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North American–Eurasian Plate Boundary in Northeast Asia

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The intracontinental portion of the boundary between the North American and Eurasian plates can be identified on the basis of seismicity, recent tectonics, and earthquake focal mechanisms. The simplest plate geometry that can explain these data involves a North American–Eurasian boundary that extends from the Nansen ridge through a broad zone of deformation in northeast Asia to the Sea of Okhotsk and thence southward through Sakhalin and Hokkaido to a triple junction in the Kuril-Japan trench. Such a configuration can account quantitatively for the slip vectors derived from earthquake mechanisms in Sakhalin and Hokkaido. On the basis of new slip vector data the North American–Eurasian angular velocity vector is revised only slightly from previous determinations. The intracontinental plate boundary is diffuse and may be controlled by ancient plate sutures. Deformation within about 10° of the rotation pole, which lies very near the boundary, cannot be modeled by rigid plate tectonics. These characteristics of intracontinental plate boundaries are related to the greater thickness and heterogeneity of continental lithosphere and to the influence of continents on the plate tectonic driving forces.

INTRODUCTION

The theory of plate tectonics is based on the idea that the earth's surface may be subdivided into a small number of rigid plates [*Morgan*, 1968; *Le Pichon*, 1968]. In oceanic areas the boundaries between major plates are readily defined by the distribution of earthquakes and characteristic bathymetric features and are typically no more than a few kilometers in width. Where plate boundaries bisect continental masses, however, the place where one plate ends and another begins is generally much more difficult to locate with confidence. The problem of identifying a plate boundary within a continent is heightened when the relative velocity of the two plates is small.

In this paper we examine in detail several aspects of one such intracontinental plate boundary: the boundary in northeast Asia between the Eurasian and the North American plates. There are several reasons for such a study. If the concept of distinct plates is valid, then each plate must be encircled by some closed curve on the earth's surface. Complete specification of the boundary of each plate is formally necessary to conduct certain tests of driving force models for plate tectonics [*Solomon and Sleep*, 1974; *Forsyth and Uyeda*, 1975; *Solomon et al.*, 1975]. More interesting are the underlying causes for the diffuse rather ill-defined nature of intracontinental plate boundaries, including the possibilities that continental lithosphere is thicker, more difficult to push or pull across the earth's surface, and more heterogeneous than oceanic lithosphere.

We begin with a review of historical seismicity and recent tectonic activity in northeast Asia. An evaluation of several possible plate configurations to explain these data is then made. The simplest explanation compatible with seismic and tectonic evidence is that the present North American–Eurasian plate boundary extends from the Nansen ridge in the Arctic Ocean through a broad tectonically active belt in northeast USSR [*Demenitskaya and Karasik*, 1969; *Grachev et al.*, 1970; *Churkin*, 1972] to the Sea of Okhotsk and thence southward through Sakhalin and Hokkaido to a triple junction at the Japan-Kuril trench. Earthquake source mechanisms are consistent with this view except in the immediate vicinity of the relative rotation pole for the two plates. Finally, some thoughts are offered on the factors affecting the location and nature of intracontinental plate boundaries.

SEISMICITY

The boundaries between plates are seismically active. Seismicity is the primary basis for identifying the North American–Eurasian plate boundary in the Atlantic and Arctic oceans as the mid-Atlantic and Nansen ridge systems, respectively. The correctness of such an identification is apparent by inspection from a global seismicity map, based on only a few years of data, such as that in Figure 1. How the plate boundary continues from the Arctic Ocean onto the Eurasian continent is by no means clear from the figure, however,

As an aid in better defining this plate boundary in northeast Asia, we have plotted in Figure 2 the epicenters of all instrumentally located shallow seismic events in the region for the period 1909–1973. The original epicenters were obtained from a number of earthquake data sources [*Linden*, 1961; *Savarensky et al.*, 1962; *Hodgson et al.*, 1965; *Sykes*, 1965; *Solov'yev*, 1965; *International Seismological Center*, 1966–1973; *National Oceanic and Atmospheric Administration*, 1970–1973; *International Union of Geodesy and Geophysics* 1923–1969; *Academy of Sciences USSR*, 1966–1973]. Where it was possible to do so, the events prior to 1952 were relocated by using modern travel time tables [*Herrin*, 1968] to obtain more accurate locations. Observed P wave and S wave arrival times are from the bulletin of the *International Union of Geodesy and Geophysics* [1923–1969]; the P wave and S wave travel time uncertainties were assumed to be 1.5 and 3.0 s, respectively. The relocated events are listed in Table 1.

Several conclusions may be drawn from these seismicity maps. In oceanic regions the plate boundary defined by the seismic belt is very narrow, possibly as little as 10 km in width (Figure 1). However, at the Eurasian continental margin the seismic belt widens to 300 km (Figure 2). A broad seismic zone extends from the Laptev Sea across northeast USSR to the northern Sea of Okhotsk. The zone is 600 km wide at its maximum width and includes both large and small earthquakes throughout its entire extent.

This broad seismically active band appears to terminate abruptly at the Sea of Okhotsk. The apparent aseismicity of the Sea of Okhotsk may be an artifact of a sparse instrumental

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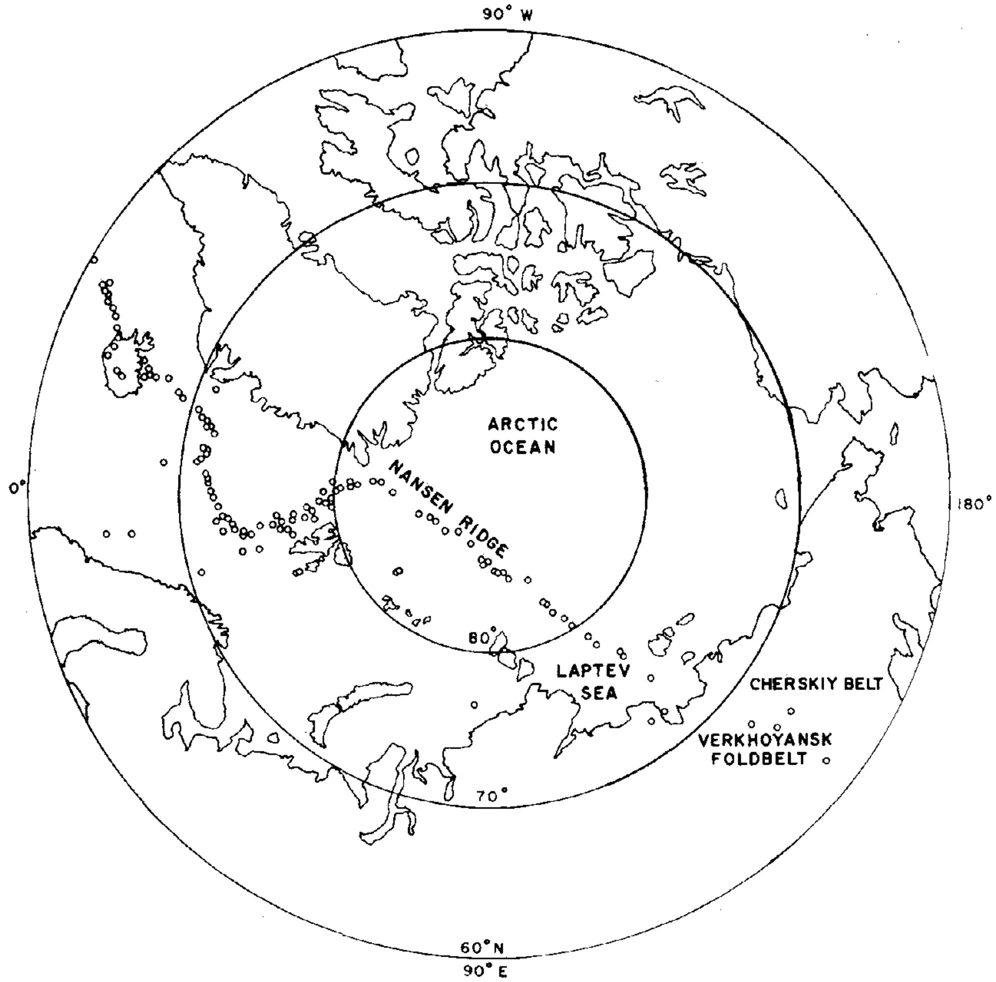

Fig. 1. Seismicity of the Arctic, 1962–1969, after *National Oceanic and Atmospheric Administration* [1970].

network or may possibly be real. Until 1968 there were few seismometers in the region; the nearest stations were Magadan (59°33′N, 150°48′E), Okha (53°33′N, 142°56′E), and Yakutsk (62°01′N, 129°43′E). A major earthquake in the region, with body wave magnitude 5$\frac{1}{4}$, occurred on May 10, 1947, at 57.9°N, 141.9°E. Prior to 1968 there were no small events recorded in this area. However, after five new seismic stations were installed in Yakutia in 1968, small events were detected in the Sea of Okhotsk close to the stations [*Academy of Sciences USSR*, 1972]. Because of this increase in reported events and the one major event it is likely that the Sea of Okhotsk region is seismically active, even though earthquakes with magnitudes greater than 4 are rare.

Another feature of Figure 2 is a zone of small magnitude earthquakes from 120° to approximately 135°E longitude at about 56°N latitude. This zone is an extension of the Lake Baikal seismic belt [*Gutenberg and Richter*, 1949]. It is not clear from the seismicity whether this zone continues eastward to the seismically active portions of the Sea of Okhotsk.

There are many shallow events on Sakhalin, an area known for its relatively high seismicity [*Solov'yev*, 1965]. The north-trending seismic belt on Sakhalin is about 300 km wide and appears to continue through Hokkaido to the Japan-Kuril trench.

There are numerous earthquakes located in the Kuril and Aleutian trenches, and many small shallow events extend inland on Kamchatka. Also on Kamchatka there appears to be a short seismic belt extending northward from the Komandorskiye islands. This belt is probably related to underthrusting of the Pacific plate [*Cormier*, 1975].

RECENT TECTONICS

A brief review of field geological and geophysical evidence for recent tectonic activity in the Sea of Okhotsk region is a necessary preliminary to the discussion of possible plate boundaries in the area and to the interpretation of earthquake focal mechanisms.

The principal Cenozoic tectonic features of central and southern Kamchatka are illustrated in Figure 3 [*Alverson et al.*, 1967]. Most faults in Kamchatka are parallel to the Kuril trench and, where presently active, are likely to be related to subduction of the Pacific plate rather than the plate boundary in question. The only major fault system that trends in an east-west direction is the Kronoki-Krutogorova fault zone [*Suprenko and Dekin*, 1968; *Suprenko et al.*, 1973]. In the Kronoki peninsula the faults in this zone are right lateral, with a maximum horizontal offset of 20–25 km. In the western portion of the Kronoki-Krutogorova fault zone the sense of motion is left lateral, opposite to the sense of motion in eastern Kamchatka. These western faults have offsets similar in amplitude to those of the faults in the Kronoki peninsula. The fault zone may form the southern boundary of a rift system, active in Plio-Pleistocene times, in the central Kamchatka basin [*Suprenko et al.*, 1973].

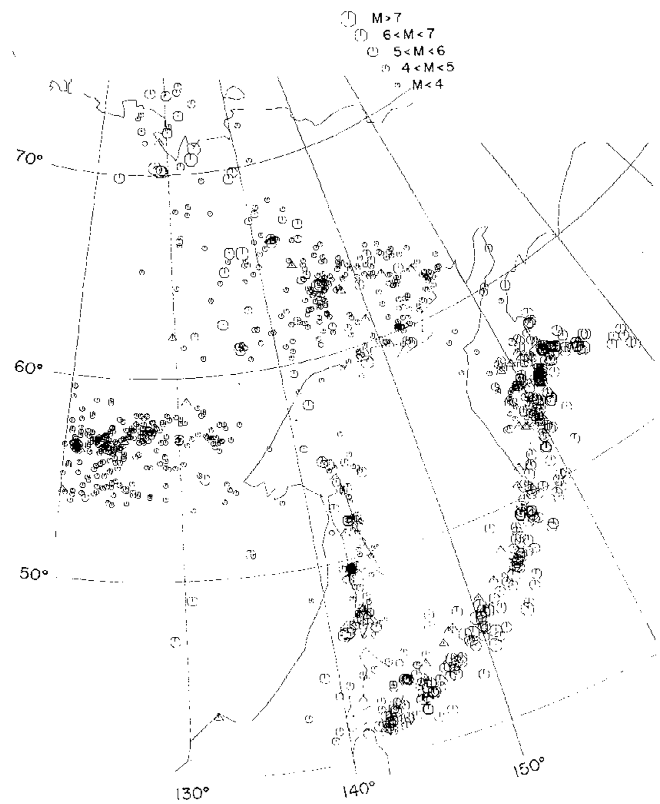

Fig. 2. Shallow seismicity of northeast Asia, 1909–1973, azimuthal equal area projection about 69.3°N, 128°E. The size of a symbol is proportional to (body wave) magnitude M. Triangles indicate a seismograph station. Only events between latitudes 41° and 75°N and between longitudes 120° and 170°E are included. For clarity, no events are plotted in the Aleutian and Kuril trenches with $M < 5.5$ or on Sakhalin with $M < 4.0$.

Sakhalin is dominated structurally by compressive features such as faults and folds that trend north-south along the longitudinal axis of the island. One of the primary faults is the central Sakhalin fault, a thrust fault with a meridional trend and a westerly dip of approximately 70°. The strike of drag folds and second-order faults indicates some right lateral movement along the main fault. This fault is dated as being active in the late Miocene and Pliocene, and it is still active today [*Zanyukov,* 1971]. Quaternary displacements have been measured, and the epicenters of crustal earthquakes are located in the fault zone.

In the Schmidt peninsula (northern tip of Sakhalin) there are also north- to northwest-trending thrust faults which exhibit some right lateral motion. The sense of horizontal displacement is indicated by the inclination of slickensides, displaced features, and drag folds. There is up to 14 km of right lateral offset. The main tectonic activity was in Plio-Pleistocene time. However, the presence of tectonic scarps, rockfalls, and slides and the reworking of stream drainage patterns indicate that the movements are continuing today [*Rozhdestvenskiy,* 1973].

That compressive forces have acted upon Sakhalin is also indicated by folding. The axes of anticlines and synclines trend north-south in Sakhalin parallel to the strike of the thrust faults [*Pushcharovskiy,* 1965; *Gal'tsev-Bezyuk,* 1968]. During the latest episode of folding, denoted the Sakhalin orogeny, Pliocene deposits were folded. This episode of folding has continued until the present. Geodetic measurements indicate that vertical crustal movements of 3–9 mm/yr are occurring in southern Sakhalin [*Zakharov and Yakushko,* 1972].

SOME POSSIBLE PLATE CONFIGURATIONS

There are a number of ways in which northeast Asia may be subdivided into plates consistent with the seismicity and recent tectonic activity discussed above. All of these plate descriptions are to some extent inadequate, for they fail to account fully for intraplate deformation and the finite width of intracontinental plate boundaries. Nonetheless, we prefer one such description that is at the same time simple, in approximate agreement with the evidence outlined in preceding sections, and useful for making quantitative predictions.

The primary test of a proposed plate model is whether the sense of motion at plate boundaries predicted by the relative angular velocity vector of the adjacent plates is consistent with seismic and tectonic evidence. To make this test, we need reasonably accurate estimates of the Eurasian-North American rotation pole and rate. A number of determinations of these quantities have been made by a variety of techniques; these are summarized in Table 2. Probably any of the three most recently published solutions are suitable for the purposes of this section. In a later section we derive a new Eurasian-North American angular velocity vector on the basis of our preferred plate boundary description and new earthquake fault plane solutions.

In addition to the Eurasian, North American, and Pacific plates, several smaller plates have from time to time been proposed.

The possible existence of a China plate has been discussed by several authors [*Morgan,* 1968, 1972; *Molnar et al.,* 1973; *Das and Filson,* 1974]. The primary evidence used to support a separate China plate is the Baikal rift. *Das and Filson* [1974] postulate a (west) China plate rotating clockwise with respect to Eurasia about a pole near the southern tip of Lake Baikal. This would account for active extension in the Baikal rift and

TABLE 1. Relocated Earthquakes in Northeast USSR

	Origin Time (GMT)				
Date	h	m	s	Latitude, °N	Longitude, °E
Nov. 30, 1918	06	48	38.2	70.704	133.363
March 13, 1924	10	41	58.7	62.772	150.062
March 15, 1924	10	31	21.3	49.176	142.570
May 27, 1924	20	09	30.3	62.452	135.056
Feb. 18, 1925	11	36	3.7	66.614	145.648
April 9, 1926	10	4	32.0	72.865	132.093
June 10, 1927	18	13	23.4	48.364	139.067
Nov. 14, 1927	00	12	7.4	70.233	128.733
Nov. 14, 1927	04	56	29.5	70.208	128.990
Nov. 15, 1927	21	48	45.7	70.275	129.069
Feb. 3, 1928	13	47	36.5	70.374	128.126
Feb. 21, 1928	19	49	6.0	67.573	−172.561
Feb. 24, 1928	14	10	25.4	67.536	−173.824
Feb. 26, 1928	01	19	12.8	67.195	−171.034
Aug. 16, 1928	07	36	44.6	69.842	123.130
Aug. 25, 1928	01	48	32.1	49.060	141.814
July 15, 1931	16	27	0.6	59.082	148.185
Oct. 10, 1931	16	37	8.4	59.504	148.027
July 10, 1932	00	43	26.3	52.642	142.052
Sept. 7, 1933	22	39	20.3	61.963	177.429
Oct. 25, 1935	17	38	14.6	51.854	142.887
Nov. 3, 1936	04	43	23.2	59.198	152.815
May 10, 1947	00	07	14.5	57.858	141.908
April 14, 1951	13	33	2.1	61.117	136.306

All depths were constrained to be 15 km.

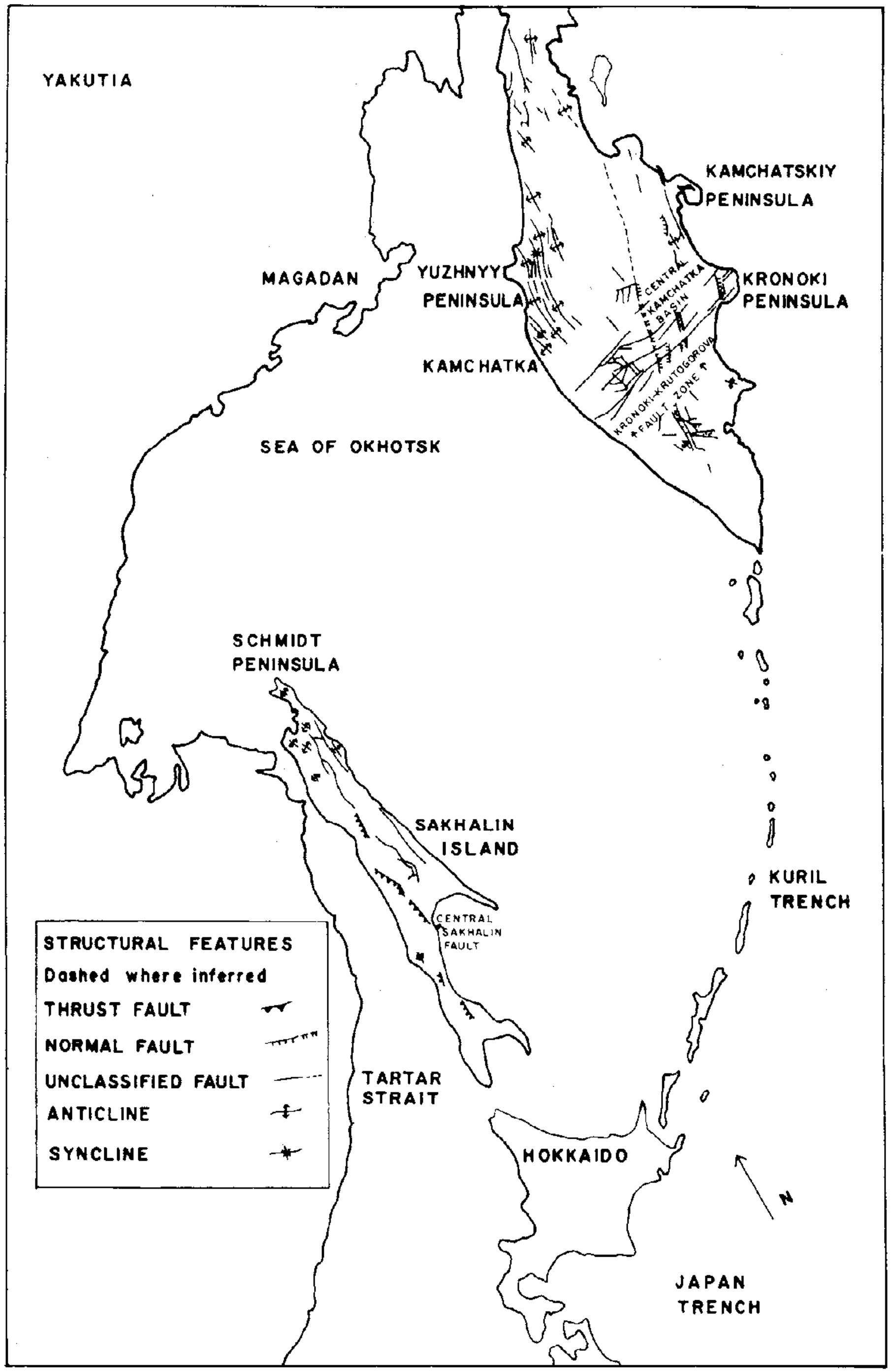

Fig. 3. Cenozoic tectonics of the Sea of Okhotsk region, simplified from *Alverson et al.* [1967].

some of the other earthquake source mechanisms in Asia. *Morgan* [1972] gives a counterclockwise China-Eurasian rotation rate of 2.4×10^{-7} deg/yr about 50°N, 127°E. *Molnar et al.* [1973] discount the utility of the China plate concept for describing Asian tectonics. The rift zone has 'spread' no more than a few tens of kilometers since the beginning of the Pliocene [*Florensov*, 1969]. This corresponds to an average half-spreading rate of 1 to 2 orders of magnitude smaller than extension at a typical midocean ridge. *Molnar and Tapponnier* [1975] speculate that the Baikal rift may be related to the collision of India and Eurasia.

Two additional plates have been postulated in the region. *Minster et al.* [1974] proposed a Bering plate, comprising western Alaska, the Bering Sea, and northeast Asia, to explain a systematic misfit of slip vectors from Aleutian and Kuril trench earthquakes to the Pacific-North American rotation pole. Though intraplate deformation in Alaska is no doubt occurring, the misfit of slip vectors can also be explained by propagation effects due to seismic velocity heterogeneities associated with subduction of the Pacific plate (E. R. Engdahl, personal communication, 1974). We do not consider a Bering plate further below. *Den and Hotta* [1973] proposed the existence of an Okhotsk plate during the Mesozoic and early Cenozoic on the basis of structural trends and orogenic belts in and around the Sea of Okhotsk, though their discussion does not require a distinct Okhotsk plate at present.

TABLE 2. Eurasian–North American Relative Angular Velocity Vector

Rotation Pole		Rotation,		
Latitude, °N	Longitude, °E	10^{-7} deg/yr	Technique	Reference
78	102	2.8	Four fracture zone trends, one rate	*Le Pichon* [1968]
64	138		Rotation of Lomonosov ridge to Eurasia	*Karasik* [1971]
68	137	2.78	Rotation of magnetic anomaly 5	*Pitman and Talwani* [1972]
48	155	2.36	Global inversion	*Chase* [1972]
60	135	2.07	Global fit	*Morgan* [1972]
63	137		Fracture zone trends	*Le Pichon et al.* [1973]
69.3	128.0	2.7	Global inversion	*Minster et al.* [1974]
61.8	130.0	2.48	See Table 4	This study

Several alternative plate descriptions for northeast Asia are considered in Figure 4. The alternatives shown do not exhaust all possibilities but include most of those commonly proposed or assumed. A shared feature of all plate models is that the boundary between the Eurasian and North American plates continues from the Nansen ridge onto the Siberian continental shelf in the Laptev Sea and along the active seismic belt in Yakutia (Figure 2). *Demenitskaya and Karasik* [1969], *Grachev et al.,* [1970], and *Churkin* [1972] have similarly drawn the plate boundary through this region on the basis of seismicity, recent faulting, and Quaternary volcanic activity. The descriptions of Figure 4 differ in how the Eurasian–North American plate boundary is continued to a triple junction with the Pacific plate or with another plate.

Description A in Figure 4 includes three plates, Eurasian, (EUA), North American (NA), and Pacific (PAC), and a Eurasian–North American boundary through Kamchatka. Given the EUA-NA pole of rotation (Table 2), such a hypothetical boundary would be a convergence zone. The boundary should be a locus of thrust faulting. However, the only faults in Kamchatka which trend in a direction approximately parallel to such a proposed boundary, those in the Kronoki-Krutogorova fault zone, are strike slip in character. Description A is thus unlikely.

Description B includes four plates: Eurasian, North American, China (CHI), and Pacific. China and Eurasia would have a boundary striking north-south through Sakhalin. Adopting *Morgan*'s [1972] pole of rotation for CHI-EUA gives almost pure (right lateral) strike-slip movement on meridional faults through Sakhalin; a EUA-CHI pole near Lake Baikal also predicts (left lateral) strike-slip motion on such faults. Neither tectonic evidence nor earthquake source mechanisms (below) bear this out. Description B also encounters the same difficulty in Kamchatka as does description A. Description B is unlikely.

Description C includes three plates (Eurasian, North American, and Pacific) with the EUA-NA border trending north-south through Sakhalin and Hokkaido to a triple junction in the Japan trench. From the EUA-NA pole of rotation, thrust faults (striking roughly north-south) with a small amount of superposed right lateral motion would be expected on Sakhalin and Hokkaido, in good agreement with the tectonic evidence discussed above and the earthquake mechanisms discussed below. We thus consider this description to be an acceptable plate tectonic interpretation of much of the seismic and geologic data, though it does not account for intraplate deformation in northeast USSR, China, or Alaska.

Description D has four plates (Eurasian, North American, China, and Pacific) with a CHI-NA boundary through Sakha-

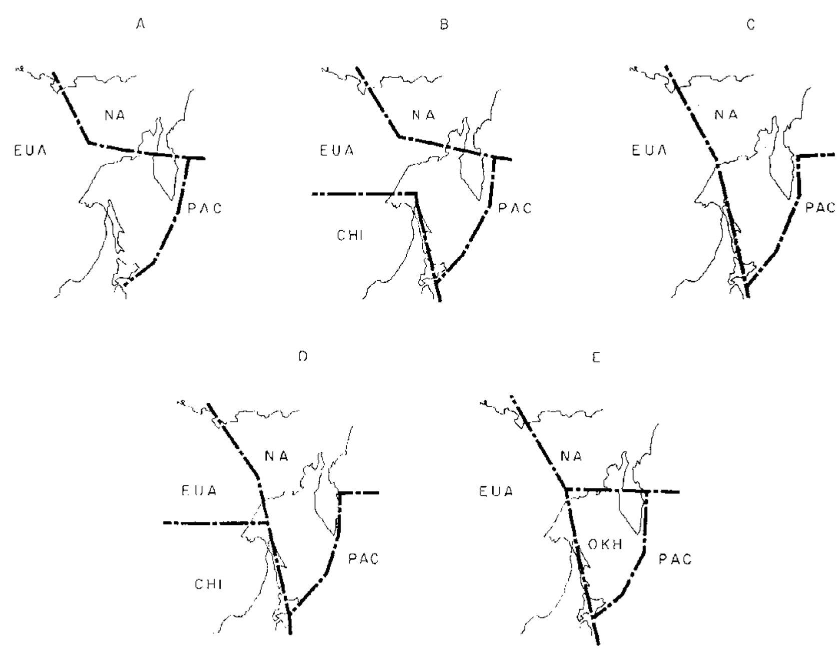

Fig. 4. Possible plate descriptions of the seismicity and tectonics in northeast Asia. The dashed lines indicate boundaries between plates (EUA, Eurasian; NA, North American; PAC, Pacific; CHI, China; OKH, Okhotsk).

lin [cf. *Morgan,* 1968, 1972]. *Morgan*'s [1972] CHI-NA pole of rotation is at 54°N, 130°E and predicts (right lateral) strike-slip motion on meridional faults in Sakhalin, in disagreement with observations. While one may argue that the motion of the China plate has large uncertainties, this exercise and the syntheses of *Molnar et al.* [1973] and *Molnar and Tapponnier* [1975] imply that the concept of a rigid China plate is of dubious value.

Description E includes the existence of a separate Okhotsk (OKH) plate [after *Den and Hotta,* 1973], along with the Eurasian, North American, and Pacific plates. This interpretation of the seismicity and tectonic data cannot be excluded; indeed, a cursory examination of the seismicity in Figure 2 lends support to the notion of a separate Okhotsk plate, though the limited seismicity in the Sea of Okhotsk precludes a definitive proof. Also because of the small rates and sparse data, no pole of rotation for OKH relative to any other plate can be computed, so the hypothesis of an Okhotsk plate has no predictive value. Therefore we see no positive reason for the addition of another plate when the data can be explained with only a three-plate configuration.

Of all the possibilities in Figure 4, then, configuration C is preferable. This description is one of the simplest, involving only three distinct plates. The description provides adequate explanation of the seismicity and tectonics of Sakhalin and Hokkaido. And as we show in a later section, this description has predictive value for describing the slip vectors of earthquakes on Sakhalin and Hokkaido.

EARTHQUAKE SOURCE MECHANISMS

As an aid in confirming the plate description discussed in the preceding section and in elucidating the tectonics of an intracontinental plate boundary we have determined the earthquake source mechanisms for all earthquakes in northeast Asia of a sufficiently large magnitude for global coverage. We present solutions for events in the continental shelf in the Laptev Sea, Yakutia, Sakhalin, the Tartar Strait, and Hokkaido.

These source mechanisms were determined by utilizing *P* wave first motions, *S* wave polarizations, and Rayleigh wave amplitudes (Figure 5 and Table 3). The technique for determining source geometry from the amplitude of the vertical component of Rayleigh waves is described by *Forsyth* [1973]. We utilized Rayleigh wave amplitudes at a period of 67 s and corrected for attenuation with a value of Q equal to 125. The solution which was compatible with the *P* wave data and had a minimum least squares error in amplitude was adopted as the correct mechanism.

Event 1 occurred on the continental shelf in the Laptev Sea, southeast of the Nansen ridge. *P* wave data determined one nodal plane, and surface wave amplitudes were used to define the other nodal plane. This event is clearly a normal faulting event and indicates that sea floor extension occurs on the shelf as a continuation of the Nansen ridge. This earthquake was also studied by *Conant* [1972], who obtained nonorthogonal nodal planes from *P* wave first motions (see also Figure 5), an artifact of the heterogeneous seismic velocity structure beneath the spreading center [*Solomon and Julian,* 1974]. *Sykes* [1967] obtained a similar solution from an earlier nearby event.

Events 2 and 3 occurred in Yakutia. *Filson and Frasier* [1972] obtained a similar solution for event 2. The location of aftershocks [*Belyy et al.,* 1971] from event 2 indicates that the fault plane for that earthquake strikes northwest. The inferred solution is almost pure left lateral strike-slip motion. Event 3, studied also by M. Oristaglio (unpublished manuscript, 1974), is similar in mechanism to event 2 but has slightly different nodal plane strikes and is less well constrained by the data. Because of the similarity in these solutions and their proximity it might be assumed that the northwest striking plane is the fault plane for event 3 also. *Lazareva and Misharina* [1965] also list strike-slip fault plane solutions for two Yakutia earthquakes in this seismic belt (72°N, 127°E and 66°N, 137°E), but we are unable to assess the quality of these solutions.

Event 4, located in central Sakhalin, appears to be almost pure thrust, but there are not enough data to constrain the solution tightly. Events 5–9 occurred in the Tartar Strait off the southwest coast of Sakhalin. Events 6–9 are part of an aftershock sequence following event 5. For this reason we required these mechanism solutions to be generally similar and at the same time still satisfy the data. We thus obtain five mechanisms which are all predominantly thrust events. The fault plane was chosen in order to satisfy several criteria: that the plane exhibit some right lateral motion to agree with the field geologic data on the faults in Sakhalin, that the plane have a strike similar to the local faults, and that the fault be in agreement with the shape of the isoseismal contours [*Solov'yev et al.,* 1973]. All five earthquakes occurred at about 20-km depth. Thus their fault plane solutions should probably agree with the strike and slip of the surface faults but not necessarily with the dip, since thrust faults are commonly shallower in dip at depth. This sequence of earthquakes has the first two mechanisms similar (5 and 6) and the last three (7–9) all similar but with a slightly different fault plane from the first group. All had a nearly identical auxiliary plane, however. It is of interest that *McKenzie* [1970] found an aftershock sequence in the Mediterranean region which similarly had a constant slip vector but a differing fault plane for each individual event.

Event 10 occurred in Hokkaido at a depth of 25 km beneath the Hidaka Mountains. We consider it to be unrelated to underthrusting of the Pacific plate because of its shallow depth and even shallower aftershock sequence and because of the orientation of the fault plane. From the aftershock distribution [*Moriya,* 1972] the shallowly dipping plane was determined to be the fault plane. It thus was a thrust fault event with a component of left lateral strike-slip motion.

A NEW EURASIAN-NORTH AMERICAN POLE

A logical question is whether these earthquake mechanism solutions are compatible with the earlier discussion of plate boundaries and with the EUA-NA pole of rotation. Event 1 implies that such a pole must be located south of 76.5°N in order to have extension on that region of the shelf. If events 2 and 3 are both interpreted as left lateral faulting occurring on a single plate boundary, the two slip vectors uniquely define a rotation pole at 65°N, 148°E. Such a pole, however, would be in systematic disagreement with fracture zone trends and earthquake slip vector data in the Atlantic and Arctic oceans. The pole would be well outside the 95% confidence ellipse of *Minster et al.* [1974]. Consequently, these two events cannot be indicative of rigid motion of the Eurasian and North American plates. Rather, they are the product of complicated deformation in a boundary between two plates near the relative rotation pole for the same plates. We comment further on this point in the following section.

If the plate tectonic description of northeast Asia is as discussed above (description C, Figure 4), then sufficiently far from the EUA-NA pole the slip vectors of earthquakes on the boundary should be predictable. When the EUA-NA angular

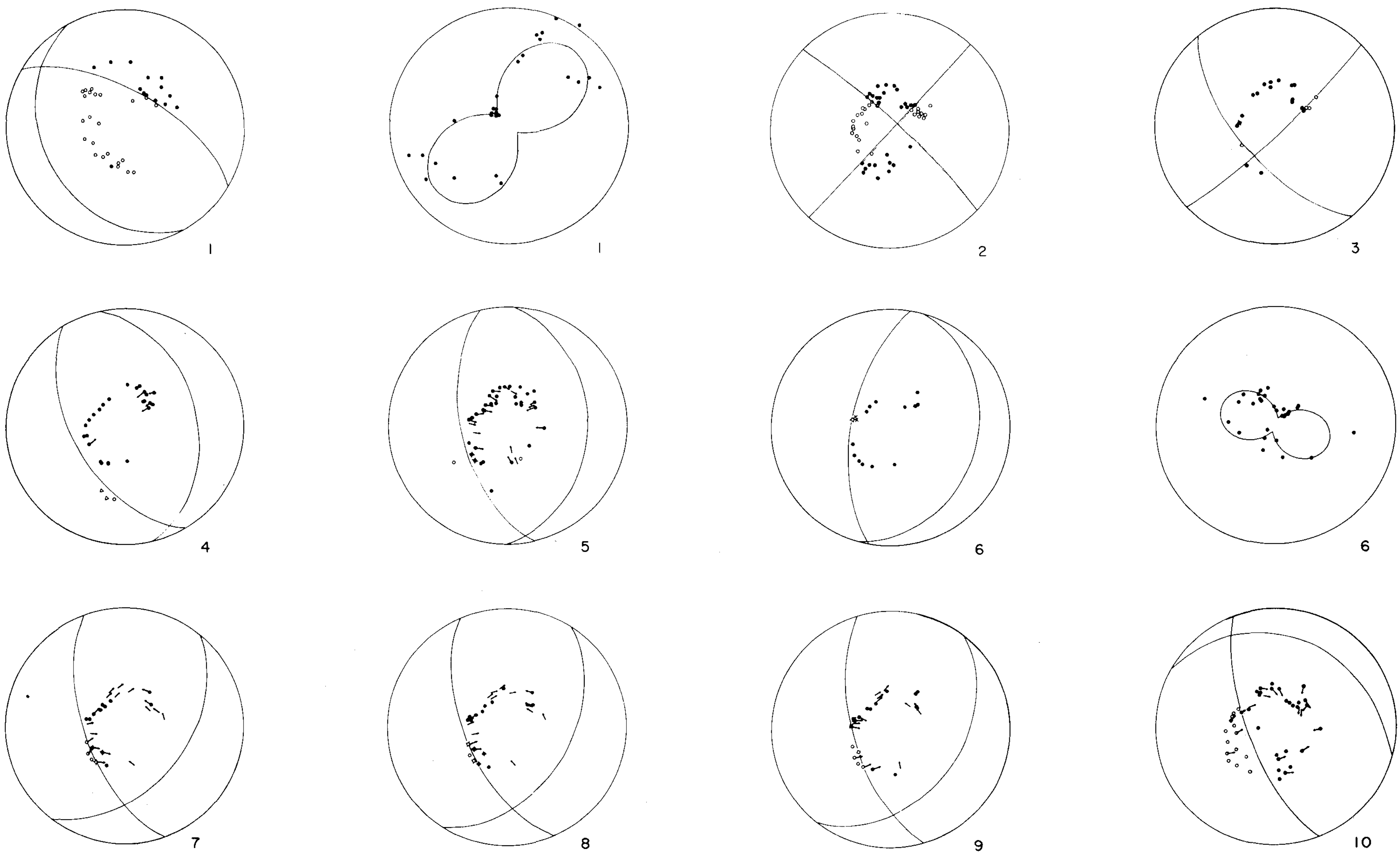

Fig. 5. Earthquake source mechanisms. Numbers refer to the event number in Table 3. Equal area projections of P wave first motions and S wave polarizations are plotted on the lower focal hemisphere; closed circles are compression, and open circles are dilatation. Triangles indicate short period data from the Bulletin of the Japanese Meteorological Agency (event 4 only). All other data were read from long-period WWSSN (World-Wide Standard Seismograph Network), Canadian network, and Lamont network seismograms. Rayleigh wave amplitude radiation patterns are shown for events 1 and 6.

TABLE 3. Epicenter and Source Mechanism Data

Event	Date	Time (GMT) h	m	s	Latitude, °N	Longitude, °E	Plane A Strike	Plane A Dip	Plane B Strike	Plane B Dip
1	April 7, 1969	20	26	30.5	76.55	130.86	120°	64°NE	332°	30°SW
2	May 18, 1971	22	44	43.8	64.0	146.1	43°	89°SE	313°	83°NE*
3	Jan. 13, 1972	17	24	23.2	61.94	147.04	320°	66°SW	47°	84°SE
4	Oct. 2, 1964	00	58	39.2	51.95	142.92	328°	54°W	348°	38°E*
5	Sept. 5, 1971	18	35	27.0	46.54	141.15	347°	58°W	0°	32°E*
6	Sept. 6, 1971	13	37	10.1	46.76	141.39	10°	63°W	16°	27°E*
7	Sept. 8, 1971*a*	11	48	25.9	46.44	141.09	340°	62°W	40°	46°E*
8	Sept. 8, 1971*b*	16	59	54.8	46.28	141.03	337°	61°W	33°	45°E*
9	Sept. 27, 1971	19	01	46.4	46.41	141.16	344°	64°W	38°	40°E*
10	Jan. 20, 1970	17	33	03.1	42.48	143.04	339°	71°W	300°	24°NE*

*Fault plane.

velocity vector of *Minster et al.* [1974] is used, the slip vectors for earthquakes on Sakhalin and Hokkaido should have azimuths of about 75°–80°. These values are very close to those observed (Figure 5 and Table 3), lending substantial credence to the above identification of the North American–Eurasian plate boundary.

A logical next step is to recalculate the EUA-NA rotation pole with the new data. Combining the slip vectors for events 4, 5, and 7–10 (the slip vector for event 6 is poorly constrained) with essentially the data set (Table 4) for EUA-NA rotation of *Minster et al.* [1974], we obtain a EUA-NA pole at 61.8°N, 130.0°E, with a rate of 2.48×10^{-7} deg/yr (Figure 6). Such a location is approximately 7° south of the *Minster et al.* [1974] pole but is within their 95% confidence ellipse. Therefore it is not a statistically significant improvement over the *Minster et al.* [1974] pole; rather, it is a pole of rotation which explains a larger data set. This pole of rotation describes the relative motion of the Eurasian and North American plates in the Atlantic and the Arctic oceans and in Sakhalin and Hokkaido. It does not describe the motion within about 10° of the rotation pole (e.g., events 2 and 3).

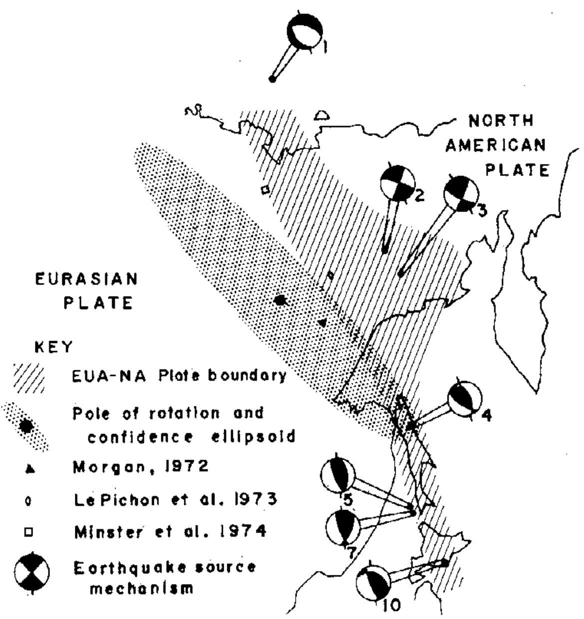

Fig. 6. The Eurasian–North American plate boundary in northeast Asia. The newly computed EUA-NA pole of rotation is shown together with the 95% confidence ellipse. Locations of the pole of rotation from other authors are also shown. Earthquake source mechanisms are taken from Figure 5; the compressional quadrants are shaded.

On the Nature of Intracontinental Plate Boundaries

The intracontinental portion of the boundary between the Eurasian and North American plates has several characteristics which distinguish it from the more common submarine plate boundaries. We comment on these characteristics in this section, with occasional generalizations to other intracontinental plate edges.

Boundary width. The plate boundary in Yakutia is very wide and diffuse. At its widest, the boundary (if indeed such a term is still appropriate) is 600 km wide. The diffuse nature of the boundary is more likely to be a property of continental lithosphere than to be due to the slow relative plate velocity. The width of the seismic zone increases markedly between the Nansen ridge (oceanic lithosphere) and its extension onto the continental shelf in the Laptev Sea (Figures 1 and 2). Other intracontinental plate boundaries of different types and with different relative plate velocities share this very extended character; western North America [*Atwater,* 1970] is a good example. That continental lithosphere is generally thicker than oceanic lithosphere may be part of the answer for the diffuse definition of the intracontinental edges of plates. More important, probably, is that continental lithosphere is very heterogeneous, a complex cementation of blocks and belts of different makeup, texture, and age. In comparison with the relatively fresh and relatively homogeneous oceanic plates, continents have generally undergone a long history of stress- and fracture-producing tectonic activity and are crisscrossed with weak zones highly susceptible to deformation when stressed.

Rotation pole location. The relative rotation pole is near the plate boundary. It is sometimes difficult to separate cause and effect in a physical phenomenon, but we speculate that the location of the Eurasian–North American rotation pole very near the intracontinental boundary between these two plates is not a coincidence. Rather, it is likely related to a greater asthenospheric resistance to moving continental lithosphere than oceanic lithosphere in general [*Solomon et al.,* 1975; *Forsyth and Uyeda,* 1975] and to a difficulty in subducting one continental block beneath another [*McKenzie,* 1969], particularly without first closing an intervening ocean. The situation is not quite that simple, since the plates are responding to a number of different types of forces [*Solomon and Sleep,* 1974]. Nonetheless, there are at least two other possible examples of where a relative rotation pole is located near the intracontinental portion of a plate boundary: the Pacific-Indian pole is not far from New Zealand, and the African-Eurasian pole is not far from the Straits of Gibraltar.

TABLE 4. Data for Computation of Pole of Rotation

		Rates, cm/yr			
Latitude, °N	Longitude, °E	Observed	Uncertainty	Error	Reference
85.0	90.0	1.0	0.4	0.1	*Rassokho et al.* [1967]
70.0	−18.0	1.6	0.3	0.4	*Johnson* [1967]
60.0	−29.0	2.4	0.2	0.1	*Talwani et al.* [1971]
45.0	−28.0	2.8	0.3	0.2	*Pitman and Talwani* [1972]
		Azimuths, deg			
Latitude, °N	Longitude, °E	Observed	Uncertainty	Error	Reference
80.2	1.0	130.	10.	2.0	*Horsfield and Maton* [1970]
79.8	2.9	137.	10.	6.3	*Conant* [1972]
79.8	2.4	134.	10.	3.7	*Chapman* [1973]
79.6	2.5	128.	10.	−2.2	*Johnson and Eckhoff* [1966]
71.0	−8.0	115.	5.	−2.0	*Johnson et al.* [1972]
70.9	−7.0	116.	10.	−1.6	*Conant* [1972]
66.7	−18.2	115.	10.	5.9	*Conant* [1972]
66.3	−19.8	107.	10.	−1.0	*Sykes* [1967]
52.9	−34.2	95.	10.	−3.1	*Solomon* [1973]
52.5	−35.0	96.	4.	−1.7	*Johnson* [1967]
52.5	−33.5	95.	4.	−3.5	*Fleming et al.* [1970]
51.9	142.9	58.	10.	−2.0	This study (4)
46.5	141.1	77.	10.	5.5	This study (5)
46.4	141.1	70.	10.	−1.7	This study (7)
46.3	141.0	67.	10.	−5.0	This study (8)
46.4	141.2	74.	10.	2.4	This study (9)
42.5	143.0	69.	10.	−3.7	This study (10)

The computed EUA-NA pole of rotation is located at 61.8°N, 130.0°E. The computed rate of rotation is 0.248°/m.y. The standard deviation is 5.38°.

Near-pole motions. The displacements during large earthquakes are not predictable near the relative rotation pole. This characteristic is related to the previous two. Because the rotation pole is near the plate boundary, the stress system in the boundary zone changes rapidly with small changes in distance. Structural heterogeneities modulate the stress field and the material response to stress. Aggravating the complexity of the stress and stress release fields is the fact that the instantaneous rotation pole is not fixed but migrates with respect to the two plates [*Pitman and Talwani,* 1972].

Relationship of modern and ancient boundaries. The modern boundary is closely related to ancient plate boundaries. The broad seismic belt in Yakutia (Figure 2) marking the location of the current Eurasian–North American plate boundary lies within the Cherskiy-Verkhoyansk fold belts, which *Churkin* [1972] has interpreted as a fossil suture marking the early Cretaceous collision of two continental blocks. The current plate boundary through Sakhalin and Hokkaido (Figure 6) follows closely a Mesozoic plate boundary marking the locus of eastward subduction of one plate beneath another [*Sugimura and Uyeda,* 1973; *Den and Hotta,* 1973]. This is a familiar story in the plate tectonic evolution of the earth's surface: fossil plate boundaries are apparently relatively weak portions of continental blocks and are the preferred sites for creation of new plate edges.

CONCLUSIONS

Though plate boundaries within continents can rarely be defined with precision, the boundary between the Eurasian and North American plates between the Arctic and Pacific oceans can be identified on the basis of seismicity, recent tectonics, and earthquake source mechanisms. The simplest plate configuration that adequately accounts for these data continues the Eurasian–North American boundary from the Nansen ridge through a broad seismically active zone in northeast USSR to the Sea of Okhotsk and thence southward through Sakhalin and Hokkaido. With this configuration the slip vectors derived from earthquake mechanisms in Sakhalin and Hokkaido are predicted from the EUA-NA relative rotation pole. A new pole, only slightly different from other recent solutions, is computed on the basis of the additional slip vector data.

The intracontinental plate boundary is spread over a width of as much as 600 km and tends to follow ancient plate margins. Deformation in the vicinity of the rotation pole, which lies near the boundary, is poorly described by rigid plate tectonics. These features can be explained by the thickness and heterogeneity of continental lithosphere and by the influence of continents on the forces moving the plates.

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The intracontinental portion of the boundary between the North American and Eurasian plates can be identified on the basis of seismicity, recent tectonics and earthquake focal mechanisms. The simplest plate geometry that can explain these data involves a North American-Eurasian boundary that extends from the Nansen ridge through a broad zone of northeast Asia to the Sea of Okhotsk and thence southward through Sakhalin and Hokkaido to a triple junction in the Kuril-Japan trench. Such a configuration can account quantitatively for

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the slip vectors derived from earthquake mechanisms in Sakhalin and Hokkaido. On the basis of new slip vector data the North American-Eurasian angular velocity vector is revised only slightly from previous determinations. The intracontinental plate boundary is diffuse and may be controlled by ancient plate sutures. Deformation within about 10° of the rotation pole, which lies very near the boundary, cannot be modeled by rigid plate tectonics. These characteristics of intracontinental plate boundaries are related to the greater thickness and heterogeneity of continental lithosphere and to the influence of continents on the plate tectonic driving forces.