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# The Amurian Plate motion and current plate kinematics in eastern Asia

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**Abstract.** We use Global Positioning System (GPS) velocity data to model eastern Asian plate kinematics. Out of 15 stations in Korea, Russia, China, and Japan studied here, three sites considered to be on the stable interior of the hypothetical Amurian Plate showed eastward velocities as fast as ~9–10 mm/yr with respect to the Eurasian Plate. They were stationary relative to each other to within 1 mm/yr, and these velocity vectors together with those of a few additional sites were used to accurately determine the instantaneous angular velocity (Euler) vector of the Amurian Plate. The predicted movement between the Amurian and the North American Plates is consistent with slip vectors along the eastern margin of the Japan Sea and Sakhalin, which reduces the necessity to postulate the existence of the Okhotsk Plate. The Euler vector of the Amurian Plate predicts left-lateral movement along its boundary with the south China block, consistent with neotectonic estimates of the displacement at the Qinling fault, possibly the southern boundary of the Amurian Plate. The Amurian Plate offers a platform for models of interseismic strain buildup in southwest Japan by the Philippine Sea Plate subduction at the Nankai Trough. Slip vectors along the Baikal rift, the boundary between the Amurian and the Eurasian Plates, are largely inconsistent with the GPS-based Euler vector, suggesting an intrinsic difficulty in using earthquake slip vectors in continental rift zones for such studies.

## 1. Introduction

The tectonics of eastern Asia is characterized by two major factors, subduction of oceanic plates such as the Pacific Plate (PA) and the Philippine Sea Plate (PH) and eastward expulsion of relatively small continental plates caused by the collision of India with Eurasia [*Molnar and Tapponnier*, 1975]. *Zonenshain and Savostin* [1981] first proposed the existence of one such plate, the Amurian Plate (AM), covering northeast China, the Korean peninsula, the Japan Sea, and the southeastern part of Russia, on the basis of regional tectonics and seismicity. In Japan it overrides PH along the Nankai Trough, subducts beneath the North American Plate (NA) or the Okhotsk Plate (OK), another plate suggested by *Zonenshain and Savostin* [1981], along the eastern margin of the Japan Sea [*Tamaki and Honza*, 1985], and possibly collides with the northeast Japan arc in the central part of Japan. Angular velocity (Euler) vectors of major plates worldwide have been determined with data obtained along their boundaries such as magnetic anomalies at mid-oceanic ridges, transform fault strikes, and interplate earthquake slip vectors [*Minster and Jordan*, 1978; *DeMets et al.*, 1990]. However, this method has not been effective for eastern Asian plates because their boundaries may be diffuse, and the relatively sparse seismicity has not yielded enough interplate earthquake slip direction data.

Euler vectors for plates with limited kinds of data (e.g., only slip directions) are often indirectly estimated relying on the closure of adjacent plate motion circuits [e.g., *Seno*, 1977]. In this way, *Seno et al.* [1996] concluded that the OK can be distinguished from NA (arguments by *Seno et al.* [1996] are based on the absence of AM, and *Wei and Seno* [1998] later proposed AM's existence). With a similar approach, *Wei and Seno* [1998] determined the Euler vector of AM using earthquake slip vectors along the Baikal rift, AM's northern margin with the Eurasian Plate (EU), and by reinterpreting the earthquakes in the eastern margin of the Japan Sea and the Nankai Trough, as AM-OK and AM-PH, respectively. They found an AM-EU Euler pole in southern Siberia with a small rotation rate that predicts eastward movement in Korea relative to EU as small as ~1 mm/yr. As suggested by *Seno and Wei* [1998], they rely primarily on slip direction data, and their solution is not strongly constrained.

Space geodetic techniques, such as very long baseline interferometry (VLBI), satellite laser ranging (SLR), Global Positioning System (GPS), and Doppler orbitography and radiopositioning integrated by satellite (DORIS) are starting to provide a new type of data, horizontal velocities of observing stations. Analysis of these data has demonstrated that movements of major plates over a geodetic time window (a few years) are consistent with those averaged over a few millions of years [*Heki*, 1996; *Sengoku*, 1998; *Larson et al.*, 1997; *Crétaux et al.*, 1998]. These data are useful especially for ill-posed

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cases of Euler vector determinations, e.g., the AM-EU case, because they provide velocities (i.e., both directions and rates) at necessary points on the plate in question. Other virtues are that they do not require exact knowledge of plate boundaries and that they can even let us draw the plate boundary when the points are densely distributed.

The Japanese nationwide GPS array GPS Earth Observation Network (GEONET) [*Tsuji et al.*, 1995; *Miyazaki et al.*, 1996, 1997], composed of nearly 1000 permanent GPS observing stations, is starting to reveal the interseismic crustal deformation field in the Japanese islands. However, an understanding of the plate tectonic setting outside Japan, including the possible existence and kinematics of AM and OK, is indispensable to proper interpretation of the results. As suggested by *Ishibashi* [1995], the majority of recent large earthquakes in Japan seem to have occurred along the eastern boundary of AM. Clarification of its kinematics is important to discuss recurrence of earthquakes along the eastern margin of the Japan Sea, as well as the distribution of the seismic coupling in the Nankai Trough.

In this article, at first we examine velocities of GPS points in eastern Asia to test for the AM's existence. If points in the region hypothesized as AM move relative to EU and do not move with respect to each other, we will estimate the AM's Euler vector and compare its relative velocity along the boundary with available geophysical data.

## 2. New GPS Sites and Data Analysis

We analyzed data from several GPS sites in eastern Asia with time spans longer than a year shown in Figure 1a. In Korea the National Geographical Institute has been operating a GPS station at Suwon (SUWN), ~50 km south of Seoul, since 1995. Another GPS station in Taejon (TAEJ), ~200 km south of Seoul, contributes to the International GPS Service for Geodynamics (IGS). In China we analyzed GPS data from three IGS points, Xi'an (XIAN), Shanghai (SHAO), and Wuhan (WUHN). In Russia, in addition to an IGS site in Irkutsk (IRKT) and a Western Pacific Integrated Network (WING) [*Kato et al.*, 1998a] GPS site in Vladivostok (VLAD), GPS data are obtained from receivers we deployed in Oxa (OXA) and Yuzhno Sakhalinsk (YUZH), Sakhalin. We also analyzed data from five GEONET stations in northern Kyushu (0087 and 0091) and the Chugoku

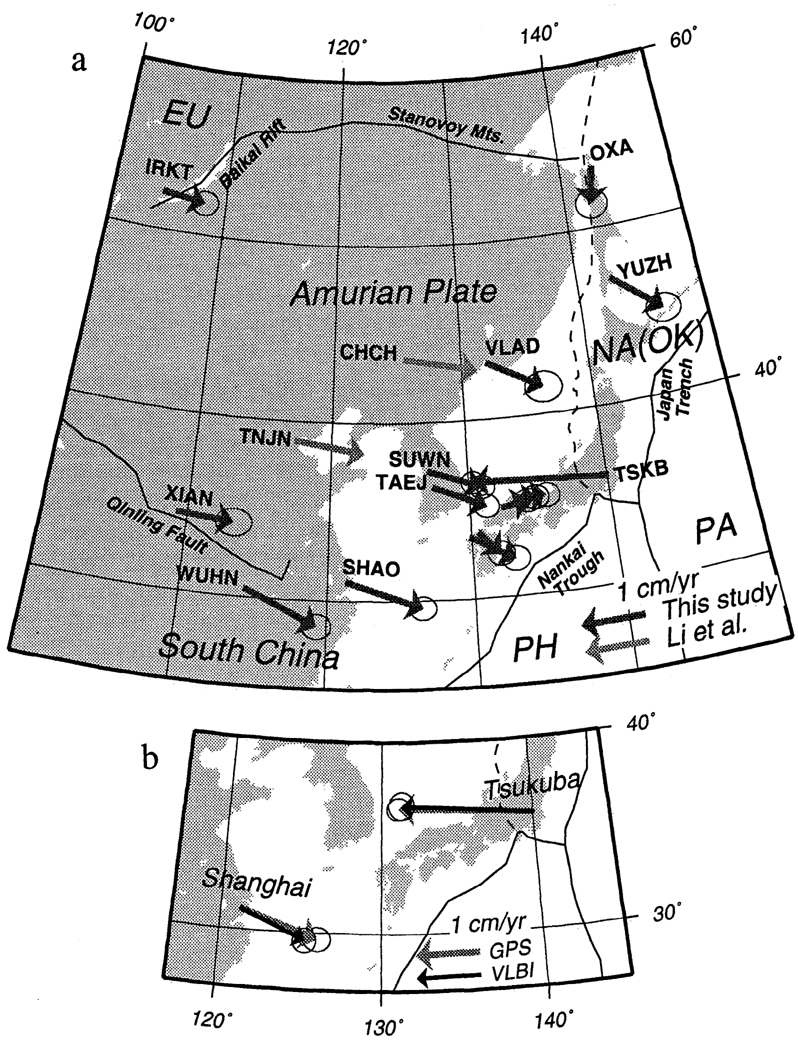


**Figure 1.** (a) Velocities of Global Positioning System (GPS) points with respect to EU and their 1σ error ellipses. Dark and light shaded arrows are those obtained by ourselves and by *Li et al.* [1998], respectively. The northern boundary of AM, after *Wei and Seno* [1998], is shown with a solid line. (b) The GPS velocities at Tsukuba, Japan, and Shanghai, China, are compared with those obtained by very long baseline interferometry (VLBI) [*Heki*, 1996]. Error ellipses also indicate 1σ uncertainties.

district (0073, 0074, and 0075), southwest Japan. Data from the Tsukuba (TSKB) IGS station in northeast Japan are also analyzed in order to compare its velocity with VLBI results.

Out of these stations, SUWN, TAEJ, and VLAD are considered to be on the stable interior of AM. IRKT, on the western flank of the Baikal rift, is just beyond AM's boundary with EU. SHAO and WUHN lie on the south China block (SC) being extruded eastward slightly faster than 1 cm per year with respect to EU [*Holt et al.*, 1995; *Peltzer and Saucier*, 1996], and XIAN lies just north of the Qinling fault, which is the eastward extension of the Altyn Tagh fault and bounds SC from the block north of it [*Peltzer et al.*, 1985]. Since the eastern margin of AM is ambiguous near Sakhalin, it is not clear at the moment whether OXA and YUZH are on AM or NA (OK). The five GEONET stations and TSKB are on AM and NA (OK), respectively, but their velocities are affected by elastic strain caused by the subduction of PH and PA.

GPS data were analyzed using the precise point positioning technique of the GIPSY/OASIS software [*Zumberge et al.*, 1997]. Figure 2 shows the time series of horizontal position of TAEJ, Korea. From these time series we estimated site velocities accurate to ~1–2 mm/yr or better (these original errors, obtained a posteriori from the dispersion of the data points around the best fit lines, are shown in parentheses in Table 1). GPS satellite orbits are based on International Terrestrial Reference Frame (ITRF), whose kinematic part is adjusted to match with the no-net-rotation (nnr)-NUVEL1a plate motion model [*Argus and Gordon*, 1991; *DeMets et al.*, 1994]. Site velocities obtained from such time series are converted to those relative to the stable part of EU by subtracting the absolute rotation of EU.

There are two factors that may make actual uncertainties of the estimated site velocities larger than those inferred by the simple linear regression. The first one is the systematic behavior of daily coordinate solutions other than linear changes. In fact, we can see patterns of various periods with amplitudes from a few millimeters to 1 cm around the best fit lines in Figure 2, possibly caused by, for example, atmospheric delay gradients [*MacMillan*, 1995] and other factors not properly modeled in the data analysis software. In estimating site velocities we assume that individual data are statistically independent, and so presence of such a correlation makes us underestimate the velocity uncertainties [*Mao et al.*, 1999]. The other factor comes from the inconsistency of the ITRF kinematic reference frame and the nnr-NUVEL1a plate motion model in eastern Asia. This arises because we did not use fixed references within the stable interior of EU but simply subtracted the EU rotation from the raw velocities of the GPS sites. To evaluate such additional errors, we compare our velocities with those derived using VLBI [*Heki*, 1996] at two of the sites, Shanghai, China, and Tsukuba, Japan (Figure 1b). The VLBI results are obtained very differently; that is, no satellite orbit information is used, time spans are much longer, and consistency with the plate motion model is performed in a global scale [*Heki,* 1996], and so the agreement of these two pairs of velocities would give an objective measure of such velocity uncertainties. We adopt 1.1 mm/yr, the root-mean-square value of the differences in the horizontal components of the two velocity pairs, as the error to be added to the original velocity uncertainties. The errors made more realistic by adding this error are given without parentheses in Table 1 and are used to estimate Euler vectors.

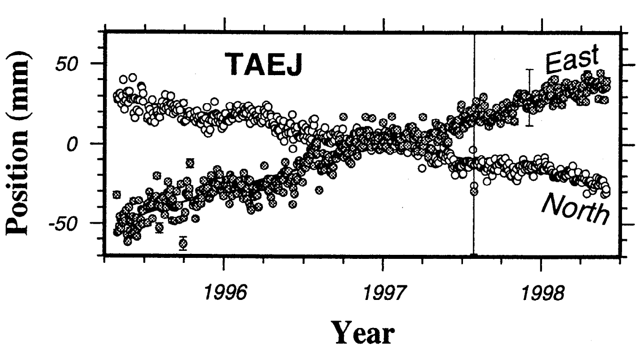


**Figure 2.** Daily horizontal positions of Taejon, Korea, ~1995–1998 with 1σ error bars. Solid lines are the best fit lines for the temporal changes of the east and north components. The variations of the coordinates are based on the kinematic part of the International Terrestrial Reference Frame (ITRF).

Figure 1a includes velocity vectors of two GPS stations on AM, Changchun (CHCH) and Tianjin (TNJN). They are reported by *Li et al.* [1998] without information on velocity uncertainties, but their observing time spans longer than 1 year suggest that they can be used as supplementary data in the parts of AM not covered by our points.

## 3. Estimation of the AM Euler Vector

Three points on the stable part of AM, namely, SUWN, TAEJ, and VLAD, are found to move by ~9–10 mm/yr toward E-ESE (Figure 1a). Such velocities are faster than those predicted by *Wei and Seno* [1998] by an order of magnitude and deflected clockwise considerably from the predictions. These three points do not have appreciable movements relative to each other and are treated here as the core stations in estimating the Euler vector of AM. Their spatial coverage is, however, not large enough to resolve accurately the pole position and the rotation rate. Hence we add two more points, YUZH and XIAN, that do not move with respect to the core sites (i.e., we rely primarily on GPS results to discern points within AM). XIAN is in the Weihe graben at the southern tip of the Ordos block, and the absence of conspicuous faults dividing this block from AM [see *Peltzer and Saucier*, 1996, Figure 2] suggests that the block moves similarly to AM. XIAN is only a few tens of kilometers north of the Qinling fault, the northern boundary of SC [*Zhang et al.*, 1995]. However, if the locking depth of the fault is not much larger than 10-15 km, the buildup of elastic strain between the blocks would affect the velocity at XIAN less than 1 mm/yr. YUZH is east of the presumed AM–NA (OK) boundary in Figure 1a, but geological and seismological records are not decisive enough to draw a clear boundary there. Here we assume that the five sites, SUWN, TAEJ, VLAD, XIAN, and YUZH, are within AM and use them for the inversion.

The southward velocity component of these sites increases to the east, implying a moderate clockwise rotation of AM, opposite to the counterclockwise sense suggested by *Zonenshain and Savostin* [1981] and *Wei and Seno* [1998]. Horizontal site velocities are the vector cross products of the Euler vector and the GPS point position vectors, and three components of the Euler vector can be estimated by the linear least squares inversion [see, e.g., *Heki,* 1996]. Here we used the five velocities and their observational errors (Figure 3a). The pole position was well constrained (Figure 3b), with the weighted root-mean-square (WRMS) of the postfit velocity residuals as small as 0.39 mm/yr. Sites CHCH and TNJN, which are not used in the inversion, seem to move consistently with the estimated movement of AM. IRKT on the EU side of the

**Table 1.** Velocities of Space Geodetic Stations With Respect to the Eurasian Plate

| Station | | | Period | | Velocity, mm/yr | | Error,[a] mm/yr | | |
|---|---|---|---|---|---|---|---|---|---|
| Name | Latitude, °N | Longitude, °E | From | To | North | East | North | East | Plate |
| *GPS Points Analyzed in This Study* | | | | | | | | | |
| SUWN | 37.3 | 127.1 | April 30, 1995 | June 9, 1998 | −2.7 | 8.4 | 1.2 (0.4) | 1.3 (0.7) | AM |
| TAEJ | 36.4 | 127.4 | April 30, 1995 | June 9, 1998 | −3.2 | 8.4 | 1.2 (0.4) | 1.3 (0.6) | AM |
| VLAD | 43.2 | 131.9 | Feb. 9, 1996 | Oct. 2, 1997 | −4.4 | 8.7 | 1.6 (1.1) | 1.9 (1.6) | AM |
| XIAN | 34.4 | 109.2 | July 11, 1996 | April 21, 1998 | −0.5 | 9.1 | 1.4 (0.9) | 1.9 (1.5) | unknown |
| YUZH | 47.0 | 142.7 | July 28, 1995 | July 30, 1997 | −6.0 | 7.4 | 1.4 (0.9) | 1.8 (1.4) | unknown |
| GEONET 0073 | 35.5 | 133.7 | July 17, 1995 | June 9, 1998 | 0.0 | 4.0 | 1.2 (0.5) | 1.4 (0.8) | AM[b] |
| GEONET 0074 | 35.4 | 133.1 | July 17, 1995 | June 9, 1998 | 0.0 | 3.6 | 1.2 (0.5) | 1.4 (0.8) | AM[b] |
| GEONET 0075 | 35.0 | 132.2 | July 17, 1995 | June 9, 1998 | 0.8 | 4.3 | 1.2 (0.5) | 1.4 (0.8) | AM[b] |
| GEONET 0087 | 33.7 | 130.5 | July 17, 1995 | June 9, 1998 | −3.5 | 3.4 | 1.2 (0.5) | 1.4 (0.9) | AM[b] |
| GEONET 0091 | 33.5 | 129.9 | July 17, 1995 | June 9, 1998 | −3.6 | 7.1 | 1.3 (0.6) | 1.5 (1.0) | AM[b] |
| IRKT | 52.2 | 104.3 | Oct. 3, 1995 | June 9, 1998 | −0.8 | 6.8 | 1.3 (0.6) | 1.4 (0.8) | EU[b] |
| OXA | 53.6 | 142.9 | July 25, 1995 | Aug. 15, 1997 | −5.6 | −1.0 | 1.5 (1.0) | 1.6 (1.2) | unknown |
| SHAO | 31.1 | 121.2 | April 30, 1995 | June 9, 1998 | −3.9 | 12.3 | 1.2 (0.4) | 1.4 (0.8) | SC |
| TSKB | 36.1 | 140.1 | April 30, 1995 | June 9, 1998 | 2.2 | −21.0 | 1.1 (0.3) | 1.2 (0.5) | NA (OK)[b] |
| WUHN | 30.5 | 114.4 | Jan. 25, 1996 | June 9, 1998 | −5.2 | 11.8 | 1.2 (0.5) | 1.5 (1.0) | SC |
| *Supplementary GPS Data* | | | | | | | | | |
| TNJN[c] | 38.9 | 117.3 | | | −1.7 | 10.9 | ...[d] | ...[d] | AM |
| CHCH[c] | 43.6 | 125.4 | | | −1.9 | 11.4 | ...[d] | ...[d] | AM |
| Taipei[e] | 25.0 | 121.5 | July 1995[f] | Oct. 1996[f] | −5.2 | 17.1 | 0.9 | 1.4 | SC |
| *VLBI Data From Heki [1996]* | | | | | | | | | |
| Seshan25 | 30.9 | 121.2 | April 10, 1988 | Aug. 12, 1992 | −4.2 | 10.3 | 1.2 | 1.2 | SC |
| Tsukuba | 35.9 | 140.1 | July 19, 1984 | Aug. 1, 1991 | 2.7 | −21 | 1.4 | 1.3 | NA (OK)[b] |

Abbreviations are AM, the Amurian Plate; EU, the Eurasian Plate; OK, the Okhotsk Plate; NA, the North American Plate; SC, the south China block; VLBI, very long baseline interferometry; GPS, Global Positioning System.

[a] Values in parentheses for GPS points analyzed by us denote raw errors obtained by linear regression.

[b] Velocity possibly affected by neighboring plates.

[c] Data from *Li et al.* [1998].

[d] Errors not available.

[e] Data from *Kato et al.* [1998a].

[f] Exact dates not available.

Baikal rift, one of the best constrained parts of the AM boundary, moves in the same direction as AM with a somewhat smaller rate (6.8 mm/yr). Since seismicity is relatively low and no major active faults are known in the northwestern flank of the Baikal rift [see, e.g., *Calais et al.*, 1998, Figure 1], most of the IRKT motion would be due to of the extensional elastic straining near a divergent plate boundary between rifting episodes [*Heki et al.*, 1993].

The AM-EU Euler vectors we obtained are summarized in Table 2. Reflecting the moderate clockwise rotation, the poles were estimated far to the south of the Amurian Plate in contrast to those in northern Siberia reported in earlier studies [*Zonenshain and Savostin*, 1981; *Wei and Seno,* 1998]. The obtained AM-EU Euler vector was combined with the EU-NA Euler vector of NUVEL1a [*DeMets et al.*, 1994] to calculate the AM-NA Euler vector of (77.9°S, 16.2°E, 0.226 deg/Myr). In order to derive the AM-PH Euler vector, it is inappropriate to use the EU-PH Euler vector of *Seno et al.* [1993], by whom earthquakes at the Nankai Trough were treated as those of EU-PH. Hence we use the one reported recently by *Kotake et al.* [1998], who derived the EU-PH Euler vector directly using relative velocities of GPS points and the velocity of Tsukuba with respect to the stable part of EU obtained by VLBI [*Heki,* 1996]. We thus obtained the AM-PH Euler vector of (44.0°S, 24.3°W, 1.482 deg/Myr).

## 4. Discussion

### 4.1. Relative Movements With the South China Block

The region north of the E-W trending Qinling fault has been vaguely referred to as the north China block [e.g., *Zhang et al.*, 1995]. The XIAN velocity obtained in this study as well as the distribution of active faults suggests that AM extends as far south as the Qinling fault, although velocities at more points are needed to rule out the possibility that the velocity field is complicated there and that the XIAN velocity coincided with the AM velocity by chance. Preliminary results of the north China GPS network of ~90 sites by *Zhao et al.* [1997] shows crustal deformation of not more than a couple of millimeters per year over a broad area covering from Ordos to the Yellow Sea coast. Hence AM seems to extend as far south as the Qinling fault, as far as current crustal movements are concerned.

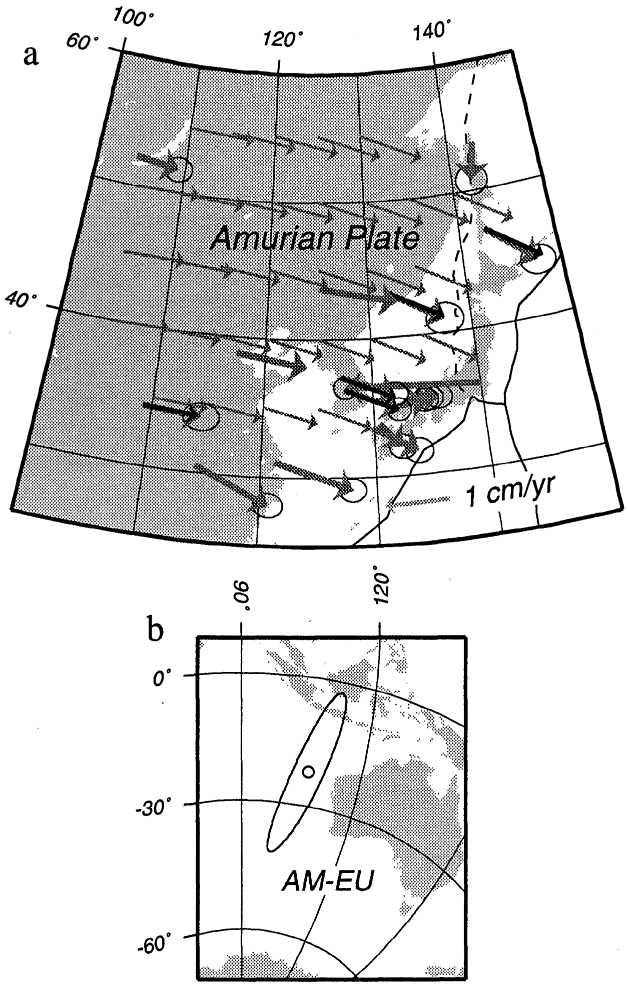


**Figure 3.** (a) Among the GPS velocities shown as thick shaded arrows, those used to estimate the AM-EU Euler vector are plotted together with thin solid arrows, which are the velocities predicted by the estimated AM-EU Euler vector. Five horizontal velocities at SUWN, TAEJ, VLAD, XIAN, and YUZH are used for inversion. Thin shaded arrows show velocities predicted by the estimated AM-EU Euler vector at grid points considered to be on AM. (b) Estimated position of the Euler pole and its 1σ error ellipse.

The observed velocities of SHAO and WUHN, on the south China (SC) block, relative to EU are very similar to the velocity field solution 3 of *Holt et al.* [1995] derived using earthquake strain rates within central and eastern Asia. These two stations hardly move relative to one another, and we estimated the SC-EU Euler vector using these two vectors (Table 2). Figure 4 shows the Euler pole positions and predicted velocities (with respect to EU) of points on SC along with the AM movement derived in this study. The velocity of Taipei after *Kato et al.* [1998a], which is not used in the inversion, is found to be fairly consistent with the obtained SC movement. SC is predicted to rotate counterclockwise about Euler pole north of Sakhalin, resulting in 11.5 mm/yr eastward movement and 6.0 mm/yr southward movement south of the Qinling fault near XIAN. This eastward movement is faster than the 8.4 mm/year that the AM-EU Euler vector predicts north of the fault, consistent with the left-lateral strike-slip movement of the E-W trending Qinling fault [*Peltzer et al.*, 1985], although the rate is somewhat smaller than the time-averaged rate of 7.2 ± 2.2 mm/yr suggested by the offsets of entrenched rivers across the Qinling fault near Xi'an [*Zhang et al.,* 1995]. Significant southward movement of SC relative to AM near Xi'an is also consistent with the NW-SE crustal extension at a graben near Xi'an, although the rate is larger than 2.0 ± 2.5 mm/yr toward N140°E estimated from seismic profiles by *Zhang et al.* [1995].

### 4.2. Baikal Rift and Stanovoy Mountains

The location of and relative motion on the AM–EU boundary are best constrained along the Baikal rift and in the Stanovoy mountains. Our estimated AM-EU Euler vector suggests almost E-W divergence along the Baikal rift and left-lateral strike-slip movement along the boundary east of it (Figure 5). The slip vectors of 13 EU–AM earthquakes along this boundary listed by *Wei and Seno* [1998] show a bimodal distribution; four of them trend nearly E-W, and the rest trend NW-SE (Figure 6a). The predicted AM-EU relative motion directions are consistent only with the former group. The AM-EU Euler pole by *Wei and Seno* [1998] is placed to explain these slip vectors and hence better explains these data than ours.

In Figure 6a are plotted 10 GPS point velocities obtained by campaign-based GPS observations around Lake Baikal over 4 years by *Calais et al.* [1998] (originally, they fixed Irkutsk, but we added the IRKT velocity and its error in Table 1 to make them relative to EU). The directions of the velocity vectors are more consistent with the AM-EU Euler vector obtained here than with the earthquake slip vectors. The inconsistency is therefore not due to the detachment of the Baikal region from AM, but would imply an inherent problem in using slip direction data in continental rift zone for Euler pole determinations. Recent comparison along the East African Rift between slip vectors and the Somali Plate velocity derived by space geodesy suggested that slip directions are controlled more by the rift geometry (i.e., slip vectors tend to be normal to the rift axis) than the plate motion [*Chen et al.*, 1998]. They speculated that such an inconsistency can be explained by the idea that when rock has preexisting faults, slip on these faults is favored over the formation of a new fracture. Moreover, the Euler vector of *Wei and Seno* [1998] mispredicts the velocities of the three core GPS stations on AM reported here; they are different in azimuths by ~30°–45° and by an order of magnitude in lengths (Figure 6b).

*Calais et al.* [1998] suggested that the crustal extension rate of the Baikal rift zone is 4.5±1.2 mm/yr in a WNW-ESE

**Table 2.** Euler Pole Positions and Rotation Rates Estimated Using GPS Data

| Plate Pair | Pole | | Angular Rate, deg/Myr | | Error Ellipse, deg | | | GPS Points Used for Inversion |
|---|---|---|---|---|---|---|---|---|
| | Latitude | Longitude | $\omega$ | $\sigma_\omega$ | $\sigma_{max}$ | $\sigma_{min}$ | $\zeta_{max}$ | |
| AM-EU | 22.3° S | 106.6° E | –0.091 | 0.016 | 20.5 | 3.5 | 19.3 | SUWN, TAEJ, VLAD, XIAN, and YUZH |
| SC-EU | 61.2° N | 142.0° E | 0.206 | 0.123 | 23.3 | 2.2 | 38.7 | WUHN and SHAO |

Parameter $\zeta_{max}$ is the azimuth of the maximum axis measured clockwise from the north.

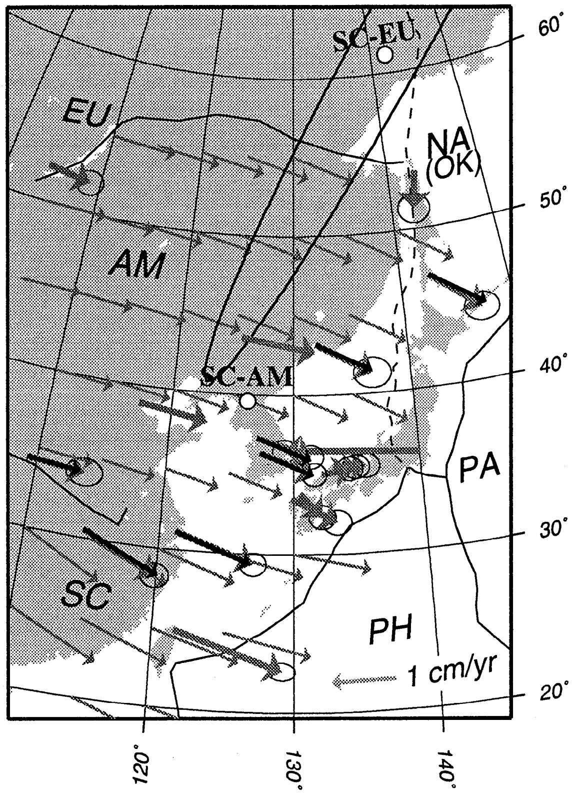


**Figure 4.** Predicted motions of AM (Figure 3a) and of SC estimated using the velocities of SHAO and WUHN. Thin shaded arrows show predicted velocities at grid points. Solid arrows show predicted velocities at GPS points whose velocities are used for the inversions. SC-EU (with 1σ error ellipse) and SC-AM Euler pole positions are shown with white circles. Velocity vector of Taipei is taken from *Kato et al.* [1998a].

direction from a local GPS network. Our results suggested that Irkutsk, their fixed reference, is not fixed to EU (i.e., crustal extension occurs NW of Irkutsk, too), and our EU-AM Euler vector suggests a "macroscopic" estimate of the extension rate, between points well separated from the rift, of ~1 cm/yr. The time-averaged extension rate in the Baikal rift zone over the last 30 Myr is considered to be slower than 1 mm/yr [*Zorin and Cordell,* 1991], and the current faster extension rate implies that AM accelerated sometime possibly in the last few Myr. One puzzling fact is that although IRKT is on the EU side of the rift, IRKT moves relative to EU at slightly faster than one half of the AM-EU divergence rate at the rift. If this excess eastward movement was significant (the excess component is <2σ), there might be some amount of extension distributed in a broad zone northwest of the rift. The present density of permanent GPS points in northern Asia, however, does not allow us to draw any conclusion on this issue.

### 4.3. Eastern Margin of the Japan Sea and Sakhalin

The present study implied that YUZH's motion is consistent with its being on AM, suggesting that the AM–NA (OK) boundary lies somewhere east of it. Movements similar to YUZH are also found in the GEONET velocity field in northernmost Hokkaido, where the eastward components gradually decrease toward the south [*Tada et al.*, 1997; *Kato et al.*, 1998b]. This fact also suggests that the AM–NA (OK) boundary is farther to the east than depicted in Figure 1a. On the other hand, OXA moves differently from AM (Figure 7a), and AM–NA (OK) boundary seems to lie west of it in the northernmost Sakhalin. The detailed velocity field over the whole island will be clarified by the future deployment of several more GPS receivers in Sakhalin.

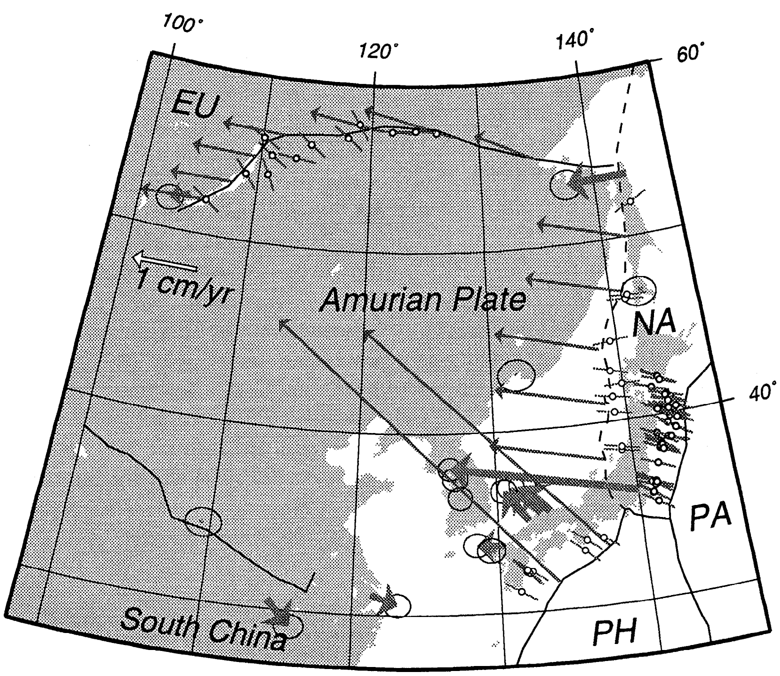


**Figure 5.** Movements of EU, NA (this part could be OK but the AM-NA Euler pole was used to calculate the relative movements in Figure 5), and PH relative to AM along its boundary are shown as thin shaded arrows. Thick arrows with 1σ error ellipses are the velocities of GPS points as viewed from AM. White circles with bars show interplate earthquake slip vector directions along these boundaries. Slip vectors in the Japan Trench (between PA and either NA or OK) are also shown here. Slip direction data and their uncertainties are after *Seno et al.* [1993, 1996] and *Wei and Seno* [1998].

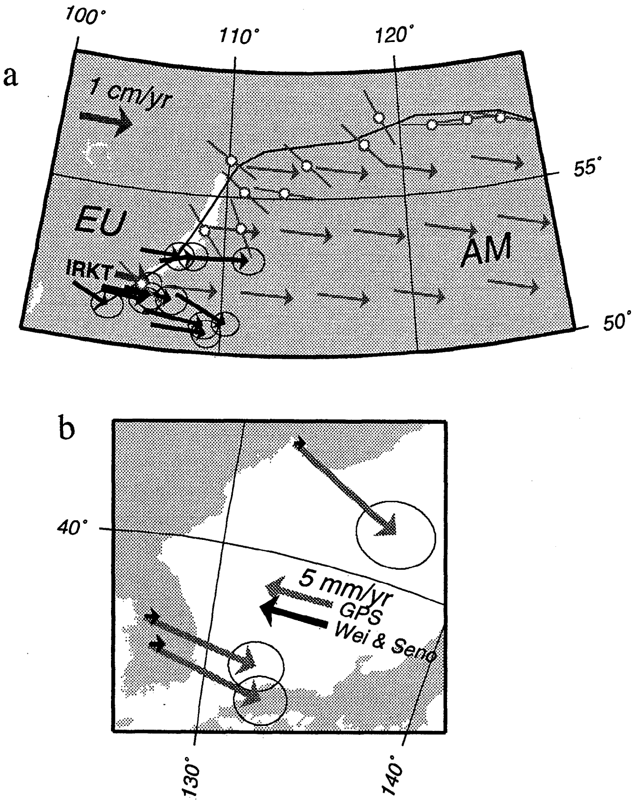


**Figure 6.** (a) Slip directions of interplate earthquakes (white circles with bars, data after *Wei and Seno* [1998]) along the AM-EU boundary of the Baikal rift and the velocities of grid points in AM predicted by our Euler pole (dark shaded arrows). Velocities (relative to EU) of GPS points in a local network by *Calais et al.* [1998] are shown with solid arrows (with 1σ error ellipses) along with the IRKT velocity (a thick shaded arrow). (b) GPS velocities at the three core sites (TAEJ, SUWN, and VLAD) compared with those predicted by the AM-EU Euler vector of *Wei and Seno* [1998]. This map is drawn with the Mercator projection pole at their AM-EU Euler pole so that the predicted velocities lie parallel with the frame.

*DeMets* [1992] suggested that NA extends south to 41°N from analysis of slip vectors in the Japan and Kuril Trenches. *Seno et al.* [1996] also confirmed that these slip vectors can be explained equally well with the NUVEL1 NA-PA Euler vector and with their own OK-PA Euler vector. *Seno et al.* [1996], however, found that slip vectors along the eastern margin of the Japan Sea and Sakhalin are not compatible with the NUVEL1 NA-EU Euler vector, and OK needs to exist to account for this deviation (AM was not assumed to exist there). In Figures 7b we compare slip directions of earthquakes along this zone (data from *Seno et al.* [1996]) with those calculated using various Euler vectors. There our AM-NA Euler vector offers a fit slightly worse than the EU-OK pole of *Seno et al.* [1996] but much better than the NUVEL1 NA-PA Euler pole (an *F* test shows that the improvement of the fit by adopting the pole of *Seno et al.* [1996] instead of our AM-NA pole is significant at the 95% confidence level). The introduction of AM reduces the slip vector discrepancy in the eastern margin of the Japan Sea, which is one of the strongest reasons to postulate OK's existence.

The diffuse seismic belt in the Cherskiy mountains, Siberia, suggested as the OK's northern margin, can never be explained by AM, and our study does not rule out the possibility of a slow movement of OK. For example, *Riegel et al.* [1993] advocated that its southward extrusion is caused by the converging motion between NA and EU, and, in fact, addition of ~2–3 mm/yr right-lateral movement in the eastern margin of the Japan Sea would deflect the convergence directions up to 10° counterclockwise, resulting in a better fit with the earthquake data. However, the slip vectors are less sensitive to trench-normal velocities added by incorporating OK, so the overall movement of OK there still remains unclear. Data in the Kuril Trench do not strongly constrain the movement of OK either, because faster plate

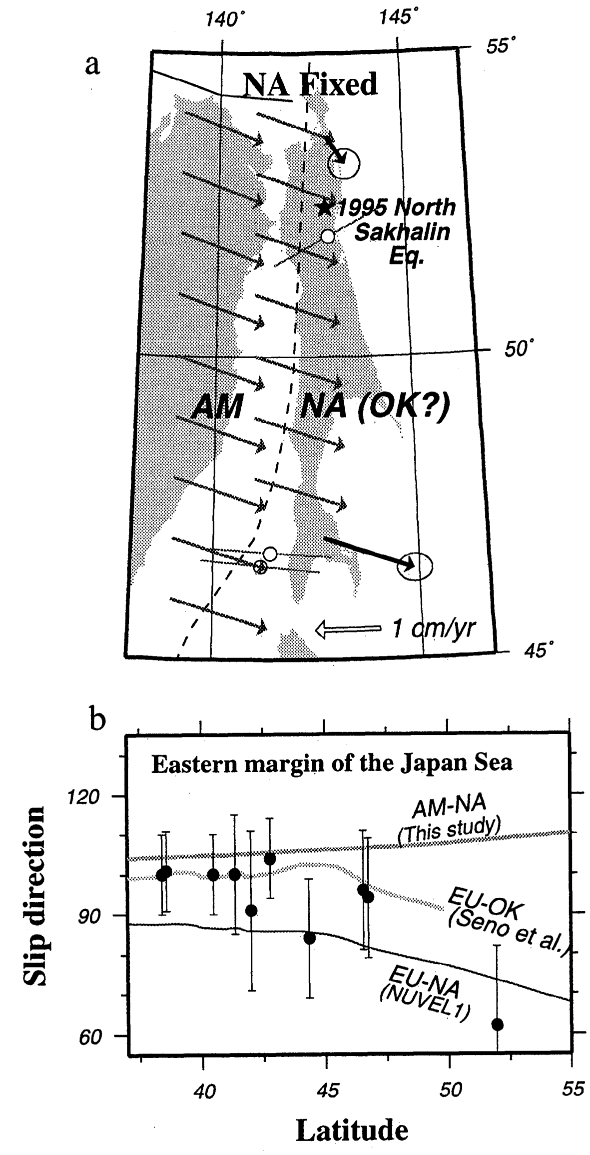


**Figure 7.** (a) Velocities of grid points in AM with respect to NA, calculated on the basis of the AM-NA Euler vector, are shown as thin shaded arrows. The AM–NA (OK) boundary shown as a dashed line is tentative and should be revised on the basis of future GPS survey results in Sakhalin. Velocities at OXA and YUZH are plotted as those relative to NA. The star shows the epicenter of the 1995 north Sakhalin earthquake. Three slip direction data are also shown. (b) The slip direction data along the eastern margin of the Japan Sea and Sakhalin are compared with those predicted by the Euler poles of AM-NA (this study, dark shaded line), EU-OK (*Seno et al.* [1996], light shaded line), and EU-NA (NUVEL1, thin solid line). Slip direction data and their uncertainties are all after *Seno et al.* [1996].

convergence there makes the slip vectors less sensitive to its trench-parallel movement. Figure 7a shows that OXA moves southeastward by ~5 mm/yr with respect to NA. The east component could be explained by the NA's interaction with AM, but its south component may not be accounted for without assuming the OK's existence and its extrusion toward the Pacific Ocean. However, it is possible that transient crustal movements following the May 28, 1995, Sakhalin earthquake ($M_w$ = 7.0, Figure 7a), detected by interferometric synthetic aperture radar (InSAR) [*S.Ozawa et al.*, 1999], affected estimates of the secular movement of this GPS site (although there is no appreciable nonlinear behavior in its movement). It is therefore premature to draw a decisive conclusion on this issue at this stage. A reliable determination of the OK Euler vector will probably come from GPS observations in Kamchatka that started a few years ago [*Takahashi et al.*, 1997].

The present study predicts that the convergence rate along the eastern margin of the Japan Sea (if assumed to be AM-NA) is ~16–18 mm/yr, which is faster and more uniform (both in rate and direction) along the margin than suggested by *Wei and Seno* [1998]. Several large earthquakes with slips as large as 3 m, e.g., the July 12, 1993, Hokkaido-Nansei-Oki earthquake ($M_W$=7.6) [*Kuge et al.*, 1996], have recently occurred there. If this is the characteristic size of the interplate earthquakes, they might recur every 200 years. Historic seismic activity studies, however, suggest that this is not the case [*Seno et al.*, 1996]. One explanation is the existence and the eastward retreat of OK that reduces the convergence rate along that boundary. Another explanation is that the seismic coupling coefficient there is significantly less than unity, like other subduction zones [*Pacheco et al.*, 1993], which makes the recurrence interval longer or visible earthquakes smaller [*Heki et al.*, 1997; *Heki and Tamura*, 1997].

### 4.4. Nankai Trough

Figure 5 shows that the earthquake slip vectors along the Nankai Trough are consistent with those predicted by the AM-PH Euler vector derived here. The Euler vectors of PH derived by *Seno* [1977] and *Seno et al.* [1993] have long been used as standards, but both of these studies did not postulate the existence of AM and treated the slip vector data along the Nankai Trough as those of PH-EU. Philosophically, we need to revise the PH Euler vector, taking account of the AM movement, but such a revision would be fairly minor because AM's eastward movement of ~1 cm/yr at the Nankai Trough deflects the vector counterclockwise by only ~2°, much smaller than typical errors of slip direction data. Anyway, in the future, GPS-based Euler vectors will be used to study the subduction of PH beneath the southwest Japan arc.

*Tabei et al.* [1996] first detected northwestward displacements of the GPS points in the outer arc of the southwest Japan arc, which are interpreted as the interseismic elastic straining of the arc crust due to the subduction of PH. With a more detailed velocity field in southwest Japan made available by GEONET, investigators are starting to model the "backslip" (interplate coupling) in the plate interface [e.g., *Sagiya,* 1998; *T.Ozawa et al.*, 1999; *S. Mazzotti et al.*, Full interseismic locking of the Nankai and Japan West Kuril subduction zones: An analysis of uniform elastic strain accumulation in Japan constrained by permanent GPS, submitted to *Journal of Geophysical Research*, 1999]. However, lack of knowledge of the kinematics of the landward plate (AM in this case) hindered proper treatment of such velocities; investigators have been either fixing an arbitrary site within the arc or using only the relative movements within the arc, leaving behind the eastward movement of the inner arc as a mystery. The five GEONET stations in Figure 5 move northwestward relative to AM, suggesting that the same kind of displacement as in the outer arc prevails also in the inner arc. Hereby we propose that AM should be fixed as a reference when interpreting the interseismic velocity field of southwest Japan in terms of the AM-PH plate convergence.

## 5. Conclusions

In the present study we conclude that, (1) The existence of the Amurian Plate has been confirmed using GPS velocity data. (2) The Euler vector of the Amurian Plate has been estimated on the basis of a posteriori plate boundaries. It is fairly different from earlier studies. (3) The resulting Euler vector predicts the Amurian Plate movement consistent with geophysical and geological observations of relative plate movements along its boundary, with the exception of slip vector data in the Baikal rift. The existence of the Okhotsk Plate needs to be examined again in light of the presence of the Amurian Plate. (4) Determination of the Amurian Plate parameters has paved the way for interseismic crustal deformation studies in southwest Japan.

Space geodetic observations have potential of revealing kinematics of tectonic plates or crustal blocks even when conventional nongeodetic approaches are not successful. In spite of difficulties in deploying GPS receivers in some of the regions, stemming from political and accessibility problems, endeavors of researchers are reducing the numbers of geophysically interesting regions without GPS measurements. We will soon be able to fully discuss the plate tectonics of eastern Asia, a region whose plate kinematics are poorly understood.

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