Detecting Possible Rotation of Earth's Inner Core

In her 3 July Perspective, "Earth's inner core: Is the rotation real?," A. Souriau (*1*) notes that several different estimates of the inner core rotation rate have been published since the appearance of the original results of Song and Richards (*2*). She discusses problems with the evidence of differential inner core rotation and comments on the significant consequences for Earth dynamics if the inner core rotates differently from the mantle and crust. She states that such a differential rotation is not firmly established. We would like to comment that (i) Souriau incorrectly summarizes our recent results (*3*) and is contradicted by other studies published since her Perspective (*4–6*); (ii) we agree in general that anisotropy variation within the inner core must be better understood before significant improvement can be made in estimates of the rotation rate; and (iii) our original method, based on a differential measurement of seismic travel times, appears more accurate than alternative methods that are based on measurement of absolute arrival times and provides the method needed for resolution of the main issues (quantifying the anisotropy variation and narrowing estimates of the inner core rotation rate).

Thus (i), Souriau cites two 1998 papers—hers (*7*) and ours (*3*)—as finding that "no travel time anomaly is observed over 25 years" for Novaya Zemlya nuclear tests observed by paths through the inner core to stations in Antarctica (*8*). But our own result (*3*, which was reported at the 1998 Spring Meeting of the American Geophysical Union) is that a travel time anomaly is indeed observed (for 19 signals from explosions over a 19-year period at the Antarctica station SBA) at the rate -0.0053 ± 0.0034 s/year. [A negative rate is expected for an easterly rotation of the inner core with homogeneous anisotropy having a fast axis, roughly as described by Song and Richards (*2*)]. There are supporting observations (for 21 Novaya Zemlya signals over 24 years at the Antarctica station NVL) of a negative rate (approximately -0.01 s/year), from an independent study (*6*). Finally, Souriau has sent us her own measurements of differential travel times for Novaya Zemlya explosions observed at the French station DRV in Antarctica, from which she makes no claim of any travel time change (*7*). Our own analysis, however, yields a small, negative, rate of change. Thus, for three seismic paths through the inner core, for the Novaya Zemlya explosions recorded in Antarctica, the estimated rate of change is consistently negative.

We agree (ii) that several studies, cited by Souriau, have now shown that anisotropy in the inner core must be heterogeneous, necessitating a long-term effort to acquire data for a variety of seismic paths through the inner core in order to separate spatial and temporal effects; and (iii) that an alternative method of Su *et al.* (*9*), which had indicated a higher rotation rate, is now understood to be inconclusive (*10, 11*)—and therefore does not speak to the main issues.

The most important evidence of Song and Richards (*2*) for a differential inner core rotation is that a certain travel time interval—between seismic waves traversing the inner core and those traveling closely in the mantle and the outer core but just missing the inner core, observed at station COL in Alaska from earthquakes in the South Atlantic—increases systematically by about 0.3 s as a function of date over the last 30 years. Creager (*12*) independently confirmed the change in travel time interval for this data set and concluded that the null hypothesis that there is no correlation (between earthquake occurrence time and change in the travel time interval) can be rejected with 99.98% confidence. A more recent analysis (*4*) for this path to COL—from earthquakes dating back even further in time (over the past 45 years)—supports the initial observations of the temporal change in travel time interval.

Observations from our laboratory (*2–5*), and the independent confirmations of travel time changes using our original method (*6, 12*), which document a pattern of change that implies differential rotation of the inner core, should not be obscured by different or negative results from methods that are less capable. We agree that observation of travel time changes must now be interpreted in the context of a more sophisticated understanding of inner core structure.

Paul G. Richards
Xiaodong Song
Anyi Li
Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA
E-mail: richards@ldeo.columbia.edu

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Response: In my Perspective (*1*), the shortness of the text and the necessity to address a broad readership (including those who are not geophysicists) required some simplifications. I tried to summarize the studies that were available at that time. I did not state that Earth's inner core is not rotating, only that more studies will be needed to firmly establish this result and to determine a rotation rate.

In their point (i), Richards *et al.* discuss two results described in a meeting abstract by Song and Li (*2*). The first result concerns the path South Sandwich Islands to station COL, Alaska, for which Song and Li (*2*) give a 0.5-s differential travel time increase over 45 years. But Song and Li indicated that the data scatter for the 1950s is large, which suggests the "need to improve event locations for early years." The second result concerns Alaska events recorded at station SPA, Antarctica, for which Song and Li note that the residuals "appear to have increased over the years." In the absence of more quantitative information, and because Perspectives references are limited in number, I did not mention this abstract (*2*).

Is there a convincing observation of residual variation for the Novaya Zemlya nuclear tests recorded in Antarctica, which could be explained by inner core rotation? Data from four Antarctic stations (SPA, SBA, NVL, and DRV) have been studied by different investigators. Li *et al*. (*3*) note a 0.34 ± 0.66 s increase of their normalized travel time residuals over 37 years at SPA (thus, a variation that is not significant), and a 0.09 ± 0.07 s decrease over 19 years at SBA [it is not clear how Richards *et al.*, in their comment, come to a slope of -0.0053 ± 0.0034 s per year. This response is based on the abstract (*3*) content]. Data from SBA give a variation of 0.09 s, which is only marginally significant from a statistical point of view because it is only 1.3 times larger than the error bar (also, the number of samples is small, at best 35 nuclear tests, and the samples are not completely independent, because of variations in structures, instruments, and observers).

With regard to the station NVL, Richards transmitted to me recently the relevant preprint by Ovtchnnikov *et al.* (*4*), and the results are puzzling. The Novaya Zemlya residuals do not exhibit smooth variations, which are expected for a homogeneous anisotropic inner core with a tilted anisotropy axis and a uniform rotation, as postulated by Song and Richards (*5*). The residual variation mostly consists in a sharp, 0.3-s decrease between 1977 and 1979. Such a sharp variation may hardly be ascribed to the ~2° per year inner core rotation as proposed (*4*), owing to the size of the PKP_{DF} Fresnel zone at 1 s period, about 9 km (*6*). Smooth residual variations are likely to occur in any case. The mean slope of ~0.01° per year computed over the whole period considered (1967–1990) is thus not representative of the residual variation through time. Maybe this variation is the result of an instrument modification in 1977–80, but Ovtchnnikov *et al.* (*4*) do not mention this possibility. It would thus be interesting to analyze the data at the nearby Antarctic stations SNA (which has a PKP_{DF} Fresnel zone that partly overlaps that of station NVL) and station SYO.

For station DRV, Richards *et al.* state that they have found "a small, negative rate of change" with the data (including error bars) I made available to them (*7*). I have computed the slope obtained with this data set [all the data except onsets, see figure 3 of (*7*)]. With the locations of Marshall *et al.* (*8*) that Richards used and made available to me, I find: −0.0018 s per year ± 0.0044 (2σ error bar) for error-free data and −0.0019 s per year ± 0.0059 (2σ error bar) when errors are taken into account. The locations of Engdahl *et al.* (*9*) that I used in my paper (*7*) lead nearly to the same result. The slope is not statistically significant (*10*).

To summarize this point, none of the Novaya Zemlya to Antarctica data allows us to detect significant smooth residual variations over decades. However, this result by itself does not preclude an inner core differential rotation. This depends on the variations of inner core anisotropy or heterogeneities that are supposed to drift beneath the path of interest during the investigated time. Song and Richards (*5*) were initially seeking for the variations expected if the anisotropy symmetry axis is tilted with respect to the Earth rotation axis, a property which is not well established (*11*). Of course, there is also no reason to expect a linear drift of the residuals with time.

Song and Richards (*5*) and by Creager (*12*) both consider the path from South Sandwich to COL; thus, these studies are to a large extent based on the same data set, that is, the records collected at COL. From this point of view, the two studies cannot be considered to be completely independent, although the phenomena used to detect the differential rotation are different. The primarily debate, however, concerns the data themselves, and the nature of the signal contained in the data. There are two problems that have to be resolved before one could firmly conclude that the signal is the result of inner core rotation: (i) the quality of focal locations and (ii) the perturbing effect of mantle heterogeneities.

In his review paper about inner core anisotropy, Song (*13*) presents his collection of COL data, which reveal a trend in the DF phases when the BC phases (the reference phase) are aligned, leading him to propose an inner core rotation. The misaligment of the AB phases, however, indicates either that the event locations are inaccurate, or that the PKP phases are strongly affected by laterally variable mantle heterogeneities. The location problem will be hard to solve. For some of the events used (Song sent me his list and residuals), the nearest station is at a distance of almost 20° (for example, on 16 January

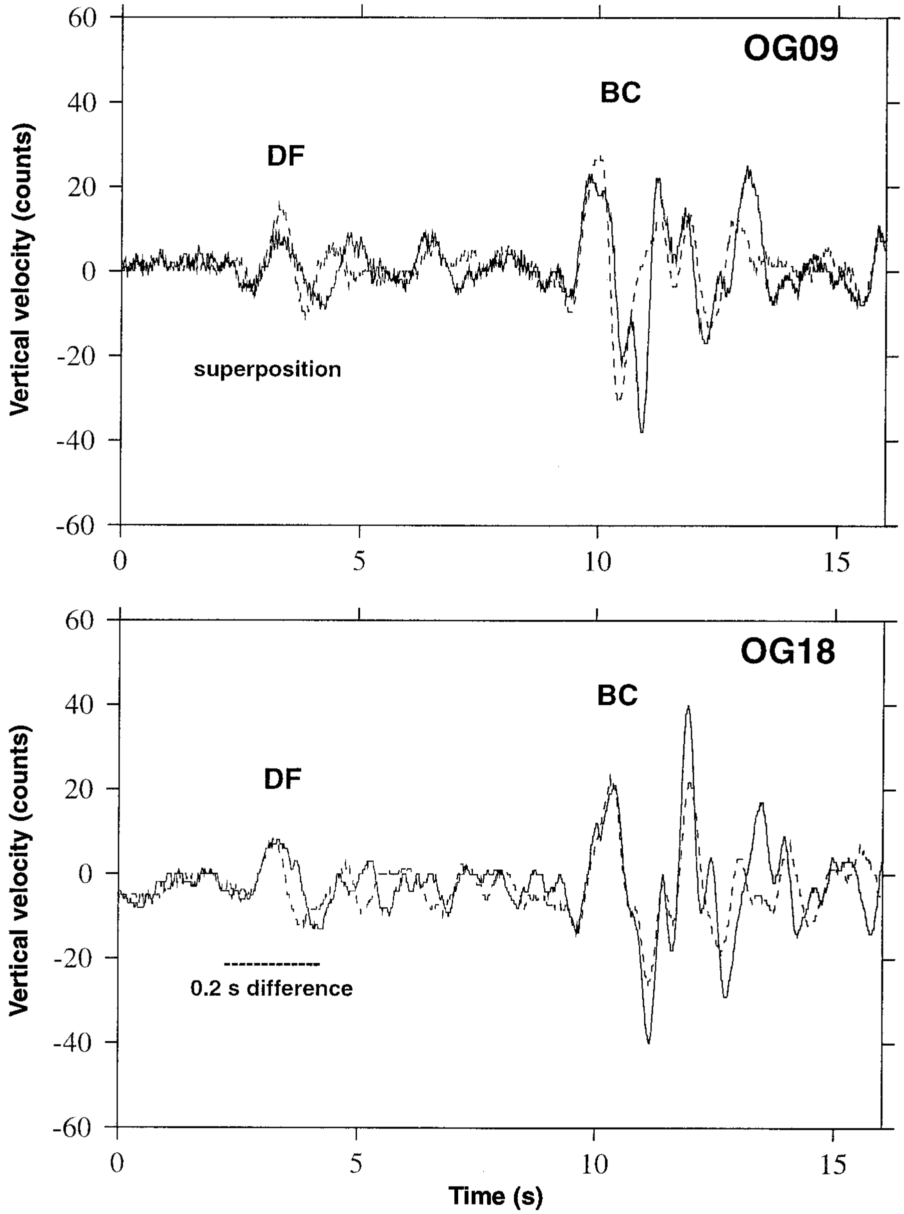

Fig. 1. Two traces that correspond to a doublet: two Tonga events from 24 February 1994 (—) and 25 February 1994 (---), whose hypocenters are distant of about 5 km. BC phases have been superimposed to each other. At top, record of the two events at station OG09 (French Alps). DF phases are well superimposed, as expected for a doublet. At bottom, records at the nearby station OG18. Maxima of the DF phases are shifted with respect to each other when the BC phases are superimposed. Crosscorrelation gives a ~0.2-s difference, not seen at OG09, which thus cannot be the result of an inner core differential rotation between 24 and 25 February (figure from G. Poupinet, Observatoire de Grenoble, Laboratoire de Geophysique Interne et Tectonophysique, personal communication).

1971): this is a large distance and may give travel times affected by the 20° P-triplication, as seen from the ISC residuals. In many cases, there are only one or two stations at distance of less than 20°, which is not adequate to provide good locations, in particular at depth. Relocating the events with the use of a joint epicenter determination method would be a possible way to solve this problem. Unfortunately, the different events are recorded by very few stations in common. For example, the six events used by Song and Richards (*5*) between 1971 and 1977 have only five stations in common in the distance range 0 to 50°. The systematic use of doublets remains probably the most convenient method. However, even so, some examples show that, in presence of complicated structures, the interpretation of a phase time shift may be difficult (Fig. 1).

The influence of mantle heterogeneities may be drastic, because there is one subduction zone at both source side and station side. This point is well documented by Creager (*12*): The rotation rate he obtains is 0.31° per year when mantle heterogeneities are not taken into account; it may fall down to 0.05° per year when mantle heterogeneities at station side are taken into account. It would be also reasonable to take into account, in addition, possible heterogeneities at source side.

The complexity of this path and the difficulty to improve the quality of the corrections were a reason for looking at simpler paths, with simpler sources whose locations are better constrained. The first attempts (Novaya Zemlya to Antarctica) do not reveal significant variations at stations DRV, SPA, and SBA. This result does not prove that there is no differential rotation, but it is of course compatible with the absence of such a rotation.

Seismological data may often be interpreted in several ways. For the present debate, the only path for which smooth residual variations are observed over several decades is the complex path from South Sandwich Island to COL, for which interpretations other than inner core differential rotation may not be completely ruled out. Thus, there is no undeniable demonstration of the existence of inner core rotation. But there is also no undeniable demonstration of the absence of rotation.

Annie Souriau
Observatoire Midi-Pyrénées
Unité Mixte de Recherche 5562
Centre National de la Recherche Scientifique,
31400 Toulouse, France
E-mail: annie.souriau@cnes.fr

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Paul G. Richards, Xiaodong Song and Anyi Li

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