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Examination of systematic mislocation of South Sandwich Islands earthquakes using station pairs: Implications for inner core rotation

Xinlei Sun,¹ Georges Poupinet,^{2,3} and Xiaodong Song^{1,3}

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[1] One of the most robust observations for the inner core rotation is that the differential PKP BC-DF traveltimes from South Sandwich Islands (SSI) earthquakes to College, Alaska (and some other stations in Alaska), have increased systematically over the past 50 years. The time shift in the differential time residuals is some 0.3 s over 30 years. This temporal change is thought to result from a shift of the inner core structure from a superrotation of the inner core. However, the observation has been hotly debated and has been suggested to be an artifact of systematic earthquake mislocation. Here we examine this issue using three mutually independent approaches, with a goal to quantify the amount of the systematic mislocation, if any. All three approaches involve differencing data between north stations at a similar azimuth as the SSI-Alaska azimuth and south stations at nearly the opposite azimuth. Mislocation along this azimuth has greatest impact on the PKP differential times. In approach 1, we examine how the double difference of P traveltimes between a north station and a south station changes with time. Because the differential apparent slowness between the P traveltimes of the pairs is 8 to 16 times that of the differential BC-DF times, mislocation would cause a time shift in the double difference an order of magnitude larger than that of BC-DF times. In approach 2, we compare directly difference in P arrival times between two SSI events that are close by and between a north and a south stations, which avoids using earthquake locations and Earth models entirely. In approach 3, we compare PKP traveltime residuals between a group of north and south stations. Because PKP traveltimes are generally not used for location in earthquake bulletins, they provide an independent data set to check earthquake location errors. The results from approaches 1 and 2, both of which use P data, are generally consistent. The mislocation is up to 3.6 ± 4.2 km (one standard deviation), explaining less than 10% of the observed COL temporal change. The results from approach 3 using PKP data show a larger mislocation but with a larger error (14.4 ± 10.8 km over 30 years). It can explain about $30\% \pm 22\%$ of the observed COL temporal change. Therefore inner-core superrotation is still the best explanation for the observed temporal change in the differential traveltimes.

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1. Introduction

[2] The first evidence for differential inner core rotation was reported from differential traveltimes of seismic PKP waves [Song and Richards, 1996]. Three branches of PKP waves are observable at distance range of about 146° to 156° : the AB branch that turns in middle outer core, the BC branch that turns at the bottom of the outer core, and the DF branch that passes through the inner core. The DF and BC ray paths

are close to each other throughout the mantle and the AB ray path is also relatively close to the BC or DF path in the upper mantle. Thus differential PKP traveltimes are often used to study the Earth's core, which reduce biases from heterogeneity of the mantle and errors in earthquake locations and origin times. Song and Richards [1996] found that BC-DF differential traveltime residuals from South Sandwich Islands (SSI) earthquakes to College station in Alaska (COL) have increased systematically by about 0.31 s over 28 years, which was interpreted as evidence for the inner core rotation.

[3] Differential inner core rotation was subsequently supported by some studies [e.g., Creager, 1997; Ovchinnikov *et al.*, 1998; Vidale *et al.*, 2000; Song and Li, 2000; Xu and Song, 2003; Li and Richards, 2003a, 2003b; Vidale and Earle, 2005; Zhang *et al.*, 2005] (see also reviews by Tromp [2001], Song

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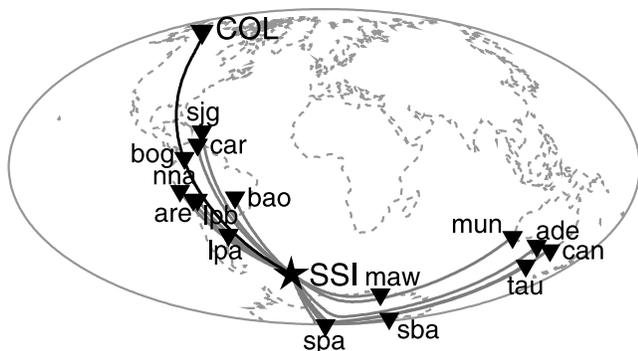


Figure 1. Map of P stations used in this study and College, Alaska (COL), station (inverted triangles) for South Sandwich Islands (SSI) earthquakes. Station codes are labeled. The stations are either at similar azimuth as SSI to COL (“north stations,” a total of 8, located in South and Central Americas) or at nearly the opposite azimuth (“south stations,” a total of 7, located in Antarctica and Australia).

[2003], and *Souriau and Poupinet* [2003]). However, other studies could not find evidence for an inner core motion [*Dziewonski and Su*, 1998; *Souriau*, 1998a; *Souriau and Poupinet*, 2000]. Estimates of the rotation from normal mode data vary [*Sharrock and Woodhouse*, 1998; *Laske and Masters*, 1999; *Laske and Masters*, 2003]. The most recent estimate yielded a small and barely significant superrotation of $0.13 \pm 0.11^\circ/\text{yr}$ [*Laske and Masters*, 2003]. Furthermore, some studies questioned that the evidence could be an artifact of the biases from earthquake location, earthquake magnitudes, and mantle heterogeneities [*Souriau et al.*, 1997; *Souriau*, 1998a, 1998b; *Souriau and Poupinet*, 1998; *Poupinet et al.*, 2000; *Souriau and Poupinet*, 2003].

[4] In this study we focus on the traveltime studies from SSI earthquakes to Alaska stations. The temporal change along the pathway is currently the most robust evidence in favor of the inner core rotation [*Song and Richards*, 1996; *Creager*, 1997; *Song*, 2000a; *Li and Richards*, 2003b; *Zhang et al.*, 2005]. The observed temporal changes are about 0.0090 to 0.0119 s/yr at COL and 0.0130 to 0.0180 s/yr at three other Alaska stations. In the meantime, the observation of the temporal change has attracted the strongest debate. A key issue is whether the observed temporal change is caused by systematic earthquake mislocation (i.e., temporal change of locations reported in earthquake catalogs) [*Poupinet et al.*, 2000; *Song*, 2000b, 2001; *Poupinet and Souriau*, 2001; *Souriau and Poupinet*, 2003]. At different times, different stations are used to locate earthquakes, thus it may be possible that earthquakes were systematically mislocated over time, causing a systematic temporal change in traveltime residuals.

[5] The most recent study by *Zhang et al.* [2005] is based directly on side-by-side comparisons of seismic waves from earthquake doublets that were identical in location and source mechanism, producing identical wave shapes. Using a total of 18 high-quality waveform doublets, they found that BC-DF differential times have changed systematically by 0.0090 ± 0.0005 s/yr, which is smaller than but very close to the original observation of 0.0109 ± 0.0014 s/yr made by *Song and Richards* [1996] or 0.0119 ± 0.0015

made later by *Song* [2000a]. In addition to time shift, *Zhang et al.* [2005] also found that the DF waves change in shape over several years, providing an independent evidence for an inner core motion. The use of waveform doublets avoids artifacts of earthquake mislocations and contamination from small-scale mantle heterogeneities, and allows them to pin down precisely that the temporal changes must have occurred in the inner core.

[6] In this paper, we examine the issue of systematic mislocation of SSI earthquakes along SSI-Alaska azimuth using three approaches, all of which involve differencing data between stations. Component of mislocation along this azimuth has greatest impact on the PKP differential times. Component of mislocation along orthogonal azimuth changes little in predicted BC-DF times for a one-dimensional (1-D) Earth model. In approach 1, our basic method is to form “double difference” between observed and predicted P wave traveltimes between a pair of stations, which follows a similar technique that was applied to PKP residuals by *Souriau and Poupinet* [2003]. One station of the pair (“north station”) is at about the same azimuth as the SSI-Alaska azimuth and the other station (“south station”) is at nearly the opposite azimuth (Figure 1). Because the difference in apparent slowness (i.e., change of traveltime with distance, also known as horizontal slowness or ray parameter) between the P travel times of the pairs is 10 to 16 times that of the differential BC-DF traveltimes, mislocation would cause a time shift in the differential P times an order of magnitude larger than that of BC-DF times. In approach 2, we compare directly difference in P arrival times between two SSI events that are close by and between a north and a south stations. In approach 3, we examine PKP traveltime residuals of a group of north and south stations. The three approaches are mutually independent. Approaches 1 and 2 are related, but because of different formulations, they do not use the same data. Approaches 2 and 3 provide independent examinations of earthquake location errors: In approach 2, earthquake locations are not used at all in comparing the arrival times; in approach 3, PKP data are not normally used for locating earthquakes in earthquake bulletins. Note the errors quoted in this paper (regressions or data bins) are one standard deviations (or 68% confidence level).

2. Approach 1: Double Difference of P Traveltimes

2.1. Methods

[7] For each event, we form P wave traveltime double difference between a pair of north and south stations as:

$$\text{DDT} = (T_{obs}^N - T_{obs}^S) - (T_{pre}^N - T_{pre}^S), \quad (1)$$

where N and S denote “north station” and “south station”, respectively; and T_{obs} and T_{pre} denote observed and predicted traveltimes (or arrival times), respectively. The traveltime double difference can also be written as $\text{DDT} = dT^N - dT^S$, where $dT = T_{obs} - T_{pre}$ denotes the observed traveltime residuals. Thus DDT also represents residual difference between a north station and a south station. This formulation of traveltime double difference is similar to the

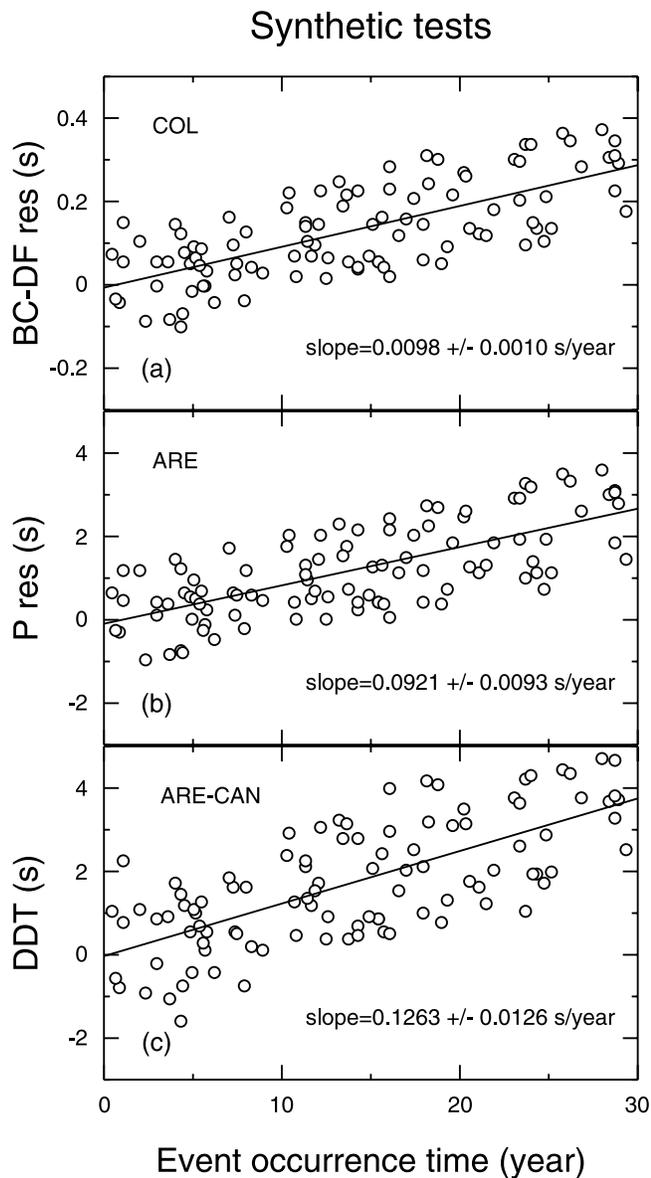


Figure 2. A demonstration of the methodology used in approach 1. We synthesize a group of SSI earthquakes (a total of 100) that have been systematically mislocated along the COL azimuth by 40 km over 30 years with the more recent events mislocated closer to COL relative to the older events. The earthquakes are randomly but uniformly distributed in time, and the amount of the systematic mislocation is proportional to event occurrence time from time 0. In addition, we add a uniformly distributed random errors of up to ± 20 km to the latitude and the longitude of the earthquakes. Using the synthesized earthquakes, we then calculate the residuals of BC-DF differential times at COL, P residuals at a north station ARE (Arequipa, Peru), and DDTs between ARE and a south station CAN (Canberra, Australia). Note timescale of the vertical axis for the BC-DF residuals in Figure 2a is 10 times smaller than those of Figures 2b and 2c.

double difference method that has been widely used for earthquake relocation [Waldhauser and Ellsworth, 2000].

[8] Our basic idea is to examine how the DDT changes with time. There are several advantages of the approach.

[9] 1. The use of the DDT reduces influences not related to horizontal source mislocation (in latitude and longitude). It removes the errors in earthquake origin time and reduces bias from mantle heterogeneities along the ray path. In addition, like the differential PKP BC-DF traveltimes, the DDT also reduces bias from location errors in source depth.

[10] 2. The distance of the P waves that we use ranges from 30° to 90° . The apparent slowness of the P waves is 5 to 8 times of the differential apparent slowness of the PKP BC-DF times. Thus the effect of mislocation is several times larger on P traveltimes than on the BC-DF times.

[11] 3. If a SSI earthquake is mislocated toward the Alaska direction from its true location, the predicted P travel time to the north station T_{pre}^N will decrease, but the predicted P traveltime to the south station T_{pre}^S will increase. Similarly, if the earthquake is mislocated toward the opposite direction, T_{pre}^N will increase but T_{pre}^S will decrease. Thus the double difference will roughly double the effect of the mislocation.

[12] The method is illustrated using a synthetic test (Figure 2). We generate a group of synthetic earthquakes that include a systematic mislocation of 40 km over 30 years toward the COL azimuth in addition to random errors in latitude and longitude. The synthesized earthquakes show systematic trends in BC-DF differential times, P residuals, as well as DDTs. The predicted temporal change in BC-DF differential times at COL (0.29 s over 30 years) from the mislocations (Figure 2a) is slightly smaller but comparable to the observed temporal change [Song and Richards, 1996; Song, 2000a]. The mislocations would predict a large temporal change at ARE (a north station) of about 2.8 s over 30 years and an even larger temporal change in the DDTs between ARE and CAN (a south station) of about 3.8 s over 30 years (Figures 2b and 2c). The predicted temporal changes are controlled by the systematic mislocation and change little with the amplitude of the random errors in the mislocations.

2.2. Results

2.2.1. Results From Earthquake Bulletin Data

[13] The first data set we used is the arrival times that have previously been used to relocate the SSI earthquakes [Song, 2000a]. The arrival times were assembled from various earthquake bulletins, including the Earthquake Data Report (EDR), the International Seismological Centre (ISC), the International Seismological Summary (ISS), and the Bureau Central International de Séismologie of France (BCIS). To form our station pairs, we select north and south stations that have the longest histories of recording and the most P readings. A total of eight north station and seven south stations are selected (Figure 1). The total number of SSI events we used is 86.

[14] Figure 3 shows some examples of the DDTs between north-south station pairs as a function of earthquake time. The results from the DDTs of individual pairs are not consistent: some pairs have positive slopes, some have negative slopes, and some don't have significant slopes. The inconsistency suggest any systematic mislocation along the COL azimuth would be smaller than other sources of

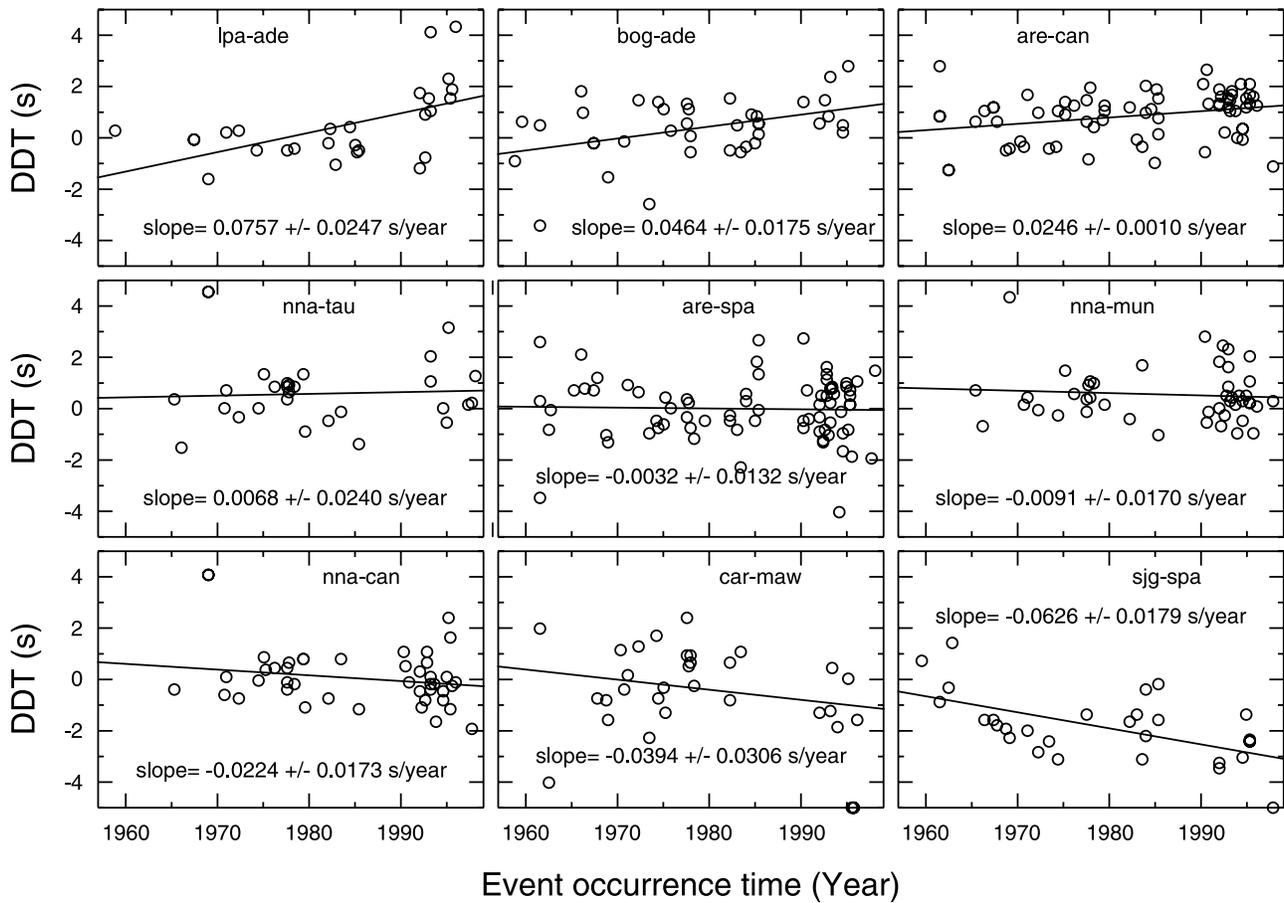


Figure 3. Examples of P traveltime double difference (DDT) from SSI earthquakes for various station pairs using earthquake bulletins. Lines are the linear regressions of the DDTs on earthquake occurrence time. The errors of the regression slopes are one standard deviation.

errors in these data. We also notice that the baselines of the DDTs for individual station pairs are different. Two possible sources of the baseline difference are (1) different mantle anomalies sampled by different paths and (2) systematic difference in picking the arrival times between station analysts.

[15] We combine all the station pairs after removing the mean of each station pair (Figure 4). Because the means for different station pairs are different, it is important to remove the means before data from different pairs are combined. Failing to do so is likely to create artificial trends from uneven temporal distribution of data between different pairs. There are a total of 56 station pairs from the eight north and seven south stations. The combined data suggest a small positive trend of 0.0094 ± 0.0026 s/yr. Note the vertical stripes of the data arise from the fact that there are multiple station pairs (among the possible 56 station pairs) for each event.

[16] Assuming this small trend is caused by a systematic mislocation, we can estimate the amount of the systematic mislocation along the COL azimuth and its impact on the BC-DF times at COL. We conduct two synthetic tests (Figure 5) on the effect of a systematic event mislocation similar to that described above. One test assumes random distribution of earthquake occurrence time and the other

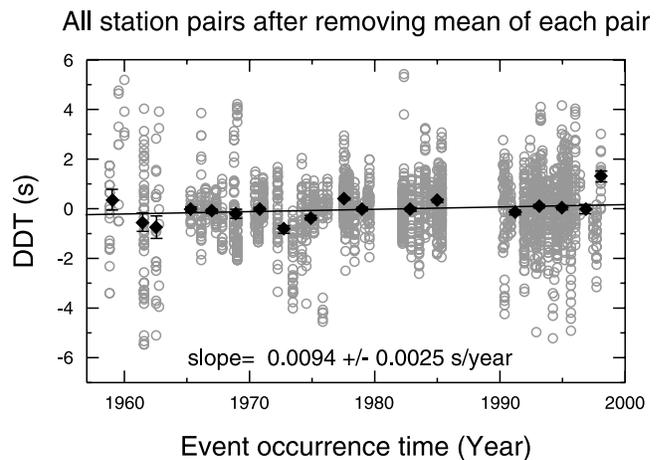


Figure 4. Combined DDTs of all station pairs using earthquake bulletin data. The mean of each station has been removed before the data are combined. The diamonds are the mean of the binned data for every 5 years, and error bars are one standard deviation of the mean.

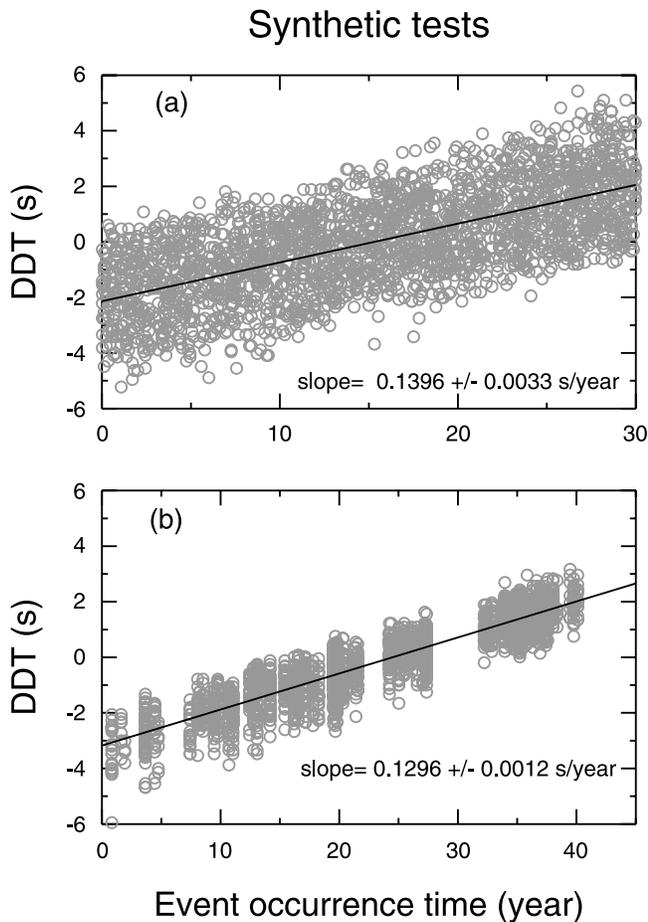


Figure 5. Synthetic tests on effect of a systematic event mislocation on DDT. We assume a systematic mislocation of 40 km over 30 years and uniformly distributed random errors of ± 20 km in latitude and longitude. In the first test (Figure 5a), we generate 40 random events over a time period of 30 years that are systematically mislocated as described, for each station pair used in our study (total of 56 pairs). We then combined the DDTs from all the station pairs after removing the means, following the same procedure for the real data. The second test (Figure 5b) is the same as Figure 5a, but we generate mislocated earthquakes for the same sets of earthquakes and station pairs as in the real data to calculate the DDTs.

assumes the same sets of earthquakes and station pairs as in the real data. The tests yield similar results: for a systematic mislocation of 40 km over 30 years toward COL, the temporal changes in DDTs are about 0.140 and 0.130 s/yr from the first and second tests, respectively.

[17] Thus we estimate the systematic mislocation along the SSI-COL direction from the slope of the observed DDTs to be 2.9 ± 0.8 km over 30 years. The mislocation would predict an increase in BC-DF differential times at COL of about 0.021 s over 30 years, which is more than 10 times less than the observed value (0.33–0.36 s over 30 years).

2.2.2. Results From Hand-Picked Data

[18] The arrival times reported by the earthquake bulletins are typically picked by different station analysts at different

times, thus they may be subject to systematic picking errors. To make consistent picks, we made a substantial effort to obtain the original analog and digital seismograms and to pick arrival times by hand. We are limited by the availability of the original seismograms to a total of six stations for this analysis, including two north stations (NNA and SJG), and four south stations (SPA, SBA, TAU and CAN) (Table 1). All the records we used are the vertical components.

[19] All the digital records were obtained from the Data Management Center, Incorporated Research Institutions for Seismology. The analog records for CAN, are paper copies of the original paper seismograms in Canberra, Australia. The analog records for the rest of the five stations were obtained from the film chip archives at the Lamont-Doherty Earth Observatory of Columbia University. The records in the films were first printed out in hard paper copies. The quality of the analog seismograms we used varies from excellent to good (Figure 6).

[20] The paper records were scanned into digital images. The arrival times were then picked in digital pixels to achieve greater accuracy than possible by a ruler. All the broadband digital records were converted to World-Wide Standardized Seismograph Network instrument response before time picking. We pay particular care to pick times consistently. Our method is to pick the intercept of the onset slope of the P arrival with the baseline.

[21] Results from the hand-picked data are shown in Figure 7. We removed a few outliers with large DDT values (greater than 3 s or smaller than -3 s). As before, the mean of each station pair has been removed before the different pairs are combined. There are a total of eight pairs from the four north stations and the two south stations. The temporal slope of the DDTs from these hand-picked data, -0.0002 ± 0.0045 s/yr, is essentially zero and even smaller than the slope obtained from bulletin data. Using the synthetic test results as above, we estimate the mislocation to be about -0.06 ± 1.4 km over 30 years from the hand-picked data. Including the outliers, the temporal slope has a larger negative value, which would predict a wrong sign in differential BC-DF times if mislocation is assumed to be the cause.

[22] How do the hand arrival time picks and bulletin picks compare directly? We have a few pairs that have both bulletin and hand-picked data for the same events (Figure 8). The differences for individual picks are clearly visible. However, the DDT slopes are quite similar (within the error bars of the data), which suggests no systematic picking errors in the bulletins for these stations.

[23] Figure 9 shows another comparison with all the data where both hand and bulletin picks are available (a total of 94 data points). Individual picks can sometimes differ by

Table 1. Sources of Original Seismograms for Picking P Arrival Times

Station	Analog	Digital
NNA	19650507-19780502	19890210-19950103
SJG	19670523-19770710	19931022-20021218
CAN	19650507-19980206	19881101-20020931
SBA	19650507-19771216	19950326-20030519
SPA	19650507-19780502	19911228-20030519
TAU	19660209-19770804	19811214-20030207

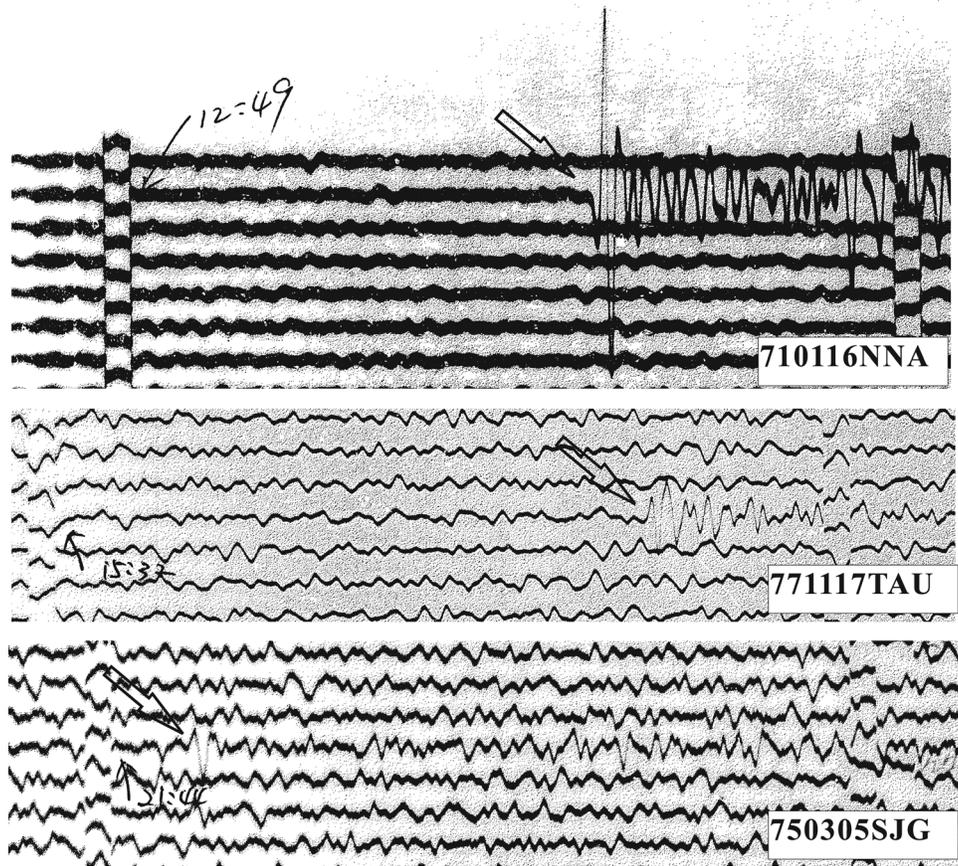


Figure 6. Examples of seismograms with (top) excellent, (middle) very good, and (bottom) good quality that we used to hand-pick the P arrival times. Arrows indicate the P arrivals.

more than 2–3 s. The standard deviation is 0.87 s. Excluding three outliers that are less than -3 s, the standard deviation is 0.57 s. On the other hand, the difference does not show a temporal trend (Figure 9a). A histogram of the difference is shown in Figure 9b.

2.3. Summary

[24] For this part of the study, we examined how the P wave double difference, formed between observed and predicted traveltimes and between a north and a south stations, changes with time. Because of its great sensitivity to mislocation, the double difference provides a powerful way to estimate systematic mislocation. Results from both arrival times reported by earthquake bulletins and our own hand picked times directly from original seismograms suggest that most of the station pairs have a very small increase of differential P residuals with time and some station pairs have a decrease of residuals with time. After removing all the means of the residuals of different station pairs, the combined data suggest an increase in P double difference time (DDT) of about 0.0094 ± 0.0026 s/yr from the bulletin data. The combined data from our own hand-picked arrival times show slightly negative trend in DDT of -0.0002 ± 0.0045 s/yr. From the temporal changes of the DDTs, we constrain the amount of systematic earthquake mislocation using synthetic tests. Assuming the observed small trends in the DDTs are caused by a systematic mislocation along the SSI-Alaska direction, we estimate

the mislocation to be about 2.9 ± 0.8 km and -0.06 ± 1.4 km over 30 years from the bulletin and hand-picked data, respectively. The mislocation would predict an increase in BC-DF differential times at COL of about 0.02 s over

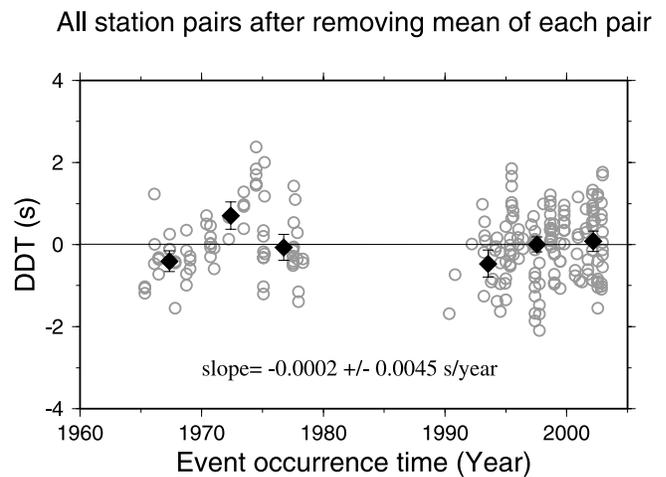


Figure 7. Combined DDTs of all station pairs using hand-picked data, after the mean of each station has been removed. Diamonds and error bars are the means \pm one standard deviation for data binned at every 5 years.

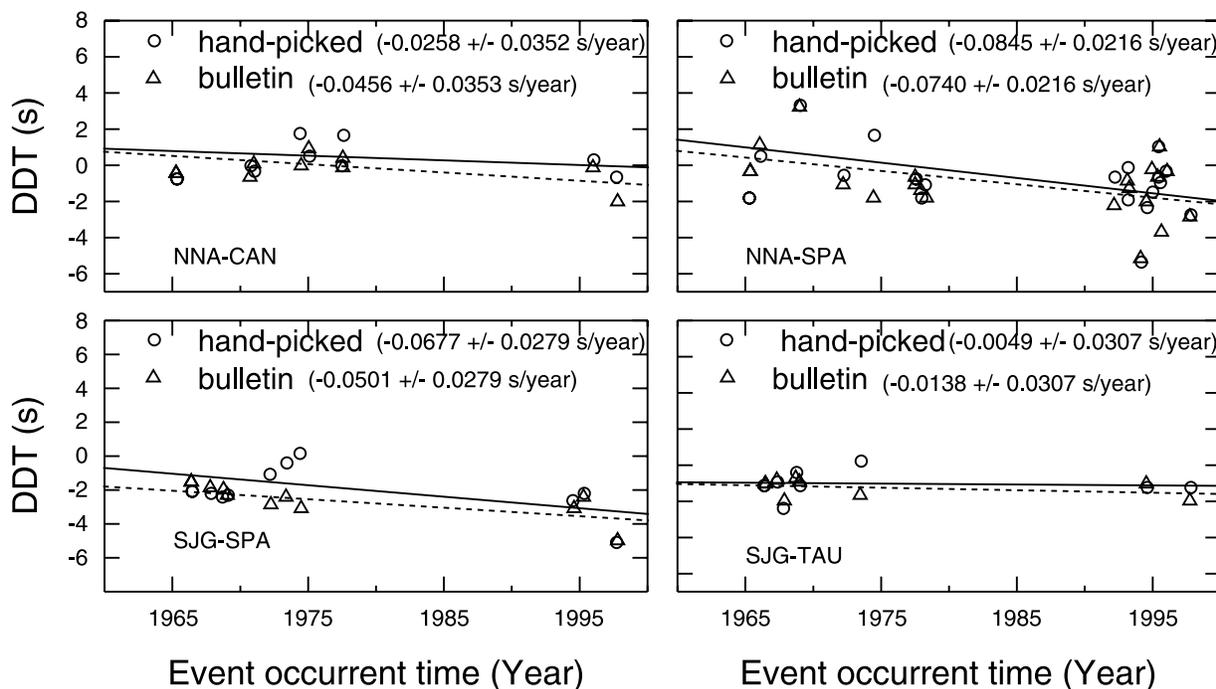


Figure 8. Comparison of DDTs from hand-picked (circles) and bulletin (triangles) data for same events and station pairs. Solid and dashed lines are linear regressions of hand-picked and bulletin data, respectively. The station pairs and regressions are labeled.

30 years, which is an order of magnitude smaller than the observed temporal change.

[25] All of the hand-picked data are from events after 1964. However, a few of the events in the bulletin data we used are before 1964, where earthquake locations were found to be particularly poor because of small number of arrival time picks available [Song, 2000a]. If we only use the events after 1964, the temporal trend for the P double difference is 0.0078 ± 0.0026 s/yr, which is even smaller than the result using all the data although the difference is not significant.

3. Approach 2: Double Difference of P Arrival Times

3.1. Method and Data

[26] Approach 2 is motivated by our desire to avoid using earthquake locations and Earth models, both of which contain errors. Such was a motivation underlying the mislocation study by *Poupinet et al.* [2000] using a “doublet” mislocation band technique or the recent report of inner core rotation by *Zhang et al.* [2005] from earthquake waveform doublets. We form a double difference of P arrival times between event i and event j that are relatively close together according to earthquake catalogs and between a north station N and a south station S as follows (Figure 10):

$$DDA(i,j) = (A_i^N - A_i^S) - (A_j^N - A_j^S). \quad (2)$$

Our objective is to examine how the arrival time double difference, DDA, changes with time as the time separation of the two events increases. Contributions to DDA include relatively small (but not precisely known) difference in the

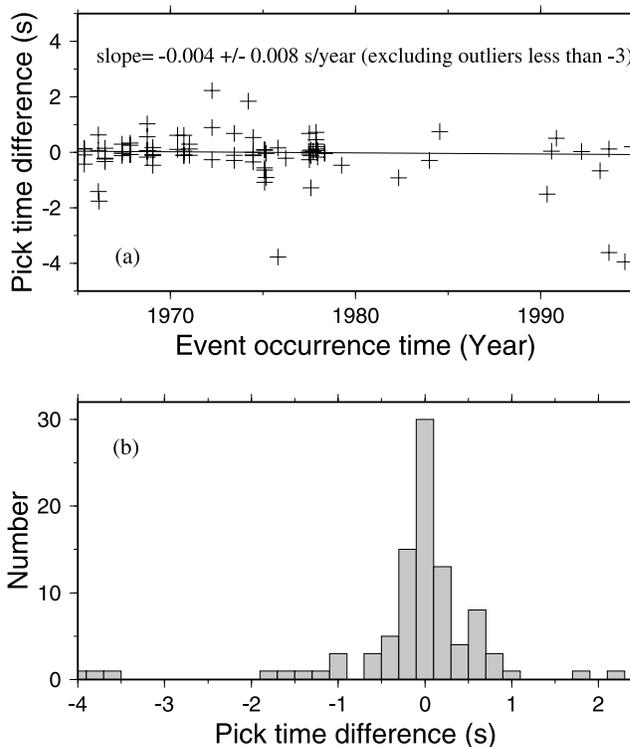


Figure 9. (a) Difference, as a function of event occurrence time, between the hand-picked arrivals and the bulletin picks for all the events and stations where both picks are available (a total of 94 data points). (b) A histogram of the difference.

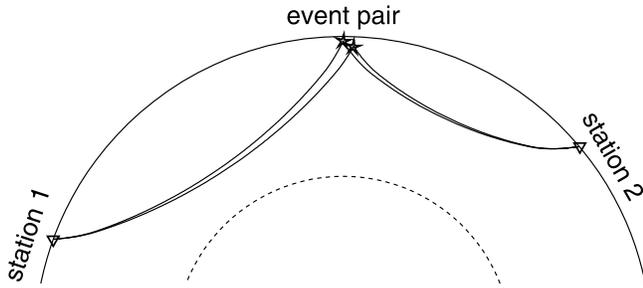


Figure 10. Schematic diagram of the arrival time double difference (DDA) method used in this study. The DDA is formed by differencing P arrival times between two stations at nearly the opposite azimuths and between two events that are close by. The dashed line indicates the core-mantle boundary. The diagram is plotted using a realistic case, but the event distance in the diagram has been exaggerated, compared to the event distance we used, to show individual ray paths.

real locations of the two events, small-scale mantle heterogeneity, and random picking errors. If there is no systematic mislocation, we expect random scatter of DDA caused by the above factors but no systematic temporal change of DDA with time separation. If the SSI events are systematically mislocated along the Alaska azimuth, we expect a systematic temporal trend in DDA as the real location difference (reflected by DDA) between two events with large time separation would be greater than the small distance indicated by the earthquake catalogs, based on which the two events are selected to form an event pair. The formulation of the arrival time double difference has similarity with the double difference method that has been widely used for earthquake relocation [Waldhauser and Ellsworth, 2000].

[27] The advantages of this approach include the ones discussed in approach 1. However, a significant addition is the fact that the calculation of DDA itself does not require any knowledge of earthquake locations or Earth models. All we need to know is that the two events in a pair are relatively close (e.g., less than 50 km, using, for example, earthquake catalogs) in order to select the pair to form the double difference. We do not need to know the precise absolute or relative locations of the events. However, the method would fail if the events in the pairs are far apart. In that case, the contribution to DDA from location difference becomes very large and overwhelms any signals from a systematic mislocation.

[28] Despite different formulations, the arrival time double difference proposed here is closely related to the double difference of travel times (DDT) proposed in approach 1. It is easy to demonstrate the following:

$$DDT(i) - DDT(j) = DDA(i,j) - \left[(P_i^N - P_j^N) - (P_i^S - P_j^S) \right], \quad (3)$$

where $DDT(i) = (A_i^N - A_i^S) - (P_i^N - P_i^S)$ is the traveltime double difference for event i , $DDA(i,j)$ is the arrival time double difference as defined in (2), and P_i^N is the predicted travel time from event i to north station N , and so forth. The term $[(P_i^N - P_j^N) - (P_i^S - P_j^S)]$ represents a model correction for the location difference of these two events as indicated

by the earthquake catalog used. When the two events are close by, this term is simply a random noise. In this case, DDT and DDA will show similar temporal trend and the two methods are equivalent. However, application of the traveltime double difference (DDT) does not have to be restricted to close-by events, as presented in approach 1. Essentially, part of the location difference is corrected by the model correction term, leaving contribution from location errors in DDT.

[29] Our basic data set is the same as part of the data used in approach 1: P arrival time picks reported by various earthquake bulletins. We choose three north stations (ARE, LPB, and NNA) and three south stations (ADE, MAW, MUN), which have the most P arrival times for the SSI earthquakes we study here (Figure 11a).

3.2. Results

[30] We conduct two studies. In the first study, we choose a group of earthquakes that are in a tight cluster within -56.5° to -55.9° in latitude and -27.9° to -26.9° in longitude (Figure 11b), so every earthquake pair are rela-

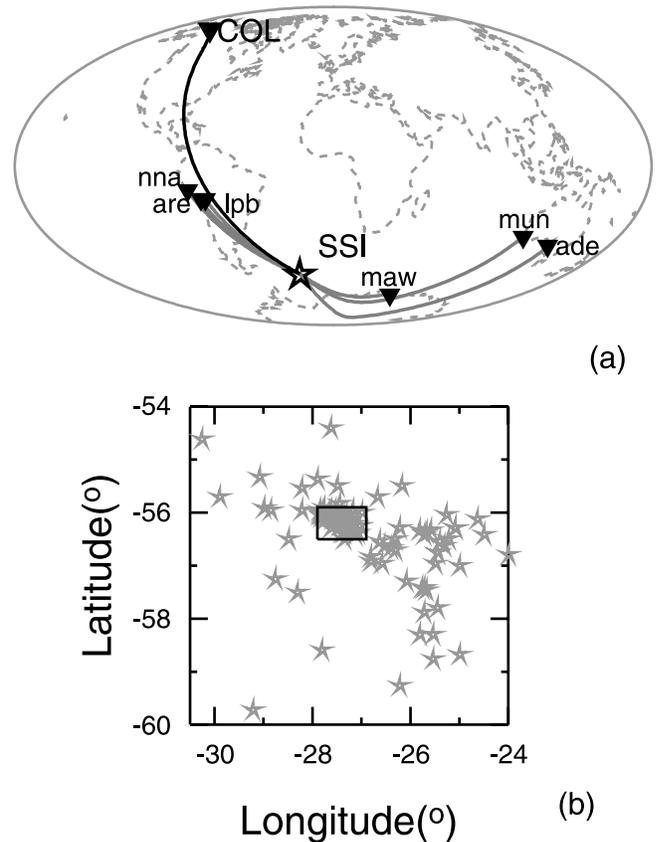


Figure 11. (a) Map of P stations used in approach 2 and COL station (inverted triangles) for SSI earthquakes. The north stations, which have similar azimuth as SSI to COL, include Arequipa, Peru (ARE); Nana, Peru (NNA); La Paz, Bolivia (LPB). The south stations, which are at nearly opposite azimuth, include Mawson, Antarctica (MAW); Mundaring, Australia (MUN); Adelaide, Australia (ADE). (b) Map of SSI earthquakes that we used in approach 2. The box centering around $(-56.2^\circ, -27.4^\circ)$ marks a cluster of earthquakes that we used for a special study.

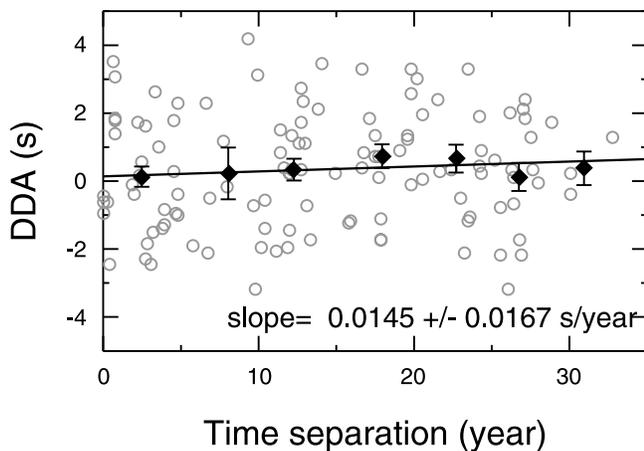


Figure 12. Observed double difference of arrival times (DDA) between the three north stations and the three south stations for the SSI earthquake cluster (Figure 11b) as a function of time separation between the two events. Diamonds and error bars are the means \pm one standard deviation for data binned at every 5 years.

tively close with each other. For each event pair, we find the DDAs for all possible nine station pairs (from the three north and three south stations). If there are at least four station pairs that have data, we select that event pair and use all the available station pairs to get an averaged DDA for that event pair. Figure 12 shows the results for the cluster. The double-difference arrival times show a small but insignificant trend (0.0145 ± 0.0167 s/yr).

[31] To estimate limit of the mislocation, we conduct synthetic tests similar to those in approach 1. We assume the earthquakes of this cluster are systematically mislocated from the real locations. Arrival times are synthesized using the “real” locations and a Earth model. These synthesized arrival times are then used to construct DDAs, which we call predicted DDAs. Because the amount of mislocation depends on time (from the assumed systematic mislocation), the predicted DDAs will change with the time separation between events. Assuming a systematic mislocation of 40 km over 30 years along the SSI-COL azimuth and uniformly distributed random errors of ± 20 km in latitude and longitude, we find the predicted DDAs have a slope of 0.159 ± 0.007 s/yr (Figure 13). Because the predicted temporal change in DDAs depends essentially on the slowness and azimuth parameters to these six stations, which change little for a small shift of event location, the temporal change is proportional to amount of mislocation over time (i.e., the averaged rate of systematic mislocation). Using the slope of the observed DDAs (Figure 12) and the synthetic test results, we estimate a systematic mislocation of 3.6 ± 4.2 km over 30 years, with the more recent events being mislocated toward Alaska relative to the older events.

[32] In the second study, we use all of our SSI events (Figure 14). We find pairs of events that are close to each other according to bulletin locations. For each event pair, we calculate the DDAs for all the station pairs (among the six stations) and then find the averaged DDA for each event pair. If we limit the distance between the epicenters of the two events for each pair to within 30 km, the DDAs have a

negligible slope of 0.0007 ± 0.0118 s/yr (Figure 14a). If we change the distance limit to within 50 km, the DDAs show larger scatter, but the slope (0.0090 ± 0.0141 s/yr) does not change significantly. A synthetic test for this scenario produces a temporal change in DDAs that is similar to the cluster case above. The predicted DDAs have a slope of 0.151 ± 0.004 s/yr for a systematic mislocation of 40 km over 30 years along the SSI-COL azimuth and a uniform random error of ± 20 km in latitude and longitude. Thus we estimate the systematic mislocation to be within 2.4 ± 3.7 km over 30 years from the second study.

[33] SSI earthquake locations before 1964 were found to be particularly poor, because of a small number of arrival

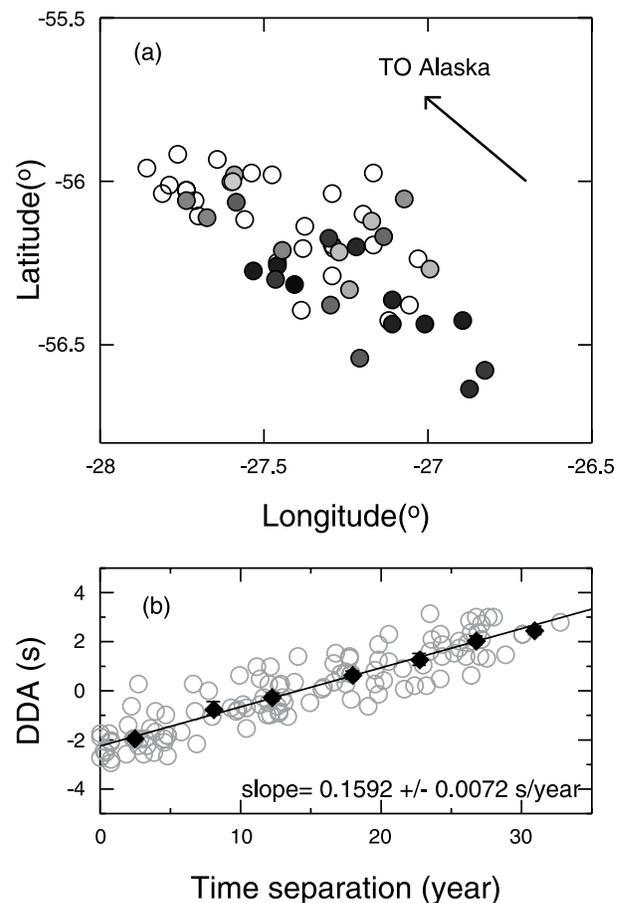


Figure 13. Synthetic test on effect of systematic event mislocation. This test uses the earthquake cluster centering around $(-56.2^\circ, -27.4^\circ)$ (Figure 11b). (a) Assuming the earthquakes reported by earthquake bulletins (open circles) are systematically mislocated by, for example, 40 km over 30 years along the COL azimuth, we reconstruct the real locations of the earthquakes (solid and gray circles). To produce systematic increase in differential PKP BC-DF times at Alaska stations, the more recent events (darker gray) are systematically mislocated toward the Alaska direction relative to the older events (lighter gray). (b) Predicted DDA as a function of event time separation, assuming ± 20 km uniform random errors in latitude and longitude as well as a systematic mislocation of 40 km over 30 years along the SSI-COL azimuth. Diamonds and error bars are means \pm one standard deviation for data binned at every 5 years.

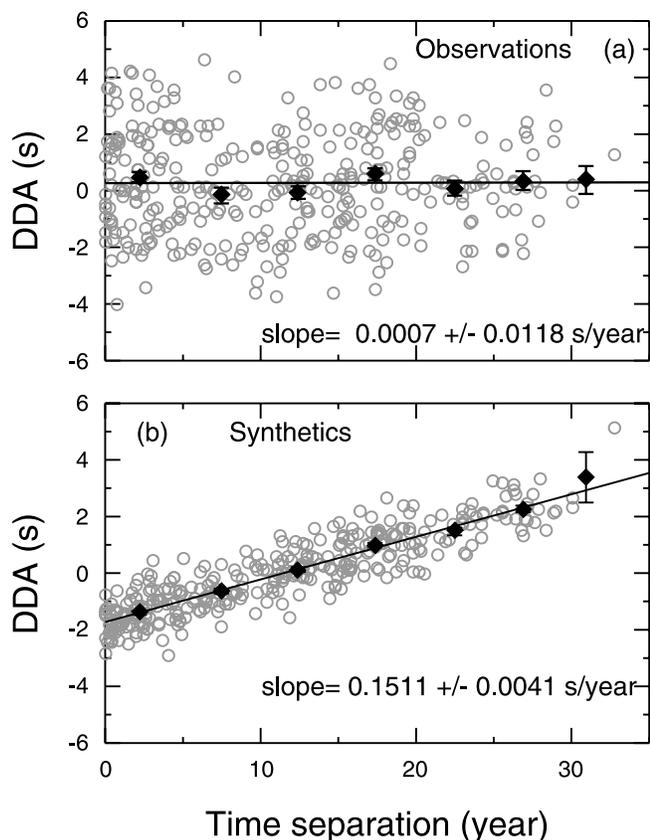


Figure 14. (a) Observed DDA for close pairs of SSI earthquakes as a function of event time separation. The epicenters of the two events of each pair are within 30 km from each other. (b) Synthetic test that is similar to Figure 13 on the same pairs used in Figure 14a. We assume a systematic mislocation of 40 km over 30 years along the SSI-COL azimuth and uniform random errors of ± 20 km in latitude and longitude. Diamonds and error bars in Figures 14a and 14b are the means \pm one standard deviation for data binned at every 5 years.

time picks available [Song, 2000a]. All the events we used in the cluster study are after 1964. A few events before 1964 were used in the second study. If we use only the events after 1964, the results do not change significantly. The DDA slope is the same for the 30 km limit on the pair distance and the slope is 0.0118 ± 0.0142 s/yr for the 50 km distance limit.

[34] In summary, results from Approach 2 using arrival time double difference suggest the systematic mislocation is very small, within 3.6 ± 4.2 km over 30 years. The mislocation would predict a shift of PKP BC-DF times at COL of 0.026 ± 0.030 s or less over 30 years, explaining a small fraction (less than 10%) of the observed temporal change (0.33 to 0.36 s over 30 years) reported for COL [Song and Richards, 1996; Song, 2000a].

4. Approach 3: Examination of PKP Traveltime Residuals

[35] PKP traveltimes are generally not used for location in earthquake bulletins, thus provide an independent data set to check earthquake location errors. Souriau and Poupinet

[2003] computed the PKP(DF) mean residual differences for stations in northern azimuths (COL, IMA, INK, MBC) and stations in southern azimuths (DDR, MAT, YSS, BOD) with respect to SSI earthquakes. They found the mean of these differences has increased with time by 0.06 s/yr, corresponding a mean shift of 22 km per 10 years along the Alaska azimuth. The systematic location shift would cause shift in differential BC-DF times at COL by about 0.16 s per 10 years, more than enough to explain the observed temporal changes at COL and other Alaska stations.

[36] Here we reanalyze the PKP data. We use both PKP(BC) and PKP(DF) traveltime residuals derived from the ISC bulletins. Unlike DF, BC is not affected by the inner core structure. It has larger apparent slowness than DF, thus it is more sensitive to mislocation. Even though BC is a secondary arrival after DF, its amplitude is generally larger than DF because of wave propagation and inner core attenuation. For BC, we select seven north stations (COL, IMA, MBC, INK, PMR, KDC, TOA) and three south stations (DDR, MAT, SHK); for DF, we also select seven north stations (same as the north stations for BC) and three south stations (DDR, YSS, MAT) (Figure 15).

[37] These stations are selected based on the following considerations.

[38] 1. They are near the SSI-COL azimuth (north stations) or the opposite azimuth (south stations). Station BOD used by Souriau and Poupinet [2003], for example, is not selected because it is nearly orthogonal to the SSI-COL azimuth.

[39] 2. The number of arrival time picks is abundant and the BC and DF picks can be separated.

[40] 3. The data coverage in time is long and uniform.

[41] All the stations we use have continuous arrival time picks for at least 17 years. Because the means of traveltime residuals at different stations are different, the uniformity of data coverage is critical in checking for systematic mislocation, when different stations are combined.

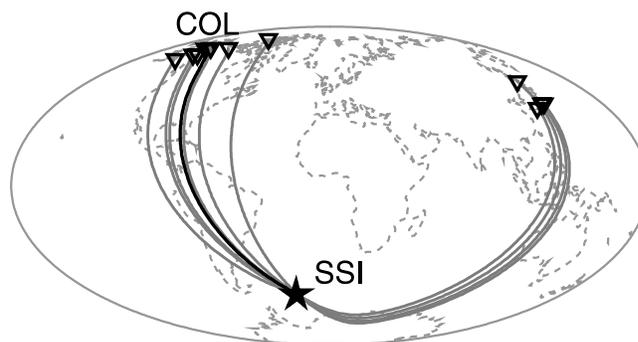


Figure 15. Map of PKP stations used in this study (inverted triangles) for SSI earthquakes. The north stations (with similar azimuth to COL) include College, Alaska (COL); Indian Mountain, Alaska (IMA); Tolsona, Alaska (TOA); Kodiak Island, Alaska (KDC); Palmer, Alaska (PMR); MOULD BAY, North West Territories (NWT), Canada (MBC); Inuvik, NWT, Canada (INK). The south stations (with nearly the opposite azimuth) include Matsushiro, Japan (MAT); Shiraki, Japan (SHK); Dodaira, Japan (DDR); and Yuzhno-Sakhalinsk, Russia (YSS).

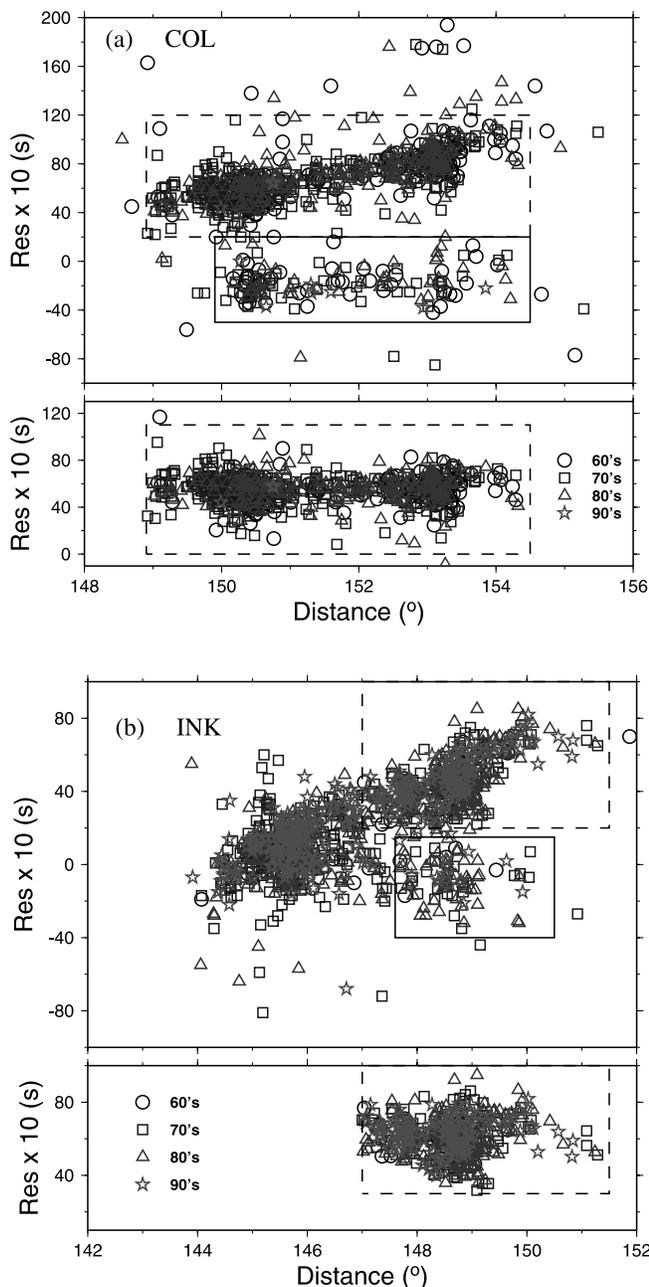


Figure 16. Examples of how we select PKP(DF) and PKP(BC) arrivals from ISC residuals. Different symbols are used for data at different decades. (a) Station COL, where DF and BC picks are clearly separated. The DF picks scatter around zero (in traveltime residuals) and the BC picks have positive residuals and a positive slope (top). After windowing out BC picks and removing the slope, we use another window to select data to have as uniform temporal coverage as possible. (b) Same as Figure 16a, but for station INK. At smaller distances, DF and BC phases come together; thus it is important to apply appropriate windows to select DF and BC picks.

[42] Figure 16 shows two examples of our selection process. We first plot all the PKP residuals as a function of distance. We then window out DF picks, which have near zero slowness, and BC picks, which have a positive slope

(because the residuals were calculated relative to the DF phase). After removing the slope of the windowed-out BC picks, we apply another window to select the BC picks. The BC picks after the removal of the slope represents the traveltime residuals of the BC phase that are used for further analysis. This process of carefully separating BC picks from DF picks is particularly important to reduce misidentification of arrival picks for stations at smaller distances where BC and DF arrival times are closer together (Figure 16b).

[43] Figures 17a and 17b show BC residuals as function of event occurrence time for all the seven north stations and the three south stations, respectively. A few outliers that differ from the mean of each plot by more than 3 s have been windowed out. The north stations show flat or small positive slopes up to 0.13 s/decade. The data for the south stations show larger scatters with the slopes varying from -0.10 to 0.42 s/decade.

[44] Figure 18 shows the combined BC residuals with the mean of each station removed. The combined northern residuals show a small positive slope (0.057 ± 0.020 s/decade) and the combined southern residuals show a small negative slope (-0.054 ± 0.100 s/decade), which are consistent with a systematic mislocation over time along the SSI-COL azimuth. The difference between the northern and the southern data binned every 2 years has a slope of 0.184 ± 0.138 s/decade. The slope of the residual difference is substantially larger than the combination of the slopes of the north and the south stations but it also has a larger error. Using similar synthetic tests as before for the same sets of earthquake and stations, we estimate a systematic mislocation of 40 km over 30 years along the COL direction would produce a temporal change of about 0.51 s/decade in the residual difference between the north and the south stations. Thus, if we assume the observed BC residual difference is caused by a systematic mislocation in the COL direction, the mislocation is about 14.4 ± 10.8 km over 30 years.

[45] Results for the combined DF residuals are shown in Figure 19. The combined north stations and south stations both show a similar positive slope (Figures 19a and 19b), thus the combined data are not consistent with a systematic mislocation. The difference between the binned residuals of the north and the south stations (Figure 19c) has a small slope of 0.063 ± 0.085 s/decade. The slope is not significant (within one standard deviation). Furthermore, the DF residuals may be affected by the inner core structure if the inner core is rotating. Nonetheless, if we attribute the DF slope to earthquake mislocation along the SSI-COL direction, we estimate the mislocation to be about 9.2 ± 12.4 km over 30 years.

[46] In summary, we compared PKP residuals between a group of north and south stations using ISC arrival time picks. The mean residual difference in BC residuals between north and south stations has a slope of 0.184 ± 0.138 s/decade, based on which the mislocation along the COL-SSI azimuth is estimated about 14.4 ± 10.8 km over 30 years. The mislocation would predict a shift of BC-DF times at COL of 0.104 ± 0.078 s over 30 years, or about $30\% \pm 22\%$ of the observed temporal change of BC-DF times at COL. The mean residual difference in DF residuals between north and south stations has a slope of 0.063 ± 0.085 s/decade, which is not statistically significant. The DF residuals may also be affected by the inner core structure if

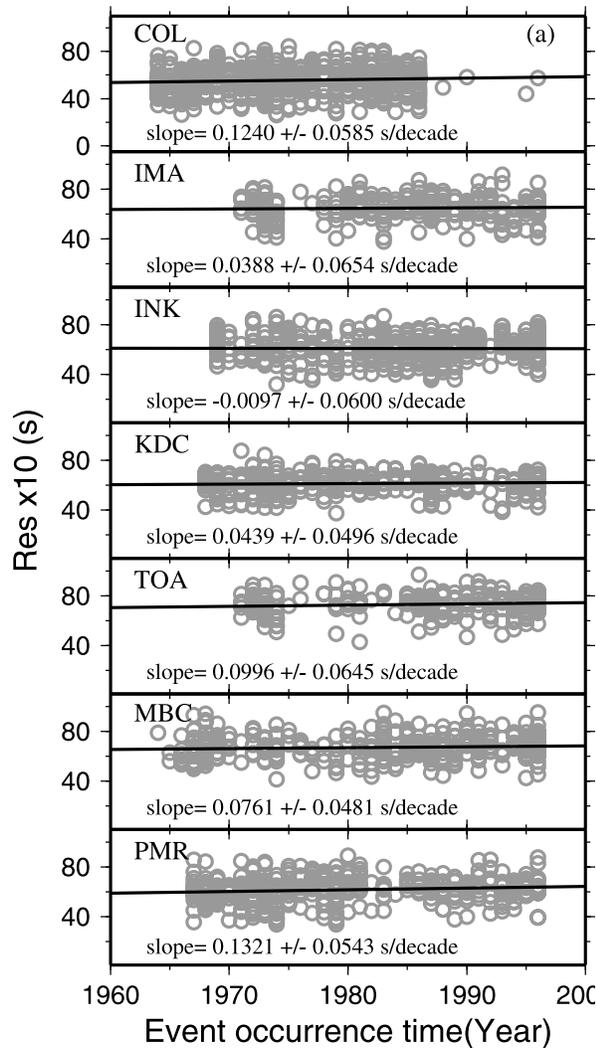


Figure 17. PKP(BC) residuals as a function of event occurrence time for (a) seven north stations and (b) three south stations, respectively. Lines are linear regressions of the data.

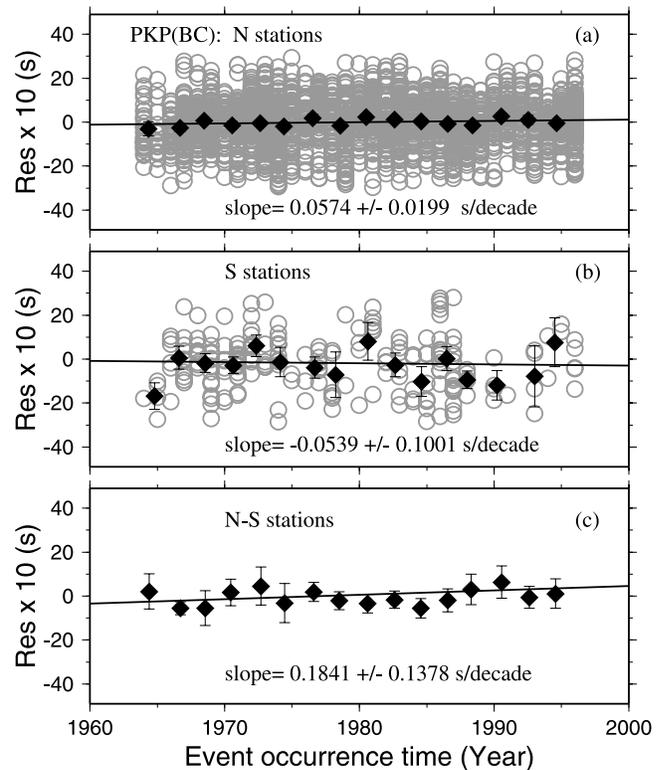
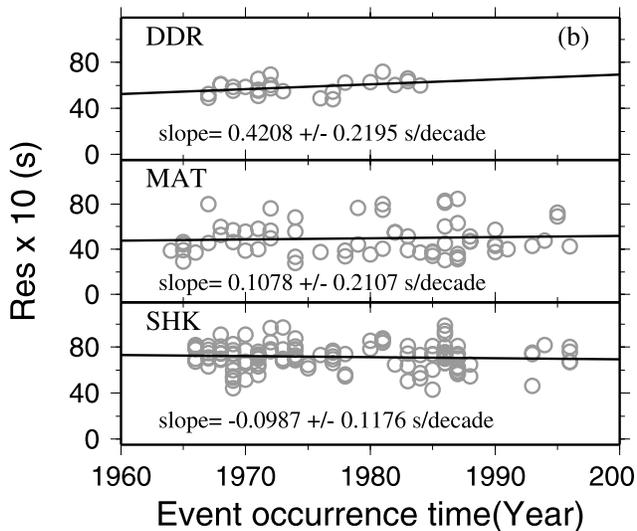


Figure 18. Combined PKP(BC) residuals (symbols) and the linear regressions (lines). Combined data (gray open circles) for (a) all the north stations and (b) all the south stations after the mean of each station has been removed. The diamonds and error bars show the means \pm one standard deviation for data binned at every 2 years. (c) Difference between binned residuals of the combined north stations and the south stations. The regression is made on the difference of the binned residuals.

the inner core is rotating. However, if we attribute the slope to mislocation along the SSI-COL direction, we estimate the mislocation to be about 9.2 ± 12.4 km over 30 years.

5. Discussion and Conclusion

[47] We use three independent approaches to estimate the extent of systematic mislocation of SSI earthquakes along the SSI-COL direction. Approach 1 examines how the P wave double difference, formed between observed and predicted traveltimes and between a north and a south stations, changes with time. Because of its great sensitivity to mislocation, the double difference provides a powerful way to estimate systematic mislocation. Approach 2 is similar to approach 1, but uses P arrival times directly, which avoids using earthquake locations and Earth models entirely. Approach 3 compares PKP residuals between a group of north and south stations using ISC arrival time picks.

[48] The basic results from these three approaches are summarized in Table 2. The results from approaches 1 and 2, both of which use P data, are generally consistent. The mislocation is up to 3.6 ± 4.2 km, explaining less than 10% of the observed COL temporal change. The results from

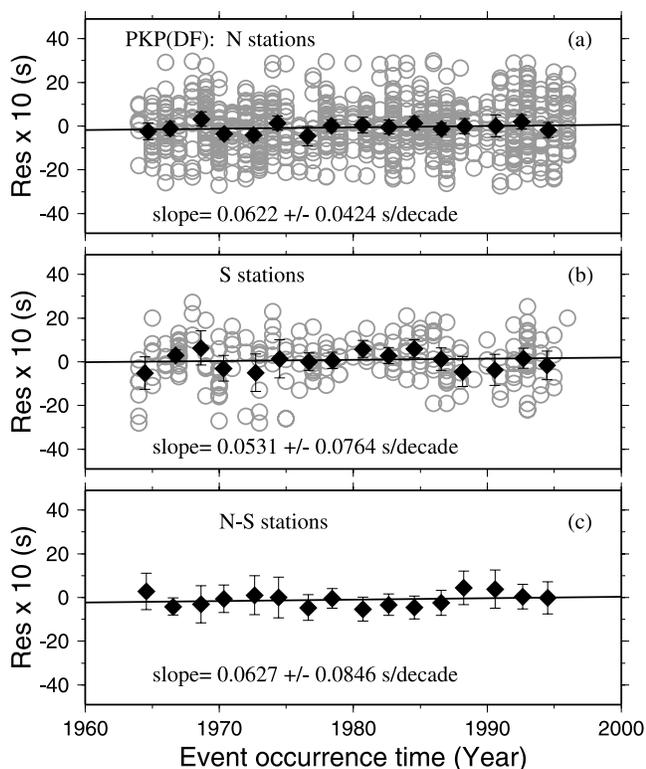


Figure 19. Same as Figure 18 but for PKP(DF).

approach 3 using PKP data show a larger mislocation but with a larger error (14.4 ± 10.8 km over 30 years). It can explain about $30\% \pm 22\%$ of the observed COL temporal change.

[49] We have so far ignored the effect of possible systematic mislocation in earthquake depth for some reasons. First, the differential BC-DF time is not sensitive to depth mislocation: a mislocation of 100 km in depth would result a change in the BC-DF time of about 0.10 s. Thus, to explain the temporal change at COL would require systematic mislocation of about 300 km over 30 years. This is not possible because of the shallow seismicity in the SSI: 98.5% of the earthquakes we used are less than 150 km in depth and 65.7% are less than 100 km. Second, it is not obvious how changes of station distribution over time would cause systematic mislocation in earthquake depth. Perhaps because of these considerations, mislocation in depth has not been proposed as a significant source of the observed temporal change of the BC-DF times.

[50] Nevertheless, our basic method above (e.g., P travel-time double difference, DDT) can also be used to test depth mislocation. If the two stations are at similar distance,

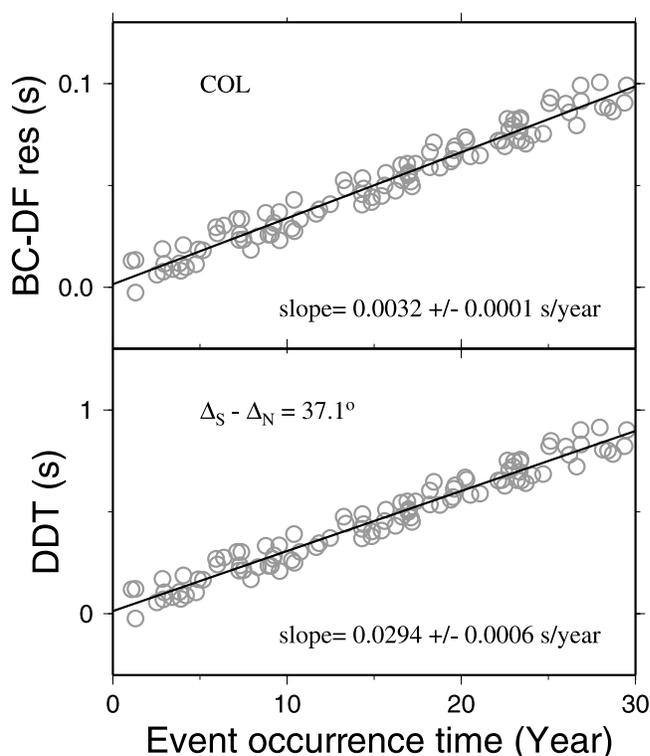


Figure 20. Synthetic tests on the effect of systematic depth mislocation. We assume SSI earthquakes have been systematically mislocated to shallower depths by 100 km over 30 years. (top) The differential BC-DF times at COL would increase about 0.10 s. (bottom) For a station pair with a north station at distance of 43.8° (station BAO) and a south station at distance of 80.9° (station TAU), i.e., distance difference of 37.1° , the DDT values would increase by 0.89 s over 30 years. Note the vertical scales differ by 10 times.

the DDT value is not sensitive to depth mislocation. However, the sensitivity increases with the distance difference. If we assume the depth is systematically mislocated to shallower depths by 100 km over 30 years, the BC-DF times at COL would increase by about 0.1 s over 30 years, while the DDT values from two stations with 37° difference in the epicentral distances would increase by 0.89 s, i.e., almost an order of magnitude larger than the BC-DF time change (Figure 20). Table 3 shows the observed DDT changes over 30 years from linear regressions of the station pairs with distance difference greater than 20° . The data used are essentially part of the data used in Figure 4 for the catalog data and Figure 7 for the hand-picked data. The

Table 2. Summary of Mislocation Results From Different Approaches

Approach	Double Difference in 30 years, s	Mislocation, km	Contribution, ^a %
1, P travel time double difference	bulletin 0.282 ± 0.078	2.9 ± 0.8	6.4 ± 1.8
	hand-picked -0.006 ± 0.135	-0.1 ± 1.4	-0.1 ± 3.0
2, P arrival time double difference	0.435 ± 0.501	3.6 ± 4.2	7.9 ± 9.1
3, PKP travel time double difference	BC 0.552 ± 0.414	14.4 ± 10.8	31.5 ± 23.6
	DF 0.189 ± 0.255	9.2 ± 12.4	20.0 ± 26.9

^aContribution is the percentage of predicted BC-DF time shift at COL from the mislocation relative to the observed temporal change.

Table 3. Observed and Synthetic DDT Changes Over 30 Years From Depth Mislocation Tests^a

Distance Difference	Catalog		Hand Picked	
	Observed	Predicted	Observed	Predicted
$\Delta_S - \Delta_N > 20^\circ$	0.47(0.11)	0.83(0.01)	0.06(0.31)	0.48(0.04)
$\Delta_N - \Delta_S > 20^\circ$	-0.18(0.22)	-0.83(0.02)	-0.06(0.19)	-0.91(0.00)

^aThe predictions assume a 100 km systematic earthquake depth change over 30 years, with random error of 10 km. Numbers in the parentheses are one standard deviation.

predictions in Table 3 use the same stations pairs and assume a systematic depth mislocation of 100 km over 30 years and a random error of 10 km. Comparing the observations and predictions for different groups of station pairs, we estimate systematic depth mislocation of 57 km to 7 km over 30 years, which explains at most 0.05 s of differential BC-DF residual change during the same period of time.

[51] Our estimate of mislocation from approaches 1 and 2 using P data (up to 3.6 ± 4.2 km over 30 years) is an order of magnitude smaller than the previous estimate of a mean location shift of 22 km per 10 years (or 66 km over 30 years), in which *Souriau and Poupinet* [2003] used the similar technique but different data (PKP residuals). Furthermore, our estimate of mislocation from approach 3 is several times smaller than that of *Souriau and Poupinet* [2003]. Approach 3 and *Souriau and Poupinet* [2003] use the same technique and the same original data set. However, there are a number of differences in data selection and processing.

[52] 1. This study focuses on SSI earthquakes only. The earlier study used a much larger region (that has the same earthquake regional number as the SSI).

[53] 2. Some of the north and south stations used are different. Station BOD, used previously but not here, is nearly orthogonal to SSI-COL azimuth and has very different azimuth with other south stations.

[54] 3. Different windows are applied here to separate and select DF and BC picks for different stations. The previous study, however, applied a uniform window of ± 4 s to the original ISC PKP residuals to select DF picks, particularly at small distances (Figure 16b). The selected DF picks were likely contaminated by BC picks.

[55] 4. In the previous study, the means of individual stations were not removed when the data from different station were combined. The result may be contaminated by uneven temporal distribution of data between different stations as discussed above.

[56] We have only examined here time-dependent mislocation along the SSI-COL azimuth. Mislocation along this azimuth causes greatest change in predicted differential BC-DF times, thus the greatest change in the observed BC-DF residuals. Mislocation along the orthogonal azimuth changes little in predicted BC-DF times for a 1-D Earth model. However, azimuthal traveltimes variation is often observed from 3-D heterogeneous Earth. A large systematic mislocation along the orthogonal azimuth can cause systematic temporal change in BC-DF times from strong lateral variations in the inner core and the lowermost mantle. This issue remains to be explored. For example, strong velocity

gradient has been observed in the inner core underneath the Central America sampled by the SSI-Alaska paths [*Creager, 1997; Song, 2000a*]. Differential BC-DF times change about 1 s over a longitudinal distance of 30 degrees. A shift of SSI earthquake location by 1° (or 111 km) along the orthogonal azimuth would shift the sampling longitude in the inner core by about 1.8° , resulting in a shift of BC-DF times of about 0.06 s. The shift cannot explain the observed temporal BC-DF change, but may contribute a small fraction.

[57] In conclusion, inner-core superrotation is still the best explanation for the observed temporal change in the differential PKP traveltimes. Earthquake mislocation is several times to an order of magnitude smaller than that needed to explain the observed temporal change.

[58] **Acknowledgments.** Brian Kennett at Australian National University gave access to old paper seismograms for Canberra, Australia, station. We thank two anonymous reviewers, the Associate Editor, and the Editor for very helpful comments. The work was supported by the UIUC/CNRS Cooperative Research Program and NSF-EAR 0409251.

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