Support for differential inner core superrotation from earthquakes in Alaska recorded at South Pole station

Xiaodong Song and Anyi Li
Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York

Abstract. Observational evidence for differential inner core rotation has recently been reported. The most convincing evidence has been restricted to one ray path from earthquakes in the South Sandwich Islands to stations in Alaska. Here we show that the differential travel times between PKP(DF) and PKP(BC) for a new ray path from earthquakes in southern Alaska to the station at the South Pole have increased by about 0.6 s over 37 years, providing support for a differential inner core rotation. We apply a newly developed technique to invert simultaneously for the inner core structure and the rotation rate. The rotation rate determined from the new pathway is about 0.6°/yr faster than the mantle, compatible with the estimates of the rate from earthquakes in the South Sandwich Islands to stations in Alaska. We also address some criticisms concerning the reported detection of the differential inner core rotation, including biases from event mislocations, biases from mantle heterogeneity, and uncertainty in the tilt of the inner core anisotropy axis. We show that although these potential biases would affect the determination of the rotation rate, they are unlikely to account for the observed time dependence in the BC-DF times. We found no evidence for a correlation between BC-DF residuals and event magnitudes as suggested previously.

1. Introduction

The early ideas that the Earth’s solid inner core, at the center of a larger fluid outer core of low viscosity, may rotate differently than the daily rotation of the mantle came from studies of the geodynamo. Cumbins [1981] first suggested that the electromagnetic forces between the electrically conducting inner core and the magnetic field generated in the fluid outer core would make the inner core rotate. His rough estimate of rotation rates gave the same order of magnitude as the westward drift of the geomagnetic field, which is ∼0.2°/yr and indicative of the flow velocity at the top of the fluid outer core. The plausibility of inner core rotation was greatly strengthened by recent three-dimensional computer simulations of the geodynamo of Glatzmaier and Roberts [1995], which predicted that the inner core is generally rotating a few degrees per year faster than the mantle.

Observational evidence for differential inner core rotation has come from relative travel times between PKP(DF) waves (which penetrate the inner core) and PKP(BC) waves (which turn at the bottom of the outer core) along certain earthquake-station pathways [Song and Richards, 1996]. In particular, we found that the BC-DF differential times along the pathway from earthquakes in South Sandwich Islands (SSI) to the station CO1 at College, Alaska, have changed systematically over 28 years by ∼0.3 s. We interpreted the temporal change as evidence for a differential inner core rotation, which shifts the orientation of the inner core’s anisotropy [e.g., Morelli et al., 1986; Woodhouse et al., 1986; Song, 1997]. We estimated the rotation rate to be ∼1°/yr assuming a homogeneous inner core anisotropy model with the anisotropy symmetry (fast) axis tilted from the spin axis. Shortly after, Su et al. [1996] used a large quantity of PKP(DF) arrival time picks reported to the International Seismological Centre (ISC) and inverted for the locations of the anisotropy axis and therefore the inner core motions by dividing the 30-year-long data set into six 5-year segments. They found that the inner core appears to rotate at ∼3°/yr eastward.

Determining the inner core rotation from the tilt of anisotropy axis, however, has been suggested to be problematic. The anisotropy symmetry axis may not be reliably determined by PKP(DF) arrival times [Sourtet et al., 1997; Dziewonski and Su, 1998]. Recent studies suggest that the inner core anisotropy is much more complex [Tanaka and Hamauchi, 1997; Creager, 1997; Song and Helmberger, 1998] than a simple homogeneous model, making it difficult to define a symmetry axis for

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1 Now at Department of Geology, University of Illinois, Urbana-Champaign.

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the whole inner core. A reassessment by Dziewonski and Su [1998] of the temporal variation of the total pattern of the inner core anomalies suggests that the inner core rotation is not detectable from the ISC data. The uncertainty of the tilt of the symmetry axis, however, does not affect the observation that the travel times at COL have apparently changed, which was confirmed by Creager [1997].

Using travel times from three SSI earthquakes in 1991 to 37 stations of the Alaska Seismic Network (ASN), Creager [1997] suggested that the lateral velocity gradient in this part of the inner core is steep so that the temporal change at COL is reinterpreted with a much smaller differential rotation rate of 0.3°/yr. Following a similar approach, Souriau [1998a] examined BC-DF times from Novaya Zemlya nuclear explosions recorded at NVV, Antarctica over 23 years. No robust temporal change in the BC-DF residuals along this path was observed. She compared the BC-DF residuals with the residuals of PKP(DF) rays sampling the neighboring longitudes of the inner core, which were calculated from ISC bulletins using events relocated by Engdahl et al. [1998]. She concluded that an eastward rotation of 3°/yr as in the work by Su et al. [1996] is not possible, but a rate of 1°/yr or lower could not be ruled out. Results from recent normal-mode studies on the inner core rotation are uncertain. Sharrock and Woodhouse [1998] appear to favor a westward rotation component; but Laske et al. [1999] found that a small eastward rotation of <0.3°/yr are consistent with their mode data.

The studies of Creager [1997] and Souriau [1998a], however, raise some problems. First, the determination of the inner core rotation from the temporal change of a fixed path trades off with the estimate of the local velocity structure in the inner core, which can be complicated by mantle heterogeneity. Depending on the estimate of the local lateral gradient, Creager's [1997] estimate of the rotation rate varies from 0.2-0.3°/yr to as low as 0.05°/yr. Second, the problem of estimating local velocity changes becomes much worse when absolute PKP(DF) times are used (as by Souriau [1998a]), which are much more severely biased by upper mantle heterogeneity than BC-DF differential travel times. Furthermore, the part of the inner core that was sampled by a fixed path (in the mantle reference frame) in the past can only be sampled by the paths that go through different parts of the mantle at a later time as the inner core rotates. Therefore, the discrepancies considered by Souriau [1998a] between the BC-DF residuals along a fixed path and the PKP(DF) residuals of the summary rays sampling different longitudes of the inner core may be the result of lateral variation in the mantle and not the inconsistency of the inner core rotation considered.

On the other hand, if BC-DF differential times from different periods of time but sampling the same patch of the inner core are used, we can invert jointly for the inner core rotation and the lateral change of inner core anisotropy. Furthermore, because mantle biases do not change as the inner core rotates, mantle biases can also be separated from time-dependent inner core structure with such a joint inversion, provided that the samples are dense enough. The technique was successfully applied to a large data set (of 611 measurements) that combines SSI earthquakes of the last 30 to 50 years to four stations in Alaska (including COL) and SSI earthquakes of the last decade to over 100 ASN stations [X.D. Song, Joint inversion for inner core rotation, inner core anisotropy, and mantle heterogeneity, submitted to Journal of Geophysical Research, 1999, hereinafter referred to as Song, submitted manuscript, 1999]. The results suggest a robust estimate of an eastward inner core rotation with the rate ranging from 0.3 to 1.1°/yr.

In this study we apply the same approach to earthquakes in southern Alaska recorded at the South Pole station (SPA). The pathway has several characteristics that help us study the inner core rotation. (1) It is a north-south path with the ray angle from the spin axis of ~15°, which was previously identified to have large BC-DF anomalies [Song and Helmberger, 1993]. The largest anomalies and lateral variations from the inner core have all been identified with north-south paths, thus a north-south path is a good start to detect travel time changes. Furthermore, if the axis of the inner core rotation is the same or close to the spin axis, the effect of the shift of a local lateral velocity gradient or a local orientation of the anisotropy from an inner core rotation on travel times is expected to be the largest for north-south ray paths (which would be perpendicular to the direction of the shift). (2) The SPA station has a long history of continuous operation. (3) The great circle paths from anywhere in the globe to SPA are along the corresponding longitudes of the sources, making it easy to sample a sweep of inner core longitudes needed to determine the lateral variation of the path sampled.

2. Data Sources

The SPA station was installed in 1956 and was equipped with the World-Wide Standardized Seismographic Network (WWSSN) instruments in February 1963 [Glover, 1977], which were replaced by broadband digital seismometers in December 1991. We obtained analog short-period WWSSN vertical seismograms of earthquakes in southern Alaska recorded at SPA from (1) original paper records from January 1958 to March 1963 at a U.S. Geological Survey (USGS) warehouse at the Federal Center in Denver, Colorado, and (2) film chip archives from 1964 to 1989 at Lamont-Doherty Earth Observatory. A few paper records in the early 1970s were obtained from the National Archives at the Denver Federal Center. The analog records were scanned into computer and digitized (Figure 1). Differential BC-DF travel times were measured using cross-correlation techniques. Digital broadband records in the 1990s obtained from the Incorporated Research Institutions for Seismology Data Management Center were first converted to the WWSSN short period instrument before time measurements. We obtained 39 BC-DF measurements
with cross correlation coefficients ≥ 0.5 for events from 1958 to 1995 that are located within the longitude range from 153.4°W to 140°1′W in Alaska (Figure 2).

3. Inferred Inner Core Rotation

An important source of error in inferring temporal changes of travel times is potential systematic event mislocation due to uneven growth with time of the global station networks used to locate the earthquakes. We thus consider earthquake locations from three sources: the USGS Earthquake Data Report (EDR), the catalog of events relocated by Engdahl et al. [1981] (EHB) and a joint hypocenter determination (JHD) in this study. The JHD computer program, provided by J. Dewey of the USGS, uses a similar set of stations for all events, thus improving relative event locations. The P arrival time picks used in the JHD were obtained from the

Figure 2. (top) Location of 39 earthquakes in Alaska used in this study. The numbers indicate of the time windows of the earthquakes: 1, 1958-1968; 2, 1968-1978; 3, 1978-1988; 4, 1988-1995. The coastline is shown in the dotted line. (bottom) Map of the ray paths from the Alaskan earthquakes to the station SPA at the South Pole.
ISC bulletins for events after 1964 and the ISS (International Seismological Summary) bulletins for earlier events. The average numbers of $P$ arrival time picks are 109, 149, 274, and 413 for events in 1958-1963, 1964-1974, 1974-1985, and 1990s, respectively. The averages of the major axes of the 90% confidence ellipses from the JHD are 14.0, 11.6, 11.3, and 16.7 km for the events in these periods, respectively.

Figure 3 shows the $BC$-$DF$ residuals as a function of the earthquake occurrence times. The residuals were calculated using event locations from EDR, EHB, and JHD, respectively. Currently, the EHB relocations are available only for events after 1964. Despite large scatter, the residuals show a clear increase with time. The slopes of the linear regressions of the residuals are $0.01553 \pm 0.00752$ ($1\sigma$), $0.01835 \pm 0.00740$, $0.01858 \pm 0.00789$ s/yr from the data sets with the EDR locations (39 events), the JHD locations (37 events), and the EHB locations (30 events), respectively. The fact that the residuals and their time dependence do not change significantly using either the original EDR locations or the relocated locations from the EHB or the JHD suggests that the time dependence is unlikely to be caused by event mislocations. The null hypothesis that the residuals have no correlation with time can be rejected at the confidence levels of 95.4%, 98.2%, and 97.4% from the three data sets with EDR, EHB, and JHD locations, respectively.

The inference of the rotation rate depends on both the time dependence of the travel times and the local inner core velocity structure sampled by the ray paths. If we use Crouch's (1997) assumption that each travel time changes are caused by shifts of a laterally-varying inner core structure due to an inner core rotation around the spin axis, the rotation rate is the temporal gradient divided by the longitudinal velocity gradient when the ray paths are parallel to the longitudinal direction as in this study. Figure 4 plots the observed travel time residuals (normalized by the travel times in the inner core) as a function of longitude and time. Plotted also are equi-residual contours of the residuals and bilinear fits (dashed lines) on longitude and time to the residuals. The temporal gradient (along horizontal direction) and the longitudinal gradient (along vertical direction) from the bilinear fits are $0.01849/\text{yr}$ and $0.02192/\text{deg}$, giving a rough estimate of the rotation rate of $0.84^\circ/\text{yr}$. Note the temporal trend and the longitudinal gradient are observable directly from both the observed residuals and the equi-residual contours.

The above analysis can be formally formulated as a joint inversion problem to infer the inner core rotation rate and the lateral velocity gradient [Song, submitted manuscript, 1999] as follows:
\[ \delta v(\theta_i, \phi_i, \xi_i, \tau_i^{IC}, T_i) = \delta v_0 + \frac{\partial v}{\partial \phi}(\phi_i - \phi_0) - \frac{\partial v}{\partial \phi}\alpha(T_i - T_0) + \frac{\partial v}{\partial \tau^{IC}}(\tau_i^{IC} - \tau_0^{IC}) + \Delta v_i^{\ell}, \]  

(1)

where \(i = 1 \ldots N \) and \(N \) is the number of observations; and \(\delta v(\theta_i, \phi_i, \xi_i, \tau_i^{IC}, T_i)\) is the inner core velocity perturbation averaged along the ray through the inner core with the total accumulated time in the inner core \(\tau_i^{IC}\), the ray angle from the spin axis \(\xi_i\), and the ray bottoming point at latitude \(\theta_i\) and longitude \(\phi_i\) with respect to the mantle reference frame at time \(T_i\). Since most of the observed BC-DF residual \(\delta t_i^{obs}\) is likely from the inner core anisotropy, \(\delta v(\theta_i, \phi_i, \xi_i, \tau_i^{IC}, T_i)\) is approximated by \(\delta t_i^{obs}/\tau_i^{IC}\). The longitudinal gradient \(\partial v/\partial \phi\) represents the velocity gradient sampled by the paths since these paths are exactly north-south. \(\alpha\) is the inner core rotation rate (positive means an eastward rotation). The \(\partial v/\partial \tau^{IC}\) term takes into account a possible change of \(\delta v\) with depth. \(\Delta v^{\ell}\) is a correction for anisotropy due to slight differences in the ray directions. For a transversely isotropic medium such as the inner core, the velocity perturbation with direction can be expressed as \([\text{c.g., Song, 1997}]\) \(b \cos^2 \xi_1 \cos^2 \xi_2\), where \(b\) and \(c\) are constants; and \(\Delta v_2 = (b \cos^2 \xi_2 \cos^2 \xi_2) - (c \cos^2 \xi_2 \cos^2 \xi_2)\), where \(\xi_0 = 14.7^\circ\) is the average of the ray angles from the spin axis. Here we use \(b = 2.56\) and \(c = 5.17\) of Song and Richards [1996]; our results do not change if other models, such as that of Cresser [1992] or Song and Helmberger [1993], are used. The reference value \(\phi_0 = -148.8^\circ\) is the average of the bottoming point longitudes; \(\tau_0^{IC} = 126.2\) s is the average of the travel times through the inner core; and we choose the reference time \(T_0 = 1995.0\) s. \(\delta v_0\) is the reference velocity perturbation corresponding to the above specified reference values. Thus the term \(-\partial v/\partial \phi\) \(\alpha(T - T_0)\) is the travel time change (as a percentage of the total time through the inner core) caused by the shift of the lateral velocity gradient due to the rotation.

The inversion scheme differs from that of Cresser [1997] in that (1) we directly parameterize velocity perturbation \(\delta v\) in terms of the coordinates of the ray in the inner core (instead of the azimuth and distance of the ray); and (2) with samples more uniformly distributed in space and time, we can invert simultaneously for the inner core lateral gradient and the rotation rate.

The results of the least squares (LSQ) inversion is shown in Table 1. The robustness of each term in the inversion can be measured by the corresponding standard deviation using Student’s \(t\) test. Following Song [submitted manuscript, 1999], we test two important null hypotheses: (1) \(\alpha = 0\) (no rotation), and (2) \(\alpha < 0\) (westward rotation). Using estimates of the \(\partial v/\partial \phi\) \(\alpha\) term in Table 1, the null hypothesis (1) can be rejected at 99.999%. For null hypothesis (2), let \(A = \partial v/\partial \phi\) and \(B = (\partial v/\partial \phi)\alpha\), then the probability that \(\alpha < 0\) is \(P(B/A < 0) = P(B > 0)P(A < 0) + P(B < 0)P(A > 0)\). Each probability on the right can be calculated using Table 1 and a one-sided \(t\) test. We found

Table 1. Least Squares Inversions for Inner Core Structure and Rotation

<table>
<thead>
<tr>
<th>(\frac{\delta v}{\delta \theta}) %/deg</th>
<th>(\frac{\delta v}{\delta \phi}) %/yr</th>
<th>(\frac{\delta v}{\delta \tau^{IC}}) %/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.417</td>
<td>-0.0306</td>
<td>-0.0197</td>
</tr>
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</table>

The numbers in the parentheses are one standard deviations of the corresponding LSQ solutions.

The observed BC-DF residuals \(\delta t_i^{obs}\) can potentially be biased by mantle heterogeneity, which were not included in the inversion above. We examined such biases by dividing the observed residuals into a time-dependent inner core part and a time-independent mantle part: \(\delta t_i^{obs} = \delta v(\theta_i, \phi_i, \xi_i, \tau_i^{IC}, T_i)\) \(\tau_i^{IC}\) + \(\delta t_i^{mantle}\). The mantle correction \(\delta t_i^{mantle}\) includes all the mantle contribution for the ray originated from the source \(s\). We grouped the sources shown in Figure 2 into five grids of 3° in latitude and 3° in longitude; all rays from the same grid have the same mantle correction. Unfortunately, the new joint inversion that includes the mantle correction terms using the 39 BC-DF residuals suggests that the mantle terms are not resolvable. Nevertheless, the time-dependent term (with \(1 \sigma\) error) \(\delta t_i^{mantle}(\partial v/\partial \phi)\alpha = -0.0166 \pm 0.0060\%)/yr is quite similar to that obtained from the inversion above without including mantle corrections (Table 1), and the null hypothesis of no rotation can be rejected at 99.0% confidence level from the new joint inversion. The mantle corrections primarily trade off with the inferred inner core lateral gradient, thus the inferred rotation rate.

Another uncertainty in the determination of the rotation rate is the undetermined tilt of the inner core anisotropy axis. We assume so far that the anisotropy axis is aligned with the spin axis in the above analyses; what give rise to the observed temporal changes in the travel times are the lateral velocity changes. If the local anisotropy axis of this patch of the inner core (not necessarily the anisotropy axis averaged over the whole inner core) is indeed tilted from the spin axis (our assumed axis of the inner core rotation), the change of the orientation of the axis as the inner core rotates
would contribute to the observed travel time change along a fixed path (i.e., the $\Delta v^E$ term in equation (1) is time-dependent), as originally proposed by Song and Richards [1996]. In fact, the entire temporal change observed at SPA can be explained by the original model of Song and Richards [1996], which has a 1.1°/yr inner core rotation and assumes homogeneous anisotropy with a tilt of the symmetry axis (Figure 3).

In a recent series of papers [Souriau et al., 1997; Souriau, 1998a, b, c], Souriau (and coworkers) discusses problems with the evidence of differential inner core rotation and states that such a differential rotation is not firmly established. The significant criticisms include (1) biases from event mislocations, (2) biases from mantle heterogeneity, (3) uncertainty in the tilt of the anisotropy axis, and (4) biases from event magnitudes.

The biases from event mislocations and mantle heterogeneity were the major concerns of Song [submitted manuscript, 1999] for the SSI-Alaska pathway and the above analyses for the Alaska-SPA pathway. The location biases were examined using events relocated by JHD or EHB. While many individual BC-DF residuals show clear shifts after relocations, the time dependences of the residuals from SSI earthquakes to COL and three other stations in Alaska and from Alaska earthquakes to SPA with or without relocations were demonstrated to be statistically highly significant (with confidence levels of over 99.97% for the SSI-Alaska paths and over 95% for the Alaska-SPA path). The mantle biases were examined from joint inversions with and without mantle correction terms. We demonstrated that the time-dependent $\alpha$ terms are statistically robust (with confidence levels of 99% for both pathways but a much much higher level than that for the SSI-Alaska pathway) regardless whether the mantle corrections are considered.

Souriau [p.55, 1998b] stated that “Song and Richards [1996] and Su et al. [1999] base their analyses on the assumption that the inner core exhibits a nearly cylindrical symmetry about an axis that is slightly tilted with respect to Earth’s rotation axis”. She then stated that both studies “raise some tough questions,” since Souriau [1997] found the tilt of the symmetry axis cannot be resolved from the ISC arrival times. Because Su et al. [1996] inferred their inner core rotation from direct inversions of the symmetry axis at various time periods using the ISC arrival times, the uncertainty in the tilt of the symmetry axis demonstrated by Souriau [1997] indeed raises a serious question whether the inner core rotation from the inversions of Su et al. [1996] is an artifact. However, Souriau’s [1998b] statements quoted above and similar statements elsewhere [Souriau, 1997, 1998a, 1998c] are not accurate and could be misleading when applied to the method and work of Song and Richards [1996] and our more recent analyses presented here and by Song [submitted manuscript, 1999].

First, the strongest evidence for a differential inner core rotation is that the BC-DF residuals along the pathways from SSI earthquakes to COL and three other stations in Alaska and the pathway from Alaska to SPA have changed systematically with time. The time dependence of BC-DF residuals along certain pathways that we have sought to detect do not rely upon whether the symmetry axis is tilted. For example, Creager [1997] provided an alternative interpretation to the temporal change observed at COL by Song and Richards [1996].

**Figure 5.** Observations obtained from earthquakes in South Sandwich Islands with magnitudes between Mb 5.4 and Mb 6.9 to College, Alaska station (COL). The events (a total of 35) are selected from Song [submitted manuscript, 1999] by excluding a few events smaller than 5.4 and larger than 6.0, which are not uniformly distributed in time. Event magnitudes before 1964-1965 are not available or not reliable. The events have been relocated [Song, submitted manuscript, 1999] using the Joint Hypocenter Determination (JHD) method. (a) The BC-DF residuals plotted as a function of event occurrence times. (b) The magnitudes of these events as a function of event occurrence times. (c) The BC-DF residuals plotted as a function of event magnitudes. The BC-DF residuals are calculated relative to PREM, normalized by the times that the rays travel through the inner core, and multiplied by the average (129.0 s) of the times in the inner core of the rays. The lines are linear regressions of the data and the slopes and 1σ error are (a) 0.0093±0.0016 s/yr, (b) -0.0019±0.0030 yr⁻¹, (c) -0.0122±0.1206 s per Mb change.
using a local lateral velocity gradient in the inner core sampled by the fixed path as the inner core rotates, an interpretation Souriau favored. Second, what matters to a fixed path is local velocity structure (lateral velocity changes and the orientation of the local anisotropy) sampled by the path as the inner core rotates. Although there may not be simple symmetry of anisotropy about an axis for the whole inner core, it is possible

that the crystal alignments along certain local patches are not exactly north-south. In fact, the complexity of the anisotropy suggested in recent studies [Tanimura and Imaiguchi, 1997; Creager, 1997; Song and Helmberger, 1998] argues in favor of varying crystal alignments from place to place. To summarize this paragraph, the details of the anisotropy structure will undoubtedly affect the estimates of the inner core rotation rate. This, however, should not be confused with our first-order observation that travel times along certain pathways have changed, which implies a differential inner core rotation.

Finally, Souriau et al. [1997] observed an apparent correlation between the differential BC-DF travel time residuals at COL used by Song and Richards [1996] to infer the inner core rotation and the magnitudes of the events. They suggested that the observed time dependence of the differential travel times could be an artifact related to the heterogeneity of the event magnitudes during the period considered, i.e., more events with smaller magnitudes were used during later time periods. To examine this, we use events of a specific magnitude range so that the magnitudes of the events are distributed uniformly in time. Figure 5 shows the results of using mb 5.4 to Mb 6.0 events from the SSI-COL data set used by Song [submitted manuscript, 1999], which extended the study of Song and Richards [1996] to include events further back in time for the pathway, and Figure 6 shows the results using mb 5.0 to Mb 5.7 events from the Alaska SPA data set in this study. The linear regressions of the event magnitude on time have slopes of close to zero (well within the corresponding 1σ errors) at COL and SPA, suggesting that the event magnitudes are distributed fairly uniformly in time. The BC-DF residuals at both COL and SPA show clear increases with time; the null hypotheses that the residuals do not correlate with time can be rejected at 99.9999% and 97.1% confidence levels for COL and SPA, respectively. However, the linear regressions of the residual on event magnitude have slopes of close to zero at both COL and SPA; the slight negative slope at COL and the slight positive slope at SPA are well within the corresponding 1σ error. Thus there is no evidence for a correlation between the travel time residuals and the event magnitudes as suggested by Souriau et al. [1997]. It is more likely that the apparent correlation observed by Souriau et al. [1997] resulted from the fact that the average magnitudes of the events considered change with time.

5. Conclusion

The new pathway from Alaska earthquakes to SPA shows a robust change in BC-DF different travel time residuals over time, providing more support for a differential inner core rotation. Both the rotation direction (eastward) and the rotation rate (0.6°/yr) determined using the SPA data are consistent with the initial estimate of an eastward inner core rotation of about 1.0°/yr from the SSI-COL pathway [Song and Richards, 1996].

**Figure 6.** Same as Figure 5 but for the Alaska earthquakes to SPA pathway. The events (a total of 29) are selected from the 39 Alaska events in this study by excluding a few events smaller than 5.0 and larger than 5.7, which are not uniformly distributed in time. Event magnitudes before 1964 are not available or not reliable. The BC-DF residuals are calculated relative to PREM, normalized by the times that the rays travel through the inner core, and multiplied by the average (126.2 s) of the times in the inner core of the rays. The EDR event locations are used to calculate the residuals. The lines are linear regressions of the data and the slopes and 1σ errors are (a) 0.01963 ± 0.00850 s/yr, (b) 0.00164 ± 0.00364 yr⁻¹, (c) 0.1475 ± 0.4892 s per Mb change.
and the more robust estimate of 0.3-1.1°/yr from dense samples of the SSI-Alaska pathway [Song, submitted manuscript, 1999].

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X.D. Song, 1301 W. Green St., Dept. of Geology, Univ. of Illinois, Urbana, IL 61801. (email: xsong@uiuc.edu)

A.Y. Li, Lamont-Doherty Earth Observatory, Palisades, NY 10964. (email: anyili@ideo.columbia.edu)

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