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A Model for the Motion of the Philippine Sea Plate Consistent With NUVEL-1 and Geological Data

TETSUZO SENO

Earthquake Research Institute, University of Tokyo

SETH STEIN AND ALICE E. GRIPP

Department of Geological Sciences, Northwestern University, Evanston, Illinois

We investigate angular velocity vectors of the Philippine Sea (PH) plate relative to the adjacent major plates, Eurasia (EU) and Pacific (PA), and the smaller Caroline (CR) plate. Earthquake slip vector data along the Philippine Sea plate boundary are inverted, subject to the constraint that EU-PA motion equals that predicted by the global relative plate model NUVEL-1. The resulting solution fails to satisfy geological constraints along the Caroline-Pacific boundary: convergence along the Mussau Trench and divergence along the Sorol Trough. We then seek solutions satisfying both the CR-PA boundary conditions and the Philippine Sea slip vector data, by adjusting the PA-PH and EU-PH best fitting poles within their error ellipses. We also consider northern Honshu to be part of the North American plate and impose the constraint that the Philippine Sea plate subducts beneath northern Honshu along the Sagami Trough in a NNW-NW direction. Of the solutions satisfying these conditions, we select the best EU-PH as 48.2°N, 157.0°E, 1.09°/m.y., corresponding to a pole far from Japan and south of Kamchatka, and PA-PH, 1.2°N, 134.2°E, 1.00°/m.y. Predicted NA-PH and EU-PH convergence rates in central Honshu are consistent with estimated seismic slip rates. Previous estimates of the EU-PH pole close to central Honshu are inconsistent with extension within the Bonin backarc implied by earthquake slip vectors and NNW-NW convergence of the Bonin forearc at the Sagami Trough.

INTRODUCTION

A variety of models have been offered for the present motion of the Philippine Sea plate (PH) with respect to the adjacent major plates, Eurasia (EU) and Pacific (PA) (see references cited by *Seno and Eguchi* [1983] and *Ranken et al.* [1984]). Determination of this motion is difficult because the Philippine Sea is mainly surrounded by subduction zones (Figure 1). Absence of an accreting boundary precludes use of magnetic anomaly or transform strike data, which are the most valuable data in determining plate motions [*Chase*, 1972; 1978; *Minster et al.*, 1974; *Minster and Jordan*, 1978]. Slip vectors of thrust earthquakes at subduction boundaries can be used to constrain relative motions, but extension in the backarc or deformation within the overriding plate can make application of slip vector data ambiguous [*Jarrard*, 1986; *DeMets et al.*, 1990]. For example, current backarc spreading in the Mariana Trough [*Karig et al.*, 1978] at a full rate of more than 40 mm/yr [*Hussong and Uyeda*, 1981] may cause the Mariana forearc to act as a sliver decoupled from the Philippine Sea plate, giving rise to a deviation of trench slip vectors from the direction of PH-PA motion [*Karig*, 1975; *Ranken et al.*, 1984]. Similarly, extension in the Okinawa Trough behind the Ryukyu Trench may cause deviation of slip vectors from the direction of EU-PH motion. Strike-slip faulting within the overriding plate, such as motion estimated along the Philippine fault in the Philippines, can have a similar effect on slip vectors [e.g., *Fitch*, 1972; *Jarrard*, 1986]. Another complexity is that subduction from the west along the Manila and minor trenches further decouples the Philippines from the Eurasian plate. These effects may explain the discrepancy (Figure 1) between E-W trending slip vectors along the Philippine Trench and NW-SE slip vectors along the Nankai Trough-Ryukyu Trench [*Seno*, 1977]. At other arcs in the Pacific and Indian oceans, slip vector directions are biased toward the trench-normal relative to the convergence direction [*Jarrard*, 1986; *DeMets et al.*, 1990; *McCaffrey*, 1992]. Moreover, the complicated collision zones around the plate boundary, such as the Luzon arc-continental margin in Taiwan, Caroline Ridge-Yap arc, and Izu arc-central Honshu, may perturb plate-wide stress and strain fields and further complicate interpretation of focal mechanism solutions.

Another complication is that part of the plate boundary geometry is uncertain. Recent results suggest that northern Honshu, commonly treated as part of the Eurasian (EU) plate, is better treated as part of the North American (NA) plate [*Nakamura*, 1983; *Seno*, 1985b; *Fallon and Dillinger*, 1992; *DeMets*, 1992]. Seismicity in Siberia extends through Sakhalin to the eastern margin of the Japan Sea [e.g., *Seno and Eguchi*, 1983; *Seno*, 1985b]. The NA-EU plate boundary may be coincident with this seismicity and pass through central Honshu as shown in Figure 1 [*Nakamura*, 1983; *Seno*, 1985b; *DeMets*, 1992]. *Seno* [1985a] and *DeMets* [1992] showed that slip vectors in the Japan-Kuril trenches are closer to the PA-NA motion than the PA-EU motion predicted from global plate motion models. *Fallon and Dillinger* [1992] calculated the motion of Kashima, located at the Pacific coast of northern Honshu, and other very long baseline interferometry (VLBI) sites from observations over several years using no net-translation and no net-rotation assumptions, and found that Kashima's motion is close to that of the North American plate derived from applying the same assumptions to NUVEL-1. Oblique convergence of the Philippine Sea plate occurs at the Sagami Trough beneath northern Honshu (Figure 1). Thus slip vectors from the Sagami

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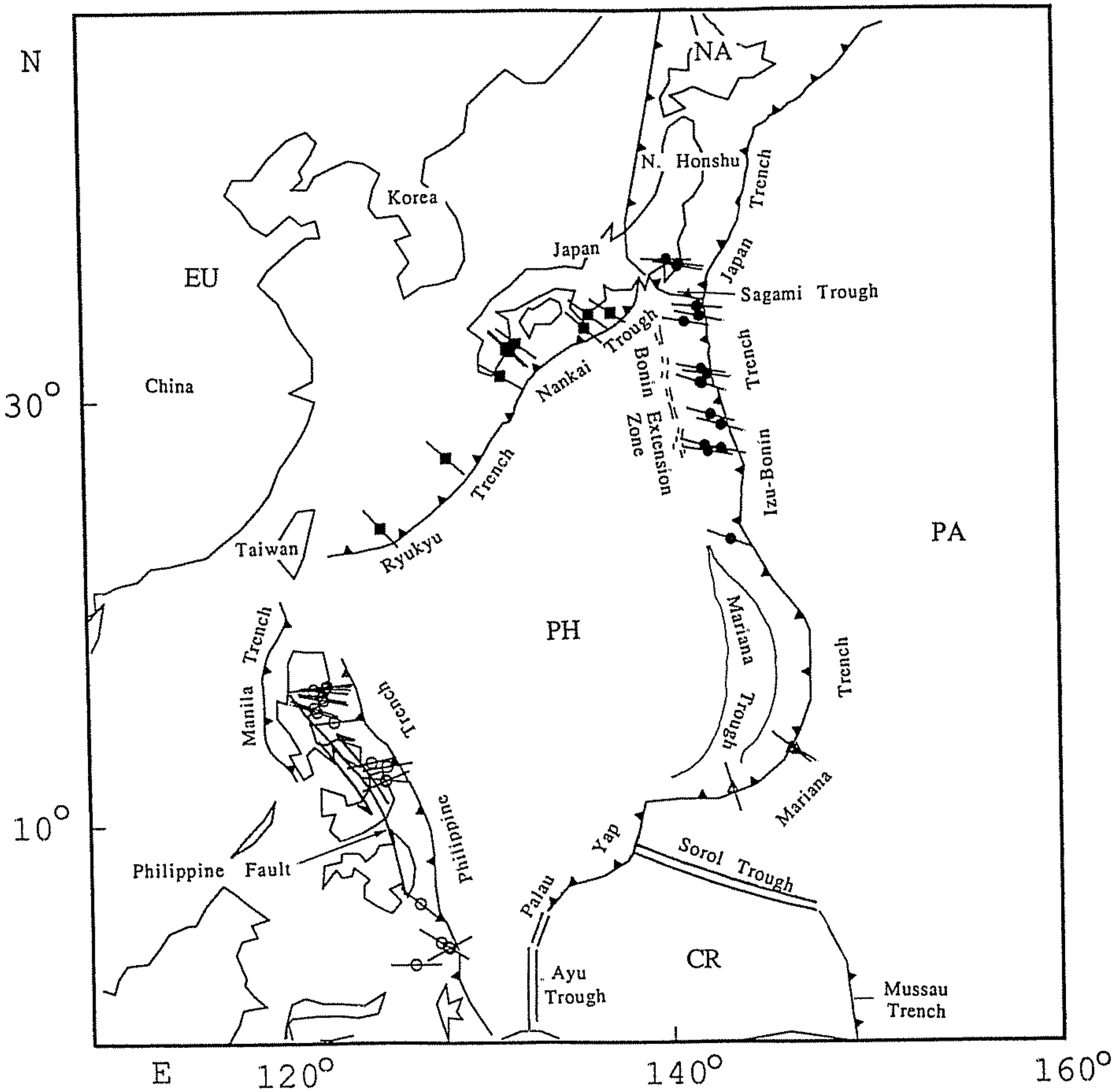

Fig. 1. Slip vectors trends (bars) of shallow thrust fault earthquakes around the Philippine Sea. Those located in the Bonin arc (solid circle) and in the Nankai Trough-Ryukyu Trench (solid squares) are used in this study; data and their sources are listed in Table 1. Those in the Philippine Trench (open circles) and in the Mariana Trench (open triangle) are not used (see text); data sources are from compilations of *Seno and Eguchi* [1983], *Hamburger et al.* [1983] and *Ranken et al.* [1984]. Basin geometry in the Bonin extension zone is from *Honza and Tamaki* [1985].

Trough may reflect NA-PH motion. However, *Heki et al.* [1990] and *Argus and Lyzenga* [1993] analyzed VLBI observations and found that Kashima is moving with respect to North American stations at velocities of 13-14 mm/yr to the NW. They attributed this as internal deformation of the North American or Eurasian plate. Thus whether northern Honshu is part of the North American, Eurasian or another plate is still in dispute.

Despite these difficulties, a number of solutions have been derived for Philippine Sea plate motion. *Seno* [1977], *Chase* [1978], and *Minster and Jordan* [1979] used slip vector data from the EU-PH (Nankai Trough-Ryukyu Trench) and PA-PH boundaries (Izu-Bonin-Mariana-Yap-Palau trenches), while ignoring backarc extension behind the Izu-Bonin-Mariana and Ryukyu trenches. The location of the EU-PH pole is quite different among these models (Figure 2), presumably due to differences in data sets. *Karig* [1975] obtained an EU-PH pole using only slip vectors along the EU-PH boundary and assumed slip rates at some localities along this boundary. Although uncertainty in assumed slip rates results in serious ambiguity, the solution has the advantage of not being biased by backarc extension behind the PA-PH boundary.

Ranken et al. [1984] devised an alternative method, in which data at various boundaries were used simultaneously to estimate the EU-PH pole and angular rate. Slip vectors along the PA-PH

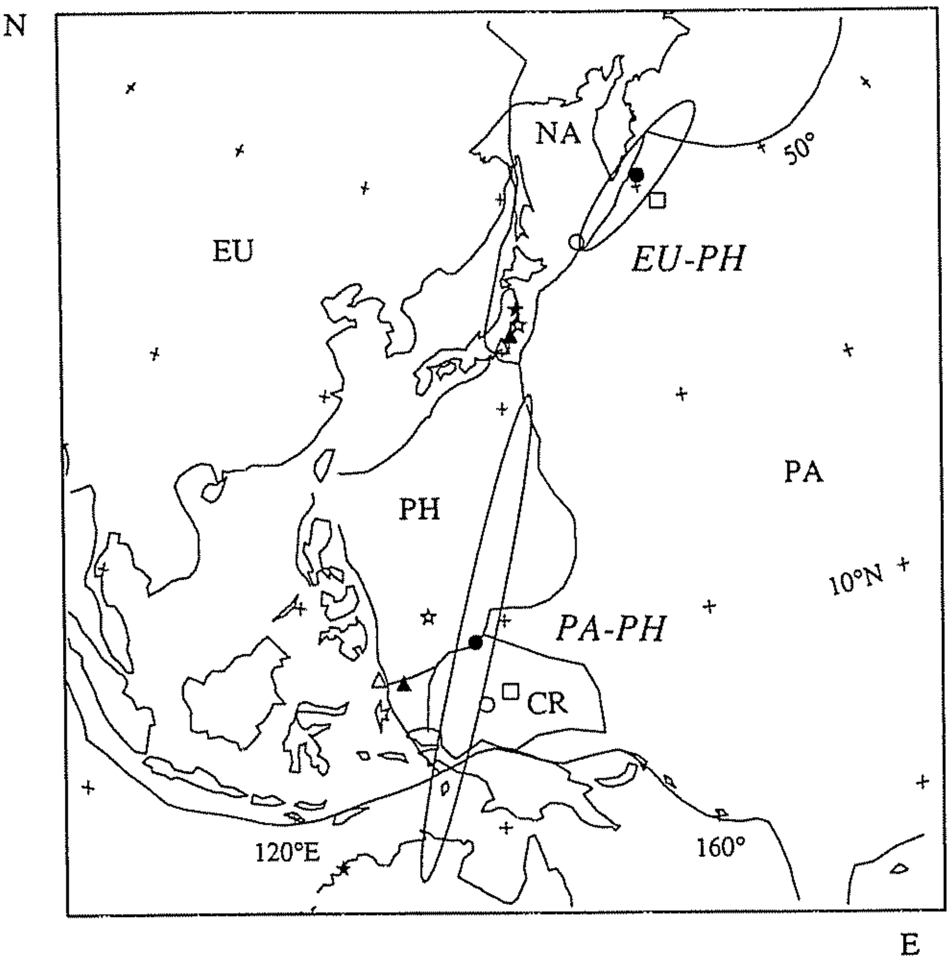

Fig. 2. EU-PH and PA-PH poles (solid circles) obtained by simultaneous inversion of data along the Philippine Sea plate boundary using the NUVEL-1 EU-PA Euler vector. One sigma error ellipses are also shown. Poles from previous work are indicated by open triangles [*Karig*, 1975], open circles [*Seno*, 1977], solid stars [*Chase*, 1978], squares [*Minster and Jordan*, 1979], solid triangles [*Ranken et al*, 1984], and open stars [Huchon, 1986].

boundary constrained the EU-PH Euler vector, so that the difference between observed and predicted PA-PH directions was consistent with spreading behind the Mariana and Bonin trenches. Predicted PA-PH motion was obtained by summing the EU-PH Euler vector and the PA-EU Euler vector of *Minster and Jordan* [1978]. *Ranken et al.* [1984] added a new constraint by considering relative motion between the Pacific and Caroline (CR) plates. The existence of a distinct Caroline plate (Figure 1) was proposed by *Weissel and Anderson* [1978]. In their model, the Yap-Palau trenches and the Ayu Trough constitute convergent and divergent CR-PH boundaries, respectively. The Sorol Trough and Mussau Trench are divergent and convergent CR-PA boundaries, respectively. *Ranken et al.* [1984] constrained the EU-PH vector to be consistent with divergence along the Sorol Trough and convergence along the Mussau Trench. The CR-PA Euler vector was estimated from the PA-PH Euler vector and a CR-PH Euler vector estimated by *Weissel and Anderson* [1978] from geological considerations. The resulting EU-PH pole (37.0°N, 141.0°E) (Figure 2, solid triangle) is very close to central Honshu.

Huchon [1986] noted that the Ranken et al. EU-PH vector predicts divergence at the triple junction of the Japan Trench, the Izu-Bonin Trench, and the Sagami Trough. He consequently favored an EU-PH pole at 38°N, 142°E, which would yield strike-slip motion at the triple junction and convergence along the entire Sagami Trough. Although this solution was considered consistent with the other conditions used by Ranken et al., it apparently does not satisfy the CR-PA condition [*Karig and Cardwell*, 1986].

In this paper, we develop an improved model that fits all of boundary conditions. Our analysis differs from earlier studies in several ways. First, we augment PA-PH boundary data with additional earthquake slip vectors from the Izu-Bonin Trench. Although there may be some extension in the Izu-Bonin backarc, the distribution of extensional basins, called the Bonin extension zone (Figure 1), is irregular [*Honza and Tamaki*, 1985; *Karig and Moore*, 1975]. The basins are rifting [*Leg 126 Shipboard Scientific Party*, 1989; *Taylor et al.*, 1991], and *Taylor et al.* [1991] estimated extensions of 2-5 km for the past 2 m.y., which implies a 1-2.5 mm/yr full extension rate. Because all previous PH motion models give convergent rates along the Izu-Bonin Trench as several centimeters per year, consistent with large absolute velocities of the Pacific plate there [*Minster and Jordan*, 1978; *Gripp and Gordon*, 1990], we derive a solution neglecting this extension. Second, we describe motion between adjacent major plates using PA-EU and PA-NA motions from the NUVEL-1 global plate motion model [*DeMets et al.*, 1990] rather than earlier global models used in previous studies. Third, we treat northern Honshu as part of the North American plate, rather than the Eurasian plate. Slip vector data along the Sagami Trough are not used as NA-PH data in the inversion directly, because the data have large uncertainties [*Seno*, 1985a]. We use, however, the convergence direction to constrain the solutions. We examine how the solutions depend on the northern Honshu North American plate assumption by using an alternative assumption that northern Honshu is the Eurasian plate, because this hypothesis is still ambiguous.

Our approach is first to simply invert slip vector data along the EU and PA boundaries of the Philippine Sea plate, by fixing the EU-PA Euler vector to the NUVEL-1 EU-PA Euler vector. We then use the CR-PH Euler vector from *Weissel and Anderson* [1978] to derive a CR-PA Euler vector and to examine whether predicted motions are consistent with observed convergence along the Mussau Trench and divergence along the Sorol Trough. *Mammerickx* [1978] interpreted the Sorol Trough as a trench, where the Caroline Basin crust would have been consumed. We disagree with this view because morphology of the trough differs from that of a trench but resembles that of a very slow spreading ridge [*Weissel and Anderson*, 1978; *Seno et al.*, 1993]. We find that the inverted solution does not satisfy these conditions along the CR-PA boundary. We thus seek a solution consistent with both slip vector data and the CR-PA conditions.

DATA

Slip vector data are listed in Table 1 and plotted in Figure 1. We corrected slip vector directions for the effect of fault plane dip [Minster and Jordan, 1978], although this correction was negligible for most slip vectors. New mechanism solutions for earthquakes in the Izu-Bonin Trench have become available since *Seno's* [1977] study. The three northernmost earthquakes are located beneath northern Honshu, behind the Japan Trench. These events occurred at 49-69 km depths and are located at the interface between the subducted PH and PA slabs [*Ishida*, 1992]. They have E-W slip vectors, which are different from that predicted from the PA-NA or PA-EU Euler vector. They are thus thought to represent slip between the subducted Philippine Sea and Pacific plates, rather than NA-PA or EU-PA motion [*Ohtake and Kasahara*, 1983; *Seno and Takano*, 1989]. In contrast, data along the Nankai Trough and Ryukyu Trench have increased little, because only one earthquake large enough for mechanism determination has occurred [*Eguchi and Uyeda*, 1983]. Subduction at the Ryukyu Trench appears to be largely aseismic and the Nankai Trough has been inactive, perhaps as a result of its being locked since the great earthquakes of 1944 and 1946. We ignored the effect of extension in the Okinawa

TABLE 1. Slip Vector Data Around the Philippine Sea

Date	Time, UT	Location °N	Location °E	Datum	σ, deg	Reference
		Pacific-Philippine Sea Slip Vectors (Izu-Bonin)				
Feb. 27, 1983	1214	35.93	140.08	n89°w	15.0	Ohtake and Kasahara (1983)
Sept. 30, 1973	0617	35.67	140.64	n80°w	15.0	Seno and Takano (1989)
Oct. 01, 1973	1416	35.76	140.70	n83°w	15.0	Seno and Takano (1989)
Aug. 10, 1973	0008	34.02	141.63	n86°w	10.0	Seno and Takano (1989)
Jan. 07, 1968	1112	33.61	141.71	n78°w	10.0[a]	Seno and Takano (1989)
Feb. 29, 1972	0922	33.38	140.97	n80°w	20.0	Yoshii (1979)
Dec. 28, 1965	2032	27.97	141.92	n74°w	15.0	Katsumata and Sykes (1969)
May 26, 1978	2358	23.71	143.20	n70°w	10.0	Moriyama (1988)
Apr. 18, 1982	0857	28.89	142.76	n75°w	15.0	Moriyama (1988)
Aug. 20, 1983	1308	27.72	142.08	n81°w	15.0	Moriyama (1988)
Nov. 15, 1983	1735	31.11	142.09	n82°w	10.0	Moriyama (1988)
July 31, 1972	0328	30.71	141.82	n72°w	15.0	Moriyama (1988)
July 31, 1972	1556	30.75	141.73	n72°w	10.0	Moriyama (1988)
July 19, 1975	0402	29.34	142.23	n75°w	10.0	Moriyama (1988)
May 24, 1976	1124	31.34	141.80	n80°w	15.0	Moriyama (1988)
Apr. 05, 1980	1623	27.84	142.76	n78°w	15.0	Moriyama (1988)
		Philippine Sea-Eurasia Slip Vectors (Nankai-Ryukyu)				
Dec. 07, 1944	0435	33.70	136.05	n54°w	10.0	Kanamori (1972)
Dec. 20, 1946	1919	33.13	135.84	n50°w	10.0	Kanamori (1972)
Oct. 03, 1963	2324	32.23	131.78	n48°w	10.0	Katsumata and Sykes (1969)
Jan. 11, 1966	1416	33.76	137.20	n57°w	10.0	Katsumata and Sykes (1969)
Apr. 01, 1968	0713	32.24	132.21	n54°w	15.0	Fitch (1972)
Apr. 21, 1969	0719	32.15	131.98	n48°w	15.0	Fitch (1972)
Sept. 17, 1969	1851	31.14	131.33	n61°w	10.0	Fitch (1972)
July 25, 1970	2241	32.26	131.78	n49°w	10.0	Fitch (1972)
July 26, 1970	0710	32.31	131.83	n48°w	15.0	Fitch (1972)
Oct. 26, 1972	1705	27.48	128.57	n48°w	15.0	Eguchi and Uyeda (1983)
July 10, 1966	1612	24.30	125.21	n43°w	10.0	Katsumata and Sykes (1969)

Hypocentral parameters are from ISC and ISS Bulletins except for the events before 1963.

TABLE 2. Euler Vectors With Respect to the Philippine Sea Plate Derived Assuming NUVEL-1 EU-PA

Plate	Euler Vector			Standard Error Ellipse			
	Latitude °N	Longitude °E	ω, deg/m.y.	σ_{max}, deg	σ_{min}, deg	ζ_{max}, deg	σ_{ω}, deg/m.y.
PA	7.945	137.268	1.0159	24.00	1.70	12.	0.42
EU	51.019	160.593	1.1922	9.13	1.88	50.	0.50
NA	47.943	164.372	0.9814	11.35	3.45	66.	0.50

Note that this set of solutions does not satisfy the PA-CR boundary conditions (see text). ζ_{max} is the azimuth of the major axis of the error-ellipse. Errors are derived from fit to data alone; no errors are propagated from NUVEL-1.

TABLE 3. Philippine Sea Plate Variance-Covariance Matrix in Fixed-Pacific (or Fixed-Eurasia) Cartesian Coorinates.

	PH		
PH	x	y	z
x	300	-203	-325
y	-203	143	214
z	-325	214	369

Units are in $10^{-7}\text{rad}^2/\text{m.y.}^2$. The x is parallel to 0°N, 0°E; y is parallel to 0°N, 90°E; and z parallel to 90°N. This matrix was calculated using only Philippine Sea data, the EU-PA Euler vector was assumed to be perfectly known.

Trough on slip vectors, because the trough is still in the stage of incipient rifting [*Japanese DELP Research Group*, 1991]. We did not use data along the Mariana Trench because slip vectors may not fully represent PA-PH motion [*Karig*, 1975; *Ranken et al.*, 1984], because the Mariana Trough is currently spreading behind the arc. Data in the tectonically-complex Yap-Palau Trench and the Philippines region were not used because slip vectors may not represent PH motion with respect to other plates.

RESULTS

We first inverted slip vector data, while constraining the EU-PA Euler vector to that from NUVEL-1. Resulting EU-PH and PA-PH poles are shown in Figure 2 (solid circles) with their one sigma error ellipses and listed in Table 2. Table 3 shows the variance-covariance matrix of the PH motion in fixed-Pacific (or equally fixed-Eurasia) Cartesian coordinates. The EU-PH and PA-PH poles of previous major solutions are also plotted in Figure 2. The PA-PH pole is located in the southern Yap Trench and the EU-PH pole is located south of Kamchatka, close to those of *Seno* [1977] and *Minster and Jordan* [1979], but far from those of *Karig* [1975], *Chase* [1978], *Ranken et al.* [1984] and *Huchon* [1986].

We examined whether this solution satisfied the CR-PA constraints. We used the CR-PH pole position (7°N, 133°E) that *Weissel and Anderson* [1978] inferred from morphology of the Ayu Trough. The appropriate rotation rate, however, is uncertain. Weissel and Anderson suggested that CR-PH spreading at 2°N, 133°E occurred at a full rate of ~40 mm/yr during 6-12 Ma and at ~8 mm/yr since then. *Ranken et al.* [1984] used 2.2 °/m.y., the average value since the middle Miocene, which gives a 21 mm/yr rate at 2°N, 133°E. We considered angular velocities between 0.6-2.2 °/m.y., corresponding to full rates of 6-21 mm/yr. For values in this range, we found that our predicted CR-PA motion did not satisfy the boundary constraints. The spreading rate in the Ayu Trough could be even less [*Weissel and Anderson*, 1978, Figure 5]. However, even a rate < 0.6 °/m.y. did not yield a CR-PA Euler vector satisfying the CR-PA constraints.

We then followed an alternative approach, by seeking solutions that satisfied the CR-PA boundary constraints and were consistent with the slip vector data. First, we obtained the best fitting PA-PH and EU-PH poles and their one sigma error ellipses (Figure 3) by fitting only the data along the Izu-Bonin Trench and along the Nankai Trough-Ryukyu Trench, respectively. Because slip vectors provide only directional data, best fitting poles rather than Euler vectors were found.

We then constrained magnitude of the PA-PH Euler vector using the NNW-NW convergence direction of PH beneath northern Honshu along the Sagami Trough. We treated this area as part of the North American plate [*Nakamura*, 1983; *Seno*, 1985b] and assumed that the N20°-50°W direction of slip vectors in the thrust zone [*Seno*, 1985a] reflects the PH-NA convergence direction. Hence, as illustrated in Figure 4, the observed PH-NA convergence direction, together with the predicted NUVEL-1 NA-PA motion, constrains PA-PH linear velocity and thus magnitude of the PA-PH Euler vector.

The PA-PH pole was adjusted on grid points within the best fit ellipse with two degree increments in azimuth and 11 equi-distance partitions in the radial direction. The PH-NA convergence direction was adjusted from N20°W to N50°W with an increment of 2.5°.

Next, for those PA-PH Euler vectors satisfying the convergence direction along the Sagami Trough criterion, we chose various CR-PH Euler vectors and tested whether the resulting CR-PA Euler vector satisfied geological constraints. To do this, the PH-CR pole was adjusted within an ellipse centered at 6.4°N, 133.5°E (Figure 3) with an increment of 30° in azimuth and three equi-distance partitions in the radial direction. The center of the ellipse was estimated from the fan-shape morphology of the Ayu Trough. The PH-CR pole of Weissel and Anderson falls within this ellipse. The PH-CR angular velocity was adjusted from 0.6 to 2.2 °/m.y. in 0.1 °/m.y. increments. We found that only PH-CR rotation rates ≤ 0.7 °/m.y. could satisfy the CR-PA constraints.

Finally, we tested the remaining possible PA-PH vectors, which had satisfied the CR-PA boundary constraints, by adding the NUVEL-1 EU-PA vector, to form EU-PH vectors, and examined whether they fell within the EU-PH best fitting pole's one sigma error ellipse. The poles surviving this procedure satisfied all required conditions; they are shown in Figure 3. We prefer the pole closest to the best fitting EU-PH pole. This and the corresponding PA-PH, NA-PH, CR-PH, and PA-CR vectors are listed in Table 4. Figure 5 shows relative velocities around PH and CR predicted by these Euler vectors.

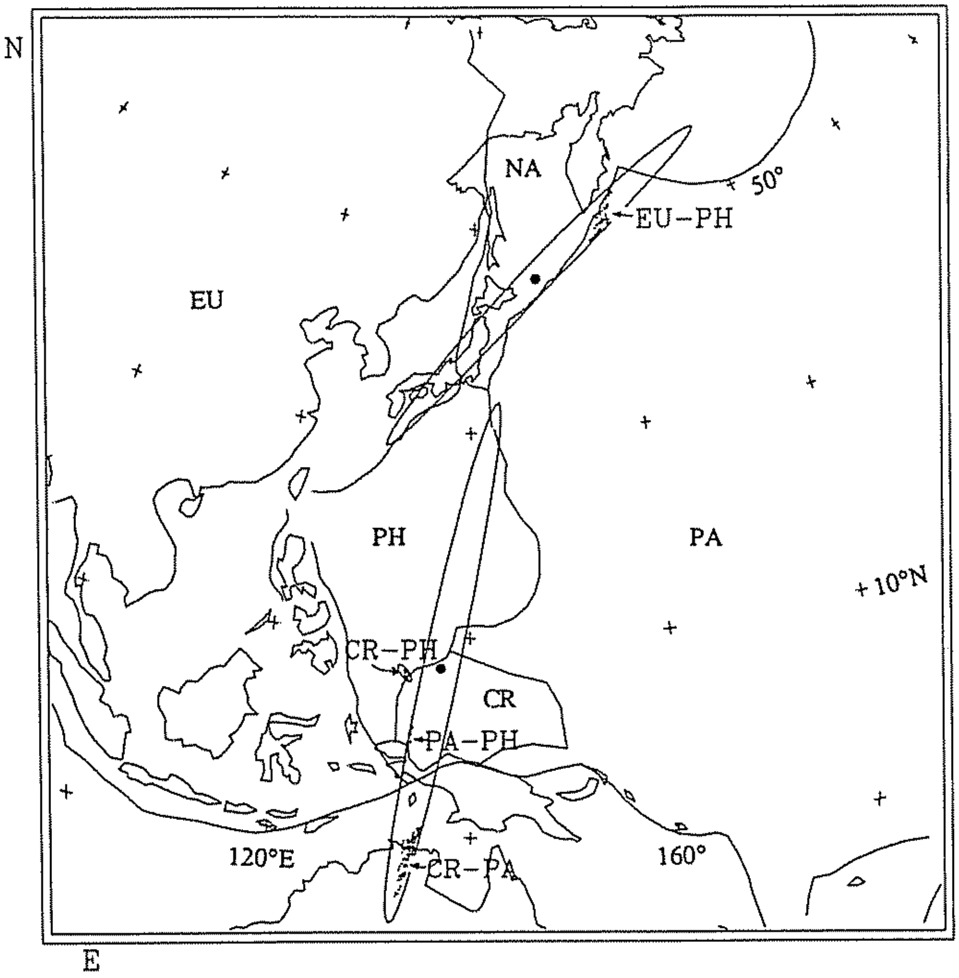

Fig. 3. The best fitting poles for PA-PH and EU-PH (solid circles) obtained using only the slip vectors for each plate pair, and their one sigma error ellipses, are shown. Rotation poles, adjusted within the ellipses, which satisfy slip vector data and PA-CR boundary conditions are shown by small dots.

DISCUSSION AND CONCLUSIONS

Our best EU-PH pole is located between those of *Seno* [1977] and *Minster and Jordan* [1979] but far from those of *Ranken et al.* [1984], *Chase* [1978], *Karig* [1975], and *Huchon* [1986], which are close to central Honshu. Predicted convergence rates along the Sagami-Nankai Trough are 30-50 mm/yr (Figure 5), slightly greater than those predicted for *Seno's* [1977] Euler vector but 25-32% less than those for *Minster and Jordan's* [1979]. In contrast, poles close to central Honshu predict much lower convergence rates in the Sagami Trough and in the northern part of the Nankai Trough. For example, predicted rates at 35°N, 139°E, at the northern Izu Peninsula between the Sagami and Nankai troughs, are 8 mm/yr and 15 mm/yr for the *Ranken et al.* [1984] and *Huchon* [1986] models, respectively. It is interesting to compare these to estimated seismic slip rates. The great 1923 Kanto earthquake ruptured the northernmost part of the Sagami Trough with a 6.7-m dislocation [*Ando*, 1971]. The previous earthquake which ruptured this segment of the trough was the 1703 Genroku earthquake, and the 220-year time interval gives a seismic slip rate of 30 mm/yr. In the Nankai Trough, the recent recurrence interval for great earthquakes with estimated slip in excess of 4-6 m is 100-150 year [*Ando*, 1975], indicating that the convergence rate is at least 27 mm/yr. Moreover, full convergence rate presumably exceeds the fraction observed seismically. Thus seismic slip rates are consistent with EU-PH and NA-PH vectors determined here, unlike rates suggested in some earlier studies.

A possible complication is that the Bonin forearc (BO) east of the Bonin extension zone (Figure 1) may move separately from the rest of the Philippine Sea plate due to backarc rifting. If so, material subducting beneath northern Honshu should be treated as a Bonin (BO) fragment, rather than the Philippine Sea plate. In this case, the best fitting pole from slip vectors along the Izu-Bonin arc (Figure 3) describes PA-BO motion instead of PA-PH motion. Similarly, the velocity diagram of Figure 4 would represent the Bonin forearc subducting beneath Honshu along the Sagami Trough, such that the BO-NA direction would be N20°-50°W. To examine this possibility, we considered PH to be BO in Figure 4 and compared it to various possible PH-NA motions. Predicted PH-NA motions of *Ranken et al.* [1984] and *Huchon* [1986] require a large NW motion of BO with respect to PH, rather than expected E-W extension. In contrast, the PH-NA motion we found permits slight extension between BO and PH due to the difference between the PA-PH pole and the best fitting PA-PH (in this case BO) pole in Figure 3. However, because the PA-PH pole is within the one sigma error ellipse of the best fitting pole, the apparent extension may not be significant. The velocity diagram implies that PA-BO slip vectors and NNW-NW convergence of the Bonin forearc beneath northern Honshu (Figure 4) require that BO moves with respect

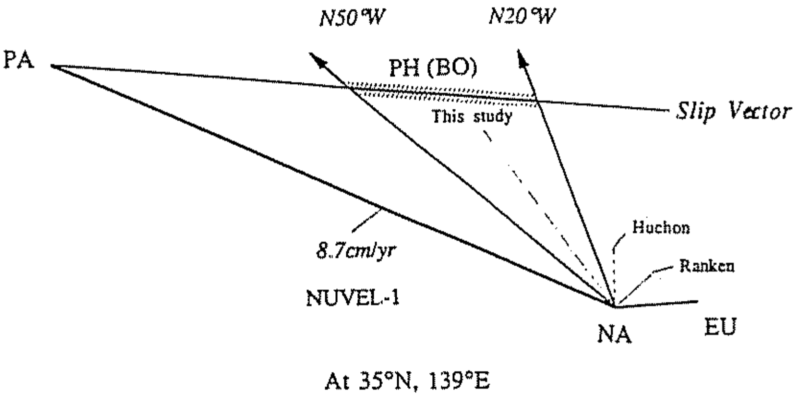

Fig. 4. Linear velocity diagram at the northern Sagami Trough (35°N, 139°E) where the Bonin forearc is subducting beneath northern Honshu. Assuming the NA(EU)-PA motion is given from NUVEL-1, the NNW-NW PH-NA(EU) convergence direction range (hatchured area) constrains the magnitude of the PA-PH rotation rate. If the Bonin forearc is decoupled from the Philippine Sea plate, the hachured area indicates the range of Bonin (BO) motion with respect to NA, EU, and PA. PH-NA motions predicted for this study (dashed line), *Huchon* [1986] (dotted line) and *Ranken et al.* [1984] (solid line) are also shown. Predicted motions by Ranken et al. and Huchon require a significant NW motion of BO with respect to PH.

to NA at a rate ≥ 40 mm/yr. Thus either little or no E-W extension between PH and BO implies that PH would move with at least a similar rate with respect to NA and thus to EU (note the small EU-NA velocity in Figure 4). This constraint precludes an EU-PH pole location close to central Honshu.

Ranken et al.'s procedure rejected poles far from central Honshu probably because they used a higher CR-PH rotation rate [*Weissel and Anderson*, 1978]. If, as discussed before, we use a lower rotation rate (0.6-0.7°/m.y.), which appears more appropriate for the Quaternary [*Weissel and Anderson*, 1978], the EU-PH pole need not be as close to central Honshu, as demonstrated by our solution. Furthermore, to be consistent with Bonin slip vectors, the EU-PH pole should be far from central Honshu. As mentioned earlier, the CR-PH rotation rate could be even smaller than the range considered here. Thus we experimented using a rate smaller than 0.6°/m.y. to obtain EU-PH and PA-PH Euler vectors by the same procedure and obtained EU-PH poles farther to the NE. Because for this smaller CR-PH rate, the EU-PH pole moves farther from the best fitting EU-PH pole, we prefer our solutions with the higher rate (0.6-0.7°/m.y.).

We experimented to see effects of assuming that northern Honshu is part of the North American plate. To do this, we assumed instead that northern Honshu is part of the Eurasian plate, used the NUVEL-1 EU-PA Euler vector, and obtained EU-PH and PA-PH Euler vectors similar to those in the present study. This is not surprising because the NA-EU relative velocity is small in south northern Honshu and we adjusted the NA-PH or EU-PH convergence direction in the Sagami Trough in a wide range (N20°W-N50°W). We then tried cases using the RM2 global plate motion model [*Minster and Jordan*, 1978] for the NA-PA and EU-PA Euler vectors, assuming northern Honshu to belong to either the North American or Eurasian plate. For these cases, we obtained EU-PH poles much closer to the best fitting EU-PH pole than in cases we used the NUVEL-1 Euler vectors. Moreover the upper limit of the allowable CR-PH rotation rate was raised to 0.8°/m.y. Thus use of NUVEL-1 is in part responsible for the EU-PH vector values in the present study.

TABLE 4. Rotation Vectors Which Satisfy Both the Slip Vector Data Around PH and the PA-CR Boundary Conditions.

Plate Pair	Pole		Rotation Rate, deg/m.y.
	°N	°E	
PA-PH	1.24	134.19	1.000
EU-PH	48.23	156.97	1.085
NA-PH	44.19	160.34	0.875
CR-PH	6.24	134.09	0.700
CR-PA	-10.13	134.43	0.309

Our best Euler vectors for motion of the Philippine Sea plate with respect to neighboring major plates satisfy both the CR-PA boundary constraints and, within the estimated errors, the slip vector data around PH. All prior models misfit the sense of relative motion along part of at least one plate boundary. Our model is a better compromise fit to all data around the Philippine Sea

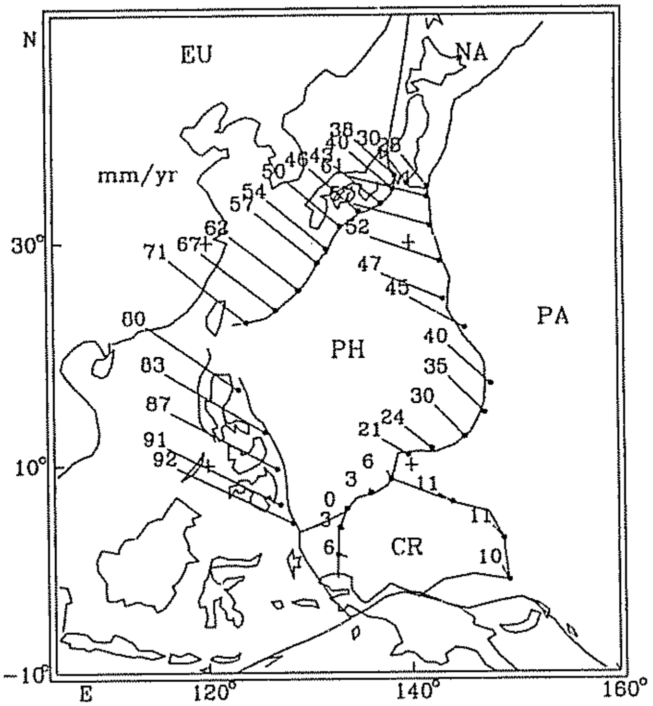

Fig. 5. Relative velocities around PH and CR. Azimuths are indicated by bars directed from circles, and rates shown are in milimeters per year. Along the EU-PH and NA-PH boundaries, PH motions with respect to EU or NA are shown; along the PA-PH and PA-CR boundaries, PA motions with respect to PH or CR are shown; and along the CR-PH boundary, CR motions with respect to PH are shown.

and Caroline plates. Estimates in this study could be improved by information on the rate and direction of backarc extension behind the Bonin and Ryukyu arcs and the spreading rate in the Ayu Trough. Moreover, direct estimates of some relative motions may be derivable from space geodesy [*Matsuzaka et al.*, 1991; *Hirahara et al.*, 1992; *Shimada and Bock*, 1992].

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T. Seno, Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan.

S. Stein and A. E. Gripp, Department of Geological Sciences, Northwestern University, Evanston, IL 60208.

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