GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L01309, doi:10.1029/2004GL021240, 2005

Evidence for inner-core rotation from possible changes with time in PKP coda

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Received 10 August 2004; revised 17 October 2004; accepted 30 November 2004; published 15 January 2005.

[1] Inner-core-grazing PKP waves from seven French nuclear tests on Mururoa Island recorded at NORSAR appear to change over a decade. We compared filtered and stacked signals from the explosions, which took place from 1977 to 1987 and were separated by less than 10 km. The PKP energy 3 to 10 s after the first arrivals differs greatly between the NORSAR subarrays, and evolves over time. The small time shifts of coda arrivals, a few tenths of a second, are qualitatively consistent with shifts predicted for point scatterers in an inner core that rotates in the range 0.05° to 0.10° per year. There are also visible changes in the envelope of the PKP energy. Although the alternative of systematic shifts in source location cannot be ruled out, the apparent time evolution of PKP supports claims of slow inner core rotation [*Song and Richards*, 1996; *Creager*, 1997; *Laske and Masters*, 1999; *Vidale et al.*, 2000] and offers a powerful new tool for its assessment.

Citation: Vidale, J. E., and P. S. Earle (2005), Evidence for inner-core rotation from possible changes with time in PKP coda, *Geophys. Res. Lett.*, *32*, L01309, doi:10.1029/2004GL021240.

1. Introduction

[2] Is the inner core locked to the mantle or does it move? The question was raised by outer-core dynamo models that predict faster inner-core rotation than rotation of the overlying mantle by up to 2° per year [*Glatzmaier and Roberts*, 1996; *Kuang and Bloxham*, 1997]. However, taking into account known mantle density heterogeneity and plausible values of inner-core viscosity, gravitational drag on the inner core by the mantle would slow differential rotation [*Buffett*, 1997; *Aurnou and Olson*, 2000]. The viscosity of the inner core is sufficiently poorly known that current core models allow a range of rotation rates from imperceptible to several degrees per year [*Buffett and Glatzmaier*, 2000]. In addition to steady super-rotation, a component of oscillatory inner core relative motion is possible, with a period of roughly decades, depending on the strength of the local magnetic field and other factors.

[3] Estimates of differential times between $\mathrm{PKP_{bc}}$ and $\mathrm{PKP_{df}}$ show marked changes for some paths from the Sandwich Islands to Alaska and less robust variations for other paths. Inference of rotation rate from the changes in differential time requires deducing the anisotropy and spatial gradients of velocity in the mantle and core [*Creager*, 1997; *Song*, 2000]. Rotation rates inferred range from near 0° per year [*Souriau et al.*, 2003], through 0.2–0.3° [*Creager*, 1997], to 0.4–1.1° per year [*Song and Xu*, 2002; *Li and Richards*, 2003; *Xu and Song*, 2003].

[4] Inner-core-sensitive normal modes may also indicate the rotation rate. The most recent and precise normal-mode study finds a rotation rate of 0.13 ± 0.11° per year [*Laske and Masters*, 2003]. Another estimate of the inner-core rotation rate comes from the side-scattered coda to PKiKP [*Vidale and Earle*, 2000; *Koper et al.*, 2005]. Changes in the coda over time indicate an inner-core rotation rate of 0.15° per year [*Vidale et al.*, 2000].

[5] Driven by the current lack of consensus, we look for changes in inner-core sampling PKP waves, which would provide a new method for tracing the journey of the inner core.

2. Experiment

[6] Our data are NORSAR recordings [*Bungum et al.*, 1971] of seven nuclear explosions in the Pacific. The explosions were the largest of the more than 100 nuclear weapons tests conducted by the French government on the island of Mururoa, and were co-located within 5–10 km, as listed in Table 1 and shown in Figure 1a. No other events from Mururoa had useable waveforms from NORSAR. Mururoa Island is an atoll growing atop an extinct volcano [*Crusem and Caristan*, 1992]. One good set of locations relies on careful relocation from first arrival time picks [*Douglas et al.*, 1993]. Another, potentially more precise set of locations are derived from double-difference and cross-correlation methods (A. Li, personal communication, 2003), however, internal inconsistencies have rendered some locations unreliable. Attempts to extract exact locations from the French test site authorities have failed because that information remains classified.

[7] The direct P waves from three of the explosions were captured by the University of Washington Regional Seismic Network, which is 70° from Mururoa at the same azimuth as NORSAR. A stack of the P waves, shown in Figure 2, reveals that the seismic signal is simple, just a second or two of energy followed by minimal coda. We have also examined records of dozens of other Mururoa explosions in the 1980s and 1990s, which all had simple P waves on the west coast of the United States. Thus, it is likely that the other four explosions also produced simple P waves. GERESS, at 145° distance from Mururoa, also recorded simple waveforms of explosions in the 1990s [*Jost et al.*, 1996], as did the short-period network in France, which spans 137° to 142° [*Houard et al.*, 1993]. We conclude that the P waveforms radiated from the explosions were probably simple, and infer that the complications shown below are most likely to arise during propagation through or reflection from the inner core.

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0094-8276/05/2004GL021240$05.00

Table 1. Large Nuclear Explosions on Mururoa Island

Date	Time	Lat. (S)	Lon. (W)	Mag
3/19/77	23:00:59.9	21.887	138.920	5.92
11/24/77	16:59:59.9	21.884	138.886	5.86
7/25/79	17:57:00.0	21.880	138.940	6.11
5/25/83	17:31:00.1	21.861	138.917	5.87
11/26/85	17:42:00.1	21.856	138.899	5.76
5/30/86	17:25:00.1	21.862	138.949	5.58
11/19/87	16:31:00.2	21.845	138.941	5.74

[8] NORSAR in the late 1970s and 1980s consisted of seven subarrays, each with 6 short-period, vertical-component seismometers. The subarrays have a 10-km diameter, and they are spread across an area with a 60-km aperture (Figure 1).

[9] We bandpass-filtered the traces to retain mainly 1 Hz motion, which improved the signal-to-noise ratio, then stacked all high SNR elements of each subarray. The NA0 and NC4 subarrays were too noisy, even in the stacks, so we present only the other five subarrays. For the 1983 event, the NC2 and NC6 subarrays were too noisy to interpret, thus they are also omitted from our presentation.

[10] Three seismic phases are expected at the 136° distance of our seismograms. Two geometric arrivals, PKP_{df} and PKP_{cd}, should appear at 1162.5 and 1164.5 s; the latter often appears with slightly larger amplitude at 1-Hz period [*Song and Helmberger*, 1992; *Song and Helmberger*, 1995]. PKP_{cd} grazes the inner core and PKP_{df} travels through the shallow inner core (Figure 3). The third PKP phase is an arrival that bottoms in the outer core, and can arrive up to 15 s earlier than PKPdf at this distance. It consists of energy scattering near the core-mantle boundary [see, e.g., *Haddon and Cleary*, 1974; *Vidale and Hedlin*, 1998]. It is visible but not prominent in our data.

3. Inner-Core-Grazing Seismic Waves Across 10 Years

[11] The stacks across each of the 5 subarrays for each of the 7 explosions are shown in Figure 2. All the records show a more complicated arrival than is seen in the direct P waves, which are also shown in Figure 2. The largest amplitude signals begin near the expected time of PKP_{cd} and just a second or so after the expected time of PKP_{df}. The complexity of the signal, the small aperture of the array, and the nearly identical predicted timing and slowness of the two arrivals precludes identifying either arrival individually.

[12] To follow our previous approach [*Vidale et al.*, 2000], one would beamform the wavefield incident on NORSAR in search of the west-receding, east-advancing pattern found with LASA for Novaya Zemlya explosions from inner-core-scattered waves. Unfortunately, it is clear in Figure 2 that we lack sufficient data for a well-resolved stack. Also, across the 10-year interval, the PKP coda waves shown here may be losing coherence more than did the inner-core scattered waves across 3 years in our previous study.

[13] The clear arrival starts around 1164 s and the first 3 s are similar for all events at all stations. Each subarray shows indications of incremental change with time in the later part of the waveform across the 10 years. On NB0 and NC6, energy near 1169 or 1170 in 1977 moves perhaps 0.2 s earlier by 1987. A late arrival fades with time for NC2 and

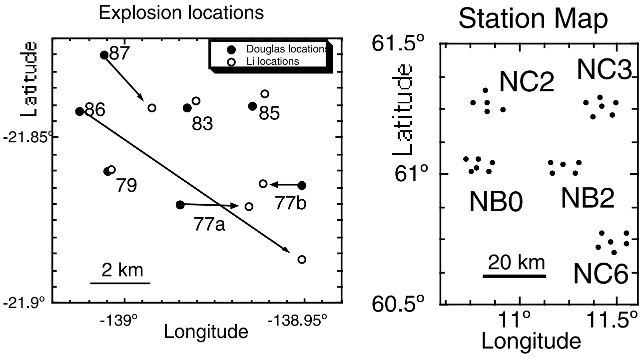

Figure 1. (left) Map of explosion locations near Mururoa Island in the Tuamoto Archipelago. Hollow circles come from the Lamont thesis work of Anyi Li, solid circles from traveltime relocations [*Douglas et al.*, 1993]. The Douglas locations are shifted 0.065°E and 0.02°N for better alignment, which is reasonable because the difference in absolute locations between the two methods are uncertain by at least that amount. (right) Map of the NORSAR stations used in this paper. Each labeled cluster of stations is a subarray.

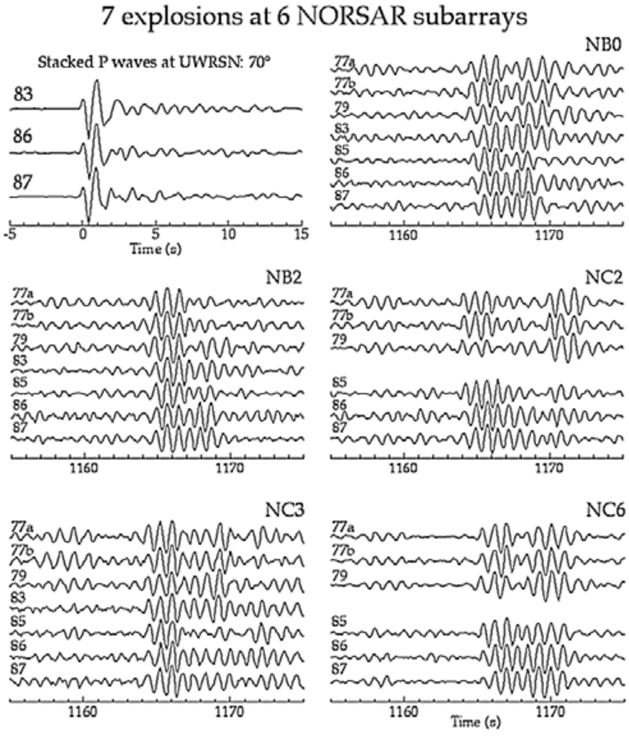

Figure 2. 1st frame - P waves of the 1983, 1986, and 1987 nuclear explosions recorded on the University of Washington Regional Seismic Network. The waveforms shown result from stacking 32, 24, and 35 seismograms, respectively. Other 5 frames - Stacks of PKP from 5 subarrays of NORSAR for 7 nuclear tests. Each subarray stack is shifted by up to a few tenths of a second, with the shifts chosen to line up with the first few seconds of subarray NB0. The same time shift is used for a given explosion for all subarrays.

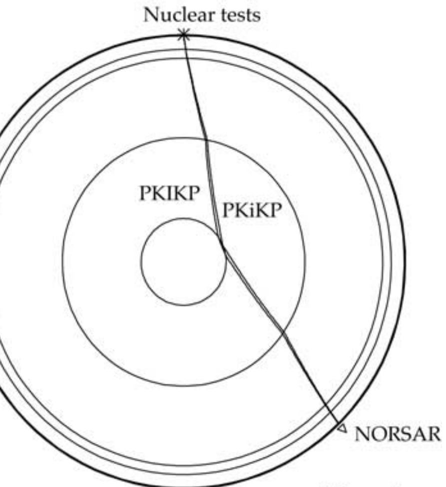

Figure 3

Figure 3. Raypaths of PKP_{df} (PKIKP) and PKP_{cd} (PKiKP) at the 136° distance of NORSAR from Mururoa Island. These two ray paths are quite proximate along their entire path.

NC3. On NB2, a later arrival grows in amplitude. The first two explosions, just 8 months apart, are practically identical. The third and fourth, 2 and 6 years later, are progressively more different. The last three explosions, which occurred within 2 years following a 2.5 year gap, are distinct from the first four and similar to each other.

[14] The alternative explanation for the temporal changes is near-source scattering effects from different locations, but it does not appear to work well for either progression of locations shown in Figure 1. The simple direct P waveforms also argue against strong near-source contributions to waveform complexity. However, a progressive change in the location of the nuclear tests would explain the apparent progressive temporal change in the PKP coda, and cannot be ruled out given the large uncertainties in the locations. A third possibility, temporal changes in the near-source or near-receiver scattering, is quite unlikely given the presence of only very minor waveform changes observed in seismograms from repeating earthquakes [*Schaff and Beroza*, 1998] and repeated explosions [*Li et al.*, 2003] in California despite the local disturbance of large earthquakes, and only even more subtle ones without large earthquakes [*Niu et al.*, 2003].

4. Implications

[15] The changes in PKP waveforms are likely, although not definitely, due to the movement of the inner core. The PKP_{df} phase is more likely to change, since its raypath travels through the outermost inner core. The shallowest inner core may be marked by less anisotropy [*Song and Helmberger*, 1998] and more attenuation [*Doornbos*, 1974] than below. The top few-hundred km of the inner core has fine-scale heterogeneity [*Vidale and Earle*, 2000; *Koper et al.*, 2005] and has been inferred to have layering [*Song and Helmberger*, 1998].

[16] PKP_{cd} could also generate the observed 10-s coda, but in this case would most naturally arise from topographic irregularities on the inner-core boundary. Changes in PKP_{cd} over time would also indicate inner core motion.

5. Modeling of Time Shifts

[17] Next, we show that the observed time shifts could arise from a plausible inner-core rotation rate. Motion of the inner core would change the scattered coda by changing the amplitude and phase of the contributions from individual velocity gradients. For a rough calculation, we consider the changes in the timing of arrivals from individual point scatterers, and neglect amplitude fluctuations, which also are visible in Figure 2. A grid of scatterers at fixed locations is distributed throughout the inner core, and their arrival times to NORSAR calculated, which is just the sum of the travel time from Mururoa Island to the scatterer plus the traveltime from the scatterer to NORSAR. We trace rays through IASP91 to find the travel times along each path. Next, the grid of scatterers is rotated about the Earth's pole of rotation and the arrival times recalculated. We compare the observed time shifts with the distribution of the differences in arrival times from particular scatterers between before and after rotation. The attenuation in the inner core is neglected and we considered only scattered waves arriving at the time of the observed code in this calculation.

[18] We calculate the time shifts that would result from an inner core rotation of 1°. This would mimic a steady rotation rate of 0.1° per year from 1977 to 1987, on the low end of recent non-zero estimates. Arrivals from individual scatterers would move earlier or later up to 0.6 s, with an rms shift of 0.25 s. This range is at least as great as the observed changes in timing of the later arrivals in Figure 2, indicating that even mild rotation rates may explain the data. More sophisticated synthetics would be necessary to model the amplitude fluctuations, and are not warranted at this point due to the low resolution of the data and uncertainty in locations.

6. Conclusion

[19] We present evidence of temporal changes in inner-core sampling PKP waves. Our technique, comparison of inner-core-grazing seismic waves, is new, and may be extended to other paths if other such repeatable sources are identified. The amplitudes of the temporal timing changes in the PKP coda are consistent with slow differential rotation of the inner core [*Creager*, 1997; *Laske and Masters*, 1999; *Vidale et al.*, 2000; *Laske and Masters*, 2003].

[20] **Acknowledgments.** We thank J. Fyen and J. Torstveit at NORSAR and Michael Hedlin for providing the seismograms. Anyi Li helped investigate explosion locations. Ken Creager, Keith Koper, Xiaodong Song, Paul Richards and two anonymous reviewers provided comments. NSF Grant EAR99-02995 and the LLNL-IGPP mini-grant program supported this work.

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