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Can the Okhotsk plate be discriminated from the North American plate?

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Abstract. The plate geometry in northeast Asia has been a long-standing question, with a major issue being whether the Sea of Okhotsk and northern Japanese islands are better regarded as part of the North American plate or as a separate Okhotsk plate. This question has been difficult to resolve, because earthquake slip vectors along the Kuril and Japan trenches are consistent with either Pacific-North America or Pacific-Okhotsk plate motion. To circumvent this difficulty, we also use slip vectors of earthquakes along Sakhalin Island and the eastern margin of the Japan Sea and compare them to the predicted Eurasia-Okhotsk and Eurasia-North America motions. For a model with a separate Okhotsk plate, we invert 10 Eurasia-Okhotsk and 255 Pacific-Okhotsk slip vectors with Pacific-North America and Eurasia-North America NUVEL-1 data. Alternatively, for a model without an Okhotsk plate, those Eurasia-Okhotsk and Pacific-Okhotsk data are regarded as Eurasia-North America and Pacific-North America data, respectively. The model with an Okhotsk plate fits the data better than one in which this region is treated as part of the North American plate. Because the improved fit exceeds that expected purely from the additional plate, the data indicate that the Okhotsk plate can be resolved from the North American plate. The motions on the Okhotsk plate's boundaries predicted by the best fitting Euler vectors are generally consistent with the recent tectonics. The Eurasia-Okhotsk pole is located at northernmost Sakhalin Island and predicts right-lateral strike slip motion on the NNE striking fault plane of the May 27, 1995, Neftegorsk earthquake, consistent with the centroid moment tensor focal mechanism and the surface faulting. Along the northern boundary of the Okhotsk plate, the North America-Okhotsk Euler vector predicts left-lateral strike slip, consistent with the observed focal mechanisms. On the NW boundary of the Okhotsk plate, the Eurasia-Okhotsk Euler vector predicts E-W extension, discordant with the limited focal mechanisms and geological data. This misfit may imply that another plate is necessary west of the Magadan region in southeast Siberia, but this possibility is hard to confirm without further data, such as might be obtained from space-based geodesy.

Introduction

Although there has been general agreement about the approximate boundaries of most major plates since the formulation of the plate tectonic paradigm, the geometry for northeast Asia has remained one of the notable exceptions. Much of the difficulty stems from the fact that although the North America-Eurasia boundary can be traced along the mid-Atlantic Ridge to the Arctic (Nansen) Ridge from seismicity, this seismicity becomes low and more diffuse once it reaches the Eurasian continent (Figure 1). *Morgan* [1968, p. 1960] hence noted that "the boundaries in Siberia and central Asia are very uncertain" and suggested that the North America-Eurasia (NA-EU) boundary might run along Hokkaido and Sakhalin Islands (Figure 2a). He pointed out, however, that "there is no compelling reason to separate China from the North American block" but that "additional subblocks may be required."

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Despite subsequent studies, the plate geometry has not been conclusively resolved because of the limited seismicity and lack of clear structures marking the boundary on land. A variety of possible geometries, some of which are shown in Figure 2, have been proposed. A primary question is whether the far east Siberia (Magadan)-Sea of Okhotsk-northernmost Japan region should be treated as part of the North American plate or as a separate Okhotsk (OK) plate [*Den and Hotta*, 1973; *Savostin et al.*, 1983; *Ishikawa and Yu*, 1984; *Sudo*, 1985; *Cook et al.*, 1986; *Riegel et al.*, 1993]. This possibility is suggested primarily on the basis of the linear zone of seismicity extending from the northeastern Kamchatka peninsula to and along the Chersky Range in Siberia (Figure 1). *Chapman and Solomon* [1976], however, assessed the limited evidence as inadequate to justify assuming a distinct Okhotsk plate.

The situation is further complicated by other issues. The southern extent of the Okhotsk (or North American) plate in the Japanese Islands has been the subject of debate. Until recently, the EU-OK (or EU-NA) boundary was presumed to extend from Sakhalin through central Hokkaido (Figure 2a) [*Den and Hotta*, 1973; *Chapman and Solomon*, 1976], on the basis of

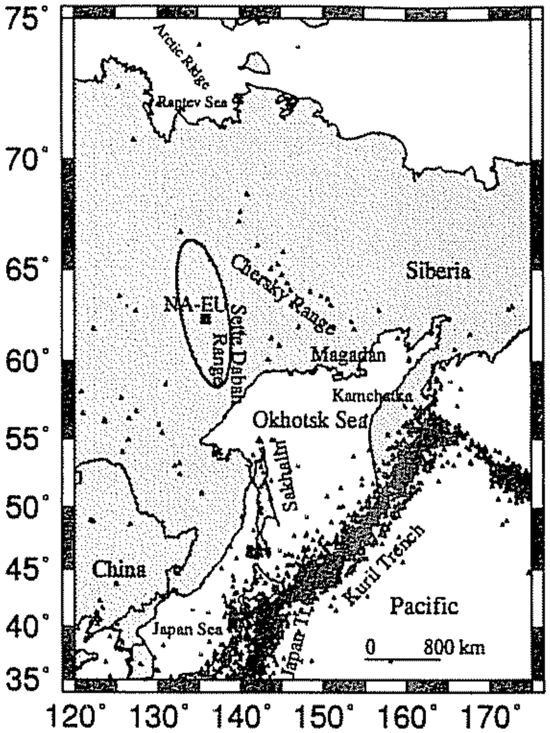


Figure 1. Shallow seismicity in northeast Asia. Earthquake locations are from the International Seismological Centre (ISC), Edinburgh during the period 1964 through 1987, for earthquakes with $m_b \geq 4.4$ and depth ≤ 60 km. The pole of the NUVEL-1 global North America-Eurasia (NA-EU) Euler vector and its 1σ error ellipse [*DeMets et al.*, 1990] are also plotted.

structures indicating a relict plate boundary in Mesozoic-Tertiary time [*Den and Hotta*, 1973]. Taking into account Quaternary-Recent tectonic activity, *Nakamura* [1983] and *Kobayashi* [1983] proposed that the boundary has subsequently shifted to the eastern margin of the Japan Sea, making northern Honshu part of the North American (or Okhotsk) plate (Figures 2b and 2c). In this scenario, subduction from the west under Hokkaido and northern Honshu is currently being initiated [*Nakamura*, 1983; *Kobayashi*, 1983; *Seno*, 1985a, b; *Tamaki and Honza*, 1985]. This possibility is supported by recent active seismicity and faulting along the northeastern margin of the Japan Sea and low-level crustal seismicity in central Hokkaido [*Fukao and Furumoto*, 1975; *Seno*, 1985b; *Tamaki and Honza*, 1985]. Still another alternative (Figure 2d) is that northern Honshu and western Hokkaido are part of a microplate distinct from either the Okhotsk or North American plate [*Seno*, 1985a; *DeMets*, 1992a]. Finally, given the extensive deformation occurring in central Asia [e.g., *Molnar and Tapponnier*, 1975; *Tapponnier et al.*, 1982; *England and Jackson*, 1989], it is unclear whether the region west of Japan and Sakhalin should be treated as part of Eurasia or whether a distinct Amurian plate in Siberia and north China need be assumed [*Zonenshain and Savostin*, 1981; *Ishikawa and Yu*, 1984].

The common approach used to investigate these types of questions, where geological data are inadequate to resolve the plate geometry, is to invert the observed relative motion data assuming different plate geometries and see which fits the data best [*Stein and Gordon*, 1984]. One can then test, for example, whether the improved fit of a model with an additional plate exceeds that expected purely from the fact that the model has more free parameters [e.g., *DeMets and Stein*, 1990]. This approach can be used either when data for the rates and directions of plate motion are available or (as in this case) when only earthquake slip vectors and hence directional data are available.

Using this approach, *DeMets* [1992a] investigated the plate geometry in northeast Asia by comparing slip vectors along the Kuril and Japan trenches with the relative motions predicted by global plate motion model NUVEL-1 [*DeMets et al.*, 1990]. He concluded that the slip vectors are sufficiently well explained by the predicted NUVEL-1 North America-Pacific (NA-PA) plate motion and that the existence of a separate Okhotsk plate could not be resolved, although it could not be excluded provided North America-Okhotsk motion were very slow (less than 5 mm yr^{-1}).

This possibility of slow motion makes the issue challenging. The NUVEL-1 NA-PA pole is located at 48.71°N, 78.17°W southeast of Hudson Bay and far from the Kuril and Japan trenches. Thus if the angular velocity of the OK-NA Euler vector were small, as would be expected from the low-level seismicity in the Chersky Range [*Fujita et al.*, 1990], the resulting OK-PA pole would be close to the NA-PA pole. The predicted NA-PA and OK-PA relative motions along the Kuril and Japan trenches would thus be very similar, making it hard to discriminate between models, given that both the models and the slip vector data have intrinsic uncertainties.

We attempted to circumvent this difficulty by testing for the existence of a distinct Okhotsk plate using also relative motion data from earthquakes along the Japan Sea and Sakhalin Island, the western boundary of a possible Okhotsk plate. It is generally agreed that the EU-NA pole is located in northern Siberia, close to the Okhotsk region (Figure 1) [*Chase*, 1978; *Minster and Jordan*, 1978; *Cook et al.*, 1986; *DeMets et al.*, 1990]. As a result, even small motion of an Okhotsk plate relative to North America would predict discernibly different EU-NA and EU-OK motions. Thus adding Japan Sea and Sakhalin slip vector data to the traditionally used Kamchatka-Kuril-Japan trench data should significantly strengthen our ability to test for an Okhotsk plate distinct from North America.

Test of Plate Geometry

Plate Geometry

We tested alternative plate geometries with and without an Okhotsk Plate (Figures 2c and 2b). We assumed that Eurasia forms the western boundary of the Okhotsk plate, as assumed in other studies [*Chapman and Solomon*, 1976; *DeMets*, 1992a]. If, however, the region to the west is part of a separate Amurian plate [*Zonenshain and Savostin*, 1981; *Savostin et al.*, 1982], the slip vectors along western Sakhalin and the eastern margin of the Japan Sea represent Okhotsk-Amuria rather than Okhotsk-Eurasia motion. This possibility is not easily tested, because the motions of Amuria with respect to the surrounding plates are not well constrained at present [*Zonenshain and Savostin*, 1981; *Ishikawa and Yu*, 1984]. Once, however, Amurian plate motions are better known, it should be possible to investigate this issue further. The northern boundary of the Okhotsk plate was assumed to follow the eastern Chersky Range seismicity (Figure 1; see also *Savostin et al.* [1982] and *Cook et al.* [1986]). Because sparse seismicity makes it difficult to delineate the northwestern boundary of the Okhotsk plate, we

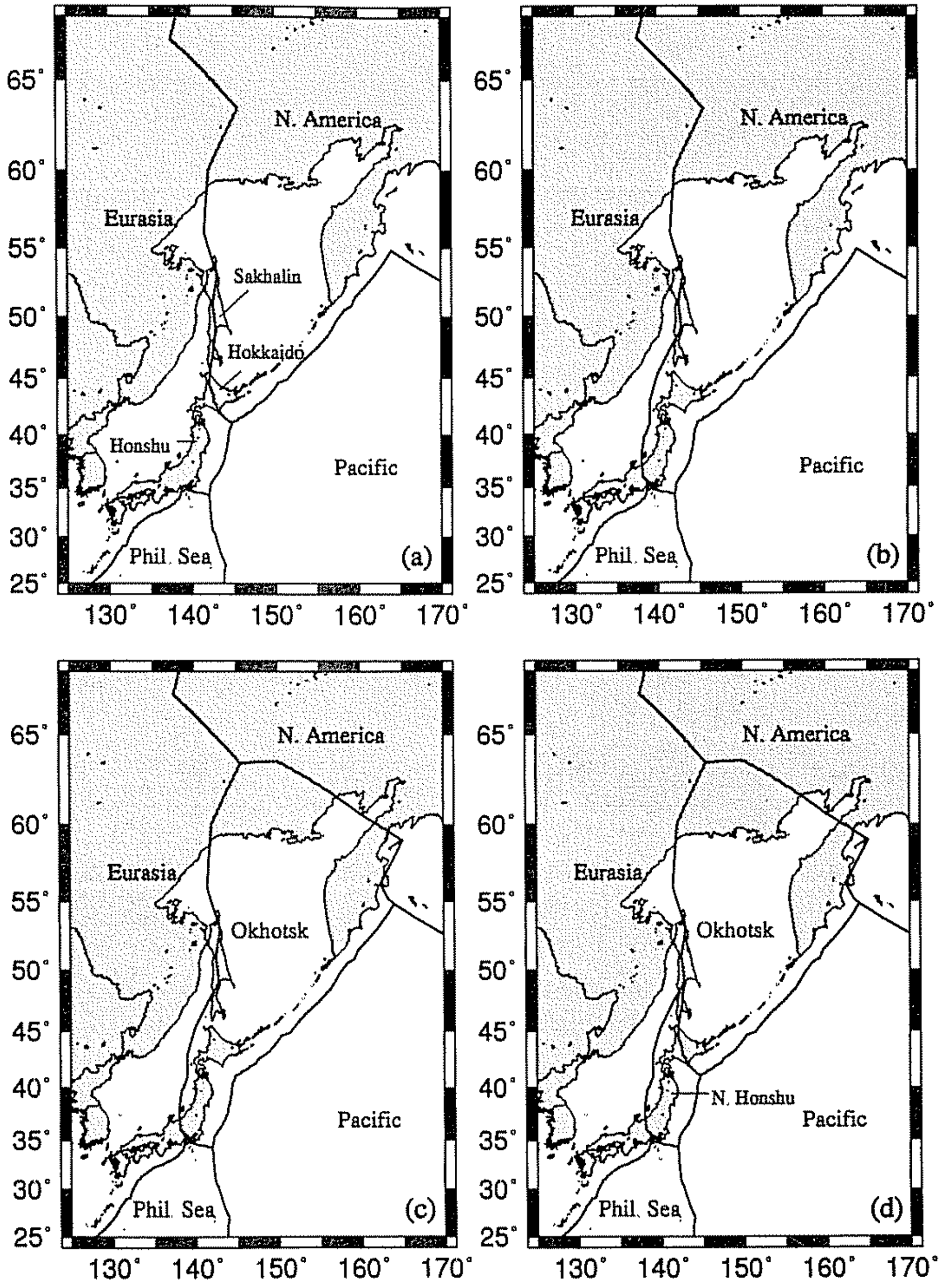


Figure 2. Possible plate geometries in northeast Asia. (a) The NA-EU boundary runs through Sakhalin and central Hokkaido [*Chapman and Solomon*, 1976]. (b) The NA-EU boundary runs along western Sakhalin and the eastern margin of the Japan Sea [*Nakamura*, 1983; *Kobayashi*, 1983]. (c) A separate Okhotsk plate (OK) exists in the Sea of Okhotsk-northern Honshu area [*Savostin et al.*, 1983; *Cook et al.*, 1986]. (d) Northern Honshu forms a microplate separate from the Okhotsk plate [*Seno*, 1985a].

simply extended the northernmost Sakhalin seismic activity northward to the east of the Sette Daban Range. This presumed Okhotsk geometry differs slightly from that in previous analyses [*Cook et al.*, 1986; *DeMets*, 1992a; *Riegel et al.*, 1993] but does not affect our results, because we do not use any data along this segment of the OK boundary.

In the south, we included northern Honshu and Hokkaido as part of OK or NA. As noted earlier, this choice is in keeping with recent geological thinking and the existence of significant seismicity and faulting along the northeastern Japan Sea margin but low seismicity in central Hokkaido [*Fukao and Furumoto*, 1975; *Nakamura*, 1983; *Kobayashi*, 1983; *Seno*, 1985b; *Tamaki* *and Honza*, 1985]. This assumption is crucial, in that our testing presumes that the Japan Sea earthquakes reflect OK-EU or NA-EU motion. From the relative motion standpoint this assumption is plausible; *DeMets* [1992a] found that earthquake slip vectors along the Japan Trench were not fit as well as those for the Kuril Trench by the predicted NUVEL-1 NA-PA motion, but the difference was statistically not significant. However, it should be noted that our analysis of the slip vectors cannot discriminate the northern Honshu microplate geometry (Figure 2d) from the Okhotsk plate geometry (Figure 2c), because the slip vector data are mostly from the boundary of the possible microplate. As noted earlier, our view is that the presently available data do not require a northern Honshu microplate.

Data

We used earthquake slip vectors along the boundaries of the possible Okhotsk plate to constrain the directions of plate motion (Figure 3). For the Kamchatka-Kuril-Japan trench slip vectors, we compiled published focal mechanism solutions for earthquakes at the thrust zone during the period 1963-1981 and Harvard Centroid Moment Tensor (CMT) solutions for 1977-1992 [e.g., *Dziewonski et al.*, 1981]. The slip vectors were rotated from the rake on the fault plane to the horizontal [*Minster and Jordan*, 1978]. To include only the thrust events presumably reflecting interplate motion, we selected events shallower than 60 km and landward of the trench and eliminated events with fault planes dipping larger than 45°. We excluded slip vector data in the Kuril arc south of 46°, because they might be disturbed by the lateral motion of the southern Kuril forearc sliver because of the oblique convergence of the Pacific plate [*DeMets*, 1992b; *McCaffrey*, 1992; *Yu et al.*, 1993].

We used only solutions whose slip vectors are relatively well constrained. Errors of 10°, 15°, and 20° were assigned to the slip vectors from published mechanism solutions depending on how well the slip vectors are constrained by P wave first motion and S wave polarization angle data. Of the CMT solutions, we excluded those with a large non-double-couple component. The magnitude of a non-double-couple component can be measured by $\varepsilon = -\lambda_2 / \max(|\lambda_1|,|\lambda_3|)$, where λ_i is an eigenvalue of the deviatoric part of the moment tensor ($\lambda_1 \geq \lambda_2 \geq \lambda_3$). Statistical analysis shows that ε has a Gaussian normal distribution, with $\sigma = 0.14$ for shallow subduction zone earthquakes [*Kuge and Kawakatsu*, 1993]. We thus excluded solutions with ε larger than 0.28. We assigned an error of 15° to solutions having $|\varepsilon| < 0.14$ and 20° to those with $|\varepsilon| \geq 0.14$. In total, 255 slip vectors were selected for this OK-PA boundary: 195 from CMT solutions and 60 from individual studies. The latter are listed in Table 1.

For the western boundary of the possible Okhotsk plate, we compiled published focal mechanism solutions for the region from Sakhalin to the eastern margin of the Japan Sea (Table 2). Only well-constrained solutions were used. Because the nodal planes of the solutions obtained by *Savostin et al.* [1983] are poorly constrained, we did not use them. The data include recent large earthquakes at the eastern margin of the Japan Sea, the 1964 Niigata (M_s=7.5) earthquake, the May 26, 1983, Japan Sea (M_s=7.7) earthquake, and the July 12, 1993, southern Hokkaido (M_s=7.8) earthquake. The slip vectors of all the events on the Japan Sea margin, including those for smaller events, are subparallel and directed E-W with a slight southeastward component. This consistency suggests that these earthquakes reflect a consistent direction of plate motion. Because the slip vectors are almost normal to the presumed convergent boundary along the eastern margin of the Japan Sea (Figure 3), oblique convergence is unlikely to significantly bias the slip vectors [*DeMets*, 1992b; *McCaffrey*, 1992; *Yu et al.*, 1993]. We did not use focal mechanism solutions from the presumed northern boundary of the Okhotsk plate, in the southeastern Chersky Range and Kamchatka peninsula, because interpretation of the fault planes is ambiguous and the number of constrained focal mechanism solutions is small [*Cook et al.*, 1986; *Fujita et al.*, 1990].

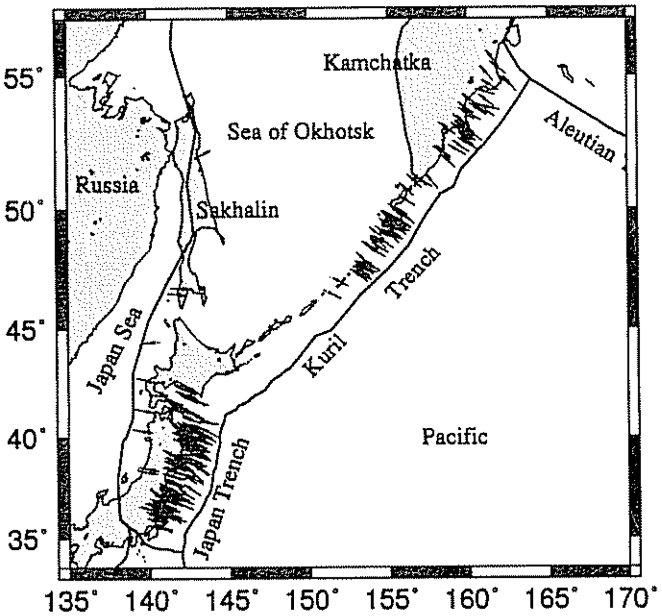


Figure 3. Earthquake slip vector directions around the possible Okhotsk plate; these data and the other NUVEL-1 NA-Pacific (PA) and NA-EU data are inverted in this study to estimate the relative motion of the Okhotsk plate.

We also used the NUVEL-1 slip vector, transform strike, and spreading rate data for PA-NA and EU-NA in combination with the data just discussed. In compiling these data, we deleted Kamchatka slip vectors from the NUVEL-1 data, because they are included as either OK (or NA)-PA data. Because the original NUVEL-1 data set includes the Kamchatka slip vectors and treats them as NA-PA, the resulting NUVEL-1 model is not in theory suitable for testing for the Okhotsk plate. In fact, the effect of these few slip vectors is so minor that the predicted NA-PA motion can be treated as independent of any possible Okhotsk plate data [*DeMets*, 1992a]. This is further supported by the fact that the NUVEL-1 solution for North America-Pacific plate motion is quite consistent with independent space geodetic data [*Argus and Gordon*, 1990; *Dixon et al.*, 1991].

Test of Plate Geometry

To test for the existence of a distinct Okhotsk plate, we compared how well the data were fit by the alternative plate geometry models in Figures 2b and 2c. In the first, the North American plate extends to northern Honshu. In the second, northeastern Siberia is part of the North American plate,

Table 1. Slip Vector Data for the Kamchatka-Kuril-Japan Trenches

Date	Time, UT	Location, °N	Location, °E	Datum, deg	σ, deg	Reference
June 12, 1978	0806	38.23	142.02	294	10	*Seno et al* [1980]
May 16, 1968	0048	40.86	143.38	298	10	*Kanamori* [1971]
March 16, 1965	1646	40.70	143.20	287	10	*Izutani and Hirasawa* [1978]
March 29, 1965	1047	40.65	143.15	298	10	*Izutani and Hirasawa* [1978]
May 27, 1970	1905	40.15	143.25	297	10	*Izutani and Hirasawa* [1978]
May 22, 1968	1929	40.25	142.57	291	10	*Izutani and Hirasawa* [1978]
Nov. 11, 1968	1441	40.12	143.42	301	10	*Izutani and Hirasawa* [1978]
May 16, 1968	2304	39.83	143.08	297	15	*Kanamori* [1971]
June 12, 1968	1341	39.47	142.89	302	10	*Yoshioka and Abe* [1976]
Nov 19, 1973	1301	38.99	141.93	294	15	*Seno and Pongsawat* [1981]
Sept. 14, 1970	0944	38.77	142.27	298	15	*Seno and Pongsawat* [1981]
July 04, 1972	0104	38.55	142.08	302	15	*Seno and Pongsawat* [1981]
April 04, 1971	1839	38.41	142.18	301	15	*Seno and Pongsawat* [1981]
Jan. 17, 1967	1159	38.33	142.20	297	15	*Seno and Pongsawat* [1981]
Jan. 18, 1981	1817	38.71	142.75	294	10	*Seno and Eguchi* [1981]
Nov. 08, 1976	0819	38.12	142.26	296	15	*Seno* [1980]
Sept. 02, 1981	0924	35.82	141.02	302	15	*Seno and Takano* [1989]
Nov. 15, 1974	2332	35.85	141.10	305	15	*Seno and Takano* [1989]
Aug. 21, 1977	0519	35.29	141.30	300	15	*Seno and Takano* [1989]
July 08, 1974	0545	36.44	141.17	303	15	*Yoshii* [1979]
Nov. 04, 1967	1326	37.39	141.71	292	15	*Kawakatsu and Seno* [1983]
Feb. 05, 1964	1130	36.47	141.02	304	15	*Kawakatsu and Seno* [1983]
July 20, 1973	0812	36.45	141.05	293	15	*Kawakatsu and Seno* [1983]
Sept. 22, 1965	2208	36.44	141.37	293	15	*Kawakatsu and Seno* [1983]
May 30, 1964	1430	36.23	141.29	288	15	*Kawakatsu and Seno* [1983]
Sept. 21, 1968	1306	42.08	142.65	300	15	*Miyamura and Sasatani* [1986]
Oct. 30, 1975	0141	42.05	142.66	296	15	*Miyamura and Sasatani* [1986]
Sept. 19, 1975	1754	41.86	142.76	290	15	*Miyamura and Sasatani* [1986]
Jan. 24, 1967	0305	41.53	142.08	289	15	*Miyamura and Sasatani* [1986]
Oct. 10, 1974	0648	41.05	143.09	286	15	*Miyamura and Sasatani* [1986]
June 22, 1968	0112	40.31	143.68	291	10	*Seno and Kroeger* [1983]
May 24, 1968	1406	40.91	143.11	298	10	*Seno and Kroeger* [1983]
Sept. 15, 1971	1455	39.17	143.39	300	10	*Seno and Kroeger* [1983]
April 21, 1968	0834	38.68	142.99	291	10	*Seno and Kroeger* [1983]
Sept. 17, 1965	1621	36.35	141.38	309	15	*Sasatani* [1971]
May 27, 1970	2235	40.24	143.08	302	15	*Miyamura and Sasatani* [1986]
Nov. 13, 1968	1841	40.17	142.65	309	15	*Miyamura and Sasatani* [1986]
Nov. 24, 1971	1935	52.85	159.22	306	15	*Kurita and Ando* [1974]
Nov. 04, 1952	1658	52.6	160.30	307	15	*Kanamori* [1976]
March 04, 1973	1757	54.8	161.6	319	20	*Stauder and Mualchin* [1976]
Nov. 18, 1965	2158	53.9	160.7	306	20	*Stauder and Mualchin* [1976]
June 28, 1970	1101	53.4	160.4	308	20	*Stauder and Mualchin* [1976]
April 12, 1973	1349	50.9	157.4	311	20	*Stauder and Mualchin* [1976]
March 12, 1973	1939	50.8	157.1	312	20	*Stauder and Mualchin* [1976]
Feb. 28, 1973	0637	50.5	156.6	311	20	*Stauder and Mualchin* [1976]
March 12, 1973	1114	50.1	156.7	302	20	*Stauder and Mualchin* [1976]
Oct. 03, 1965	1445	49.5	156.5	311	20	*Stauder and Mualchin* [1976]
June 13, 1969	0848	49.4	155.5	308	20	*Stauder and Mualchin* [1976]
Aug. 19, 1971	2215	49.3	155.4	321	20	*Stauder and Mualchin* [1976]
Aug. 04, 1972	1751	49.2	156.1	310	20	*Stauder and Mualchin* [1976]
May 20, 1968	1034	48.8	154.7	307	20	*Stauder and Mualchin* [1976]
June 14, 1967	0805	47.5	154.4	291	20	*Stauder and Mualchin* [1976]
June 12, 1967	2322	47.4	154.3	289	20	*Stauder and Mualchin* [1976]
July 24, 1964	0812	47.2	153.8	306	20	*Stauder and Mualchin* [1976]
July 24, 1964	1702	47.1	153.6	302	20	*Stauder and Mualchin* [1976]
July 24, 1964	1325	47.0	153.7	309	20	*Stauder and Mualchin* [1976]
April 01, 1967	0557	46.3	152.00	297	20	*Stauder and Mualchin* [1976]
May 16, 1968	1613	39.7	143.6	295	20	*Stauder and Mualchin* [1976]
June 17, 1968	1153	41.0	143.00	300	20	*Stauder and Mualchin* [1976]
Nov. 24, 1968	2120	40.3	142.3	299	20	*Stauder and Mualchin* [1976]

Hypocentral parameters are from the International Seismological Centre (ISC), Edinburgh.

whereas the Kamchatka-Sea of Okhotsk-northern Honshu area forms an Okhotsk plate. In the first case, we found a best fitting North America-Pacific Euler vector using the Kamchatka-Kuril-Japan trench slip vectors and the other NUVEL-1 PA-NA data and a best fitting North America-Eurasia Euler vector from the NUVEL-1 EU-NA data and the Sakhalin-eastern margin of the Japan Sea slip vectors. Although in northeastern Asia the only data available are directions of plate motions from slip vectors, the full Euler vectors can be found because the data include spreading rates from other portions of these boundaries. In the second case, we found Euler vectors for the four-plate OK-PA-NA-EU system using the NUVEL-1 data (excluding Kamchatka) for NA-PA and EU-NA data, the Kamchatka-Kuril-Japan trench data for OK-PA data, and the Sakhalin-eastern margin of the Japan Sea data for EU-OK data. We inverted these Euler vectors simultaneously using *Minster and*

Table 2. Slip Vector Data for Sakhalin-N.E. Japan Sea

Date	Time, UT	Location, °N	Location, °E	Datum, deg	σ, deg	Reference
June 16, 1964	0401	38.40	139.26	100	10	*Hirasawa* [1965]
July 12, 1964	0145	38.58	139.30	101	10	*Hirasawa* [1965]
May 26, 1983	0259	40.48	139.09	100	10	*Satake* [1985]
June 21, 1983	0625	41.35	139.10	100	15	*Ishikawa et al.* [1984]
Aug. 07, 1993	1942	41.99	139.95	091	20	*Sipkin*'s CMT
July 12, 1993	2217	42.78	139.20	104	10	*Tanioka et al.* [1993]
Aug. 01, 1940	1508	44.35	139.46	084	15	*Fukao and Furumoto* [1975]
Sept. 05, 1971	1835	46.54	141.15	096	15	*Fukao and Furumoto* [1975]
Sept. 06, 1971	1337	46.76	141.39	094	15	*Yoshii* [1979]
Oct. 02, 1964	0058	51.95	142.92	062	20	*Chapman and Solomon* [1976]

Hypocentral parameters are from ISC except for the 1940 events, whose parameters are from the relocation of *Fukao and Furumoto* [1975]. CMT, Centroid Moment Tensor.

Jordan's [1978] algorithm. We had 366 data in total, with 255, 10, 62, and 39 on the OK-PA, OK-EU, PA-NA, and EU-NA boundaries, respectively. Table 3 lists the χ^2 for each boundary segment.

As expected, the four-plate model with a separate Okhotsk plate fits better, as shown by the reduction in the χ^2 misfit from 86.65 to 77.74. To see if this reduction exceeds that expected from the fact that the additional plate provides three more parameters, we use an F ratio test. The statistic F comparing the two cases is

$$F_{3,\,N-9} = \frac{[\chi^2(\text{three plates}) - \chi^2(\text{four plates})] \,/\, 3}{\chi^2(\text{four plates}) \,/\, (N-9)}$$

where N is the total number of data [*Stein and Gordon*, 1984]. The F value is 13.66, significantly higher than the 99% risk level value of 3.97, indicating that the improved fit is very unlikely to have occurred by chance. Hence by this test, an Ohkotsk plate can be resolved as distinct from the North American plate.

Euler Vectors

Euler vectors for the four plate system are listed in Table 4. The rotation rates were scaled to correspond to those in NUVEL-1a [*DeMets et al.*, 1994] by multiplying by the timescale shift term 0.9562. Because we used only data for the EU, NA, PA, and OK plates, the EU-NA and NA-PA vectors were determined essentially from data on the EU-NA and NA-PA boundaries but were affected slightly by the OK data because of the closure of the Euler vectors. As a result, our EU-NA and NA-PA Euler vectors are similar to the NUVEL-1 EU-NA and NA-PA best fitting vectors, those derived only from data at the boundary between the two plates in question.

Figure 4a shows the corresponding linear velocities relative to the Okhotsk plate predicted along its boundaries. For comparison, Figure 4b shows the relative velocities predicted assuming this region is part of the North American plate. The predicted differences are small but can be seen, especially in the direction of motion along the western margin of the possible Okhotsk plate. The NA-OK Euler vector has an angular velocity which is small compared with those for major plate pairs but not negligible. As a result, discernible left-lateral strike slip at 8 mm yr^{-1} is predicted in the eastern Chersky Range and northern Kamchatka peninsula. Because of the rotation of OK with respect to NA, the predicted convergence velocities in the Kuril Trench differ slightly from those for NA-PA convergence.

The EU-OK vector has a pole in northernmost Sakhalin and predicts 5-13 mm yr^{-1} convergence at the eastern margin of the Japan Sea. The predicted north-to-south variation is larger than predicted for EU-NA motion, with a EU-NA pole located further north in Siberia (Figure 1, Figures 4a and 4b). North of Sakhalin, slow extension (2-8 mm yr^{-1}) is predicted in the Sette Daban Range.

Figure 5 compares the observed slip vectors with the convergence directions predicted from the two models and the NUVEL-1 global NA-PA and NA-EU Euler vectors. Along the Kamchatka-Kuril-Japan trenches (Figure 5a), there is essentially no difference between the predictions for the overriding plate being Okhotsk or North America, in accord with *DeMets*' [1992a] results. In contrast, along Sakhalin and the eastern margin of the Japan Sea (Figure 5b), the observed slip vectors are noticeably better fit by predicted EU-OK motion than EU-NA. The χ^2 for the Sakhalin-Japan Sea segment is 1.80 for the OK plate case but 8.69 for the three-plate case, showing that almost all the change in χ^2 comes from this segment (Table 3).

Table 3. χ^2 for Three- and Four-Plate Models

Boundary	Number of Data	χ^2 (Three-Plate)	χ^2 (Four-Plate)
OK-PA	255	56.86	57.08
NA-PA	62	14.54	14.53
EU-NA	39	6.56	4.33
EU-OK	10	8.69	1.80
Total	366	86.65	77.74

OK, Okhotsk; PA, Pacific; NA, North America; EU, Eurasia. NA-PA boundary excludes the Kamchatka-Kuril-Japan trenches (OK-PA boundary). Similarly, NA-EU boundary excludes the Sakhalin-eastern margin of the Japan Sea (EU-OK boundary). In the three-plate model, OK is treated as part of NA.

Table 4. Euler Vectors for Four-Plate Model

Plate Pair	Euler Vector			Standard Error Ellipse		
	Lat., °N	Long., °E	ω, deg/m.y.	σ_{max}, deg	σ_{min}, deg	ζ_{max}, deg
OK-PA	35.65	-67.05	0.710	89.71	4.92	-67.9
EU-OK	53.02	142.09	0.405	13.52	3.44	-71.8
NA-OK	41.71	147.33	0.195	39.93	13.37	81.8
NA-PA	49.51	-77.26	0.714	4.24	0.31	-35.0
EU-NA	62.77	134.44	0.219	34.73	7.41	-77.3
EU-PA	62.61	-85.18	0.831	6.16	5.29	-12.0

The variable ζ_{max} is the azimuth of the major axis of the error ellipse.

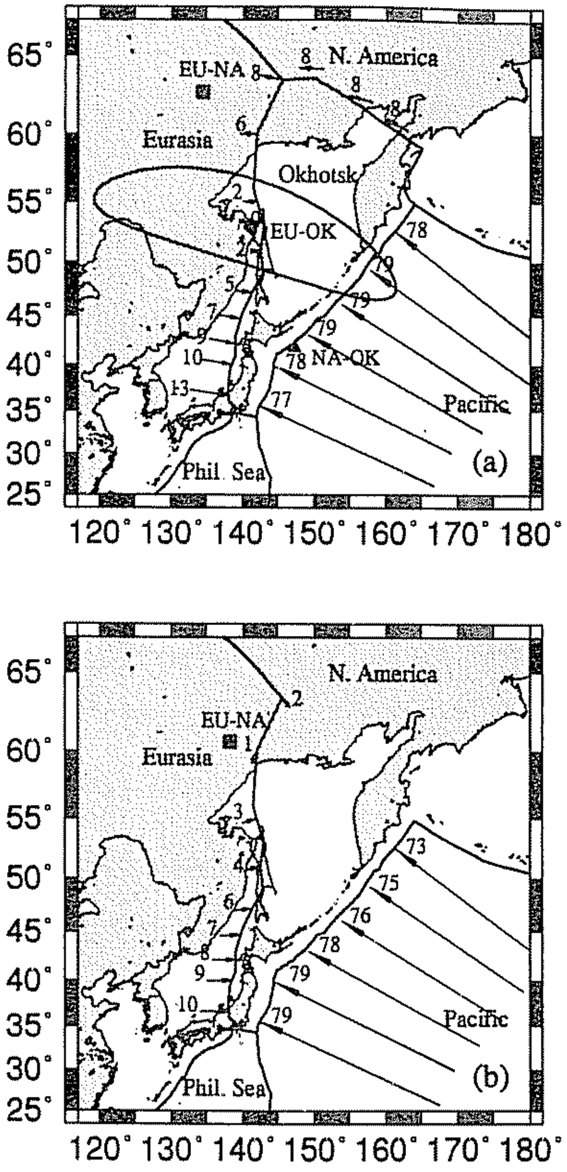


Figure 4. (a) Relative velocities predicted by the Euler vectors of the OK-PA-NA-EU plate system. Arrows indicate the relative motion directions of other plates with respect to OK. The EU-OK, EU-NA, and NA-OK poles and EU-OK 1σ error ellipse are also plotted. Relative velocities, which reflect the NUVEL-1A timescale, are given in millimeters per year. (b) Relative velocities predicted by the Euler vectors for the PA-NA-EU plate system estimated in this study. Arrows indicate the relative motion directions of other plates with respect to NA. The EU-NA pole is also plotted. Relative velocities, which reflect the NUVEL-1A timescale, are given in millimeters per year.

Discussion

Relative Motion at the Eastern Margin of the Japan Sea

The eastern margin of the Japan Sea has considerable interest for Japanese earth scientists, because it was the location of large recent earthquakes: the May 26, 1983, Japan Sea (M_s=7.7) and the July 12, 1993, southern Hokkaido (M_s=7.8) earthquakes. The predicted convergence rate is ~ 10 mm yr^{-1} either for EU-OK or EU-NA motion (Figure 4). The predicted EU-OK direction, however, is more southeasterly than for EU-NA and more consistent with the observed slip vectors (Figures 3 and 5).

The seismic slip in these large earthquakes is ~3 m, suggesting an approximately 300-year recurrence for such earthquakes. However, no historical earthquake is known to have preceded these events [*Usami*, 1987; *Hatori and Katayama*, 1977], suggesting either that the historic record is incomplete before the year 1700, that much of the plate motion occurs by aseismic slip, or that the earthquake recurrence is irregular, perhaps becaue of nonlinear interaction with other segments of the boundary.

An alternative recurrence estimate can be made from a study by *Savostin et al.* [1983]. They assumed that northeast Asia formed an Amurian (AM) plate, and determined the AM-OK Euler vector using earthquake mechanisms and post-Miocene fault slip data in Sakhalin. Though their AM-OK pole is located west of northernmost Sakhalin and close to our EU-OK pole, they find a rotation rate twice what we find. This predicts a 150-year recurrence for large earthquakes in the Japan Sea, which seems incompatible with any historic earthquake preceding the 1983 and 1993 events since the year 1700 for which the historic record seems almost complete [*Usami*, 1987; *Hatori and Katayama*, 1977].

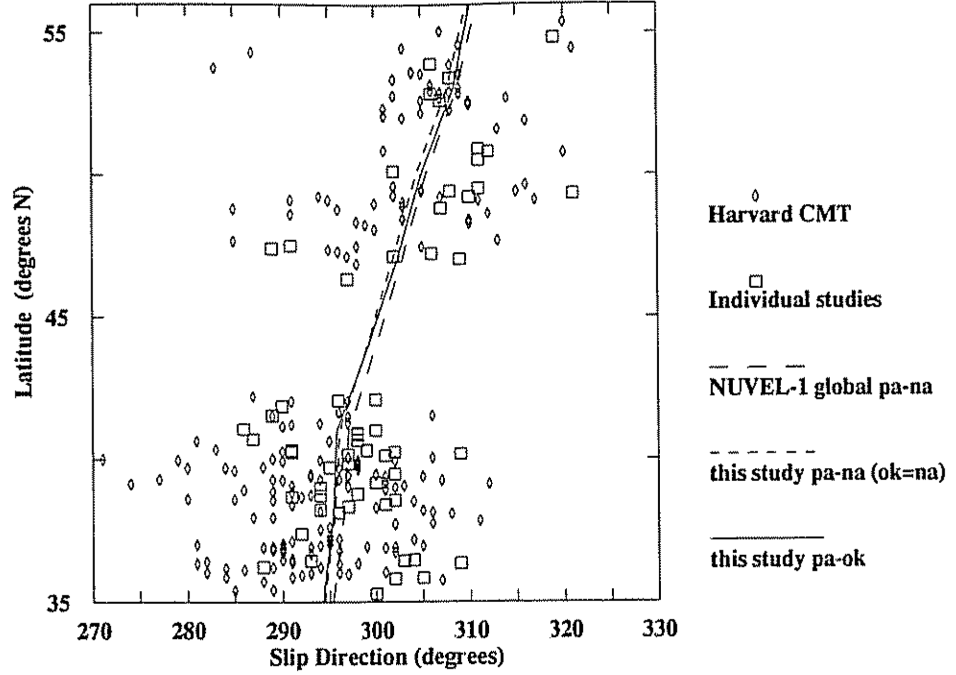
The May 27, 1995, Neftegorsk Earthquake

The focal mechanism of the Neftegorsk earthquake of May 27, 1995 (M_w=7.0), which occurred beneath northernmost Sakhalin, showed right-lateral strike slip on a vertical fault striking NNE-SSW (CMT solutions by the Earthquake Research Institute at the University of Tokyo and Harvard University). This solution is consistent with a 36-km-long surface strike-slip rupture [*Suzuki et al.*, 1995] and coseismic deformation shown by Global Positioning System (GPS) [*Takahashi et al.*, 1995], both of which show ~4-5 m average strike-slip displacement. Seismicity in this area (Figure 1) suggests that a plate boundary runs within Sakhalin Island, at least in its central-northern part. This possibility is supported by sporadic seismicity along the N-S striking Tym-Poronaysk fault in central Sakhalin island, a Paleogene suture zone from the collision between Eurasia and Okhotsk [*Fournier et al.*, 1994]. In the north, this central fault is obscure, but near the east coast, some Neogene faults have been mapped [*Kimura et al.*, 1983; *Fournier et al.*, 1994], along one of which the Neftegorsk earthquake occurred.

The strike-slip mechanism of the Neftegorsk earthquake differs from the other well-constrained earthquake mechanisms in and around Sakhalin, which show thrusting with roughly E-W trending *P* axes [*Seno and Stein*, 1995]. It is thus interesting to consider whether this large earthquake in the plate boundary zone reflects the plate motion. The direction of EU-OK relative motion at the center of the surface faulting (52.90°N 142.91°E, *Takahashi et al.* [1995]) is predicted to be N14°E, which coincides with the slip vector of the CMT solutions (N19°E for Harvard and N16°E for Earthquake Research Institute CMT solutions) and surface faulting (N15°E, [*Suzuki et al.*, 1995]). Given that the Neftegorsk earthquake occurred to the east of the EU-OK pole, it would be on a transform fault if this is on a plate boundary (Figure 4a). The other, thrust earthquakes to the south would then represent EU-OK convergence.

A difficulty in interpreting these earthquakes tectonically, however, is that they occur close to the predicted Euler pole.

(a) Kamchatka - Kuril - Japan trenches



(b) Sakhalin - eastern margin of the Japan Sea

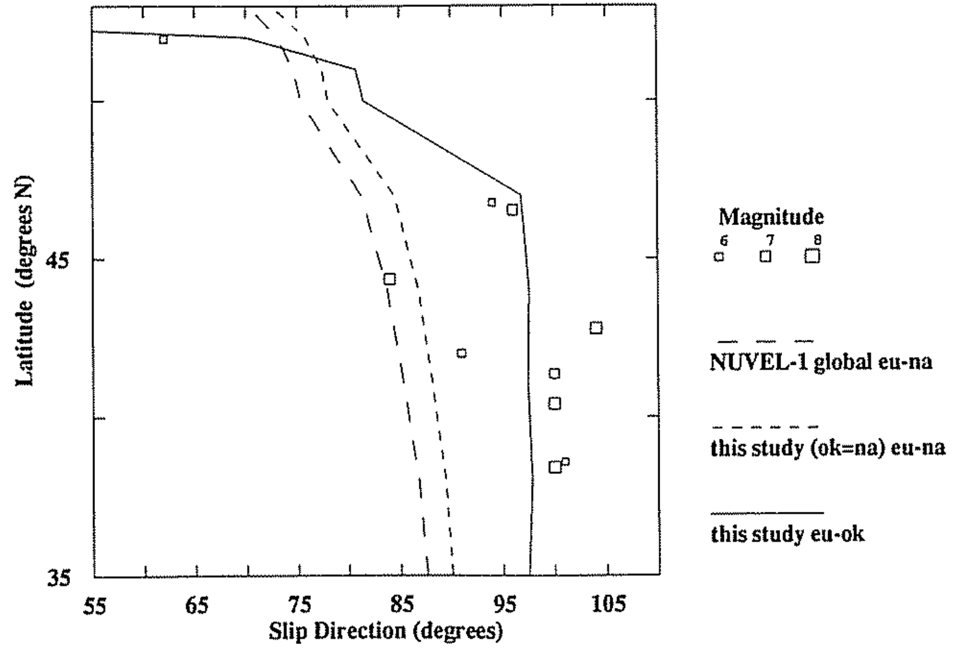


Figure 5. (a) Comparison between the slip vector directions and the relative motion directions predicted from the PA-OK and PA-NA Euler vectors along the Kamchatka-Kuril-Japan trenches. Directions are clockwise from north. The predicted PA-OK direction (solid curve), that from the PA-NA NUVEL-1 global Euler vector (long-dashed curve), and that from the PA-NA Euler vector we found for the NA-PA-EU plate system (short-dashed curve) are similar and fit the data about equally well. (b) Comparison of the slip vector directions along Sakhalin and the eastern margin of the Japan Sea with the relative motion directions predicted from the EU-OK and EU-NA Euler vectors. Directions are clockwise from north. The model with an Okhotsk plate predicts the slip vectors better than the one in which this area is treated as North America.

As a result, the predicted directions of motion would vary significantly for different acceptable assumptions about the pole location. In addition, the predicted rates of motion are slow. For example, the 4-m average slip in the Neftegorsk earthquake and the 0.5 mm yr^{-1} predicted rate imply a recurrence time of ~8,000 years. Hence we consider it plausible, but by no means required, that the Neftegorsk earthquake reflects interplate motion between EU and OK.

An alternative model, extrusion of OK due to contraction between NA and EU [e.g., *Riegel et al.*, 1993; *Fournier et al.*,1994; *Faust and Fujita*, 1995] can also explain the strike-slip faulting of the earthquake. However, this extrusion would not be consistent with the motion observed along the SW portion of the presumed Okhotsk plate boundary, that is, E-W thrusting in central-southern Sakhalin and the eastern margin of the Japan Sea, even if we introduce the Amurian plate, as discussed in the next subsection. On the other hand, if one does not assume a distinct Okhotsk plate, the Neftegorsk earthquake would be an intraplate event in either the North American or Eurasian plate, and the thrust events would reflect NA-EU convergence.

Sette Daban Range

The EU-OK pole in northern Sakhalin predicts slow extension in the Sette Daban Range, northwest of the Sea of Okhotsk (Figure 4a). Few focal mechanisms are available for this area. *Riegel et al.* [1993] inferred that right-lateral strike slip occurs on N-S trending faults from one poorly constrained focal mechanism and Russian geological literature. Combining this inference with the left-lateral motion at the southeast Chersky Range inferred by focal mechanisms, they suggested that the Okhotsk plate has been pushed away to the southeast because of closure between NA and EU. *Cook et al.* [1986] also suggested from seismicity that OK is compressed between its larger neighbors in the Sette Daban Range. Hence our model prediction of E-W extension is inconsistent with previous inferences for motion in this area.

Though the data are insufficient to resolve this issue, some possibilities are worth noting. Assuming that what we treat as EU-OK motion actually reflects motion between Okhotsk and an Amurian plate [*Zonenshain and Savostin*, 1981; *Faust and Fujita*, 1995] in north China does not resolve the problem. A preliminary study [*Wei and Seno*, 1995] finds that the Amuria-Eurasia rotation pole is located northwest of the Baikal Rift and the Amurian plate motion with respect to Eurasia is calculated to be north in the Sette Daban Range, so Eurasia would move SW with respect to OK, opposite the direction inferred by *Riegel et al.* [1993]. *Savostin et al.* [1982; 1983] estimated the Amuria-Eurasia pole to be 300 km farther south than the estimation by *Wei and Seno* [1995]. Combined with the Amuria-Okhotsk motion, they similarly estimated left-lateral strike slip as EU-OK motion on the NE-SW striking plate boundary in the Sette Daban Range. The issue is also not resolved by the possibility, suggested by *Cook et al.* [1986] and recent global GPS plate motion measurements [*Argus and Heflin*, 1995], that the EU-NA pole is in the Laptev Sea, more than 1000-2000 km farther north than in NUVEL-1. *Cook et al.* [1986] suggested the EU-NA pole has migrated to the north during the past 3 million years. We tested how such a pole shift affects the predicted relative velocity in the Sette Daban Range (K. Fujita, personal communication, 1995) by inverting the four-plate model data but fixing the NA-EU pole following *Cook et al.* [1986] or *Argus and Heflin* [1995]. Because the EU-OK pole shifted a few degrees north but still predicted extension in the Sette Daban Range, such a change in pole position does not resolve the issue. Hence until more data on the deformation in this region are available, it is difficult to compellingly argue for any specific plate geometry, including a plate other than Eurasia juxtaposing the Magadan area at the Sette Daban Range.

Chersky Range-Kamchatka Peninsula

The NA-OK Euler vector we found predicts 8 mm yr^{-1} motion in the Chersky Range and Kamchatka peninsula (Figure 4a). The predicted motion is E-W in the eastern Chersky Range and WNW-ESE in the northeast Sea of Okhotsk-northern Kamchatka peninsula. *Cook et al.* [1986] and *Fujita et al.* [1990] inferred NW-SE and E-W left-lateral motion in the eastern Chersky Range and north of the Sea of Okhotsk-northern Kamchatka, respectively, from earthquake mechanisms. This estimate is not much different from ours given the large error ellipse of the NA-OK pole (Table 4).

A difficulty with the *Cook et al.*'s [1986] result is what their OK-NA pole implies for motion along the Japan Sea. Taking this pole, located near northeastern Siberia at 72.4°N, 169.8°E, we calculated an EU-OK Euler vector assuming an angular velocity producing 5-10 mm yr^{-1} slip at the eastern Chersky Range and the NA-EU NUVEL-1 global Euler vector. This yielded an EU-OK pole in the Indian Ocean which predicted an opening along the eastern margin of the Japan Sea, rather than the observed convergence. One possible explanation is that the earthquakes in northern Kamchatka used by *Cook et al.* [1986] may in fact represent motion between Kamchatka and the western Aleutian forearc sliver due to the oblique convergence of the Pacific plate.

Future Studies

We anticipate that most future insight into the issue of the relative motions of the northern Japanese islands with respect to North America and the surrounding plates and the related issues of the location of the plate boundary in Sakhalin, that is, which plate exists west of the Magadan area, whether China moves significantly relative to the remainder of Eurasia, and whether an Amurian plate exists in north China and southern Siberia, will come from the increasing availability of relevant space geodetic data [e.g., *Heki et al.*, 1990; *Robbins et al.*, 1993; *Ryan et al.*, 1993; *Robaudo and Harrison*, 1993; *Tsuji*, 1995; *Argus and Heflin*, 1995]. Given that much of the area is close to the trenches, a challenge for this purpose will be separating the possible effects of deformation due to the seismic cycle from plate motion [e.g., *Heki et al.*, 1990; *Argus and Lyzenga*, 1993].

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