation rate has long been suggested in studies of the geomagnetic field [*Steenbeck and Helmis*, 1975]. *Gubbins* [1981] showed that a toroidal magnetic field could produce torque on the inner core that was of sufficient size to change the rotation rate quite quickly. His analysis addressed the possibility that the angular velocity of inner core rotation is about 0.2° per year westward relative to the mantle, which is similar to the westward drift of the observed geomagnetic field. *Glatzmaier and Roberts* [1995a, 1995b] developed the first three-dimensional self-sustaining numerical simulation of the geodynamo, which generated a magnetic field similar to the real field of the Earth. In their simulation, the inner core rotates faster than the mantle by several degrees per year [*Glatzmaier and Roberts*, 1996] due to magnetic and viscous coupling with fluid flows at the inner core boundary and the rotation rate changes on a timescale of about 500 years. In *Kuang and Bloxham*'s [1997] numerical dynamo model with viscous stress free boundary conditions, the inner core rotates alternately eastward and westward relative to the mantle with a period of oscillation of several thousand years. But when a viscous no-slip boundary condition is imposed, only eastward rotation is observed in the simulation. *Buffett and Glatzmaier* [2000] incorporated into their numerical simulation the effect of gravitational coupling between the topography of the inner core boundary and the density anomalies in the mantle, and allowed the inner core to have finite viscosity. They predicted an oscillatory inner core differential rotation, with short intervals of westward rotation, and a mean rate of 0.02° per year eastward.

[5] On the seismological side, our knowledge of inner core structure has improved greatly over the last 20 years. To explain anomalies first reported by *Masters and Gilbert* [1981] and *Poupinet et al.* [1983], *Morelli et al.* [1986] and *Woodhouse et al.* [1986] proposed that the inner core is cylindrically anisotropic with symmetry axis parallel to the Earth's rotation axis. Several subsequent studies assumed the anisotropy is homogeneous and suggested that the fast axis of inner core anisotropy is tilted a few degrees from the Earth's spin axis [*Creager*, 1992; *Su and Dziewonski*, 1995; *McSweeney et al.*, 1997]. However, later studies showed that the inner core anisotropy is inhomogeneous, changing not only radially but also laterally. Thus *Tanaka and Hamaguchi* [1997] reported a degree one heterogeneity pattern for inner core anisotropy in the uppermost 500 km. Further studies by *Creager* [1999] based on nearly 2000 PKP differential travel times between the inner core phase PKP(DF) and outer core phases PKP(BC) and PKP(AB) indicated that the inner core anisotropy is weak in the uppermost 400–700 km of a quasi-eastern hemisphere (40°–160°E) but strong throughout all other parts of the inner core.

[6] The phase PKP(DF), sometimes referred to as PKIKP, goes through the Earth's inner core. It

appears in seismic records at distances greater than about 114°. While PKP(BC) turns at the bottom of the outer core and appears in the distance range from about 146° to about 155°, phase PKP(AB) turns higher than PKP(BC) in the outer core and is visible in records from about 146° until about 177°. Ray paths of PKP(DF) and PKP(BC) are close to each other in the crust, the mantle, and most of the outer core. So PKP(BC) is a good reference against which to measure PKP(DF). The differential travel time BC−DF is insensitive to most of the uncertainties due to heterogeneous Earth structures above the core. At distances beyond 155° when PKP(BC) is not available, PKP(AB) is used instead to form the travel time difference AB−DF. We discuss this point further, below, in presenting the merits of doublet events for purposes of investigating inner core rotation.

[7] Motivated in part by geomagnetic studies and using a model of inner core anisotropy, *Song and Richards* [1996] were the first to present seismological evidence for inner core differential rotation relative to the mantle and the crust. Their main observation is a systematic BC−DF differential travel time increase, which they interpreted as a decrease of PKP(DF) travel time inside the inner core, of about 0.3 s over a period of 28 years for the ray path from earthquakes in the South Sandwich Islands (SSI) region to station College, Alaska (COL) at Fairbanks. Assuming that the Earth's inner core is cylindrically anisotropic with a fast symmetry axis tilted about 10° from the Earth's spin axis, they explained the observed travel time change as being due to the change of angle between the direction of the fixed ray path and the direction of the fast axis (which moves with the inner core). They concluded that the inner core rotates eastward, about 1° per year faster than the mantle, around the same spin axis as that of the whole Earth.

[8] *Creager* [1997] analyzed 36 BC−DF differential travel time residuals recorded at station COL from SSI earthquakes and confirmed the systematic PKP differential travel time increase of about 0.3 s over about three decades. However, his analysis of 51 BC−DF times recorded at 37 stations of the Alaska Seismic Network (ASN), from three SSI events that occurred in 1991, revealed significant lateral heterogeneity in P wave velocity for the part of the inner core beneath Central America sampled by ray paths from SSI to Alaska. He showed the lateral gradient is positive in the westward direction, and thus provides an alternative explanation for the PKP differential time increase due to an eastward rotating inner core. His estimated rotation rate was smaller than that of *Song and Richards* [1996] to explain the same observed change in travel time, and his result is 0.2−0.3° per year eastward, with a lower limit of 0.05° per year. *Song* [2000] measured 611 BC−DF differential travel times from 92 earthquakes in the SSI region, which were relocated using the joint hypocenter determination (JHD) technique and recorded at COL and ASN stations. He extended the COL data to span over 45 years. The ASN data in his study spanned 22 years. A joint inversion technique was used to estimate time-independent mantle biases in the differential travel time data, and the lateral gradient of the inner core region traversed by ray paths from SSI to Alaska. He concluded that the rotation rate ranges from 0.3° to 1.1° per year eastward and that a westward rotation can be ruled out.

[9] Using ray paths other than SSI to Alaska, *Song and Li* [2000] analyzed 39 BC−DF differential travel times at station South Pole, Antarctica (SPA) from Alaska earthquakes distributed generally along a line of latitude, and observed a differential time increase of about 0.6 s over 37 years. Their inferred inner core rotation rate is about 0.6° per year eastward. *Vidale et al.* [2000b] used a large array to stack PKP(CD) (a phase reflected at the inner core boundary, alternatively called PKiKP) coda signals recorded in Montana from two very large nuclear explosions at Novaya Zemlya, USSR. They concluded that the coda was due to back scatter from fine-scale heterogeneity in the inner core (itself an important result [*Vidale and Earle*, 2000a]), and that change in the coda arrival times was due to the inner core rotating about 0.15° per year faster than the mantle. *Li and Richards* [2003] studied PKP differential travel time changes for ray paths from nuclear explosions at Novaya Zemlya, USSR to four Ant-

arctica stations, and supplied additional support for inner core differential rotation.

[10] However, not all studies agree that the inner core is in motion. *Souriau* [1998a] studied Dumont d'Urville, Antarctica (DRV) records from Novaya Zemlya nuclear explosions and found no obvious trend of BC−DF residuals over calendar time, thus suggesting no differential rotation of the Earth's inner core. Her results did not, however, rule out the possibility of eastward rotation of up to 1° per year. *Souriau* [1998b] used this study to question the evidence for inner core differential rotation claimed by *Song and Richards* [1996] and *Creager* [1997]. But as described by *Li and Richards* [2003], the Novaya Zemlya to DRV ray path goes through an inner core region with very weak anisotropy. The averaged P wave velocity perturbation along this path is only about 0.5%. Thus any BC−DF travel time change caused by inner core rotation would be small and hard to detect for this path.

[11] *Laske and Masters* [1999] applied a new method for analyzing free oscillation splitting functions that is insensitive to earthquake source, location and mechanism, and concluded that the mean value of inner core differential rotation rate lies between ±0.2° per year over the past 20 years. *Souriau and Poupinet* [2000] tested for inner core rotation on a worldwide scale using both absolute PKP(DF) residuals and BC−DF differential travel time residuals. Minimum standard deviations were obtained for the null rotation rate, although rates less than 1° per year cannot be ruled out.

[12] All these studies constrain the rate of inner core differential rotation to be small, for example, less than 1° per year. Stronger evidence is still needed to distinguish slow rotation from the special case of an inner core locked to the mantle.

[13] For those studies of inner core rotation based on free oscillation methods, all the inner core sensitive modes have most of their energy in the mantle, and so are prone to effects of mantle heterogeneities. For those inner core studies using PKP differential travel time data, although the ray paths of PKP(DF) and PKP(BC) are close to each other, they are still several hundred kilometers apart at the core mantle boundary. So BC−DF data could also be affected by small scale (hundreds of kilometers) heterogeneous deep mantle structures [*Breger et al.*, 1999]. AB−DF data could be affected even more because PKP(DF) and PKP(AB) rays are more than one thousand kilometers apart at the core mantle boundary [*Breger et al.*, 2000]. We also note that phases PKP(DF), PKP(BC) and PKP(AB) have different take-off angles, so that signals from events separated by tens of kilometers may be affected quite differently by local heterogeneities in source and receiver regions, potentially contaminating the differential BC−DF or AB−DF travel times. Event mislocation, especially for events in the 1960s and 1970s, may also contaminate the interpretation of travel time data.

[14] To avoid these problems, and to detect the small PKP(DF) travel time change, we have searched for doublets to study inner core rotation. A doublet is a pair of seismic events, which occurred at different times but essentially at the same spatial position. For study of inner core rotation, we want this origin time difference to be as large as possible. In this study the defining property of a doublet is that the waveforms of the two doublet events are highly similar for whole records and at all stations. To have high waveform similarity, the two doublet events must have similar source characteristics such as focal mechanism, rupture process, etc., not only the same hypocenter location. Ray paths from the two doublet events to any station are nearly identical, so signals have almost the same contamination from heterogeneities, which can be eliminated in forming the change in travel time. Even small-scale heterogeneities at the base of the mantle as described by *Breger et al.* [1999] can be ignored for true doublets.

[15] The high similarity of waveforms enables us to measure PKP(BC) (or PKP(DF)) time shift between the two doublet events by cross correlating the two PKP(BC) (or PKP(DF)) waveforms with high precision. The change of BC−DF differential travel time is simply the PKP(BC) time shift minus the PKP(DF) time shift: $(BC_1 - DF_1) - (BC_2 - DF_2) = (BC_1 - BC_2) - (DF_1 - DF_2)$. This

technique takes full advantage of properties of doublets and avoids the problem that PKP(DF) and PKP(BC) have somewhat different waveforms (because they travel on different paths, for example, having different attenuation), so that their cross correlation may not have a high value.

[16] In this paper, we report our search for doublets in the South Sandwich Islands region, which has been intensively studied to show PKP differential travel time changes at Alaska stations [*Song and Richards*, 1996; *Creager*, 1997; *Song*, 2000]. We found 17 doublets in total. However, only one doublet event pair has clear PKP(DF) phases in COL records. PKP(DF) is clearly faster for the later event, supplying solid new evidence supporting inner core differential rotation relative to the mantle. We have also analyzed the precision of seismic event locations from the Preliminary Determinations of Epicenters (PDE) catalog and from the Bulletin of the International Seismological Centre (ISC) using our 17 doublets.

2. Data Analysis and Results

2.1. Search for Doublets

[17] To increase the chance of finding doublets, we searched seismic regions with a high density of earthquakes. The South Sandwich Islands (SSI) region is a suitable candidate. Furthermore, stations in Alaska are at distances from the SSI region such that seismic waves from SSI to Alaska sample the inner core well. We know this path has a high lateral gradient of P wave velocity in the inner core [*Creager*, 1997; *Song*, 2000] so a small inner core rotation would produce a noticable change of P wave travel time through the inner core. Station COL has a long operating history, and digital records have been available since 1982.

[18] From the PDE catalog we selected 906 seismic events that occurred in the SSI region from January 1982 to December 1998, with body wave magnitude (m_b) values at least 4.5. As shown in Figure 1, there are several areas with high density of event occurrence. Note the two flat lines in depth distribution plots Figures 1b and 1c at 10 km and 33 km respectively. They are the default PDE depth values for shallow earthquakes with uncertain depth.

[19] From the Data Management Center (DMC) of the Incorporated Research Institutions for Seismology (IRIS), we requested vertical component, short period and broad-band waveform records for each SSI event at all possible stations in the IRIS archive. Arrival times of compressional seismic phases (P, PKP, etc.) were computed using the *iasp91* model [*Kennett and Engdahl*, 1991] and combined with every record to mark phases. A total of 64,419 records with P (or PKP) phases were selected for further analysis.

[20] We next combined the 906 earthquakes into pairs. Our criterion was that the event source separation, or the straight line distance in three dimensions between the two event sources (hypocenters), be less than 40 km by using their PDE locations. The 16,126 event pairs were formed in this way.

[21] For each event pair, we then compared the waveform similarity of seismic records at all stations shared by these two events. We looked only at those records with clear P (or PKP) phases: the signal-to-noise ratio was required to be greater than 3. If the two records belonging to one event pair recorded at the same station had different instrument responses, we made them the same by changing the newer response to the older one and changing the broadband type to the short period type. If the two records had different sampling intervals, we changed the record with smaller sampling interval to have the larger interval (e.g., change from 0.025 s to 0.05 s). The typical sampling interval was 0.05 s. The records were then bandpassed through a third order Butterworth filter with corner frequencies at 0.6 Hz and 3.0 Hz. Cross correlation was used to compare the waveform similarity of the event pair. The time window was set from 3 seconds before the *iasp91* predicted P phase arrival until 11 seconds after it. Since PKP(DF) is generally weak in seismic records, PKP(BC) was used to search for doublets if it appeared in the records. If there was no PKP(BC), we used PKP(AB) instead. If both PKP(BC) and PKP(AB) phases appeared in the records, the time window was set as 3 seconds before PKP(BC), to

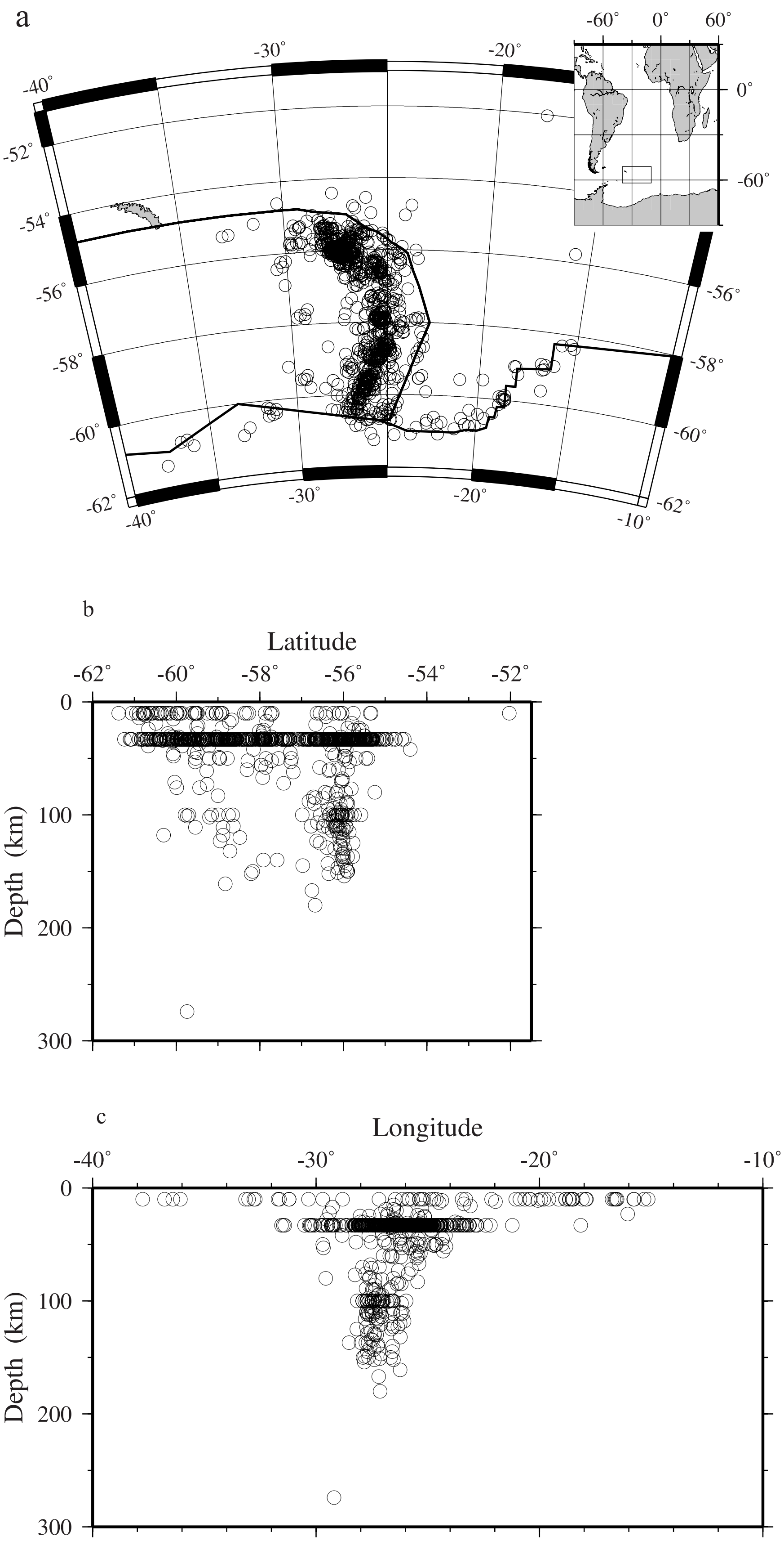
a
-40°
-30°
-20°
-10°
-52°
-54°
-56°
-58°
-60°
-62°
-60°
0°
60°
b
Latitude
-62°
-60°
-58°
-56°
-54°
-52°
Depth (km)
0
100
200
300
c
Longitude
-40°
-30°
-20°
-10°
Depth (km)
0
100
200
300

Table 1. Information on 17 Doublet Event Pairs[a]

No.	Date, Year m d	Time, h m s	Latitude °	Longitude °	Depth, km	m_b	Sou.Sep., km	No.Sta.
1	1986 11 18	12 02 27.8	−57.933	−25.392	67	5.6	37.3	1
	1994 01 12	10 10 25.8	−57.940	−25.655	33	5.2		
2	1985 09 08	20 35 35.4	−56.343	−26.589	61	5.2	28.5	1
	1995 10 24	09 25 33.0	−56.297	−26.558	33	4.7		
3	1985 08 29	06 25 38.8	−57.273	−25.427	45	5.2	12.2	1
	1995 12 27	15 21 20.2	−57.274	−25.395	33	5.2		
4	1997 10 22	08 31 40.4	−57.950	−25.501	33	4.8	11.8	1
	1982 08 17	13 33 45.5	−57.928	−25.305	33	5.2		
5	1997 04 04	02 35 44.8	−57.893	−25.599	33	4.8	6.5	4
	1994 03 04	13 33 04.6	−57.880	−25.492	33	5.2		
6	1997 01 27	10 32 13.3	−55.981	−26.605	33	4.9	18.0	2
	1993 10 15	19 38 21.4	−56.091	−26.819	33	4.6		
7	1995 08 14	08 21 43.9	−57.874	−25.397	33	5.2	5.0	3
	1987 03 28	05 04 10.8	−57.919	−25.386	33	5.5		
8	1994 12 09	19 24 09.0	−55.845	−27.038	33	5.3	35.4	1
	1989 07 17	15 09 27.9	−55.695	−26.535	33	5.1		
9	1994 03 04	13 33 04.6	−57.880	−25.492	33	5.2	11.0	1
	1987 02 14	06 55 43.0	−57.952	−25.363	33	5.1		
10	1994 03 04	13 33 04.6	−57.880	−25.492	33	5.2	8.2	1
	1989 06 23	16 37 56.8	−57.925	−25.382	33	5.3		
11	1993 10 15	19 38 21.4	−56.091	−26.819	33	4.6	25.1	1
	1985 03 14	04 03 30.3	−55.977	−26.467	33	5.6		
12	1993 05 03	03 17 40.6	−56.183	−25.553	33	5.2	7.2	1
	1991 01 19	14 47 17.8	−56.211	−25.659	33	5.4		
13	1991 01 05	04 09 49.8	−58.039	−25.296	33	5.3	12.3	1
	1982 08 17	13 33 45.5	−57.928	−25.305	33	5.2		
14	1989 06 23	16 37 56.8	−57.925	−25.382	33	5.3	5.3	1
	1982 04 27	11 04 37.7	−57.899	−25.307	33	4.9		
15	1989 06 23	16 37 56.8	−57.925	−25.382	33	5.3	3.2	2
	1987 02 14	06 55 43.0	−57.952	−25.363	33	5.1		
16	1987 11 10	13 31 34.5	−57.939	−25.418	33	4.9	6.7	1
	1982 08 17	13 33 45.5	−57.928	−25.305	33	5.2		
17	1987 02 14	06 55 43.0	−57.952	−25.363	33	5.1	6.7	1
	1982 04 27	11 04 37.7	−57.899	−25.307	33	4.9		

[a] Event origin time, location and magnitude are from the PDE catalog. Sou.Sep. means the source separation (straight line distance) between the two doublet events according to PDE locations. No.Sta. means number of stations used to identify this event pair as a doublet.

9 seconds after PKP(AB). The purpose of this time window setting was to use the strongest compressional phase in the records and to cover its whole waveform or at least most of the waveform, in order to get better comparison of waveform similarity. Cross correlation coefficients were then computed for the two data segments at each station of the event pair as quantitative expressions of waveform similarity for the two events. For those event pairs with at least one coefficient greater than 0.8, we plotted all the records in a larger time window of several minutes and checked the waveform similarity by eye, and only then made the concluding decision as to whether an event pair was a doublet.

2.2. Doublet Results

[22] By this process, 17 event pairs were identified as doublets from the more than 16 thousand candidates. Table 1 lists the PDE parameters, event source separation, and number of stations used for

Figure 1. (opposite) Spatial distribution of South Sandwich Islands earthquakes from January 1982 to December 1998 based on PDE locations. (a) Mapview, (b) latitude-depth distribution, (c) longitude-depth distribution. Circles show event locations. Mapview (Figure 1a) represents the box in the inserted map. In Figure 1a, thick lines are plate boundaries, and the island is South Georgia. The two horizontal lines in depth distribution Figures 1b and 1c are at 10 km and 33 km, respectively. They are the default depth values assigned by the PDE catalog to shallow earthquakes with uncertain depth. Lengths along latitude and longitude are in the same scale, and the depth scale is enlarged 3 times.

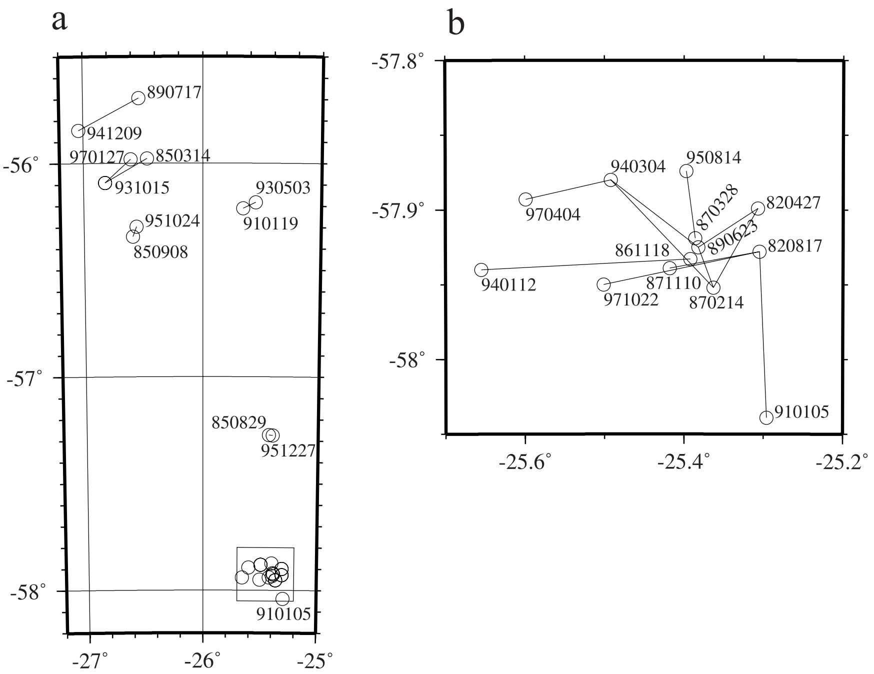

Figure 2. (a) Mapview distribution of 17 doublets using PDE locations. Each circle represents an event, with its id code marked nearby. Event id is composed from origin time year, month, and day. The two events of each doublet are connected by a line. (b) A blow-up view of the box at the lower right corner in Figure 2a. Events 850314, 931015, and 970127 may form a triplet. Events 820817, 871110, 910105, and 971022 may form a multiplet of four. Events 820427, 870214, 890623, 940304, and 970404 may form a multiplet of five.

these 17 doublets. Figure 2 shows their mapview distribution. Figure 3 exhibits some of their clear records. It is apparent that the waveform matches are very good.

[23] As seen in Table 1, Figures 2 and 3, events 820427, 870214, and 890623 are a triplet, having similar waveforms at station BCAO (doublet 14, 15 and 17). Events 870214, 890623, and 940304 are another triplet, all observed at station COL (doublet 9, 10, and 15). Note that the records of number 10 in Figure 3e are broadband. They are not similar to the records of number 9 in Figure 3d and the records of number 15.2 in Figure 3g, which are short period. Additionally, event 970404 is a doublet counterpart to event 940304 (doublet 5). So they may form a multiplet group of five events. Event 820817 is counterpart to three events: 871110, 910105, and 971022 (doublet 4, 13 and 16), so they appear to form a group of four events, but they have no station in common for all these events and so are not directly comparable to each other. Event 931015 forms doublets with two events 850314 and 970127 (doublet 6 and 11), which are not directly comparable either. They may constitute a triplet.

[24] Among these doublets and multiplets, unfortunately, only one pair has clear PKP(DF) phases at both COL records: the event of 14 August 1995 (950814) and the event of 28 March 1987 (870328), which is the doublet event pair number 7 in Table 1 and Figure 3d. The cross correlation coefficient of their COL PKP phases is very high, 0.962 in a time window of 22 seconds. These two seismograms, aligned on PKP(BC), also match remarkably well for a full 3 min following PKP(BC) (Figure 4). However, the two PKP(DF) phases have an obvious time shift. Enlarged waveforms in Figures 5a and 5b show this more clearly.

[25] This special doublet event pair has digital records at another station: Longmire, Washington (LON), at a distance of about 130.9°. However, the digital data file of the LON record of event 870328 has a defect (a sharp spike) in the PKP (DF and CD) phase vibrations, making the PKP waveform unlike that of event 950814. But the later-arriving

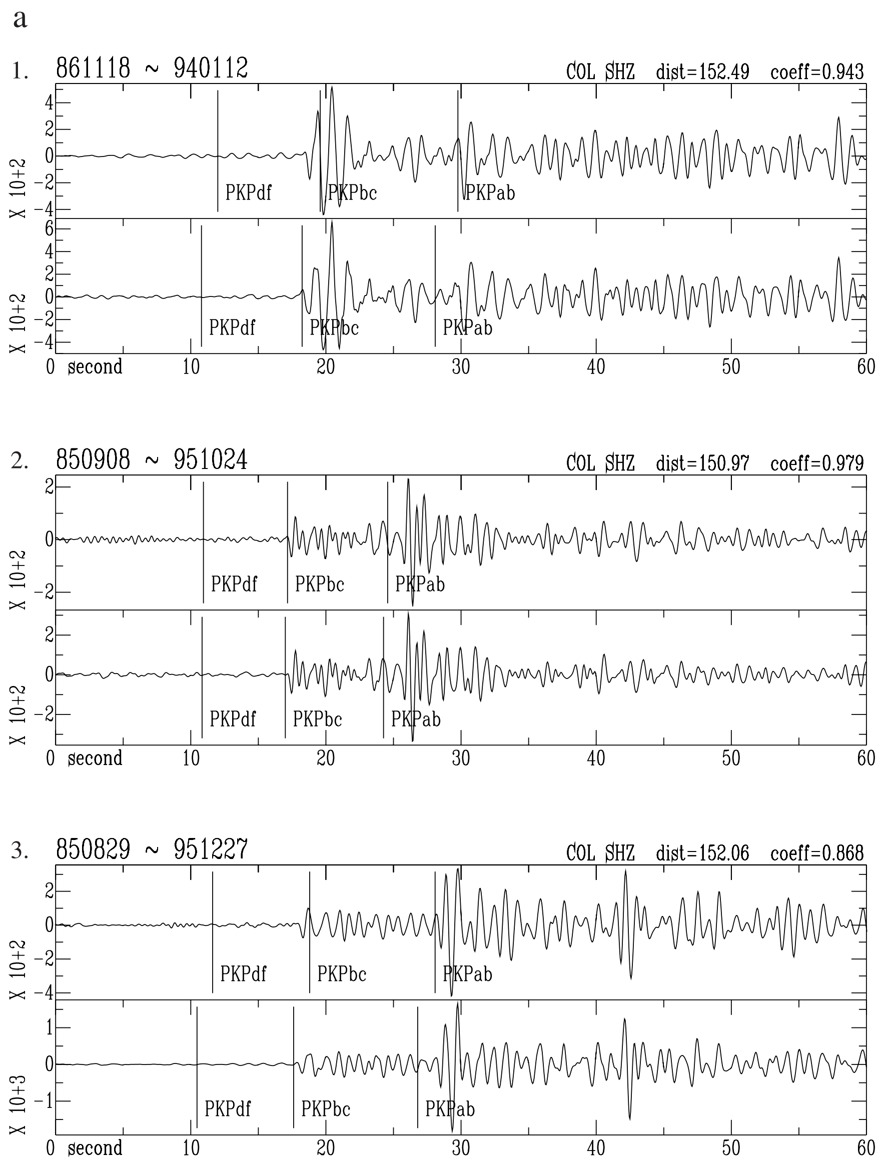

Figure 3. Seismic waveforms of 17 doublets. Each frame shows two records of 60 s duration at the same station from the two events of a doublet. Id codes of the two events in each doublet are shown in the upper left corner of the frame. Station name, component, distance and waveform cross correlation coefficient are shown in the upper right. Theoretical arrival times as shown are computed with the *iasp91* model. The two records in each frame have the same instrument response. All the records except 6.2 are bandpass filtered with a third order Butterworth filter having corner frequencies at 0.6 Hz and 3.0 Hz. The two records marked asterisks in frame 6.2 are filtered with corner frequencies at 0.8 Hz and 1.5 Hz. All the frames are numbered the same way as in Table 1.

SKP and PKS waveforms are similar to each other for these two events as shown in Figure 6a. Their cross correlation coefficient is 0.879 over a time window of 30 seconds. To have more confidence in this doublet event pair, we checked the film chip library at Lamont-Doherty Earth Observatory for event 870328. Film chips were not produced after 1991 when digital records became available. We found one more station, South Pole, Antarctica (SPA), shared by these two events. The distance is about 32.3°. We printed the 870328 SPA record on paper, scanned and digitized it. We then changed the SPA digital record of event 950814 to have the same instrument response as that of event 870328. The computed cross correlation coefficient is 0.878, showing high similarity of P

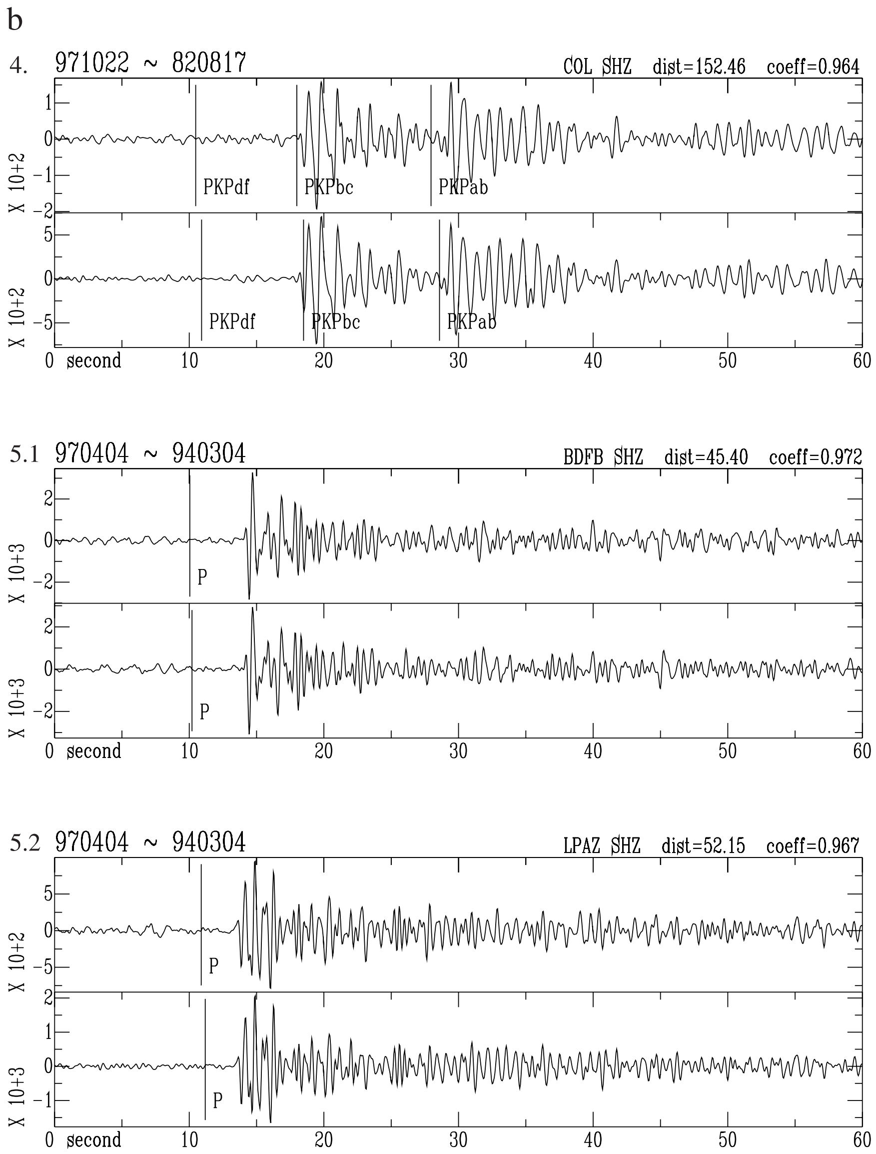

Figure 3. (continued)

phase waveforms, as shown in Figure 6b. However, the following P wave codas do not match well. The reason for the coda mismatch is that station SPA is at the South Pole in the Antarctica continent. Its seismometer sensors have an elevation of 2927 m. These sensors are set not on rock, but in glacial snow, which moves about 9 m per year. So the seismometers are leveled at least once a week to be kept functioning at the South Pole. Thus the site effect of SPA station is always changing, which decreases the waveform similarity, especially for coda waves. From our experience, it is rare to have similar initial P waveforms at SPA from SSI events, and the correlation coefficient 0.878 is a very high value at this station. On the basis of the high waveform similarity at station COL, LON and SPA, we are confident that events 950814 and 870328 form a doublet.

2.3. Measurement of Travel Time Change and Inner Core Rotation

[26] For the events 950814 and 870328 we picked out the PKP(DF), PKP(BC) and PKP(AB) phases in the COL records for this doublet, and used cross correlation to measure time shifts between the two PKP(DF) phases ($DF_{87} - DF_{95}$), the two PKP(BC)

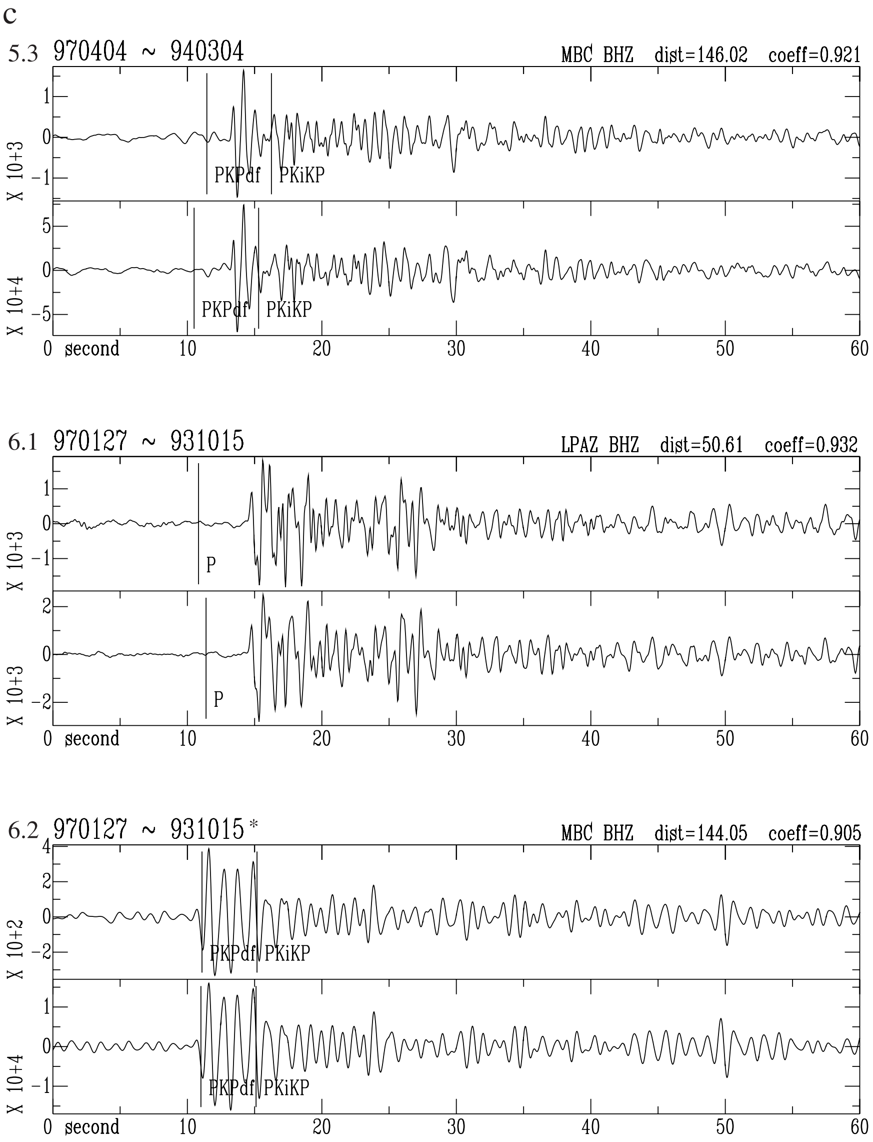

Figure 3. (continued)

phases ($BC_{87} - BC_{95}$), and the two PKP(AB) phases ($AB_{87} - AB_{95}$). In practice we did this by aligning the records on PKP(BC) and noting the necessary shift in time. A technique described by *Levin et al.* [1999] (equation (7)) was applied to estimate the variance of cross correlation time measurement. Both the PKP(BC) time shift and the PKP(AB) time shift are zeros with standard deviation less than 0.001 s. So ($AB_{87} - BC_{87}$) − ($AB_{95} - BC_{95}$) equals zero. But the measured PKP(DF) relative time shift is 0.15 s with standard deviation of 0.02 s. That is to say, ($BC_{87} - DF_{87}$) − ($BC_{95} - DF_{95}$) equals −0.15 s. We concluded that the PKP(DF) phase of event 950814 spent less time to reach COL than that of event 870328.

[27] To have higher confidence on the PKP(DF) time shift, we re-processed the original 950814 and 870328 COL records with narrower filter corner frequencies at 0.8 Hz and 1.5 Hz. As shown in Figure 5b, the waveforms are then cleaner. Again, the measured PKP(BC) and PKP(AB) time shifts are zeros with standard deviation less than 0.001 s. Measurements with two different time window settings for the PKP(DF) phase result in PKP(DF) time shifts of 0.14 s and 0.16 s, respectively, with

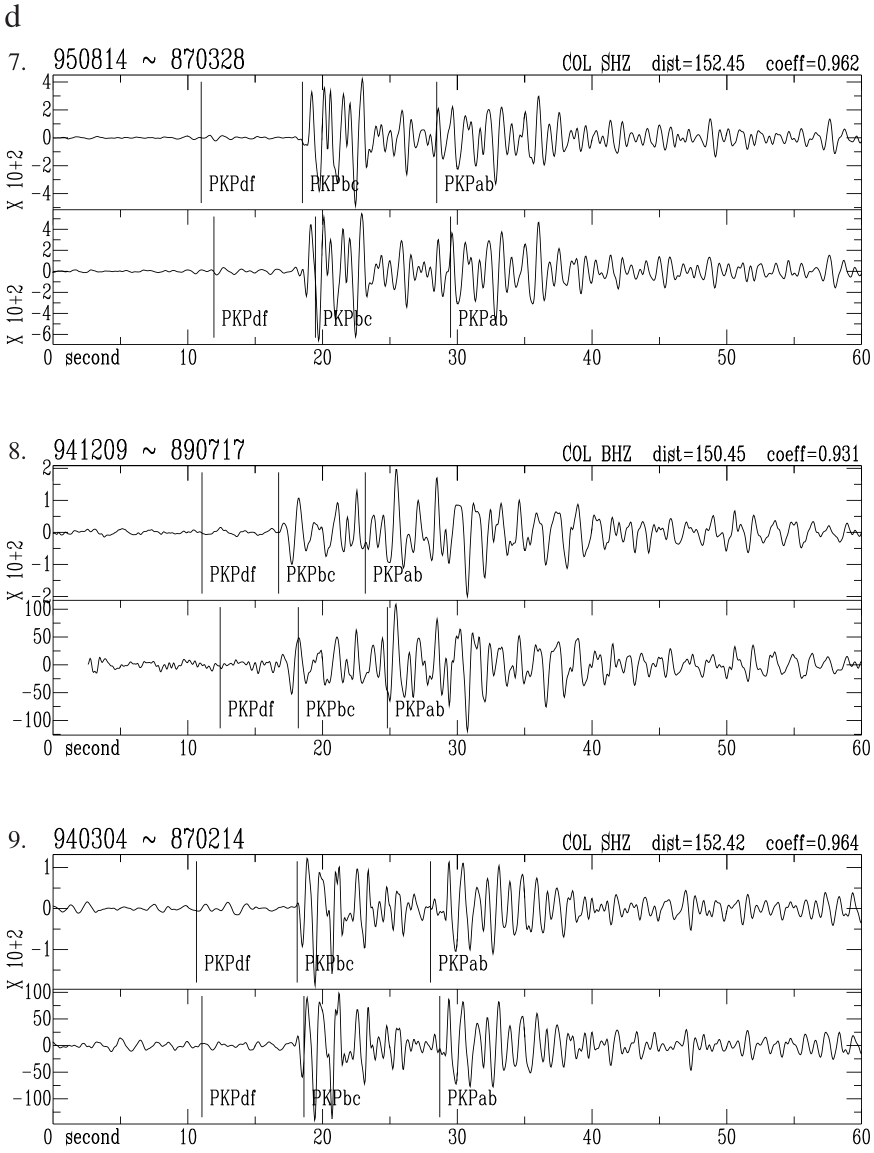

Figure 3. (continued)

standard deviation 0.02 s. We took 0.15 ± 0.02 s as the PKP(DF) time shift, since it is the average of the three measurements.

[28] This result is the strongest evidence, using whole waveforms, for PKP(DF) travel time change in the path from SSI to COL, because the ($BC_{87} - BC_{95}$) − ($DF_{87} - DF_{95}$) data have the highest quality with the least contamination from heterogeneous structures outside of the Earth's inner core. It is possible that this travel time change is due to some type of internal deformation of the inner core during the eight years between the two earthquakes of the doublet. The simplest example of such a deformation (with respect to the mantle) is a rigid rotation. From our measured value of 0.15 ± 0.02 s for the PKP(DF) travel time change we can estimate the rotation rate from knowledge of the lateral gradient of the P wave velocity in the inner core sampled by SSI to Alaska ray paths. *Creager* [1997] gave two lateral gradient values: −0.019 and −0.027%/° eastward for his two kinds of models. *Song*'s [2000] results using a larger data set are −0.0145, −0.0176 and −0.0278%/° eastward with station and source correction, station correction only, and no correction respectively. Our

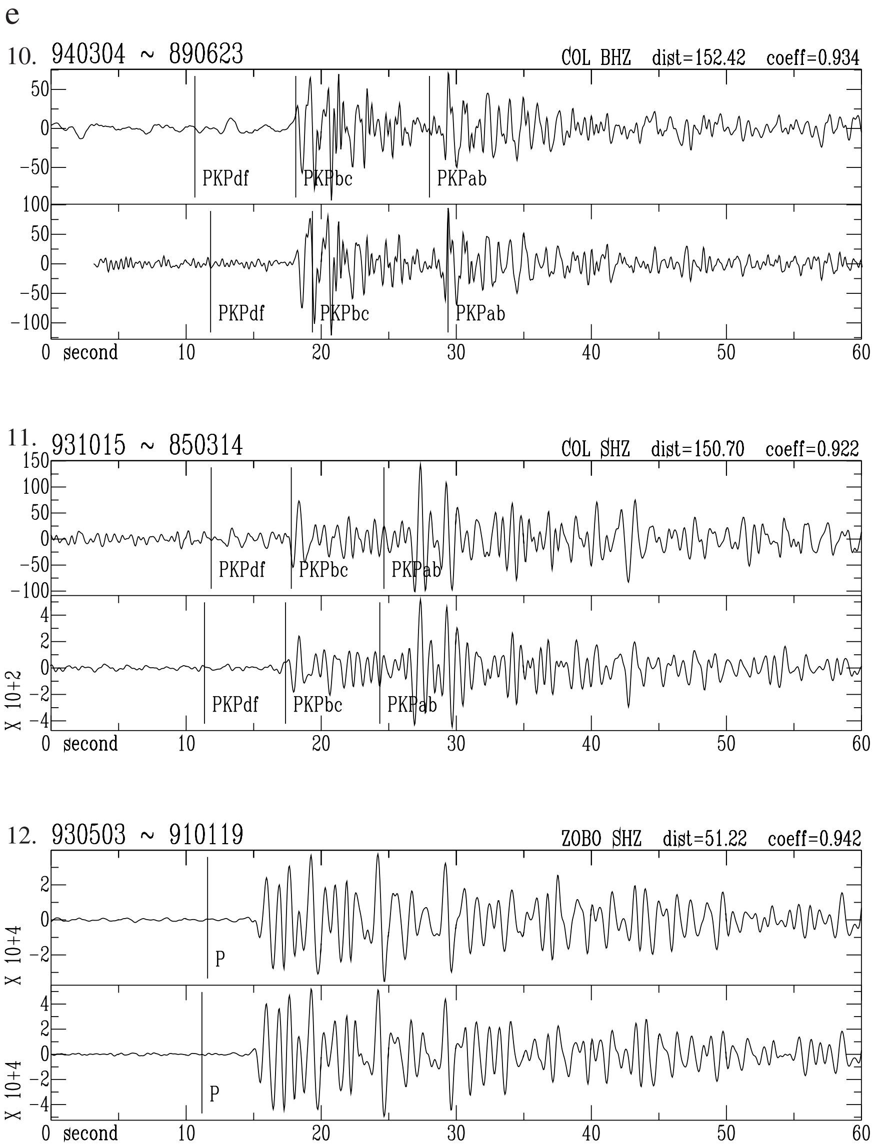

Figure 3. (continued)

derived rotation rate ranges from 0.41° to 0.66° per year eastward using *Creager*'s [1997] results and ranges from 0.48° to 1.05° per year eastward when using *Song*'s [2000] results. The best estimates are from 0.44° to 0.99° per year eastward as listed in Table 2. This is the main conclusion of our study. The more general case of internal deformation (rather than rigid rotation) can be explored, only to the extent that significantly more data and better earthquake locations become available.

2.4. Catalog Precision

[29] An important by-product of our study is that the whole set of 17 doublets can be used to analyze the precision of event locations supplied by PDE and ISC catalogs. Since the two events composing a doublet are at essentially the same location, their source separation computed using locations from a catalog is directly related to the random error of event locations of that catalog. If the random error of catalog event locations has a Gaussian distribution, which is appropriate in practice, and if the random location error of one event of a doublet is not correlated with the random location error of the other doublet event, then the variance of catalog event locations is half the variance of relative departures between the two events composing a doublet. Note that this estimate concerns only the

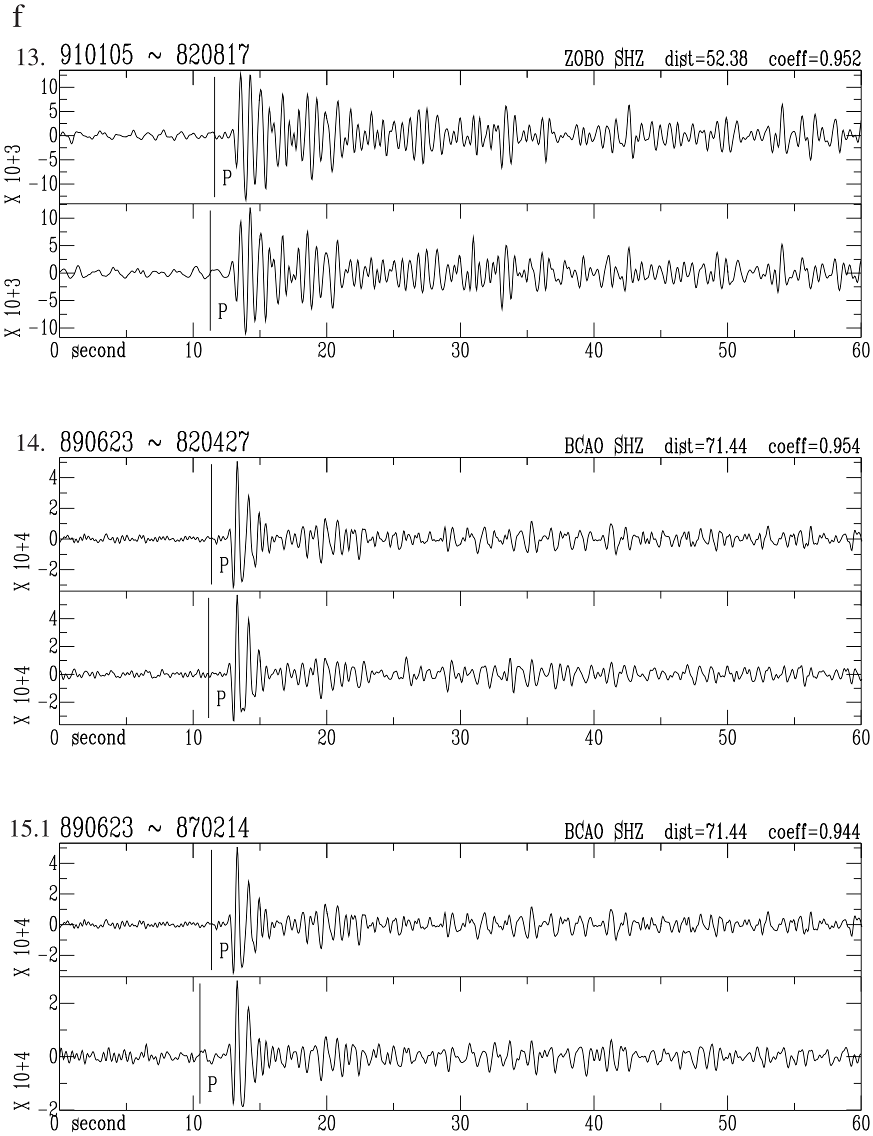

Figure 3. (continued)

precision of relative locations, and not the accuracy of absolute event locations, which may be effected by bias that applies to both events in a doublet. It is only the precision that concerns us, when we are assessing the quality of SSI event locations used for example by *Song and Richards* [1996], *Creager* [1997], and *Song* [2000] in the interpretation of changes in differential travel times such as BC−DF in terms of inner core rotation.

[30] We computed the variances of location differences between the two events of a doublet for latitude, longitude, and depth separately with PDE and ISC locations, and list the standard deviations of PDE and ISC event locations in Table 3. The depth deviation of PDE locations is not significant because the default depth value of 33 km was assigned to 31 of the 34 doublet events we found as shown in Table 1. This value is listed only as a reference.

3. Discussion

3.1. Doublets

[31] This is the first study to use doublets in the investigation of inner core rotation. We were successful in finding doublets in the SSI region using

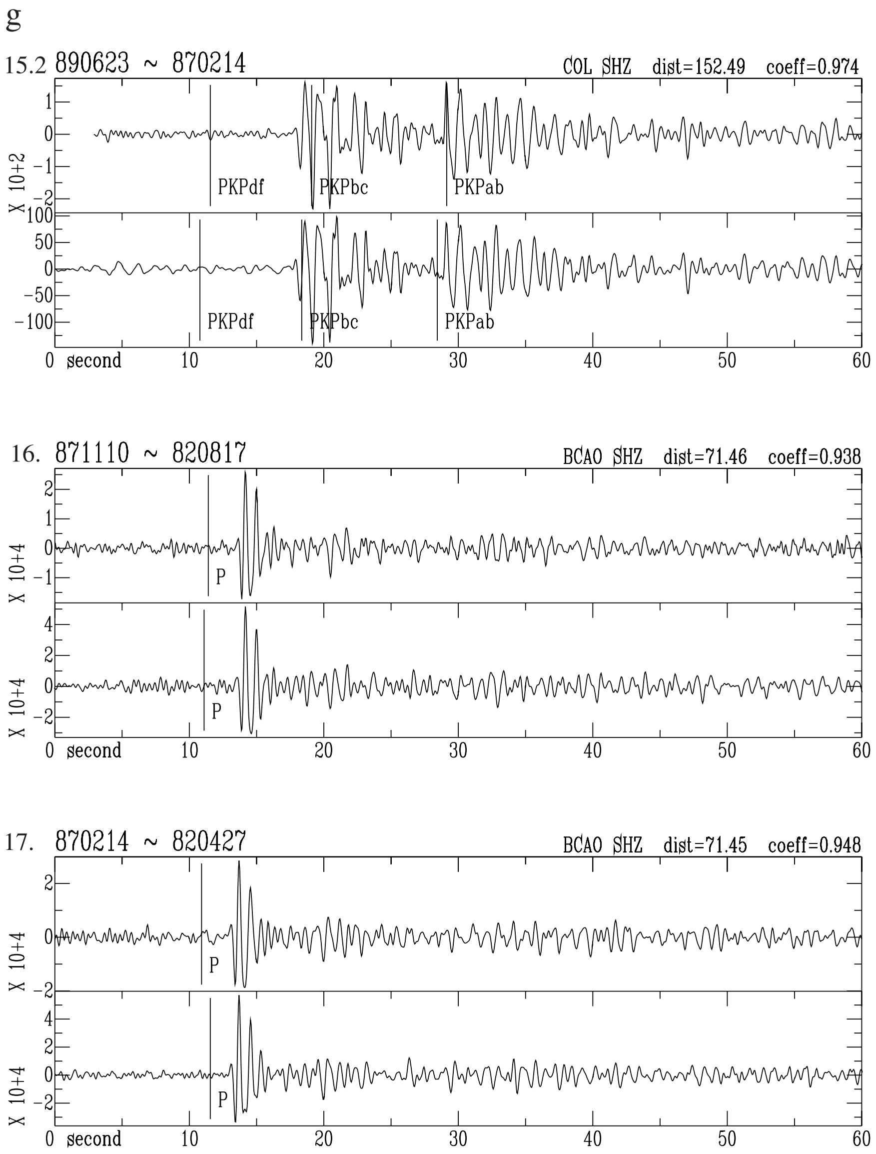

Figure 3. (continued)

teleseismic data. Note that in some other studies [e.g., *Lay and Kanamori*, 1980], a doublet is taken to be a pair of earthquakes which occurred quite close together in both space and time, but not necessarily close enough in space for the two events to have similar waveforms. To distinguish our approach, we call the doublets we have found ‘‘waveform doublets.’’

[32] The Tonga event pair called a doublet by *Souriau* [1998c] is not a waveform doublet, because their waveforms are not similar. The same holds for the event pairs in the study of *Poupinet et al.* [2000] as pointed out by *Song* [2001]. Thus the source separations between two events of the event pairs in *Poupinet et al.* [2000] are possibly large enough to affect the BC−DF and AB−DF times, affecting their results and conclusions on inner core rotation.

[33] By using the doublet approach based on waveform similarity, we do not need to know the absolute locations of seismic events. We only need to know that the two doublet events locate together. It has been suggested by many studies [*Geller and Mueller*, 1980; *Frankel*, 1982; *Ito*, 1985; *Fremont and Malone*, 1987; *Nadeau et al.*, 1995] that, to have high similarity of waveforms, the source

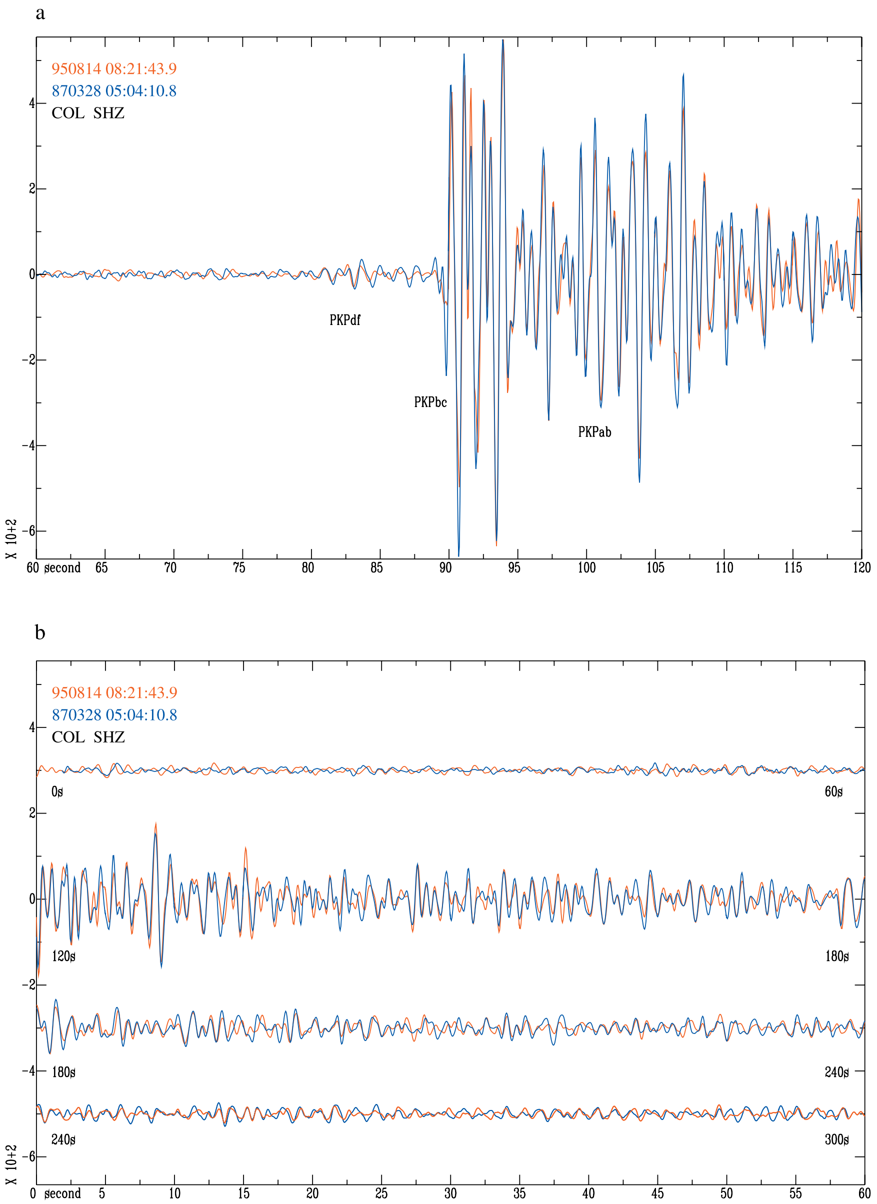

Figure 4. Comparison of seismic records of 5 minutes duration at station COL from event 950814 (red curve) and 870328 (blue curve). The two records are aligned on the PKP(BC) phase. (a) PKP(DF), PKP(BC) and PKP(AB) phases. (b) Preface and coda. The five record segments have the same X and Y scales. The red and blue records have the same instrument response, and are filtered by the same third order Butterworth filter with corner frequencies at 0.6 Hz and 3.0 Hz.

separation between the two events should be less than a quarter of the corresponding wavelength, especially when the waveforms were compared throughout a large time window. *Thorbjarnardottir and Pechmann* [1987] studied vertical component records of 14 mine blasts in Utah with known locations. Their waveform cross correlation results support the quarter wavelength hypothesis. *Nadeau et al.* [1995] showed that waveform similarity decreases exponentially with the event source separation, with the scale of a wavelength. *Menke* [1999] suggested that waveform similarity information (cross correlation coefficients of waveforms) can be used to invert for event locations. According to the quarter wavelength hypothesis, the maximum possible source separation between the two doublet events of the 17 doublets in this study is about 2 km. Since these doublets have very

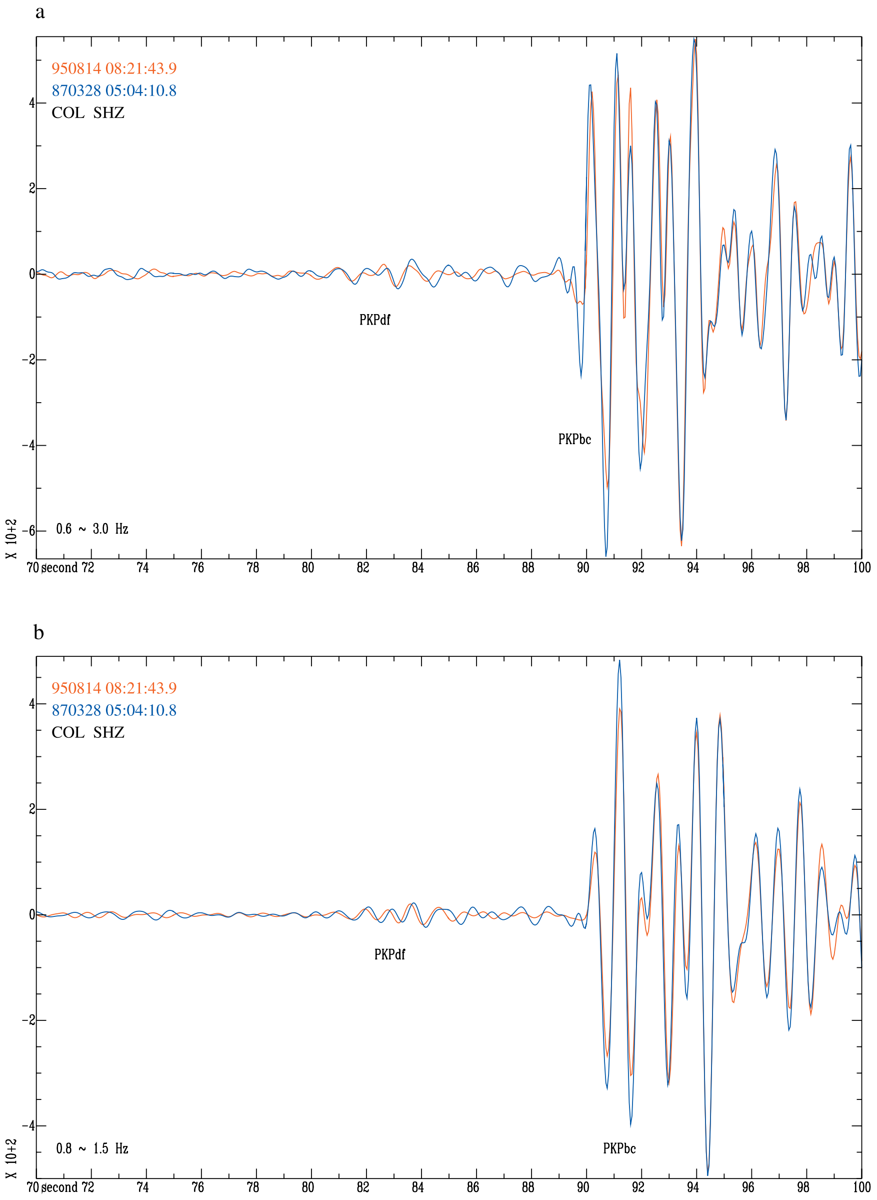

Figure 5. Enlarged plot of COL records of event 950814 (red curve) and 870328 (blue curve) to show the PKP(DF) and PKP(BC) phases clearly. Records in Figure 5a are bandpass filtered through a third order Butterworth filter having corner frequencies at 0.6 Hz and 3.0 Hz. Records in Figure 5b have corner frequencies at 0.8 Hz and 1.5 Hz, respectively. Waveforms are aligned on PKP(BC). The PKP(DF) phases show a clear travel time shift. PKP(DF) of event 950814 traveled faster through the Earth than that of event 870328.

high waveform similarity (cross correlation coefficients are greater than 0.9 in time windows of 14 s or more), their actual event source separation may be much less than 2 km. So the rupture areas of the two doublet events are mostly overlapped. Because the width of Fresnel zones of short period PKP waves is more than one hundred kilometers [*Creager*, 1997], a 2 km source separation actually has negligible effect on PKP travel times to a teleseismic station. Therefore the PKP(DF) travel time change we measured from doublet event pair 950814 and 870328 is significant evidence in support of inner core differential rotation.

[34] Only 17 doublets were found among the 906 SSI earthquakes from January 1982 to December 1998, although there are more than 16 thousand event pairs whose event source separations are less

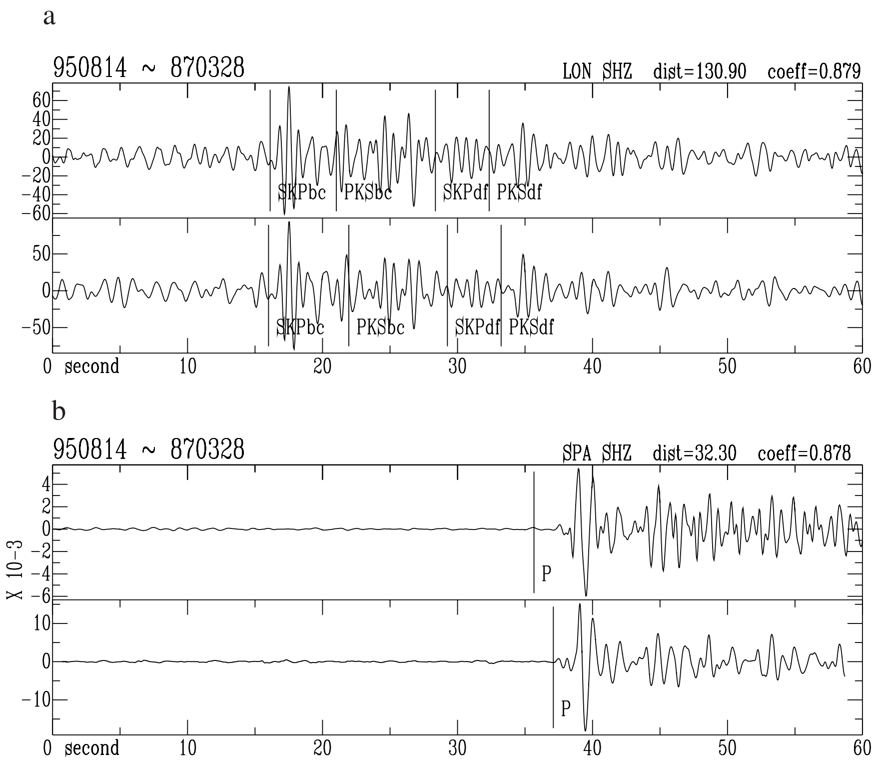

Figure 6. Additional waveform comparison to show event pair 950814 and 870328 as a doublet. (a) SKP and PKS waveforms at station LON. (b) P waveforms at station SPA. See Figure 3 for plot explanation.

than 40 km according to their PDE locations. There are several reasons why we found only about one doublet per thousand candidate pairs.

[35] First, for SSI earthquakes listed in the PDE catalog, their body wave magnitudes are at least 4.5. It is expected to be a rare occurrence for strong rupture ($m_b \geq 4.5$) to take place at essentially the same location twice within 17 years (1982–1998). Although there are examples of doublet occurrence within a few days or even within several minutes (to release the accumulated strain) at other active seismic regions, e.g., the Tonga region [*Isacks et al.*, 1967; *Wiens and Snider*, 2001], we have not found such cases at the SSI region among the event pairs we have checked. This suggests that tectonic properties of the SSI region may be different from other seismic regions, so that the earthquake occurrence has different characteristics.

[36] Second, for events with m_b values around 4.5 and slightly larger, their seismic signals are gener-

Table 2. Estimates of Inner Core Rotation Rate

		BC − *DF* Change		
		0.14 s	0.15 s	0.16 s
Inner Core Lateral P Wave Velocity Gradient (%/°)		Eastward Rotation Rate α°/year		
Creager [1997]	−0.019	0.58	0.62	0.66
	−0.027	0.41	0.44	0.47
Song [2000]	−0.0145	0.92	0.99	1.05
	−0.0176	0.76	0.81	0.87
	−0.0278	0.48	0.52	0.55

Table 3. PDE and ISC Location Precision[a]

	$\sigma_{latitude}$	$\sigma_{longitude}$	σ_{depth}
PDE	0.031° (3.5 *km*)	0.095° (5.6 *km*)	7.4 *km*
ISC	0.023° (2.5 *km*)	0.076° (4.5 *km*)	9.2 *km*

[a] σ is standard deviation. The depth deviation for PDE locations lacks significance because most of the doublet events have the PDE default depth value 33 km. The listed value is only a reference.

ally weak at long distance. Their records tend to be noisy and not useful for comparison of waveform similarity. For events with m_b values around 6.0 and larger, although their signals are strong enough to have clear records, their rupture process tend to be complex, and the rupture areas tend to be large, so that it is rare to have a repeat event at the same position within two decades to generate similar waveforms. Therefore the magnitude range to find doublets in the SSI region is limited. The doublet events we found have m_b values around 5.2 as shown Table 1.

[37] Third, the two events of one pair (less than 40 km apart as determined from PDE locations) may not have any common station. So their waveforms can not be compared, and their status as a doublet is undetermined. This occurs often for those event pairs for which both occurred in early 1980s, or for which one occurred in the early 1980s and the other in the late 1990s. Events that occurred in the 1980s generally have few digital records available, especially for events in earlier years. This is the direct result of the operation history of early digital stations. Closure of some of these stations results in no data available at the same station for the later event of a candidate pair. Movement of the seismometer sensor to a new location, even one nearby, leads to new site effects and loss of waveform similarity. Long lasting stations with stable operating history are strongly preferred.

[38] Fourth, even if the two events of one pair have one or more stations in common, the records may be too noisy at these stations to be comparable. The signal-to-noise ratio of 3 we used is only a suggestive criterion to omit very noisy records and not to lose possible good records, because the theoretical arrival times computed by the *iasp91* model may not match the actual phase arrivals (as shown in Figure 3). The disagreement is generally within several seconds. In many cases the actual arrivals for these SSI events are earlier than the predictions (which in some cases is presumably an effect of anisotropy).

[39] The third and fourth reasons lead to a failure to make the determination of whether a candidate pair is a doublet.

[40] Owing to the time needed to accumulate stress, the probability of finding doublets is generally higher if the origin time difference is larger between the two events of a candidate pair. But in practice, given the operating history of digital stations, more comparable records are available for event pairs with a shorter origin time difference. These are two trade-off factors affecting our searching for doublets.

[41] An additional defect of the magnitude limitation to find doublets in the SSI region is that it is unusual to have clear PKP(DF) waveforms for both of the doublet events at the same station, for example at COL, because PKP(DF) is a weak phase for SSI events recorded in Alaska.

3.2. Inner Core Rotation

[42] We checked point-by-point the original COL digital records obtained from IRIS for events 950814 and 870328. The waveforms from 90 seconds before PKP(BC) to 210 seconds after it are all naturally recorded seismograms, including noises and seismic signals. No interruption was observed, such as a zero line, an abrupt jump, or a sharp spike, which can be generated when connecting two record segments into one piece. COL is a high quality station with a long operating history. Its normal clock precision is at least 10^{-6} s, high enough for this study. Furthermore, these two records match remarkably well for several minutes long, even for some segments before PKP(DF) (they may be some kind of precursor scattered waves). Therefore, we believe the COL records of events 950814 and 870328 have no data tear, and the measured

PKP(DF) travel time shift referenced to PKP(BC) is reliable.

[43] On the rotation rate, a point to note is that usage of a γ factor in *Creager* [1997] and in *Song* [2000] is different. $\gamma = 1.1$ is a dimensionless factor relating the change in distance (°) along AB (a vertical cross section profile of SSI to Alaska ray turning points, which is perpendicular to the average ray direction) to change in longitude. In equation (3) of *Creager* [1997], the inner core rotation term is written as: $-\gamma \cdot \frac{\partial \nu}{\partial \xi} \cdot \alpha T_i$ (ν is the dimensionless fractional velocity anomaly averaged along ray paths through the inner core, ξ is the azimuth of the ray turning point relative to a reference source location (56°S, 27°W) at the mean position of the used SSI earthquakes, α is the inner core differential rotation rate, positive eastward, and T_i is the event origin time in years since a reference time of 1991.8). However, in equation (2) of *Song* [2000], the inner core rotation term is $-1/\gamma \cdot \frac{\partial v}{\partial l} \cdot \alpha(T - T_0)$ (v is the inner core velocity perturbation averaged along the ray through the inner core, l is distance along AB, T is calendar year, and T_0 is 1998.0). The different usage of the γ factor is based on different assumptions on the gradient direction of the lateral heterogeneity of P wave velocity structure in the inner core region sampled by rays from SSI to Alaska. If we assume the gradient direction is perpendicular to the longitude line (assumption A), then the usage in equation (3) of *Creager* [1997] is correct. In *Song* [2000], the assumed direction of lateral P velocity gradient is perpendicular to the average ray direction (assumption B), so the length projection factor γ should be used as $1/\gamma$. In fact, this is a two dimensional gradient problem (gradient in depth can be dealt with separately) although the velocity anomalies derived from travel times are averaged along the whole ray paths within the inner core. To constrain the actual average gradient direction in this inner core region, gradients along both the l direction and the ray direction are needed. Equivalently we can use gradients along longitude and latitude directions. The estimates of inner core rotation rate in Table 2 are based on the corresponding assumptions of *Creager* [1997] and *Song* [2000]. If we take assumption A only, then the rotation rates derived from *Song*'s [2000] lateral gradient results should approximately be divided by $\gamma^2 = 1.21$. If we take assumption B, then the rates derived from *Creager*'s [1997] results should approximately be multiplied by γ^2. In light of other uncertainties, the different uses of γ are not a major issue.

3.3. Catalog Precision

[44] From Table 3 we can see that both the PDE and ISC standard deviations in latitude and longitude are relatively small (less than 6 km). The latitude deviation is less than the longitude deviation, which could be explained by station distributions used to locate SSI earthquakes. Nearby stations are located in South America, Africa and Antarctica. Few are along the east-west direction, so in this direction the location constraint is relatively weak. PDE and ISC catalogs have better location constraints in horizontal directions than in depth. From horizontal deviations only, it appears that ISC locations have smaller errors than PDE locations. But here we could not give a definite conclusion because the doublet approach itself has an uncertainty range of about 2 km when using short period P wave records as discussed before.

[45] Given the precision results we have been able to demonstrate for PDE locations, we believe that event mislocation is small enough to have little impact in the interpretation of BC−DF differential travel times. Note that to have 0.1 s change of BC−DF time, a displacement of about 12 km in distance, or a depth change of about 100 km, is needed around 152° using the *iasp91* model. To see if there is systematic mislocation that changes with time, for each doublet, we compute origin time difference, latitude difference, and longitude difference between the two events in each doublet. Plots in Figure 7 show for 17 doublets that latitude difference and longitude difference are not correlated with origin time difference. This suggests that there is no obvious systematic mislocation that changes with time for SSI events from 1982 to 1998. Therefore, we are confident that the 0.3 s change of BC−DF differential travel times over about 3 decades reported by *Song and Richards* [1996] and

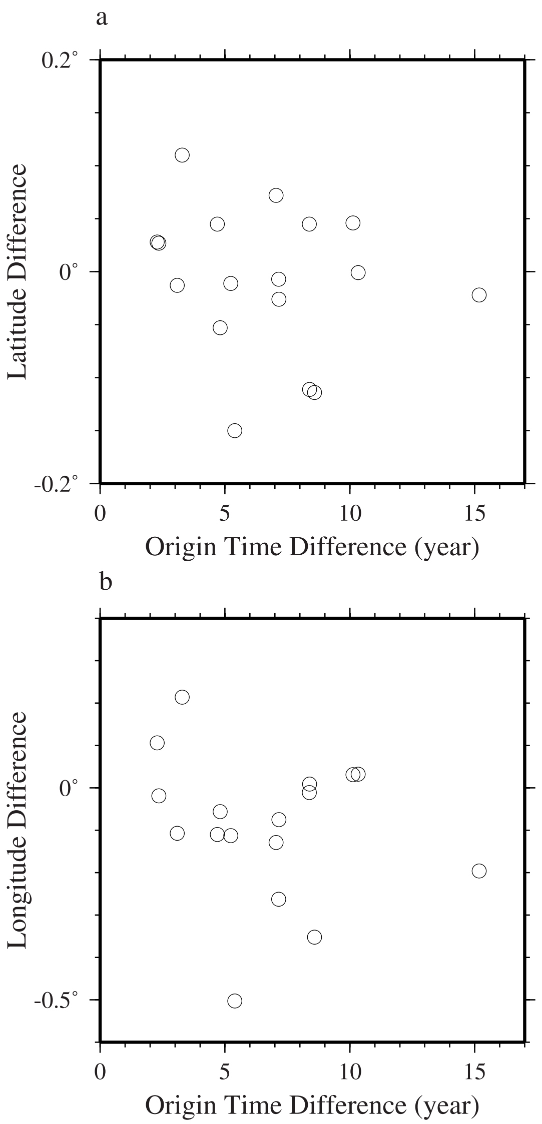

Figure 7. (a) Plot of latitude difference versus origin time difference between the two events of each of the 17 doublets. (b) Plot of longitude difference versus origin time difference.

Creager [1997] as evidence for inner core differential rotation is far too large to be an artifact of event mislocation, although earlier events may have larger location uncertainty, as noted by *Song* [2000].

4. Conclusion

[46] We searched for doublets at the South Sandwich Islands region among 906 earthquakes from January 1982 to December 1998 by means of waveform similarity on vertical seismic records. From about 16 thousand candidate event pairs, we determined 17 to be waveform doublets.

[47] Among these 17 doublets, only the doublet pair of events 950814 and 870328 have clear PKP(DF) phases at the COL station in Alaska. These have been used to detect inner core differential rotation by PKP(DF) travel time change. We used cross correlation method to measure the time shifts of phases PKP(DF), PKP(BC), and PKP(AB) between the COL records of these two events. Results show that the AB−BC differential travel time did not change over calendar time, but the BC−DF time changed 0.15 s over about 8 years, with standard deviation 0.02 s. Because events 950814 and 870328 are a doublet, located essentially at the same spatial position, we infer that the observed BC−DF travel time change is due to a change in PKP(DF) travel time through the inner core, and not to effects of heterogeneity in the mantle or crust. This result is strong support for differential rotation of the Earth's inner core relative to the mantle, and excludes the special case of a locked inner core with zero relative rotation rate.

[48] While we derived the inner core rotation rate to be between 0.4° and 1° per year eastward using the inner core lateral velocity gradient results of *Creager* [1997] and *Song* [2000], the actual rate depends on knowledge of the lateral velocity gradient in the part of the inner core sampled by ray paths to COL for SSI events 950814 and 870328. Furthermore, this lateral velocity gradient could be affected by inner core internal deformation that is caused by rotation.

[49] We also utilize the 17 doublets we found in this study to estimate the precision of PDE and ISC locations. They both have quite good precision in latitude (less than 4 km) and longitude (less than 6 km), though bias may apply to a general source region, making absolute location errors significantly greater. It seems that the ISC locations have slightly better precision than the PDE locations.

[50] Based on the precision results of catalog locations, we conclude that previous claims of

travel time change in core phases are not an artifact of event mislocation, and are indeed due to changes in the Earth (e.g., inner core rotation).

Acknowledgments

[51] We thank William Menke and Won-Young Kim for their valuable suggestions, the IRIS Consortium for digital seismic records, and the Lamont computer supporting staff for their kind help. We also thank Kenneth C. Creager, John E. Vidale, Jeroen Tromp, and other reviewers for helpful remarks. This research was supported by the U.S. National Science Foundation under grant EAR 01-25691. This is Lamont-Doherty Earth Observatory contribution number 6486.

References

Breger, L., B. Romanowicz, and H. Tkalcic, PKP(BC–DF) travel time residuals and short scale heterogeneity in the deep earth, *Geophys. Res. Lett.*, *26*, 3169–3172, 1999.

Breger, L., H. Tkalcic, and B. Romanowicz, The effect of D$''$ on PKP(AB–DF) travel time residuals and possible implications for inner core structure, *Earth Planet. Sci. Lett.*, *175*, 133–143, 2000.

Buffett, B. A., Geodynamic estimates of the viscosity of the Earth's inner core, *Nature*, *388*, 571–573, 1997.

Buffett, B. A., Earth's core and the geodynamo, *Science*, *288*, 2007–2012, 2000a.

Buffett, B. A., Dynamics of the Earth's core, in *Earth's Deep Interior: Mineral Physics and Tomography from the Atomic to the Global Scale*, *Geophys. Monogr. Ser.*, vol. 117, edited by S.-i. Karato et al., pp. 37–62, AGU, Washington, D. C., 2000b.

Buffett, B. A., and G. A. Glatzmaier, Gravitational braking of inner-core rotation in geodynamo simulations, *Geophys. Res. Lett.*, *27*, 3125–3128, 2000.

Creager, K. C., Anisotropy of the inner core from differential travel times of the phases PKP and PKIKP, *Nature*, *356*, 309–314, 1992.

Creager, K. C., Inner core rotation rate from small-scale heterogeneity and time-varying travel times, *Science*, *278*, 1284–1288, 1997.

Creager, K. C., Large-scale variations in inner core anisotropy, *J. Geophys. Res.*, *104*, 23,127–23,139, 1999.

de Wijs, G. A., G. Kresse, L. Vocadlo, D. Dobson, D. Alfe, M. J. Gillan, and G. D. Price, The viscosity of liquid iron at the physical conditions of the Earth's core, *Nature*, *392*, 805–807, 1998.

Frankel, A., Precursors to a magnitude 4.8 earthquake in the Virgin Islands: Spatial clustering of small earthquakes, anomalous focal mechanisms, and earthquake doublets, *Bull. Seismol. Soc. Am.*, *72*, 1277–1294, 1982.

Fremont, M.-J., and S. D. Malone, High precision relative locations of earthquakes at Mount St. Hellens, Washington, *J. Geophys. Res.*, *92*, 10,223–10,236, 1987.

Gans, R. F., Viscosity of the Earth's core, *J. Geophys. Res.*, *77*, 360–366, 1972.

Geller, R. J., and C. S. Mueller, Four similar earthquakes in central California, *Geophys. Res. Lett.*, *7*, 821–824, 1980.

Glatzmaier, G. A., and P. H. Roberts, A three-dimensional convective dynamo solution with rotating and finitely conducting inner core and mantle, *Phys. Earth Planet. Inter.*, *91*, 63–75, 1995a.

Glatzmaier, G. A., and P. H. Roberts, A three-dimensional self-consistent computer simulation of a geomagnetic field reversal, *Nature*, *377*, 203–209, 1995b.

Glatzmaier, G. A., and P. H. Roberts, Rotation and magnetism of Earth's inner core, *Science*, *274*, 1887–1891, 1996.

Gubbins, D., Rotation of the inner core, *J. Geophys. Res.*, *86*, 11,695–11,699, 1981.

Hollerbach, R., and C. A. Jones, A geodynamo model incorporating a finitely conducting inner core, *Phys. Earth Planet. Inter.*, *75*, 317–327, 1993a.

Hollerbach, R., and C. A. Jones, Influence of the Earth's inner core on geomagnetic fluctuations and reversals, *Nature*, *365*, 541–543, 1993b.

Hollerbach, R., and C. A. Jones, On the magnetically stabilizing role of the Earth's inner core, *Phys. Earth Planet. Inter.*, *87*, 171–181, 1995.

Isacks, B. L., L. R. Sykes, and J. Oliver, Spatial and temporal clustering of deep and shallow earthquakes in the Fiji-Tonga-Kermadec region, *Bull. Seismol. Soc. Am.*, *57*, 935–958, 1967.

Ito, A., High resolution relative hypocenters of similar earthquakes by cross-spectral analysis method, *J. Phys. Earth*, *33*, 279–294, 1985.

Jacobs, J. A., The Earth's inner core, *Nature*, *172*, 297–298, 1953.

Kennett, B. L. N., and E. R. Engdahl, Traveltimes for global earthquake location and phase identification, *Geophys. J. Int.*, *105*, 429–465, 1991.

Kuang, W., and J. Bloxham, An Earth-like numerical dynamo model, *Nature*, *389*, 371–374, 1997.

Laske, G., and G. Masters, Limits on differential rotation of the inner core from an analysis of the Earth's free oscillations, *Nature*, *402*, 66–69, 1999.

Lay, T., and H. Kanamori, Earthquake doublets in the Solomon Islands, *Phys. Earth Planet. Inter.*, *21*, 283–304, 1980.

Lehmann, I., P$'$, *Publ. Bur. Cent. Seismol. Int. Trav. Sci.*, *A14*, 87–115, 1936.

Levin, V., W. Menke, and J. Park, Shear wave splitting in the Appalachians and the Urals: A case for multilayered anisotropy, *J. Geophys. Res.*, *104*, 17,975–17,993, 1999.

Li, A., and P. G. Richards, Study of inner core structure and rotation using seismic records from Novaya Zemlya underground nuclear tests, in *Earth's Core: Dynamics, Structure, Rotation*, *Geodyn. Ser.*, vol. 31, edited by V. Dehant et al., pp. 23–30, AGU, Washington, D. C., 2003.

Masters, G., and F. Gilbert, Structure of the inner core inferred from observations of its spheroidal shear modes, *Geophys. Res. Lett.*, *8*, 569–571, 1981.

McSweeney, T. J., K. C. Creager, and R. T. Merrill, Depth extent of inner-core seismic anisotropy and implications for geomagnetism, *Phys. Earth Planet. Inter.*, *101*, 131–156, 1997.

Menke, W., Using waveform similarity to constrain earthquake locations, *Bull. Seismol. Soc. Am.*, *89*, 1143–1146, 1999.

Morelli, A., A. M. Dziewonski, and J. H. Woodhouse, Anisotropy of the inner core inferred from PKIKP travel times, *Geophys. Res. Lett.*, *13*, 1545–1548, 1986.

Nadeau, R. M., W. Foxall, and T. V. McEvilly, Clustering and periodic recurrence of microearthquakes on the San Andreas fault at Parkfield, California, *Science*, *267*, 503–507, 1995.

Poirier, J. P., Transport properties of liquid metals and viscosity of the Earth's core, *Geophys. J.*, *92*, 99–105, 1988.

Poupinet, G., R. Pillet, and A. Souriau, Possible heterogeneity of the Earth's core deduced from PKIKP travel times, *Nature*, *305*, 204–206, 1983.

Poupinet, G., A. Souriau, and O. Coutant, The existence of an inner core super-rotation questioned by teleseismic doublets, *Phys. Earth Planet. Inter.*, *118*, 77–88, 2000.

Song, X. D., Joint inversion for inner core rotation, inner core anisotropy, and mantle heterogeneity, *J. Geophys. Res.*, *105*, 7931–7943, 2000.

Song, X. D., Comment on "The existence of an inner core super-rotation questioned by teleseismic doublets" by Georges Poupinet, Annie Souriau, and Olivier Coutant, *Phys. Earth Planet. Inter.*, *124*, 269–273, 2001.

Song, X. D., and A. Li, Support for differential inner core superrotation from earthquakes in Alaska recorded at South Pole station, *J. Geophys. Res.*, *105*, 623–630, 2000.

Song, X. D., and P. G. Richards, Seismological evidence for differential rotation of the Earth's inner core, *Nature*, *382*, 221–224, 1996.

Souriau, A., New seismological constraints on differential rotation of the inner core from Novaya Zemlya events recorded at DRV, Antarctica, *Geophys. J. Int.*, *134*, F1–F5, 1998a.

Souriau, A., Is the rotation real?, *Science*, *281*, 55–56, 1998b.

Souriau, A., Detecting possible rotation of Earth's inner core, response to comments by P. G. Richards, X. D. Song, and A. Li, *Science*, *282*, 1227a, 1998c.

Souriau, A., and G. Poupinet, Inner core rotation: A test at the worldwide scale, *Phys. Earth Planet. Inter.*, *118*, 13–27, 2000.

Steenbeck, M., and G. Helmis, Rotation of the Earth's solid core as a possible cause of declination, drift and reversals of the Earth's magnetic field, *Geophys. J. R. Astron. Soc.*, *41*, 237–244, 1975.

Stixrude, L., and R. E. Cohen, High-pressure elasticity of iron and anisotropy of Earth's inner core, *Science*, *267*, 1972–1975, 1995.

Su, W. J., and A. M. Dziewonski, Inner core anisotropy in three dimensions, *J. Geophys. Res.*, *100*, 9831–9852, 1995.

Takahashi, T., and W. A. Bassett, High-pressure polymorph of iron, *Science*, *145*, 483–486, 1964.

Tanaka, S., and H. Hamaguchi, Degree one heterogeneity and hemispherical variation of anisotropy in the inner core from PKP(BC)–PKP(DF) times, *J. Geophys. Res.*, *102*, 2925–2938, 1997.

Thorbjarnardottir, B. S., and J. C. Pechmann, Constraints on relative earthquake locations from cross-correlation of waveforms, *Bull. Seismol. Soc. Am.*, *77*, 1626–1634, 1987.

Vidale, J. E., and P. S. Earle, Fine-scale heterogeneity in the Earth's inner core, *Nature*, *404*, 273–275, 2000a.

Vidale, J. E., D. A. Dodge, and P. S. Earle, Slow differential rotation of the Earth's inner core indicated by temporal changes in scattering, *Nature*, *405*, 445–448, 2000b.

Wiens, D. A., and N. Snider, Repeating deep earthquakes: Evidence for fault reactivation at great depth, *Science*, *293*, 1463–1466, 2001.

Woodhouse, J. H., D. Giardini, and X.-D. Li, Evidence for inner core anisotropy from free oscillations, *Geophys. Res. Lett.*, *13*, 1549–1552, 1986.