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A Test of Present-Day Plate Geometries for Northeast Asia and Japan

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Alternative geometries for the present-day configuration of plate boundaries in northeast Asia and Japan are tested using NUVEL-1 and 256 horizontal earthquake slip vectors from the Japan and northern Kuril trenches. Statistical analysis of the slip vectors is used to determine whether the North American, Eurasian, or Okhotsk plate overlies the trench. Along the northern Kuril trench, slip vectors are well-fit by the NUVEL-1 Pacific-North America Euler pole, but are poorly fit by the Pacific-Eurasia Euler pole. Results for the Japan trench are less conclusive, but suggest that much of Honshu and Hokkaido are also part of the North American plate. The simplest geometry consistent with the trench slip vectors is a geometry in which the North American plate extends south to 41°N, and possibly includes northern Honshu and southern Hokkaido. Although these results imply that the diffuse seismicity that connects the Lena River delta to Sakhalin Island and the eastern Sea of Japan records motion between Eurasia and North America, onshore geologic and seismic data define an additional belt of seismicity in Siberia that cannot be explained with this geometry. Assuming that these two seismic belts constitute evidence for an Okhotsk block, two published kinematic models for motion of the Okhotsk block are tested. The first model, which predicts motion of up to 15 mm yr^{-1} relative to North America, is rejected because Kuril and Japan trench slip vectors are fit more poorly than for the simpler geometry described above. The second model gives a good fit to the trench slip vectors, but only if Okhotsk-North America motion is slower than 5 mm yr^{-1}.

INTRODUCTION

The boundary between the Eurasian and North American plates in northeast Asia is one of the most poorly understood of the major plate boundaries. Although the oceanic part of the Eurasia-North America boundary, which comprises the north Atlantic and Arctic ridge systems, is easily located from seismicity (Figure 1), the plate boundary becomes much harder to define south of the Lena River delta, where the Arctic ridge intersects the Siberian continental shelf (Figures 1 and 2). Prior studies have identified two belts of earthquakes in northeast Asia that emanate from the Lena River delta. Either or both of these belts could accommodate the present-day motion between Eurasia and North America. One of these belts, here called the Cherskii Mountains seismic belt (Figure 2), terminates near the intersection of the Kuril and Aleutian trenches off the coast of north-central Kamchatka [*Cook et al.*, 1986]. The other belt, here called the Sakhalin seismic belt, appears to connect the Lena River delta to northern Sakhalin Island, where it continues south to the island of Hokkaido and terminates at a triple junction somewhere along the Japan trench [*Chapman and Solomon*, 1976].

Because the continental part of the Eurasia-North America plate boundary is so poorly defined, it is unclear whether lithosphere in the region of the Sea of Okhotsk is part of the Eurasian plate, the North American plate, or possibly, a third plate that moves slowly relative to Eurasia and North America (Figure 3). Early models of present-day global plate motions assumed distinctly different plate geometries for northeast Eurasia, presumably because of the lack of strong kinematic or geologic evidence for a given geometry [*Le Pichon*, 1968; *Morgan*, 1968; *Chase*, 1972; *Minster et al.*, 1974]. Interestingly, none of these studies rigorously tested whether earthquake slip vectors along the Kuril and Japan trenches were more consistent with the Pacific-North America, or Pacific-Eurasia direction of motion predicted by a rigid plate model. *Chapman and Solomon* [1976] were the first to attempt to define the regional configuration of plate boundaries through analysis of geologic and seismologic data from northeast Asia. They concluded that the simplest plate boundary configuration that is consistent with the regional pattern of deformation is a geometry in which deformation associated with Eurasia-North America motion is concentrated along a line of diffuse seismicity that connects the Lena Rivera delta to the Sakhalin seismic belt (Figure 3, geometry A). In this model, only three plates are required, North America, Eurasia, and the Pacific plate.

Although this geometry has been incorporated into subsequent models of present-day global plate motions [*Chase*, 1978; *Minster and Jordan*, 1978; *DeMets et al.*, 1990], the *Chapman and Solomon* [1976] analysis raises an important question about whether it is appropriate to test the validity of rigid plate geometries with data from zones of continental deformation. The rigid plate assumptions that work well for describing displacements along narrow oceanic plate boundaries rarely apply to plate boundaries within continental lithosphere, which are often characterized by distributed deformation that is a complicated, time-dependent function of rheology and the orientation of the stress field relative to pre-existing crustal weaknesses [*Molnar and Chen*, 1982; *McKenzie and Jackson*, 1983; *England and Jackson*, 1989].

The purpose of this paper is to determine the simplest configuration of plate boundaries in northeast Asia that satisfies reliable plate kinematic observations and plate circuit closures between the Pacific, Eurasian, and North American plates. The optimal plate geometry is defined through a systematic comparison of shallow-thrust earthquake slip directions along the Japan and Kuril trenches, which record motion between the subducting Pacific plate and the overlying litho-

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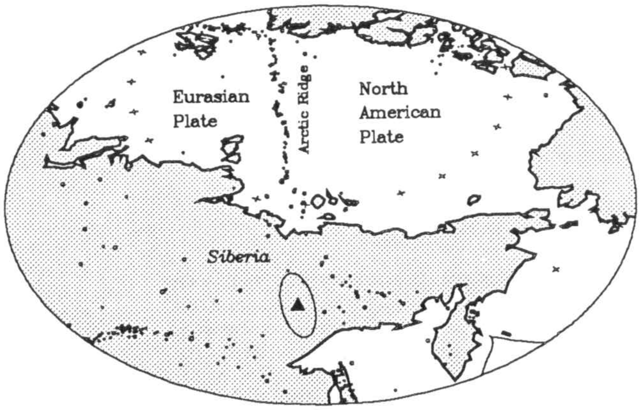

Fig. 1. Continental versus oceanic seismicity for the Eurasia-North America plate boundary. All 1963-1989 shallow earthquakes are shown as solid circles. The NUVEL-1 Eurasia-North America Euler pole is shown as a solid triangle, along with its 1σ error ellipse.

sphere, with the present-day directions of motion between the Pacific and North American, and Pacific and Eurasian plates. The Pacific-North America and Pacific-Eurasia convergence directions are determined from the NUVEL-1 model for present-day global plate velocities [*DeMets et al.*, 1990]. A statistical comparison of the fits of the Pacific-North America and Pacific-Eurasia Euler poles to the Japan and Kuril trench slip vectors is used to determine whether the overlying lithosphere is part of the North American, Eurasian, or neither plate.

This analysis differs from prior studies of plate configurations and deformation in northeast Asia in several important respects. First, the criterion for identifying a preferred plate geometry is well-defined – the preferred geometry is the geometry with the minimum number of plates required to fit trench slip vectors from the Kuril and Japan trenches. In contrast to the approach used by *Chapman and Solomon* [1976], there is no requirement that the preferred geometry explain deformation along the seismic belts in northeast Asia. Instead, it is assumed that any distributed deformation in northeast Asia will ultimately be modeled using techniques that are better suited for characterizing deformation within continents [*McKenzie and Jackson*, 1983; *Minster and Jordan*; 1984].

A second factor that distinguishes this work from prior studies is the large data set now available for the examination of alternative plate geometries for northeast Asia. This study uses a newly compiled set of 397 horizontal slip vectors derived from the focal mechanisms of shallow-focus subduction earthquakes along the Kuril and Japan trenches [*DeMets*, 1992].

Finally, the plate geometries tested here differ from those assumed in previous kinematic models in an important respect. Each of the geometries tested here implicitly includes a southern Kuril sliver plate. Results presented in *Jarrard* [1986] and in *DeMets* [1992] demonstrate that a systematic discrepancy between the predicted Pacific-North America convergence direction and the directions given by shallow subduction zone earthquake slip vectors from the southern Kuril trench implies that a sliver of the southern Kuril forearc has detached from the rigid overlying plate and is presently moving to the southwest along the trench at an estimated rate of 6-11 mm yr^{-1}. This result is corroborated by geologic, geodetic, and

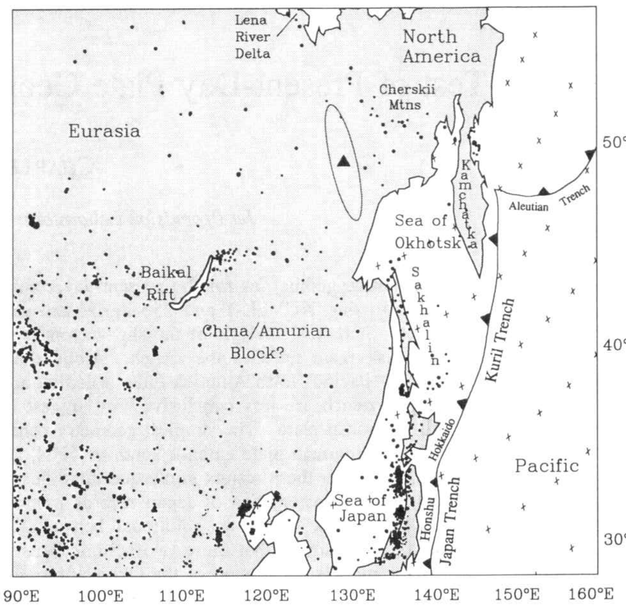

Fig. 2. Seismicity of northeast Asia and Japan. All 1963-1989 earthquakes shallower than 60 km are shown; however, for clarity, earthquakes located within 300 km of the trench axis have been omitted. Epicenters are taken from the Earthquake Data File of the National Geophysical Data Center. The NUVEL-1 Eurasia-North America Euler pole (solid triangle) and 1σ error ellipse are located in a seismically quiescent region, as would be expected for the region of negligible motion close to the rotation pole.

plate kinematic studies of present-day deformation in central Hokkaido and oblique convergence along the southern Kuril forearc [*Kaizuka*, 1975; *Seno*, 1985*a*, *b*; *Kimura*, 1986; *Hashimoto and Tada*, 1988; *Tada and Kimura*, 1987].

The questions posed here include the following: (1) Are slip vectors located north of the southern Kuril forearc more consistent with Pacific-North America, Pacific-Eurasia, or possibly, Pacific-Okhotsk motion? (2) Do slip vectors from the Japan trench imply that southern Hokkaido and much of the island of Honshu are part of the North American or Eurasian plate, or possibly, a Japan microplate? (3) How does the fit of an Euler vector that best fits all northern Kuril trench and Japan trench data compare to the fits of the Pacific-North America and Pacific-Eurasia Euler vectors? (4) Do the trench slip vectors require the existence of an Okhotsk plate, and if not, what are the upper limits for motion of the Okhotsk plate relative to North America?

PROPOSED GEOMETRIES

The post-1963 seismicity of northeast Asia suggests that present-day motion between the Eurasian and North American plates is partitioned between the Cherskii Mountain and Sakhalin seismic belts (Figure 1). It is unknown whether the relative motion across these two seismic belts is divided nearly equally, or is concentrated along just one of the belts. This uncertainty gives rise to several plausible geometries for the regional plate boundaries, each of which is described below (Figure 3).

Geometry A, which is the geometry preferred by *Chapman and Solomon* [1976], assumes that Eurasia-North America motion is concentrated along the Sakhalin seismic belt, and terminates near the intersection of the Japan and Kuril

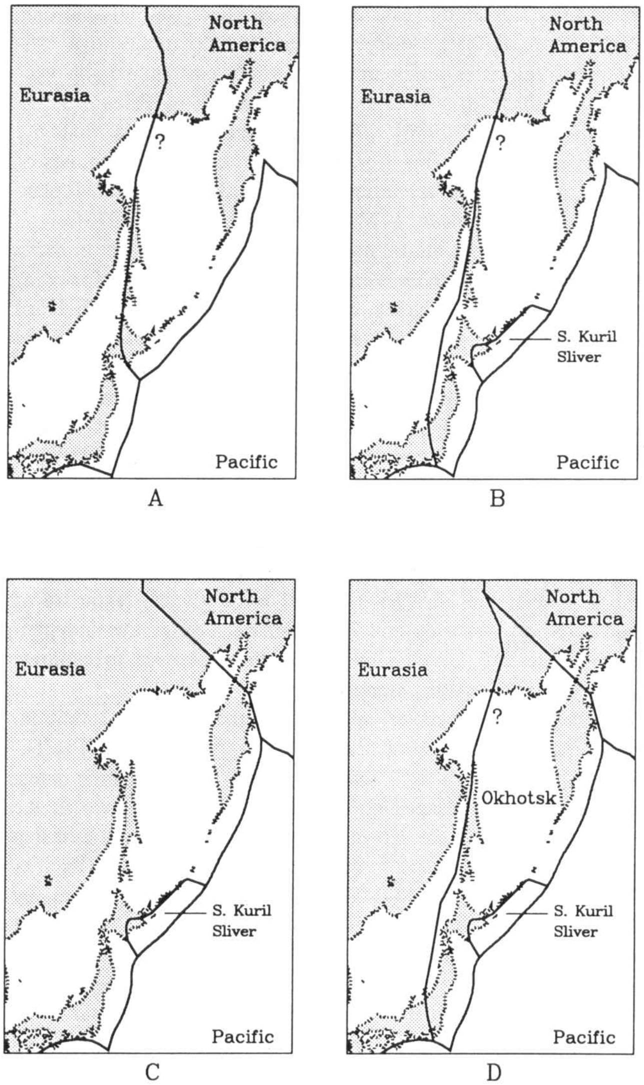

Fig. 3. Plate geometries examined in this paper. Geometry A is the geometry preferred by *Chapman and Solomon* [1976]. Geometry B is the simplest geometry that leads to a model that fits all of the trench slip vectors.

trenches. This geometry is not considered here because *DeMets* [1992] demonstrates that geometries that exclude a southern Kuril sliver plate cannot simultaneously fit all slip vectors along the Kuril and Japan trenches.

Geometry B requires that the entire plate margin that overlies the trench north of central Honshu, except for the southern Kuril forearc, is part of the North American plate. As with geometry A, this geometry implies that most Eurasia-North America motion is concentrated along the Sakhalin seismic belt, rather than the Cherskii Mountains seismic belt. Unlike geometry A, southern Hokkaido and much of the island of Honshu are assumed to be part of the North American plate, as proposed by *Kobayashi* [1983] and *Nakamura* [1983]. Some evidence supports the hypothesis that Hokkaido and northern Honshu are part of North America, rather than Eurasia. *Seno* [1985*a*] reviews geologic evidence that suggests that recent deformation of the island of Hokkaido is better explained by a model in which the southern Kuril forearc sliver is colliding with southern central Hokkaido than by a model in which the Eurasia-North America plate boundary traverses the island, as required by geometry A. *Seno* [1985*b*] further finds that 27 slip vectors derived from shallow thrust earthquakes along the Japan trench are more parallel to the Pacific-North America direction predicted by the RM2 plate motion model [*Minster and Jordan*, 1978] than to the Pacific-Eurasia direction.

Geometry C implies that nearly all deformation between the Eurasian and North American plates is concentrated along the Cherskii Mountains seismic belt. This geometry is similar to a geometry that was previously rejected by *Chapman and Solomon* [1976] because it implied that convergence between Eurasia and North America occurs across the Cherskii Mountains seismic belt and in northern Kamchatka. More recent studies of earthquakes and tectonics along the Cherskii Mountain seismic belt and in Kamchatka suggest that much of the seismic belt accommodates either convergence or strike-slip motion, although deformation along this seismic belt is still poorly understood [*Cook et al.*, 1986; *Riegel et al.*, 1991]. In light of this new evidence, geometry C is reconsidered.

Finally, geometry D incorporates an Okhotsk plate, which has been proposed elsewhere in order to explain deformation along the Cherskii Mountains and Sakhalin seismic belts [*Savostin et al.*, 1983; *Cook et al.*, 1986]. *Savostin et al.* [1983] further propose that an Amurian plate is required to explain a belt of deformation that connects the Baikal rift to the Sakhalin Island seismic zone (Figure 2); however, no attempt is made here to test this hypothesis because it is too difficult to select kinematic data that reliably record inter-plate motions within areas of diffuse continental deformation.

DATA AND TECHNIQUES

Present-Day Subduction Directions Along the Kuril and Japan Trenches

The direction of the subducting Pacific plate relative to the overriding lithosphere along the Kuril and Japan trenches is calculated from 397 horizontal slip directions (Figure 4) derived from the focal mechanisms of thrust earthquakes that occurred above 50 km depth, which is assumed here to be the maximum depth of inter-plate coupling. The data used here represent a relatively comprehensive compilation of shallow-depth earthquakes along the Kuril and Japan trenches for the period January 1963 to April 1991. Only those earthquakes with focal mechanisms and locations that are consistent with slip along the subduction zone interface are included. Of the 397 slip vectors, 141 slip vectors from 41°N to 46°N are excluded because they record motion of the Pacific plate relative to the southern Kuril forearc, rather than the rigid overlying plate. The remaining 256 slip vectors are located between 35.5°N, where the Izu trench intersects the southern Japan trench, and 54.0°N, where the northwest end of the Hawaii-Emperor seamounts subduct beneath Kamchatka. Detailed information about all 397 earthquakes is available from the author.

The horizontal slip directions are computed by rotating the slip direction determined from the focal mechanism to the horizontal in the manner described in *Minster and Jordan* [1978]. The uncertainties assigned to the horizontal slip directions are 15°, 20°, or 25°, depending on whether the seismic moment release is greater than 10^{18} N m, between 10^{17} and 10^{18} N m, or less than 10^{17} N m, respectively. These criteria are identi-

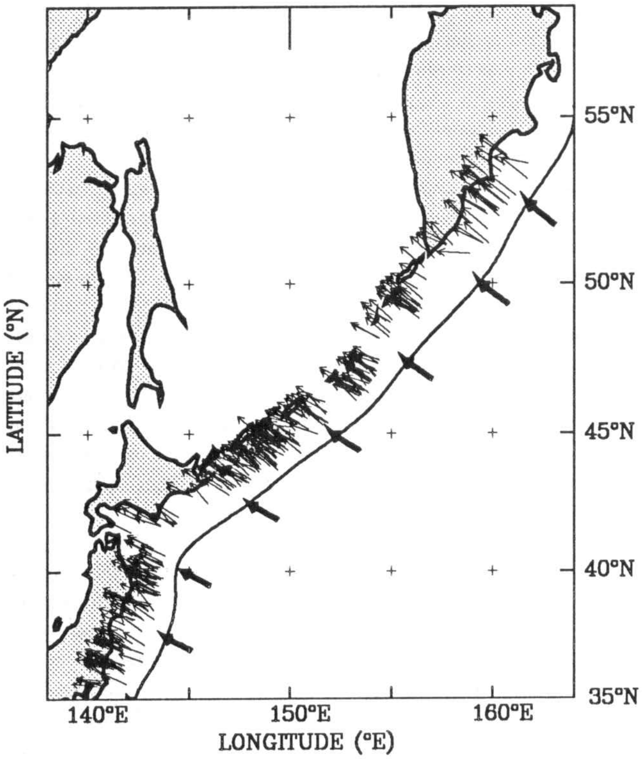

Fig. 4. Locations and directions of the 397 slip vectors used to determine the direction of subduction of the Pacific plate along the Kuril and Japan trenches. The head of each slip vector is located at its epicenter. For comparison, bold vectors show the direction of the Pacific plate beneath North America as predicted by the NUVEL-1 model.

cal to those used to assign slip vector uncertainties in the NUVEL-1 data set.

As discussed by many previous authors, slip vectors from subduction zones are subject to a number of effects that can cause systematic rotation from the rigid plate convergence direction. These include deformation within the forearc of the overlying rigid plate [*Jarrard*, 1986], which clearly occurs along the southern Kuril trench, and a systematic bias of earthquake focal mechanisms due to anomalous mantle velocity structure beneath subduction zones [*Engdahl et al.*, 1977]. Unmodeled mantle heterogeneities do not appear to affect focal mechanisms from the Kuril trench [*Engdahl et al.*, 1977]; however, it is unclear whether unmodeled heterogeneities in the mantle beneath the Japanese islands cause any systematic rotation of slip vectors along the Japan trench. As the results of this study suggest, this topic will need to be addressed to gain a better understanding of the kinematic relationship between the major overlying plates and the islands of Honshu and Hokkaido.

Use of the NUVEL-1 Rigid Plate Model to Test Alternative Plate Geometries

The NUVEL-1 model for present-day global plate motions is used to estimate Pacific-Eurasia, Pacific-North America, and Eurasia-North America velocities. This model offers important advantages for this analysis. Most importantly, the NUVEL-1 Euler vectors satisfy global plate circuit closure constraints, which guarantees that information from plate boundaries with high-quality data such as spreading rates and transform fault azimuths will propagate through the model and help to determine velocities along plate boundaries where few reliable data exist. In particular, closure constraints help to improve estimates of velocities along trenches, where earthquake slip vectors are subject to systematic biases induced by forearc deformation [*Jarrard*, 1986]. A second advantage is that the NUVEL-1 model is free from significant biases in estimates of Pacific basin plate velocities that affected prior global plate motion models [*Chase*, 1978; *Minster and Jordan*, 1978].

The NUVEL-1 model must satisfy two conditions in order to provide rigid plate convergence directions suitable for comparison to the convergence directions given by the 256 Kuril and Japan trench slip vectors. First, the velocity of the Pacific plate relative to Eurasia and North America must not have changed significantly over the 3.0-m.y. averaging interval of the NUVEL-1 model. If plate motions have changed since 3 Ma, the direction given by the 3.0-m.y. average NUVEL-1 model could differ in an unknown way from the directions given by Kuril and Japan trench slip vectors, which record strain accumulated over the several century or less intervals between major subduction zone earthquakes. The second condition is that the NUVEL-1 model must give an estimate of Pacific-North America and Pacific-Eurasia velocities independent of the 256 trench slip vectors that are used to estimate convergence directions along the trench.

The NUVEL-1 model appears to satisfy the first condition. Independent estimates of Pacific-North America and Pacific-Eurasia motion are available from very long baseline interferometric (VLBI) measurements between sites located in the stable interiors of the North American, Pacific, and Eurasian plates. An analysis of 1983-1987 VLBI data gives Pacific-North America velocities that differ from those given by NUVEL-1 by no more than 4±7 mm yr^{-1} and 3°±4° anywhere along their mutual boundary [*Argus and Gordon*, 1990]. Analysis of 1984-1989 VLBI measurements also suggests that Pacific-Eurasia velocities determined from VLBI are not measurably different from Pacific-Eurasia velocities predicted by NUVEL-1 (D. F. Argus and R. G. Gordon, Crustal deformation from VLBI, to be submitted to *Journal of Geophysical Research*, 1992).

Because the NUVEL-1 data set includes 15 slip vectors from the northern Kuril trench, the NUVEL-1 model fails to satisfy the condition that the model provide an estimate of Pacific-North America and Pacific-Eurasia velocities that is independent of the 256 trench slip vectors that are used to estimate convergence directions along the trench. Fortunately, it is easy to demonstrate that the 15 slip vectors contribute a negligible amount of information to the NUVEL-1 model, and for all practical purposes, NUVEL-1 gives an independent estimate of Pacific-North America and Pacific-Eurasia velocities. The 15 slip vectors were deleted from the 1122 NUVEL-1 data, and the remaining data were reinverted to derive a modified global plate motion model. Comparison of the two models shows that modified Pacific-North America and Pacific-Eurasia Euler vectors predict velocities along the Kuril and Japan trenches less than 0.1° and 0.1 mm yr^{-1} different than those predicted by the NUVEL-1 Euler vectors.

TEST FOR RIGID PLATE GEOMETRY FOR NORTHEAST EURASIA AND JAPAN

In order to conduct a step-by-step statistical analysis that defines the optimal plate geometry for northeast Asia, the 256 slip vectors are divided into two subsets. One data set consists of 116 slip vectors located along the Kuril trench north of the southern Kuril sliver plate at 46°N. The other subset consists of the 140 Japan trench slip vectors. For each of these data sets, three questions are posed. Are the slip vectors more consistent with a model in which the overlying plate is North America, Eurasia, or neither? These are the minimum number of questions sufficient to determine the simplest plate geometry that permits a good fit to all of the slip vectors.

For a given set of slip vectors, χ^2, which is defined as the total, weighted, least squares misfit of a model to the data, is determined for three models. First, χ^2 is determined for the best fitting Euler pole, which is derived only from the trench slip vectors and thus best fits those data. The least squares misfits of the NUVEL-1 Pacific-North America and Pacific-Eurasia Euler poles for the same data are then compared to χ^2 for the best fitting Euler pole. The F ratio test is used to determine whether there is a significant difference in the fits of these models. F is computed as follows:

$$F_{2,N-2} = \frac{\left[\chi^2(\text{model 1}) - \chi^2(\text{best fit})\right] / 2}{\chi^2(\text{best fit}) / (N-2)} \qquad (1)$$

where χ^2 (model 1) is the least squares misfit of the Pacific-North America or Pacific-Eurasia Euler pole, χ^2 (best fit) is the least squares misfit of the best fitting model, N is the number of slip vectors, and 2 represents the two parameters, latitude and longitude, required to specify the best fitting Euler pole. The F ratio test used here is specifically designed to compare the fits of two Euler poles to a set of directional data, in contrast to that derived by *Stein and Gordon* [1984], which is meant to compare models with different numbers of plates. The 99% confidence level is adopted as the cutoff for a significant difference between the fits of two models. For values of 2 versus ~100-250, which apply to this study, $F_{0.01} = 4.7$. A more detailed description of the least squares fitting algorithm used here is given by *DeMets et al.* [1990].

The above approach has an important shortcoming of which the reader should be aware, namely, it does not factor uncertainties in the NUVEL-1 model into the analysis. For instance, a significant difference between convergence directions predicted by NUVEL-1 and some or all of the trench slip vectors does not necessarily imply that the trench slip vectors would not have been well fit had they been used to derive the NUVEL-1 model in the first place. To overcome this shortcoming, a somewhat more complicated analysis in which the fits of global plate motion models derived with and without the 256 Japan and Kuril trench slip vectors were compared for alternative plate geometries. This approach did not yield significantly different results than the simpler approach described above. For brevity, the results from this part of the analysis are not discussed here.

Do Slip Vectors North of 46°N Record Motion of the Pacific Plate Relative to North America or Eurasia?

To begin the analysis, a best fitting pole is derived for the 116 slip vectors located between 46°N and 54°N. The Euler pole that best fits the 116 directions has χ^2 = 13.68. The NUVEL-1 Pacific-North America Euler pole gives a misfit of χ^2 = 13.83 for the 116 slip vectors, and the NUVEL-1 Pacific-Eurasia Euler pole, which predicts directions ~3°-5° counterclockwise from the Pacific-North America direction for this section of the trench (Figure 5), gives a misfit of χ^2 = 18.14. The Pacific-North America Euler pole fits the data nearly as well as the best fitting Euler pole, which suggests that the northern Kuril trench accommodates convergence between the Pacific and North American plates. Comparison of χ^2 for the best fitting model to χ^2 for the Pacific-North America and Pacific-Eurasia models gives $F = 0.6$ and $F = 18.6$, respectively. The misfit of the Pacific-Eurasia Euler pole is thus significant at well above the 99% confidence level.

When the slip vectors are reduced to weighted residual directions from the directions predicted by the NUVEL-1 Pacific-North America and Pacific-Eurasia Euler poles, the weighted residual directions associated with the Pacific-North America Euler pole form a Gaussian distribution centered on the origin (Figure 6). In contrast, the weighted residual directions associated with the Pacific-Eurasia Euler poles form a Gaussian distribution that is centered 4.4° counterclockwise from the origin (Figure 6).

Is the 4.4° mean discrepancy between the observed slip directions and the predicted Pacific-Eurasia direction significant after uncertainties in the NUVEL-1 Pacific-Eurasia Euler pole are accounted for? For the northern Kuril trench, the computed uncertainty in the Pacific-Eurasia direction is ±2°

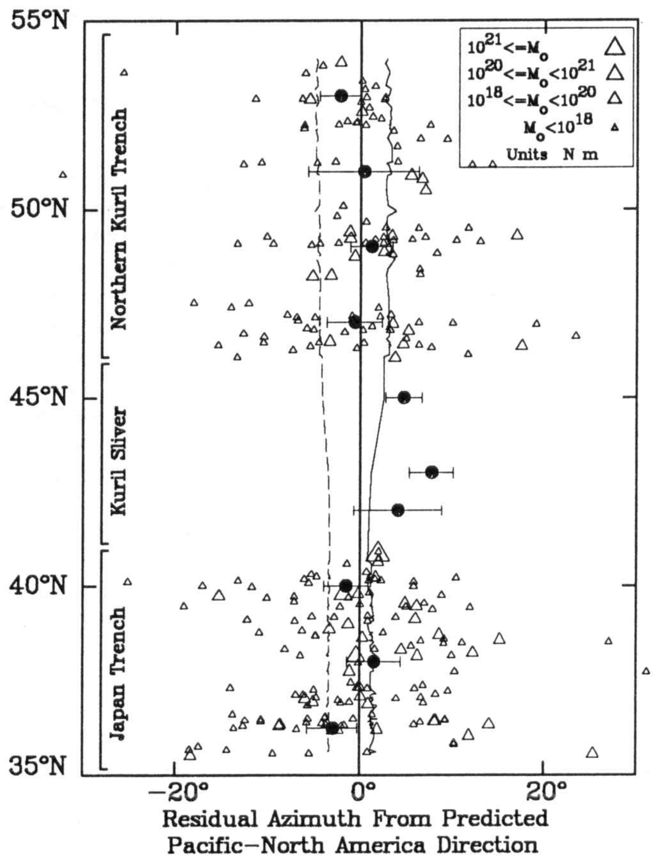

Fig. 5. The 256 northern Kuril and Japan trench slip vectors (open triangles) shown as residual azimuths from the azimuths predicted by the NUVEL-1 Pacific-North America Euler vector (vertical solid line). The dashed line, which shows the directions predicted by the NUVEL-1 Pacific-Eurasia Euler pole, differs by ~3°-5° on average from the directions predicted by the Pacific-North America Euler pole. Also shown are the Okhotsk-Pacific directions predicted by the *Savostin et al.* [1983] model (thin solid line). The mean slip directions and 1σ uncertainties computed in *DeMets* [1992] are shown as circles.

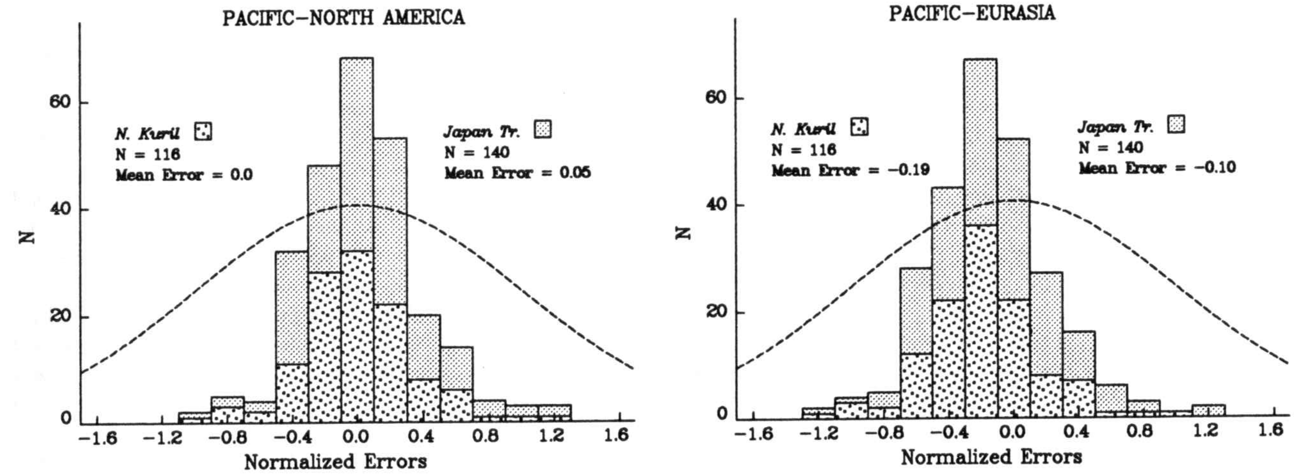

Fig. 6. Histogram of the distribution of normalized residual directions [(observed - predicted)/σ] for the 256 northern Kuril and Japan trench slip vectors. On the left, the normalized differences from the predictions of the NUVEL-1 Pacific-North America Euler pole are shown, and on the right, the normalized differences from the predictions of the NUVEL-1 Pacific-Eurasia Euler pole are shown. The dashed line shows the Gaussian distribution of normalized residual directions assuming the slip vector uncertainties have been properly estimated.

at the 95% confidence level. Thus, even when uncertainties in the NUVEL-1 model are included, it appears safe to conclude that the 116 northern Kuril trench slip vectors do not record motion between the Pacific and Eurasian plates.

Are Southern Hokkaido and Northern Honshu Part of North America or Eurasia?

The Euler pole that best fits the 140 slip vectors from the Japan trench south of the Honshu/Hokkaido bend gives χ^2 = 18.87. The NUVEL-1 Pacific-North America Euler pole gives χ^2 = 20.16, which corresponds to an average difference of 1.2° from the mean slip direction (Figure 6). The NUVEL-1 Pacific-Eurasia Euler pole gives χ^2 = 21.60, which corresponds to an average difference of 2.1° from the mean slip direction (Figure 6). Comparison of these values of χ^2 using (1) gives $F = 4.7$ and $F = 10.0$ for the Pacific-North America and Pacific-Eurasia Euler poles, respectively. Both of these values equal or exceed the 99% confidence limit for a statistically significant discrepancy.

Although the F ratio test suggests that northern Honshu and southern Hokkaido are not part of the North American or Eurasian plates, it is important to remember that the uncertainties in the NUVEL-1 Pacific-North America Euler pole are not factored into the above comparison. The 2σ directional uncertainty for the NUVEL-1 Pacific-North America Euler pole is ±1.6° along the Japan trench, which is greater than the 1.2° average misfit of the Pacific-North America Euler pole to the Japan trench slip vectors. Additionally, the three largest earthquakes along the Japan trench (May 16, 1968; June 12, 1978; November 1, 1989) have slip directions of N62°W, N65°W, and N66°W, which differ little from the N64°-N65°W Pacific-North America direction predicted by NUVEL-1. Within the uncertainties, the Japan trench slip vectors do not appear to differ significantly from the direction predicted by the Pacific-North America Euler pole.

The most realistic conclusion may be that the Japan trench slip vectors do not contain enough information to determine conclusively whether southern Hokkaido and northern Honshu are part of the North American, Eurasian, or possibly the Okhotsk plates. The average misfit of the Pacific-Eurasia Euler pole to the Japan trench slip vectors is 2.1°, which is comparable to the 1°-2° uncertainty in the predicted direction. Given that the directions predicted by the Pacific-North America and Pacific-Eurasia Euler poles only differ by 3°-5° along the trench, the convergence direction across the Japan trench would have to be measured to an accuracy of 1°-2° in order to distinguish whether Honshu and Hokkaido move with the North American, Eurasian, or neither plate. Trench slip vectors are often affected by small systematic biases induced by hard-to-measure processes such as oblique convergence or an incompletely known shallow velocity structure beneath the Japan island arc, hence, it seems unlikely that the Japan trench slip vectors can give the convergence direction to within the required 1°-2°. A more conclusive test will probably require high accuracy geodetic measurements between sites on Honshu and the adjacent plates.

Test of Geometries B and C

The above results suggest that the North American plate overlies the northern Kuril trench and possibly, the Japan trench. If this is the case, geometries B and C can be tested through comparison of the fit of the Euler pole that simultaneously best fits all 256 Kuril and Japan trench slip vectors to the fits of Pacific-North America and Pacific-Eurasia Euler vectors. For all 256 slip vectors, the best fitting Euler pole has χ^2 = 33.72, the NUVEL-1 Pacific-North America Euler pole gives χ^2 = 33.99, and the NUVEL-1 Pacific-Eurasia Euler poles gives χ^2 = 39.73. For these values, (1) gives $F = 1.0$ and $F = 22.5$ for the Pacific-North America and Pacific-Eurasia Euler poles, respectively. Thus, the NUVEL-1 Pacific-North America Euler pole fits the 256 slip vectors nearly as well as the best fitting pole, but the NUVEL-1 Pacific-Eurasia Euler pole fits them poorly, in accordance with the results reported above. It is important to remember that this result depends on the questionable assumption (as demonstrated above) that southern Hokkaido and northern Honshu are part of the North America plate.

Geometry D: Tests of Two Models for the Present-Day Motion of the Okhotsk Plate

The excellent fit of the NUVEL-1 Pacific-North America Euler pole to the 116 northern Kuril trench slip directions suggests that within the resolution of the trench slip directions, continental northeast Asia moves with the North American plate. Provided that the good fit of the NUVEL-1 Pacific-North America Euler pole to the northern Kuril trench slip vectors is not accidental, this implies that the addition of an Okhotsk plate to the regional geometry is not required by the kinematic data considered here.

Despite these results, the pattern of seismicity in northeast Asia clearly suggests the existence of an independent block that is bordered by the Cherskeii Mountains and Sakhalin Island seismic belts (geometry D). *Savostin et al.* [1983], *Cook et al.* [1986], and more recently, K. Fujita et al. (Extrusion tectonics of the Okhotsk plate, northeast Asia, manuscript in preparation, 1992) interpret this pattern of seismicity as evidence for the existence of the Okhotsk plate, which moves slowly relative to both North America and Eurasia. If this is assumed to be the case, then the northern Kuril trench slip vectors, which would record motion of the Pacific plate relative to Okhotsk, can be used along with regional plate circuit closures imposed by NUVEL-1 to place constraints on the motion of the Okhotsk plate. Here, two previously proposed models for the present-day motion of the Okhotsk plate are used in combination with the northern Kuril trench slip vectors and NUVEL-1 circuit closures to estimate the rate at which the Okhotsk plate moves relative to North America.

Savostin et al. [1983] and *Cook et al.* [1986] have derived kinematic models for the present-day motion of an Okhotsk plate relative to North America and Eurasia using seismic and geologic data from northeast Asia. The accuracies of these models can be tested by a simple two-step method. First, each of the two Okhotsk-North America Euler vectors is combined with the NUVEL-1 Pacific-North America Euler vector to determine a Pacific-Okhotsk Euler vector. The fit of the resultant Pacific-Okhotsk Euler pole to the 116 northern Kuril trench slip vectors is then determined. If the proposed models for Okhotsk-North America motion are accurate, then the Okhotsk-Pacific Euler vector derived from closure of the North America-Okhotsk-Pacific plate circuit should fit the northern Kuril trench slip vectors.

The Okhotsk-Pacific Euler vector derived from summation of the *Savostin et al.* [1983] Okhotsk-North America Euler vector (47.01°N, 144.85°E, 0.478°/m.y.) with the NUVEL-1 North America-Pacific Euler vector (48.71°N, 78.17°W, 0.783°/m.y.) is located at 16.9°S, 118.4°E with an angular rotation rate of 0.82°/m.y. This Euler vector fits the 116 northern Kuril trench slip vectors more poorly than the NUVEL-1 Pacific-North America Euler vector (Figure 5). The Okhotsk-Pacific Euler pole gives χ^2=15.74 for the 116 slip vectors, which is higher than χ^2=13.83 for the NUVEL-1 Pacific-North America Euler pole. Comparison of these two values of χ^2, where χ^2 for the Pacific-North America Euler pole is now substituted for χ^2 (best fit) in (1), gives $F = 7.9$, which is significantly higher than value of $F = 4.7$ expected for a difference that is significant at the 99% confidence level. This indicates that the Okhotsk-North America Euler vector derived by *Savostin et al.* [1983] does not allow a good fit to the northern Kuril trench slip vectors when it is required to be consistent with the NUVEL-1 plate circuit closures. If the constraints imposed by the NUVEL-1 plate circuit closures are accurate, this implies that the *Savostin et al.* [1983] Okhotsk-North America Euler vector does not accurately describe the relative motion between the Okhotsk and North American plates.

The *Cook et al.* [1986] Okhotsk-North America Euler pole, which is derived from the slip directions of eleven earthquake focal mechanisms from the southern Cherskii Mountains and northeast Kamchatka, is more difficult to test because it does not include an estimate of the Okhotsk-North America rate of rotation. To overcome this, a series of increasingly higher Okhotsk-North America angular rotation rates is assumed, and for each assumed rotation rate, an Okhotsk-Pacific Euler pole is determined through summation with the NUVEL-1 Pacific-North America Euler vector. The least squares misfit to the 116 trench slip vectors is then determined for each of the Okhotsk-Pacific Euler poles. Finally, (1) is used to determine the angular rotation rate for which the fit of the Pacific-Okhotsk Euler pole becomes statistically different from the fit of the NUVEL-1 Pacific-North America Euler pole.

For the Okhotsk-North America Euler pole (72.4°N, 169.8°E) derived by *Cook et al.* [1986], an angular rotation rate of 0.25°/m.y. leads to a significantly degraded fit to the 116 trench slip vectors (as determined from the F ratio test). This suggests that if the Okhotsk-North America angular rotation rate is less than ~0.25°/m.y., any difference between the fits of the Pacific-Okhotsk and NUVEL-1 Pacific-North America Euler poles to the 116 trench slip vectors will be statistically indistinguishable. This allows an estimate of the upper limit of Okhotsk-North America motion. Along the southern Cherskii Mountains (67°N, 141°E), which is identified as *Cook et al.* [1986] as the likely location for the Okhotsk-North America plate boundary, an Okhotsk-North America Euler pole of 72.4°N, 169.8°E with an angular rotation rate of 0.25°/m.y. predicts 5 mm yr^{-1} of slip. If this Okhotsk-North America Euler pole is accurate, then slip in the southern Cherskii Mountains that is slower than 5 mm yr^{-1} could not be detected through analysis of the northern Kuril trench slip vectors. Because these results depend on the accuracy of the Okhotsk-North America Euler pole given in *Cook et al.* [1986], the amount of estimated slip could vary considerably if their Okhotsk-North America pole is inaccurately located.

Discussion

The results presented above can be summarized with the simple statement that geometry B is the simplest configuration of plates in northeast Asia that permits a good fit to slip vectors along the Kuril and Japan trenches, although the possibility that southern Hokkaido and the northern half of the island of Honshu are a separate microplate cannot be excluded. Consideration of the large-scale pattern of seismicity in northeast Asia and Japan supports this conclusion. The most prominent concentration of seismicity occurs along the Sakhalin/Sea of Japan seismic belt, with an apparent southward increase in seismicity (Figure 2). The southward increase in seismicity and seismic moment release is consistent with the southward-increasing convergence rate predicted by the Eurasia-North America Euler vector. For example, the velocity of Eurasia relative to North America for central Sakhalin Island (50°N, 142.5°E) is 6±1 mm yr^{-1}, N76°E±4°, and for a location in central Honshu (36°N, 138°E), the velocity is 11±2 mm yr^{-1}, N88°E±4°. The latter prediction is roughly consistent with the 100-year, 400-year, and late Quaternary average east-west shortening rates of 12.2, 8.7, and 8.6 mm yr^{-1} determined from historic seismicity and geologic observations of late Quaternary active faults in central and southwestern Honshu [*Wesnousky et al.*, 1982].

The east-northeast shortening direction predicted for central Sakhalin Island also appears to be consistent with the shortening directions inferred from earthquake focal mechanisms from the region. Earthquake focal mechanisms from the Harvard centroid moment tensor solutions [e.g., *Dziewonski et al.*, 1990; *Chapman and Solomon*, 1976; *Savostin et al.*, 1983] suggest there is ~E-W shortening across much of the island, and some right-lateral strike-slip motion as well. The overall ENE-NE shortening direction is roughly consistent with the Eurasia-North America direction predicted by NUVEL-1.

The unsatisfying features of geometry B are its failure to explain why there is a belt of seismicity along the Cherskii Mountains, and why there is very little seismicity along the hypothetical Eurasia-North America boundary north of northern Sakhalin Island. It is unclear how Eurasia-North America motion might be partitioned between these two seismic belts. The sparse seismicity and small size of the earthquakes along the Cherskii Mountains suggests deformation is limited to a few mm yr^{-1} [*Cook et al.*, 1986]. The slow slip rate postulated by *Cook et al.* [1986] agrees with the crude 5 mm yr^{-1} upper limit permitted by the regional circuit closures. In contrast, the *Savostin et al.* [1983] model for the present-day motion of the Okhotsk plate relative to North America, which predicts ~15 mm yr^{-1} of left-lateral slip along the Okhotsk-North America boundary, gives a poor fit to the northern Kuril trench slip vectors. This suggests that estimates of Okhotsk-North America motion as high as 15 mm yr^{-1} may be too high.

Unfortunately, it is difficult to determine the true upper bound for Okhotsk-North America motion because such a determination requires accurate knowledge of the location of the Okhotsk-North America Euler pole. Current estimates of the Okhotsk-North America Euler pole rely on inversion of earthquake slip vectors and geologic data from northeast Asia [*Savostin et al.*, 1983; *Cook et al.*, 1986]. The accuracy of the Euler poles derived from these analyses depends on a questionable assumption, namely, that seismogeologic data from continents can be inverted to determine Euler poles that describe relative block motions. Unlike oceanic plate boundaries, deformation along continental plate boundaries often varies rapidly and unpredictably depending on the width of the belt of deformation, the local lithology, and the orientation of pre-existing faults [*England and Jackson*, 1989]. It is thus unclear whether an accurately located Okhotsk-North America Euler pole can be determined through an inversion of data from the zone of complex deformation that separates the two plates. Given this, the upper bound derived here for the motion of the Okhotsk plate relative to North America should be used with caution.

A further uncertainty in this analysis is the degree to which slip directions that are determined from older focal mechanisms that are derived solely from first-motion *P* and *S* wave data might "contaminate" the presumably more reliable slip directions determined from the Harvard centroid-moment tensor solutions. If all of the statistical tests discussed above are repeated using only slip directions determined from CMT solutions, only one result changes - the fit of the NUVEL-1 Pacific-North America Euler pole to the Japan trench slip vectors becomes significantly worse while the fit of the NUVEL-1 Pacific-Eurasia Euler pole remains roughly the same as before. If the CMT solutions are more representative of the long-term slip directions than the first-motion solutions, Honshu and Hokkaido may move relative to both North America and Eurasia, as suggested above.

The most reliable test of alternative models for deformation in northeast Asia will probably come from future geodetic observations between sites dispersed throughout northeast Asia. The ever-increasing number of earthquake focal mechanism solutions for this region are also beginning to define the nature of the regional deformation. In addition to the Sakhalin and Cherskii Mountains belts of seismicity, earthquake focal mechanisms from a belt of seismicity east of and including the Baikal rift suggest that lithosphere to the south is moving roughly southeast relative to the Eurasian plate. It is still unclear how this motion is related to deformation on Sakhalin Island or in the Sea of Japan, although *Peltzer and Tapponier* [1988] suggest that at least some of the regional deformation associated with the Baikal rift seismicity and possibly, the linear belts of seismicity that divide China (Figure 2) may be related to the eastward extrusion of crustal blocks in response to the northward-directed motion of India with respect to Asia some 3000 km to the south. Further progress in characterizing the regional kinematics and understanding the cause of the deformation will require a more extensive seismic data base coupled with careful field geologic and geodetic studies.

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