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An updated digital model of plate boundaries

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[1] A global set of present plate boundaries on the Earth is presented in digital form. Most come from sources in the literature. A few boundaries are newly interpreted from topography, volcanism, and/or seismicity, taking into account relative plate velocities from magnetic anomalies, moment tensor solutions, and/or geodesy. In addition to the 14 large plates whose motion was described by the NUVEL-1A poles (Africa, Antarctica, Arabia, Australia, Caribbean, Cocos, Eurasia, India, Juan de Fuca, Nazca, North America, Pacific, Philippine Sea, South America), model PB2002 includes 38 small plates (Okhotsk, Amur, Yangtze, Okinawa, Sunda, Burma, Molucca Sea, Banda Sea, Timor, Birds Head, Maoke, Caroline, Mariana, North Bismarck, Manus, South Bismarck, Solomon Sea, Woodlark, New Hebrides, Conway Reef, Balmoral Reef, Futuna, Niuafo'ou, Tonga, Kermadec, Rivera, Galapagos, Easter, Juan Fernandez, Panama, North Andes, Altiplano, Shetland, Scotia, Sandwich, Aegean Sea, Anatolia, Somalia), for a total of 52 plates. No attempt is made to divide the Alps-Persia-Tibet mountain belt, the Philippine Islands, the Peruvian Andes, the Sierras Pampeanas, or the California-Nevada zone of dextral transtension into plates; instead, they are designated as "orogens" in which this plate model is not expected to be accurate. The cumulative-number/area distribution for this model follows a power law for plates with areas between 0.002 and 1 steradian. Departure from this scaling at the small-plate end suggests that future work is very likely to define more very small plates within the orogens. The model is presented in four digital files: a set of plate boundary segments; a set of plate outlines; a set of outlines of the orogens; and a table of characteristics of each digitization step along plate boundaries, including estimated relative velocity vector and classification into one of 7 types (continental convergence zone, continental transform fault, continental rift, oceanic spreading ridge, oceanic transform fault, oceanic convergent boundary, subduction zone). Total length, mean velocity, and total rate of area production/destruction are computed for each class; the global rate of area production and destruction is 0.108 m^2/s, which is higher than in previous models because of the incorporation of back-arc spreading.

Components: 28,925 words, 19 figures, 3 tables, 4 datasets.

Keywords: Plate tectonics; Euler pole.

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1. Definitions of Plates and Orogens

[2] An idealized plate of lithosphere is a region which rotates (with respect to some other specified plate) without internal deformation about an imaginary axis through the center of the planet [*Morgan*, 1968]. This axis intersects the surface of the idealized spherical planet at two points known as Euler poles. One variant of this definition describes plates as features of the neotectonic velocity field (on timescales of 10^0 to 10^6 years), in which case the rotation may be described by an Euler vector from the center of the planet toward the Euler pole, with magnitude measured in degrees per million years (or other rotation-rate units). A second variant describes plates as features in a finite-displacement field (on timescales of 10^6 to 10^9 years) in which case the rotation is described by an Euler vector with magnitude in degrees or radians. This paper concerns neotectonics, and begins from the former definition.

[3] On the real Earth, it is understood that any plate model is only an approximation. First, elastic strain accumulation around temporarily-locked faults is always discounted, although it may not always be clear in practice which strain rates are elastic and which are anelastic. Second, it has been conventional to overlook small amounts of anelastic deformation within one "plate" provided that (1) the "plate" is surrounded by boundary zones in which anelastic strain rates are an order of magnitude higher than they are in the interior; and (2) the velocity anomalies with respect to the best-fitting ideal-plate model are near, or below, the threshold of current measurement technologies. This approach, in which the plate model is treated as a useful approximation rather than literal truth, is continued here. I overlook measured or suspected internal velocity variations of as much as 2 to 8 mm/a; the lower threshholds apply in regions of slow relative plate motion (e.g., North America, Atlantic Ocean, Mediterranean, Africa) and the higher thresholds apply to regions of rapid relative plate motion (e.g., Indian and Pacific oceans and their margins).

[4] Even with such a relaxed definition, there are clearly regions (such as the Alpine-Himalayan mountain belt) in which it is very difficult to define plates, because there is so much seismic, geologic, and geodetic evidence for distributed anelastic deformation [*Gordon*, 1995]. One approach is to define a large number of very small plates, as in the *Bird and Rosenstock* [1984] model of 22 very small plates in southern California alone. This is data-intensive and time-consuming, and not yet practical on a global basis. It may also fail in the case of true viscous deformation, which would be so evenly distributed as to fail criterion 1 stated above. A second reasonable approach would be to conduct local kinematic modeling using the continuum approaches of *Holt et al.* [1991, 2000], *Haines and Holt* [1993], *Jackson et al.* [1995], *Bird* [1998], *Lamb* [2000], or *Kreemer et al.* [2000]. This is also too difficult to attempt in one global survey paper. Alternatively, certain regions can simply be labeled as zones of unmodeled complexity, where more data are needed (either to define very small plates, or to rule out their existence). In this paper, I take this easy third approach; I will refer to these complex regions (which may include regions of truly distributed deformation) as "orogens" (i.e., regions of mountain-formation, or at least topographic roughening). Thirteen of these zones are identified in Figure 1. Perhaps it should be emphasized that the designation of an "orogen" is not purely a statement about the nature of the kinematics in that region; it is a culturally-relative statement that the velocity field in that region has more degrees of freedom than present data can constrain.

[5] For some applications of a plate model, it may be more important to have global coverage than high precision. One such application is the spherical-harmonic expansion of plate velocities to examine torroidal versus poloidal components. Another is use of plate velocities as a boundary condition in modeling of mantle convection. A third example is the computation of element and isotope cycling by creation and subduction of crust. To accommodate such applications, I have treated the set of orogens as an overlay layer (giving warning of unmodeled complexity) rather than as a set of polygons competing with the plates for planetary surface area. By simply ignoring the

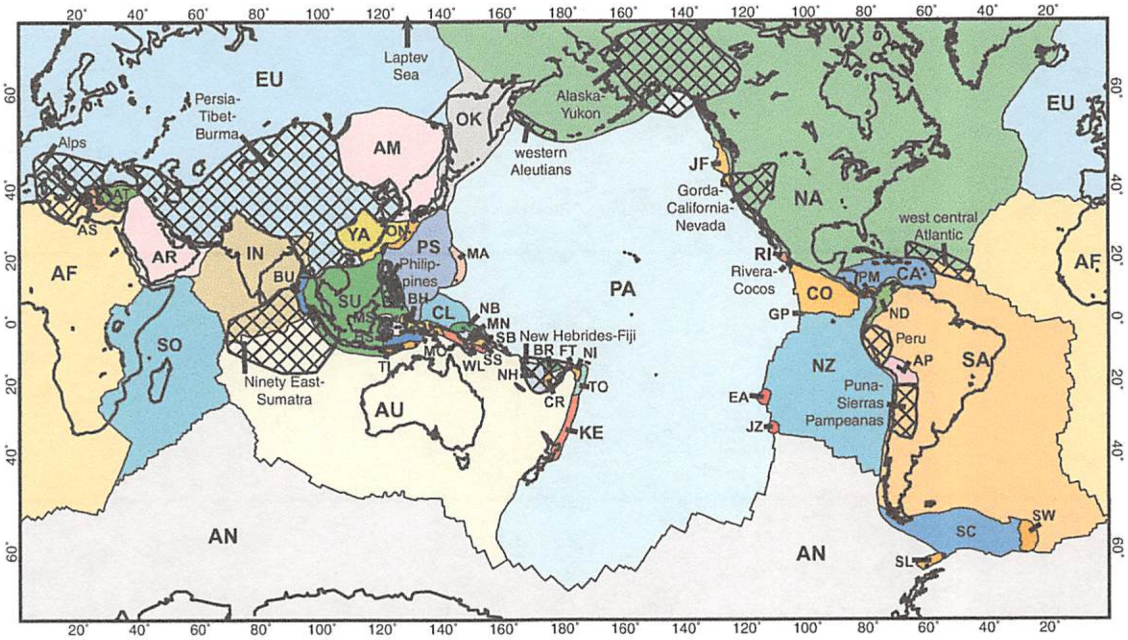

Figure 1. The 52 plates of model PB2002 are shown with contrasting colors. Two-letter plate identifiers are explained in Table 1. The 13 cross-hatched areas with are "orogens" in which an Eulerian plate model is not expected to be accurate. Labels of small plates and orogens are offset (with leader lines) for clarity. Mercator projection.

overlay layer, the reader will find a finite globe-covering set of plates for applications which require one. Plates in this set will always obey criterion 1, but may locally fail to satisfy criterion 2. Another advantage of this "overlay" format is that there is less chance that unsophisticated users will (incorrectly) infer elevated seismic hazard at the boundaries of the orogens (where no velocity discontinuity is implied). A third advantage is that it maximizes continuity with previous usage of plate terminology, so that the shapes of the familiar large plates are not arbitrarily modified without compelling reasons.

2. Previous Plate-Boundary Models

[6] Considering the lengthy and successful development of plate tectonic models, it is surprising that there are no generally-accepted standard references on plate boundary locations worldwide. The list of published resources is short. Authors of global inverse solutions for Euler poles of large plates [*Minster and Jordan*, 1978 (RM2); *DeMets et al.*, 1990 (NUVEL-1)] provided boundaries of the largest plates in the form of small-scale maps, plus lists of locations of discrete plate-boundary data used in the inversion. *Stoddard* [1992] digitized transform faults worldwide from an assortment of maps, but did not address spreading and subduction zones. *Zoback* [1992] published boundaries for large plates as part of the World Stress Map. *Gordon* [1995] distinguished plates (85% of Earth) from deforming zones (15%), and roughly sketched the shapes of 5 small plates in eastern Asia, plus a Somalia plate, a Capricorn plate, a Caroline plate, a Rivera plate, and a Scotia Sea plate (totalling 24). The Paleo-Oceanographic Mapping Project (POMP) at the University of Texas created a rough set of plate boundaries which emphasized major mid-ocean spreading ridges and large plates; their boundaries and gridded digital model of oceanic lithosphere age were published by *Mueller et al.* [1997]. More recently, the PLATES project at the University of Texas Institute of Geophysics (led by Lawrence Lawver and Ian Dalziel) maintains a site (http://www.ig.utexas.edu/research/projects/plates/plates.htm) which offers an incomplete working set of

plate boundaries, some of which are highly detailed.

3. Assembly of Plate Boundaries

[7] Probably the lack of a standard reference results from a combination of logistics and professional caution: few groups had the resources to assemble the necessary maps, and no person or group felt prepared to claim adequate knowledge of the whole Earth. However, the task has become much easier in recent years due to the publication of global digital data sets on topography, seismicity, seafloor age, and geodetic velocity. Using these aids, I undertook to assemble a set of plate boundaries because it is required for a project to estimate global seismic hazard based on plate tectonic theory. This present version of the plate boundaries, called PB2002, is a major refinement of the preliminary model PB1999 that was used in *Bird et al.* [2002]. The principal change is the inclusion of 38 small plates (Figure 1) in addition to the 14 large plates that were mapped in the previous version. Most of these boundaries were proposed (and many also mapped in detail) in published sources, so they do not represent new research results; their assembly and digitization was editorial work involving occasional applications of editorial judgment.

[8] The single most important basis for model PB2002 was the set of digitized boundaries created by POMP, and published by *Mueller et al.* [1997]. In areas of seafloor spreading with magnetic anomaly bands, my editorial changes were very minor: I edited out boundaries that are only relevant to paleotectonics, ensured that the active plate boundaries meet at triple-junction points that are common to all digitized boundary segments, and replaced non-transform offsets on spreading ridges with idealized transforms. (Boundaries from the PLATES model under development at the University of Texas Institute of Geophysics were not used in PB2002, but some boundaries may be the same because of common inheritance from *Mueller et al.* [1997].)

[9] Most boundaries other than mid-ocean spreading ridges (e.g., continental, subduction, and back-arc boundaries) were selected manually, using graphical software which permits me to overlay: (1) gridded seafloor ages from POMP with 6′ resolution; (2) gridded topography/bathymetry from ETOPO5 [*Anonymous*, 1988] with 5′ resolution; (3) 1,511 subaerial volcano locations from the Smithsonian Institution's Global Volcanism Program [*Simkin and Siebert*, 1995]; (4) moment tensors of shallow earthquakes from the Harvard Centroid Moment Tensor (CMT) catalog and epicenters from the International Seismological Centre (ISC) catalog; and (5) previous boundary selections digitized from figures in the literature. These were combined by giving highest priority to seafloor ages, second priority to topographic lineaments, and third priority to the principle that volcanism highlights extensional boundaries, but consistently lies 200–250 km to one side of subduction boundaries. Seismicity was used as the primary basis for plate boundaries in a few difficult cases (North America-South America boundary, India-Australia boundary, Okhotsk-North America boundary, inland boundaries of Amur and Yangtze plates, southern part of Africa-Somalia boundary). Generally, these are places where new plate boundaries are developing in former plate interiors, or where small plates are nearly surrounded by orogens.

[10] In the complex southwest Pacific region, a valuable resource was the Plate-Tectonic Map of the Circum-Pacific Region, which was published in 6 sheets and is available in at least two editions [*Circum-Pacific Mapping Project*, 1981, 1986]. A few boundaries were digitized directly from this map set (e.g., western parts of the Solomon Sea plate, west boundary of the Kermadec plate). In other cases, it served as a valuable source of informed opinion (as of the publication date) about which arcs and topographic lineaments represent active boundaries.

[11] Among the small oceanic plates lying east of the Sunda plate, convergence is dominant, and Quaternary magnetic anomaly lineations are unknown. In this area, Global Positioning System (GPS) geodesy gives the best estimate of the relative velocities of those plates which include islands within their interiors. The interpretation of project GEODYSSEA results by *Rangin et al.*

[1999] was a primary resource in this area. Unfortunately, geodesy does not precisely delimit plate boundaries, and gives only the minimum extent of any plate. There may be additional regions of very low anelastic strain rate which cannot be surveyed because of a lack of islands. Also, episodic fault locking and unlocking (seismic coupling) causes temporary elastic strain changes around many plate edges, which typically modifying the benchmark velocity component in the direction of the velocity of a neighboring plate. Therefore, I have used geodetic velocities as a rough guide to plate shapes and Euler poles, but have not felt obliged to fit any single divergent velocity vector observation by introducing a new plate, except where there is supporting evidence such as topographic and/or seismic lineaments. The Australia-Pacific (AU-PA) plate boundary south of New Zealand was taken directly from *Massell et al.* [2000].

4. Euler Poles

[12] It is necessary to estimate poles jointly with plate boundaries because (1) the expression of any plate boundary in topography and seismicity depends on its sense of relative velocity, and (2) it is often by attempting to quantitatively fit velocity and azimuth data that discrepancies indicating additional plates or orogens are discovered. For each small plate in model PB2002, an Euler vector is estimated with respect to a large neighboring plate. Then, relative rotation rates of large plates from a published "framework" model are used to express these Euler vectors in the Pacific plate reference frame in Table 1. The many new poles for small plates in this paper are mostly approximate and not the results of formal inversions (unless performed by the authors cited). Many are likely to be revised in the future based on new geodetic results.

[13] The "framework" set of Euler poles for the 14 large plates in this paper is the model known as NUVEL-1A. *DeMets et al.* [1990] performed a global inversion to determine the relative rotation rates of the 12 largest plates (the NUVEL-1 model), and noted that published information also constrains the relative motions of the Philippine Sea and Juan de Fuca plates. *Seno et al.* [1993] then updated the pole for the Philippine Sea plate. Although their result was questioned on procedural grounds by *Heki et al.* [1999], it has been geodetically confirmed [*Kato et al.*, 1998; *Rangin et al.*, 1999]. Finally, *DeMets et al.* [1994] adjusted the rates of all the vectors by a constant factor to give the NUVEL-1A solution.

5. Small Plates

[14] As a majority of the small plates on Earth are located along the western margin of the Pacific Ocean, this presentation will progress counterclockwise around that margin, and then eastward around the world. The naming of plates generally follows precedents in the literature. Since a plate is a geologic structure, I follow the geologic convention that the word "plate" is not capitalized, and that the type locality of the plate is never modified to form an adjective. (For example, "North American Plate" is non-standard, and the preferred term is "North America plate".) I continue another longstanding tradition by using a two-letter abbreviation as a short form for each plate name; to avoid duplication, a few of these abbreviations are necessarily different from abbreviations used by previous authors.

5.1. Okhotsk Plate (OK) and Amur Plate (AM)

[15] In early 14-plate models of the Earth such as RM2 and NUVEL-1, the North America plate (NA) was considered [*Chapman and Solomon*, 1976] to extend across the Bering Sea and include the Kamchatka Peninsula, the Sea of Okhotsk, and northern Honshu. This proposed slender projection of NA would be subject to compressional tractions on its western boundary with the Eurasia or Amur plate (EU or AM) in the vicinity of Sahkalin Island, and a mixture of topographic relative tension and tectonic compression on its eastern boundary with the Pacific plate (PA) in the Kuril Trench. Unless these tractions are very well-balanced, high deviatoric stresses and faulting would be expected near the narrow neck of the projection, in the northern Sea of Okhotsk (Shelikov Bay) and northern Kamchatka.

Table 1. Plate Identifiers, Areas, and Euler Poles[a]

Identifier	Plate Name	Area, Steradian	Pole Latitude, deg. N.	Pole Longitude, deg. E	Rotation Rate, deg./Ma	Reference
AF	Africa	1.44065	59.160	−73.174	0.9270	*DeMets et al.* [1994]
AM	Amur	0.13066	57.645	−83.736	0.9309	*Heki et al.* [1999]
AN	Antarctica	1.43268	64.315	−83.984	0.8695	*DeMets et al.* [1994]
AP	Altiplano	0.02050	33.639	−81.177	0.9160	*Lamb* [2000]
AR	Arabia	0.12082	59.658	−33.193	1.1616	*DeMets et al.* [1994]
AS	Aegean Sea	0.00793	74.275	−87.237	0.6497	*McClusky et al.* [2000]
AT	Anatolia	0.01418	56.283	8.932	1.6400	*McClusky et al.* [2000]
AU	Australia	1.13294	60.080	1.742	1.0744	*DeMets et al.* [1994]
BH	Birds Head	0.01295	12.559	87.957	0.3029	this paper
BR	Balmoral Reef	0.00481	45.900	−111.000	0.2000	this paper
BS	Banda Sea	0.01715	16.007	122.442	2.1250	*Rangin et al.* [1999]
BU	Burma	0.01270	8.894	−75.511	2.6670	*Circum-Pacific Map Project* [1986]
CA	Caribbean	0.07304	54.313	−79.431	0.9040	*Weber et al.* [2001]
CL	Caroline	0.03765	10.130	−45.570	0.3090	*Seno et al.* [1993]
CO	Cocos	0.07223	36.823	−108.629	1.9975	*DeMets et al.* [1994]
CR	Conway Reef	0.00356	−12.628	175.127	3.6050	this paper
EA	Easter	0.00411	28.300	66.400	11.4000	*Engeln and Stein* [1984]
EU	Eurasia	1.19630	61.066	−85.819	0.8591	*DeMets et al.* [1994]
FT	Futuna	0.00079	−10.158	−178.305	4.8480	this paper
GP	Galapagos	0.00036	9.399	79.690	5.2750	*Lonsdale* [1988]
IN	India	0.30637	60.494	−30.403	1.1034	*DeMets et al.* [1994]
JF	Juan de Fuca	0.00632	35.000	26.000	0.5068	*Wilson* [1988]
JZ	Juan Fernandez	0.00241	35.910	70.166	22.5200	*Anderson-Fontana et al.* [1986]
KE	Kermadec	0.01245	47.521	−3.115	2.8310	this paper
MA	Mariana	0.01037	43.777	149.205	1.2780	this paper
MN	Manus	0.00020	−3.037	150.456	51.3000	*Martinez and Taylor* [1996]
MO	Maoke	0.00284	59.589	78.880	0.8927	this paper
MS	Molucca Sea	0.01030	11.103	−56.746	4.0700	*Rangin et al.* [1999]
NA	North America	1.36559	48.709	−78.167	0.7486	*DeMets et al.* [1994]
NB	North Bismarck	0.00956	−4.000	139.000	0.3300	*Tregoning et al.* [1998]
ND	North Andes	0.02394	58.664	−89.003	0.7009	*Trenkamp et al.* [1996]
NH	New Hebrides	0.01585	13.000	−12.000	2.7000	this paper
NI	Niuafo'ou	0.00306	6.868	−168.868	3.2550	*Zellmer and Taylor* [2001]
NZ	Nazca	0.39669	55.578	−90.096	1.3599	*DeMets et al.* [1994]
OK	Okhotsk	0.07482	55.421	−82.859	0.8450	*Cook et al.* [1986]
ON	Okinawa	0.00802	48.351	142.415	2.8530	this paper
PA	Pacific	2.57685	0.000	0.000	0.0000	(abritrary choice of reference frame)
PM	Panama	0.00674	54.058	−90.247	0.9069	*Kellogg et al.* [1995]
PS	Philippine Sea	0.13409	−1.200	−45.800	1.0000	*Seno et al.* [1993]; *Kato et al.* [1998]
RI	Rivera	0.00249	26.700	−105.200	4.6923	*DeMets and Traylen* [2000]
SA	South America	1.03045	54.999	−85.752	0.6365	*DeMets et al.* [1994]
SB	South Bismarck	0.00762	10.610	−32.990	8.4400	*Tregoning et al.* [1999]
SC	Scotia	0.04190	48.625	−81.454	0.6516	*Pelayo and Wiens* [1989]
SL	Shetland	0.00178	63.121	−97.084	0.8558	(hypothetical; see text)
SO	Somalia	0.47192	58.789	−81.637	0.9783	*Chu and Gordon* [1999]
SS	Solomon Sea	0.00317	19.529	135.017	1.4780	this paper
SU	Sunda	0.21967	55.442	−72.955	1.1030	*Rangin et al.* [1999]
SW	Sandwich	0.00454	−19.019	−39.640	1.8400	*Pelayo and Wiens* [1989]
TI	Timor	0.00870	19.524	112.175	1.5140	this paper
TO	Tonga	0.00625	28.807	2.263	9.3000	*Zellmer and Taylor* [2001]
WL	Woodlark	0.01116	22.134	132.330	1.5460	*Tregoning et al.* [1998]
YA	Yangtze	0.05425	69.067	−97.718	0.9983	*Heki et al.* [1999]

[a] All poles are expressed in the Pacific-plate reference frame. Rotation about each pole is counterclockwise when seen from outside the Earth. All Euler vectors are stated with high precision to avoid round-off error in differencing, but accuracy is much less.

[16] *Savostin et al.* [1982, 1983] were possibly the first to use the name "Okhotsk plate" for the region lying south of a chain of small sedimentary basins in the Cherskii Mountains, which they interpreted as active grabens in an extensional OK-NA boundary. *Cook et al.* [1986] studied a chain of moderate ($5 < m_b < 6$) earthquakes in this region, and found focal mechanisms along the proposed OK-NA boundary to be sinistral-transpressive, rejecting the previous interpretation that the small sedimentary basins are active grabens. They used slip vectors to estimate an OK-NA pole position at (72.4°N, 169.8°E) in the East Siberian Sea, but could not address the rate of relative movement. *DeMets* [1992] used 256 slip vectors from the highly seismic Kuril Trench to test for the significance of proposed OK-NA motion in a three-plate study, and concluded that if there is such motion it is no faster than 5 mm/a. *Seno et al.* [1996] added slip vectors of earthquakes in the Sakhalin Island-Japan Sea lineament to the data base, solved for OK-EU and OK-NA poles, and found that the improvement to the fit by adding a separate OK plate was statistically significant. Their estimate of the OK-NA velocity was 8 mm/a. Based on slip vectors of local earthquakes, they defined the OK plate as extending south to central Honshu, so that major earthquakes in the eastern Japan Sea are occurring on the EU-OK boundary (or Amur-OK boundary; see below).

[17] Thrusting events along the eastern coast of northern Kamchatka also provide evidence that the North America plate does not extend into the Sea of Okhotsk, but converges with a separate Okhotsk plate. This belt of seismicity was first discussed by *Lander et al.* [1996], who used it as the basis for a proposed "Beringia" plate; however, I consider it to be a part of the OK/NA boundary (Figure 2), sharing the same northern Euler pole quoted above.

[18] The name "Amur microplate" was also proposed by *Savostin et al.* [1982, 1983] for the parts of eastern Mongolia, north China, and southeastern Russia which lie southeast of the Lake Baikal extensional province. Their proposal was that this block moves southeast with respect to EU between a sinistral transform system in the Stanovoy Mountains on the northeast and a second transform system on the southwest (possibly at the Qinling fault, but more likely further north in the Yellow Sea). The southeastern boundary of the plate would include the seismically active fold-and-thrust belt in the eastern Japan Sea offshore northern Honshu, then cut across central Honshu, and continue as the Nankai Trough subduction zone boundary with the Philippine Sea plate. *Miyazaki et al.* [1996] combined GPS velocities from Japan and Korea with seismic slip vectors from Baikal and the Stanovoy Mountains to confirm that this motion occurs at several millimeters per year. *Wei and Seno* [1998] performed a six-plate analysis (PA, NA, EU, OK, PS, AM) of earthquake slip vectors and NUVEL-1 data, including an Amur plate distinct from EU, and still concluded that OK is distinct from NA. Their AM-OK and EU-OK poles are both located in northern Sakhalin Island, near the AM-OK-EU triple junction, so that all relative plate velocities decrease to small values in this complex region. They derived a slow AM-EU velocity of only 0.4–0.7 mm/a. This is questionable because it conflicts with geodetic results which they did not use in their inversion: both the previous results of *Miyazaki et al.* [1996], and newer results of *Calais et al.* [1998] which showed extension around the Baikal Rift to be at 4.5 ± 1.2 mm/a.

[19] Additional GPS geodetic results of *Takahashi et al.* [1999] were interpreted as confirming the *Miyazaki et al.* [1996] model for AM-EU motion, but again showing that the AM-EU motion predicted by the *Wei and Seno* [1998] model is too slow by a factor of 5. Also, they point out that a station in south Sakhalin Island moves with the Amur plate, requiring the AM-OK boundary to lie east of this point. (However, elastic strain accumulation could also explain this vector, especially if the AM-OK boundary in Sakhalin is an east-dipping thrust.) Unfortunately, the only remaining stations on the OK plate were one in north Sakhalin (which only confirms the proximity of the EU-OK pole) and two in Kamchatka (which were not useful due to elastic strain accumulation in the adjacent subduction zone).

[20] The most recent geodetic study on Amur plate motion is *Heki et al.* [1999]. Using 15 GPS stations, they find that AM separates from EU at

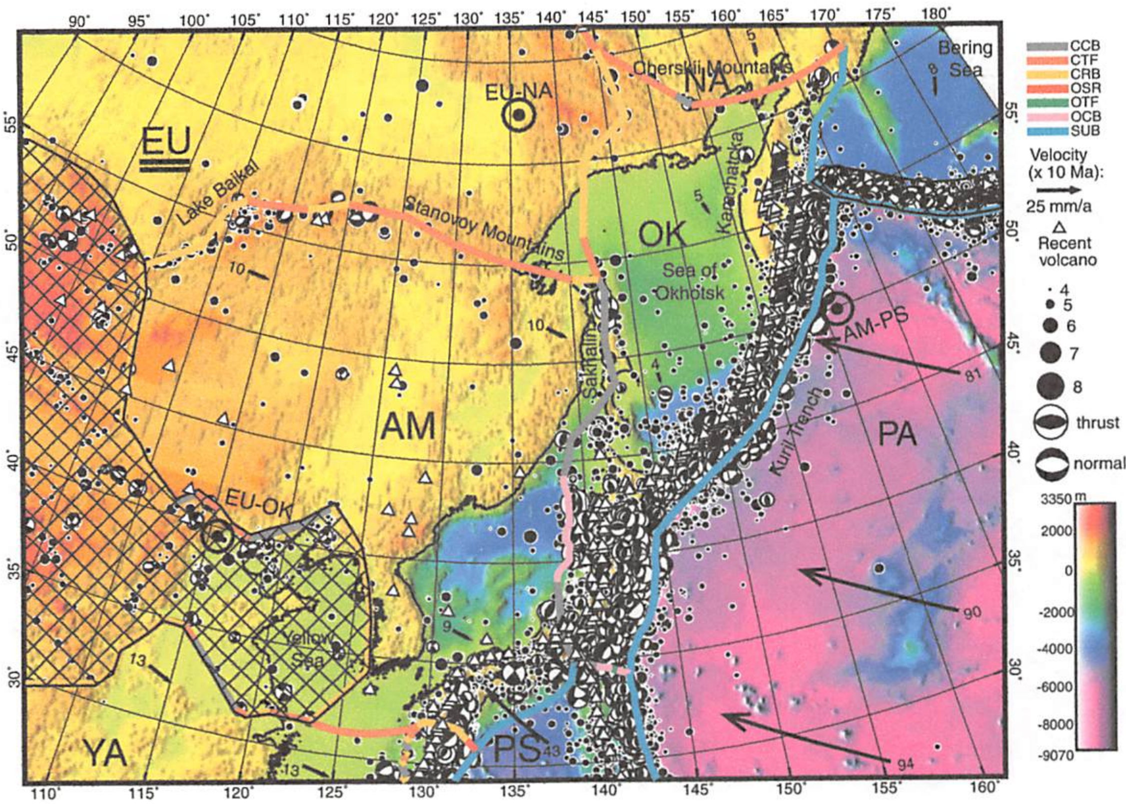

Figure 2. Boundaries of the Okhotsk (OK) and Amur (AM) plates. Surrounding plates include Eurasia (EU), North America (NA), Pacific (PA), Philippine Sea (PS), and Yangtze (YA). Boundary types are: CCB continental convergent boundary, CTF continental transform fault, CRB continental rift boundary, OSR oceanic spreading ridge, OTF oceanic transform fault, OCB oceanic convergent boundary, SUB subduction zone. Cross-hatched regions are orogens. Color shows topography from ETOPO5. Solid dots are shallow (<70 km) hypocenters from ISC catalog, 1964–1991; beachballs are lower-hemisphere projections of douple-couple parts of moment tensors of shallow centroids from Harvard CMT catalog, 1977–1998. White triangles are subaerial Recent volcanoes from *Simkin and Siebert* [1995]. Black vectors give model velocities (with numbers in mm/a) relative to plate whose identifier is underlined. Black circles are locations of Euler poles, about which the first-named plate rotates counterclockwise relative to the second. Oblique Mercator projection with great circle passing E-W through (135°E, 48°N).

9–10 mm/a, and compute its Euler pole. Their direction of relative velocity at Baikal is nearly E-W, which conflicts with seismic slip vectors pointing SE-NW; this is an unresolved problem. An important implication of their results is that seismic slip vectors and convergence in the Japan Sea and offshore Sakhalin Island are largely explained by AM-NA motion, and do not require the invocation of an OK plate separate from NA.

[21] My interpretation is that the seismic evidence for an OK-NA boundary [*Cook et al.*, 1986; *Lander et al.*, 1996] still stands, as does the constraint of *DeMets* [1992] that relative velocity on this boundary be less than 5 mm/a. However, the poles and rates determined by *Seno et al.* [1996] and *Wei and Seno* [1998] are in doubt because of their neglect, or underestimation, of EU-AM relative motion. Therefore, for an Euler pole I adopt the OK-NA pole position of *Cook et al.* [1986] and rather arbitrarily assign a relative velocity of 3 mm/a to this boundary (0.14°/Ma at the OK-NA pole). I compute AM plate motion from the latest geodetic result, that of *Heki et al.* [1999]. My plate boundary locations are generally based on the map of *Wei and Seno* [1998], since geodesy is not yet able to define plate boundaries with the resolution that topography and seismicity provide. However, I have modified the OK-NA boundary to more closely follow seismicity recorded in the ISC and CMT

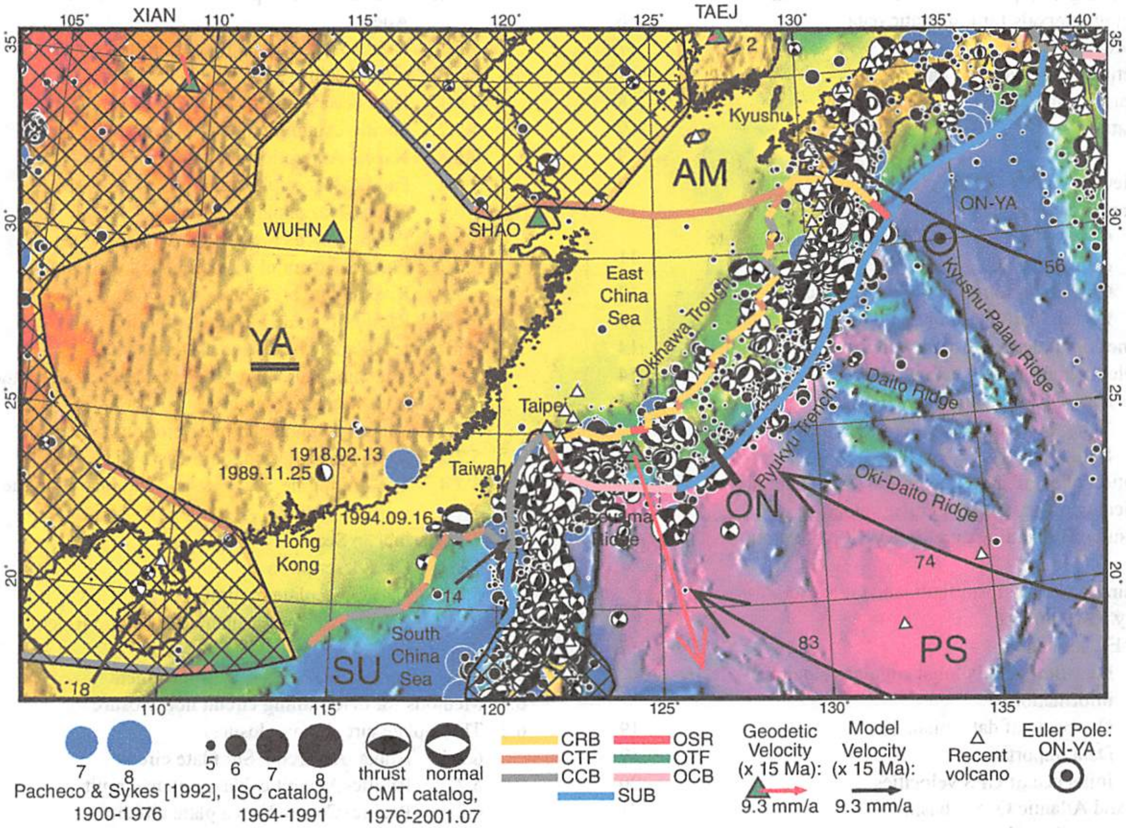

Figure 3. Boundaries (heavy colored lines) of the Yangtze (YA) and Okinawa (ON) plates. Surrounding plates include Sunda (SU), Philippine Sea (PS), and Amur (AM). Conventions as in Figure 2. Additional epicenters in blue ($m_w > 7$, 1900–1976) are from *Pacheco and Sykes* [1992]. Geodetic velocity of Ishigaki Island from *Kato et al.* [1998] is plotted relative to YA. Oblique Mercator projection with great circle passing E-W through (127°E, 27°N).

catalogs (Figure 2). Also, along the southwestern parts of the AM-EU boundary, I have placed the boundary north of the highly seismic Tanlu fault and other NE-trending faults around Bo Hai. These regions of complex distributed seismicity are assigned to an eastern extension of the Persia-Tibet-Burma orogen. *Heki et al.* [1999] have shown that GPS stations southwest of AM move ESE with respect to stable (northern European and Siberian) Eurasia. Several of these appear to define a distinct Yangtze plate.

5.2. Yangtze Plate (YA)

[22] There is an aseismic region in southeastern China [*Giardini et al.*, 1999] which seems to be unaffected by the Himalayan continental collision (Figure 3). GPS geodesy [*Heki et al.*, 1999] has shown that the region contains at least 3 stations whose velocity is consistent with the hypothesis that they belong to a rigid plate: WUHN (Wuhan), SHAO (Shanghai), and Taipei. Their common motion is different from that of Eurasia by about 13 mm/a to the ESE (Euler pole 61.2°N, 142°E, 0.206°/Ma), well in excess of measurement errors.

[23] Geodesists have sometimes referred to this region as the "South China" plate, but that name was already established in the literature to describe the (larger) Paleozoic plate which collided with the Sino-Korean plate to form the Dabie Shan and adjacent Hercynian ranges [e.g., *Benpei et al.*, 1998]. For the neotectonic (and possibly Tertiary) plate, I prefer the name "Yangtze" [*Gordon*, 1995] for one of its most prominent Tertiary-Quaternary features.

[24] The only distinct boundary of the Yangtze plate (YA) is in the east, where it collides with the

Philippine Sea plate (PS) in Taiwan, and separates from the Okinawa plate (discussed below) in the Okinawa Trough. If both AM and YA are rigid plates, there should be a short, slow-moving boundary between them, where velocities would be determined by the differential YA-AM Euler pole, here computed to be (39.9°N, 125.8°E, 0.23°/Ma) by differencing the two geodetic poles with respect to stable EU cited above. As there are only a few strike-slip earthquakes and no obvious bathymetric lineament in the relevant area of the East China Sea, I suggest a possible sinistral transform boundary (Figure 3) which would have slip rates of only about 4 mm/a.

[25] Southwest of Taiwan, a boundary should occur between YA and the Sunda plate (SU; discussed below). Since the YA-SU pole is computed (using poles of *Heki et al.* [1999] and *Rangin et al.* [1999]) to be near (4°N, 133°E), motion along this boundary should be sinistral-transpressive, with rates on the order of 15 mm/a. Largely on the basis of the 1994.09.16 $m_w = 6.7$ thrust event, I have assumed that this boundary follows the ocean-continent boundary along the northern margin of the South China Sea, becoming a compressive boundary in each of the right steps. However, if the geodetic velocity of Taipei had not been available, it would also have been reasonable to draw a YA-SU plate boundary along one of the SW-trending sinistral faults which occur on land in the provinces between Shanghai and Hong Kong. Seismicity here is low and ambiguous (Figure 3): a large ($m_w \cong 7.3$) event on 1918.02.13 was located somewhere near (24°N, 117°E) by *Pacheco and Sykes* [1992] but its mechanism is unknown. A more recent and smaller earthquake was located by the CMT catalog (1989.11.25; $m_w = 5.6$) but it had a dip-slip solution with NW-striking nodal planes, inconsistent with any SW-NE-trending boundary. Six small ($m_b < 5$) events are also found in the ISC catalog. The ambiguity of this data suggests that additional geodetic stations are needed to determine the reality and location of the expected YA-SU boundary, and place it either near the continental margin, or alternatively onshore.

[26] Most of the remaining southwest, northwest, and northeast boundaries of stable YA are treated as nominal boundaries with with EU, but these parts of EU are deforming within the Persia-Tibet-Burma orogen. These boundaries are rather subjectively drawn to outline only the region of low seismicity as the YA plate. Like other proposed boundaries of orogens, these lines are not necessarily faults, and there is no implication of special seismic hazard there. See the preceding section on the Amur plate for a discussion of their short mutual boundary.

5.3. Okinawa Plate (ON)

[27] The Ryukyu trench and arc is the site of rapid subduction of Philippine Sea plate. The Ryukyu forearc is separating from Asia by NW-SE extension in the Okinawa Trough, which has been inferred from marine geology and seismic reflection [*Sibuet et al.*, 1987; *Park et al.*, 1998], island geology and normal-faulting earthquakes [*Fabbri and Fournier*, 1999], paleomagnetism [*Miki*, 1995], and geodesy [*Kato et al.*, 1998; *Hu et al.*, 2001]. Therefore, the forearc is a small plate (Figure 3), which was called the "Okinawa platelet" by *Sibuet et al.* [1987].

[28] The southwest end of the Okinawa plate (ON) is in or near the north end of Taiwan, where there is a sharp reversal in subduction polarity [*Lallemand et al.*, 1997a]. Its southeast boundary with PS is the Ryukyu trench. Its southwestern boundary, also with PS, appears to be a former subduction zone which is now highly oblique. Based on swath bathymetry of *Lallemand et al.* [1997b] and seismic refraction results [*Liu et al.*, 1997], I interpret that the dextral Yaeyama Ridge fault zone within the Ryukyu forearc has become the primary plate boundary between 122° and 123°E. The northwestern boundary of the Okinawa plate in the Okinawa Trough is primarily with the Yangtze plate discussed previously. I have digitized this YA-ON boundary by connecting linear zones of localized extension mapped by *Letouzey and Kimura* [1985] and/or *Sibuet et al.* [1987]; the implied transform faults linking these zones are hypothetical, although the CMT seismic catalog shows several events in the Trough with appropriately oriented strike-slip mechanisms. The suggested northeastward termination of ON (and boundary

with AM) in southern Kyushu is based on two features: a strong gradient in geodetic velocities observed by the GEONET array of the Geographical Survey Institute (http://mekira.gsi.go.jp), and a transverse belt of ISC epicenters and Harvard CMT centroids with diverse mechanisms (Figure 3). Admittedly, a clear topographic lineament and master fault are not evident.

[29] The Okinawa Trough does not contain linear magnetic anomalies of seafloor-spreading origin to constrain its Euler pole and spreading rate. *Sibuet et al.* [1995] attempted to determine ON-EU (or ON-YA?) poles based primarily on azimuths of normal faults, and calculated that these poles lie southwest of the Trough. However, spreading may be oblique, in which case normal fault azimuths yield inaccurate poles, and transform azimuths or rate data must be used. In the Okinawa Trough, transform faults are obscure or nonexistant, and the geologic and gravity evidence suggests decreasing total extension to the northeast, inconsistent with a southwestern pole position. *Sibuet et al.* [1995] estimated net extensions between 80 and 25 km on different profiles, decreasing northeastward. *Park et al.* [1998] used Quaternary normal faults visible in seismic reflection sections to measure spreading rates of 11 and 20 mm/a, respectively, on two adjacent transects. (They acknowledge that these rates are minima because additional extension by distributed pure shear and/or dike intrusion would probably not be visible with seismic reflection.)

[30] The data most useful for determining the neotectonic ON-YA pole are geodetic results from the Ryukyu arc, although any single velocity or local group of velocities observed there may be strongly affected by transient locking and unlocking of the subduction zone. A GPS geodetic station on Ishigaki Island (central ON plate) moved 55 ± 2.2 mm/a toward 150 ± 2° azimuth with respect to stable EU [*Kato et al.*, 1998], which means that it moved about 47 mm/a toward 163° with respect to adjacent YA. Voluminous data (from 36 continuous GPS stations) collected by the GEONET array of the Geographical Survey Institute and made available electronically (http://mekira.gsi.go.jp) show similar velocities at Ishigaki Island, and a consistent decrease of southeastward velocities (with respect to either YA or EU) toward the northeast, all the way to central Kyushu. I fit this dataset by maximum-likelihood (allowing 10% chance of contamination of each velocity by other processes) and estimated the ON-YA pole to be (29.8°N, 133.9°E, 2.42°/Ma). The implied rates of back-arc spreading are greater in the southwest, where the Philippine Seafloor is deep and smooth, than they are in the northeast, where the Kyushu-Palau, Daito and Oki-Daito Ridges are entering the Ryukyu Trench.

5.4. Sunda Plate (SU)

[31] The Sunda plate (Figure 4) includes most of southeast Asia, the South China Sea, the Malay Peninsula, most of Sumatra, Java, Borneo, and the intervening shallow seas [*Rangin et al.*, 1999]. The very low rate of shallow earthquakes is evidence of its low anelastic strain rates.

[32] In early 14-plate models of the Earth like RM2 and NUVEL-1, this region was considered part of the Eurasia plate (EU). However, the history of the India-Eurasia continental collision in the Himalaya has involved large relative movements of south China and southeast Asia with respect to the European-Siberian core of Eurasia [e.g., *Peltzer and Tapponnier*, 1988]. So, any previous connection to Eurasia was broken early in the Tertiary. Kinematic connections to other adjacent plates can only be attempted through interpretation of seismic slip vectors, since SU is separated from the Australia (AU) and Philippine Sea (PS) plates by subduction zones. However, slip vectors may be misleading if there is slip partitioning in an oblique subduction zone. Therefore, it was necessary to use space geodesy to determine its motion.

[33] *Genrich et al.* [1996] used GPS to define a "Sunda shelf block" which was indistinguishable from a rigid body, but they lacked the network breadth to precisely fix its rotation with respect to Eurasia. The GEODYSSEA geodetic campaigns of 1994 and 1996 in and around "Sundaland" resulted in a consensus solution which has the SU-EU pole of (33.2°S, 129.8°E, −0.286°/Ma) [*Chamote-Rooke and Le Pichon*, 1999; *Rangin et al.*, 1999]. This has been confirmed