Global Forecast of Shallow Earthquakes Using Geodesy on Land and Plate Tectonics at Sea

01HQGR0021

Peter Bird

Department of Earth and Space Sciences, University of California, Los Angeles, CA 90095-1567

Telephone: (310) 825-1126 FAX: (310) 825-2779 pbird@ess.ucla.edu

http://element.ess.ucla.edu

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Investigations Undertaken

1. Analysis of all Harvard Centroid Moment Tensor (CMT) earthquakes associated with spreading ridges and oceanic transform faults worldwide, to determine the best-fitting tapered Gutenberg-Richter frequency/magnitude models, and search for variations of their parameters with relative plate velocity, fault length, or lithosphere age. (This investigation was conducted using an older plate boundary model, PB1999.)

2. Compilation of an updated global plate boundary model (PB2001), based on sources in the literature. Unlike the established NUVEL-1A model, PB2001 provides greater detail in plate boundary locations, at the cost of less formal precision in the determination of Euler vectors.

3. Association of all large shallow earthquakes in the 20th-century with one of 7 plate boundary classes, or with plate interiors, or zones of distributed deformation. Estimation of tapered Gutenberg-Richter frequency/magnitude models for each class. Computation of mean coupled seismogenic lithosphere thickness, and mean coupling, for each plate boundary class.

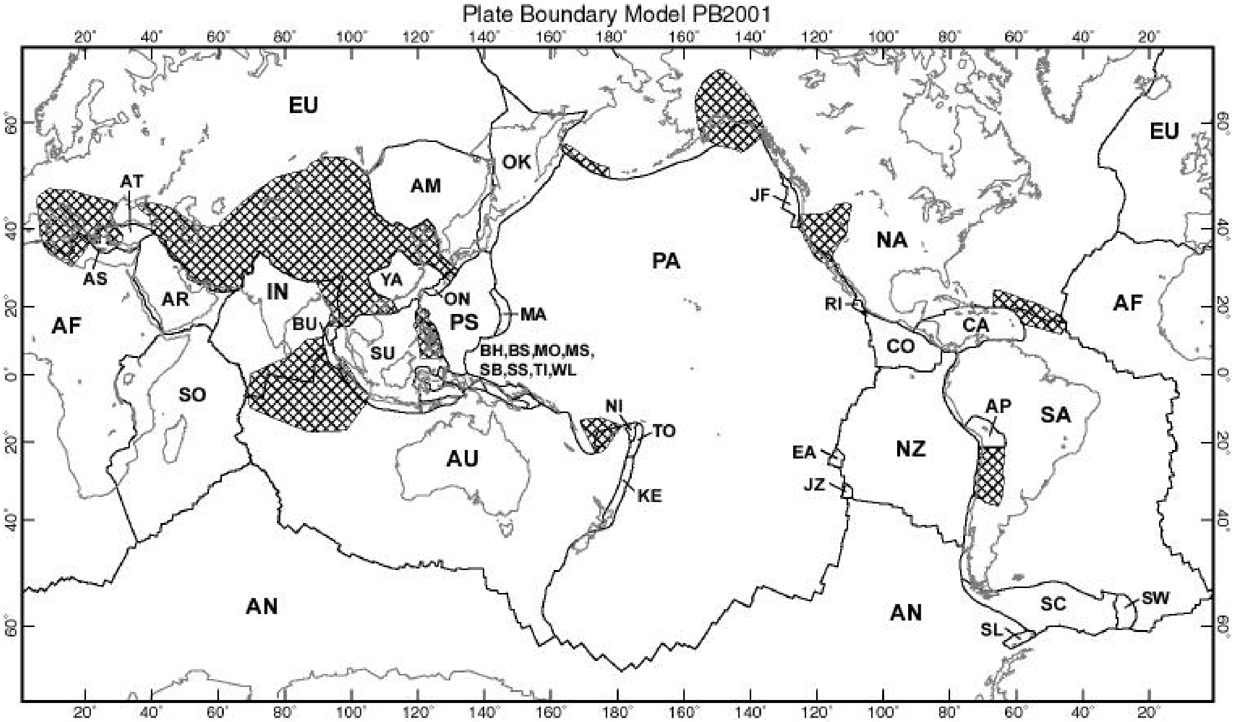
Results

1. We use the CMT catalog to separate ocean-ridge seismicity into spreading and transform sub-catalogs. We use tapered Gutenberg-Richter distributions to estimate the total seismic moment rates of plate-boundary zones from limited catalogs of large events. We use plate boundary model PB1999 to associate marine earthquakes with particular plate boundary segments. We then combine these tools to estimate corner magnitudes (m_c), spectral slopes ($\boldsymbol{b}$), and coupled lithosphere thicknesses for all spreading ridges and oceanic transform faults. The distribution of spreading earthquakes is consistent with "normal" $\boldsymbol{b} = 2/3$ (although $\boldsymbol{b}$ is not well constrained) and with uniform $m_c = 5.8$. Coupled lithosphere thickness along ridges decreases quasi-exponentially (from about 500 m to under 50 m) as spreading rate increases. Oceanic transform faults also have "normal" $\boldsymbol{b} \cong 2/3$, but their corner magnitudes decrease from about 7.1 to about 6.3 with increasing relative plate velocity. Oceanic transform faults also show a quasi-exponential decrease in coupled lithosphere thickness (from about 3000 m to about 300 m) as relative plate velocity increases. Perhaps this is due to formation of serpentine along slow ridges and transforms and its absence from fast ridges and transforms. Spreading ridges and oceanic transform faults both have imperfect seismic coupling because: (i) all detailed local studies of seismogenic lithosphere thickness exceed our mean values for coupled thickness, and (ii) if coupling were perfect, and seismogenic lithosphere thickness were as small as our estimated coupled thickness, it would require unreasonable stress drops or rupture shapes to explain the moments of the largest earthquakes.

2. 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 PB2001 includes 28 small plates (Okhotsk, Amur, Yangtze, Okinawa, Sunda, Burma, Molucca Sea, Banda Sea, Timor, Birds Head, Maoke, Mariana, South Bismarck, Solomon Sea, Woodlark, Niuafo'ou, Tonga, Kermadec, Rivera, Easter, Juan Fernandez, Altiplano, Shetland, Scotia, Sandwich, Aegean Sea, Anatolia, Somalia), for a total of 42 plates. No attempt is made to divide the Alps-Persia-Tibet orogen, the Philippine Islands, the Fiji Plateau, the southern Andes orogen, or the California-Nevada taphrogen into microplates; instead, they are designated "zones of distributed deformation" in which this rigid-plate model is not accurate. The cumulative-number/area distribution for this model follows a power-law for plates of less than 1 steradian of area, suggesting that future work is very likely to define more and smaller plates within these zones. 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 zones of distributed deformation; 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, and 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 0.107 m^2/s, which is higher than in previous models because of the incorporation of back-arc spreading.

Plate Boundary Model PB2001



3. We use two catalogs to describe shallow seismicity in the 20th century: (1) the Harvard CMT catalog, which is complete for moment magnitudes m > 5.7 and available for 1977.01.01 to

2001.07.31; (2) the 1900-1976 portion of *Pacheco and Sykes* [1992] catalog of shallow earthquakes, which claims to be complete for $M_S > 7$. For each catalog, we plot histograms of epicenter distance from each of the 7 plate boundary classes to determine their effective width. (Effective width is a composite measure of event mislocation, plate boundary mislocation, event offset due to fault dip, and event offset due to plate boundaries with multiple faults.) These widths range from 120 km for spreading ridges to 300 km for continental convergent boundaries to 600 km for subduction zones (200 km before the trench, and 400 km after). Then we associate earthquakes with particular plate boundary steps, in a two-part process: Primary classification attempts to match an event of known focal mechanism (normal, strike-slip, or thrust) with a nearby plate boundary of corresponding type. Secondary classification associates events of nonconforming focal mechanism (e.g., normal events in subduction zones; thrust events in transpressive transform faults) or unknown focal mechanism with the nearest plate boundary step (or with plate interiors, if the distance is excessive). In all of this processing, plate boundary steps and epicenters falling within any of the 11 "zones of distributed deformation" of model PB2001 are discarded, because the rates and directions of relative velocity are uncertain. Next we fit the frequency/magnitude distribution for each class with a tapered Gutenberg-Richter distribution, which has four parameters (threshold magnitude m_t, corner magnitude m_c, spectral slope $\boldsymbol{b}$, and total earthquake count). Distributions are fit to each catalog separately, and also to a composite frequency-magnitude distribution obtained by adding the two catalogs and then scaling the frequency of $5.7 < m < 7.1$ events which come only from CMT. The CMT fit consistently gives higher $\boldsymbol{b}$, which we consider more reliable because of the risk that *Pacheco and Sykes* may have missed some smaller events early in the last century. The *Pacheco and Sykes* catalog and the composite catalog both give higher corner magnitude for subduction zones, due to the inclusion of the 1960 Chilean earthquake sequence. Results are shown in the table below, but it should be emphasized that these are only preliminary, because they are based on subjective manual fitting. Objective maximum-likelihood analysis will result in some revisions, especially of corner magnitudes.

Moment Rates and Coupled Lithosphere Thicknesses
by Plate Boundary Class

Abbreviation	CCB	CTF	CRB	OSR	OTF	OCB	SUB
Class	Contin-ental Con-verg ent Boundary	Contin-ental Trans-for m Fault	Contin-e ntal Rift Boundary	Oceanic Spread-in g Ridge	Oceanic Trans-for m Fault	Oceanic Con-verg ent Boundary	SUBduction zone
CMT moment rate*, N m/s	1.4E12	3.2E12	3.1E11	2.2E11	2.9E12	5.5E12	5.9E13
Events per 24.58 years*	222	336	92	362	1,104	205	4,160
over threshhold, m_t	5.40	5.50	5.53	5.40	5.50	5.40	5.40
slope, $\boldsymbol{b}$	0.60	0.67	0.67	0.67	0.67	0.50	0.62
20th-c. corner magnitude, m_c	7.7	8.0	7.1	5.8	6.9	8.2	8.7 - 9.8

Model moment rate*, N m/s	2.2E12	4.0E12	4.2E11	3.3E11	3.7E12	8.4E12	1.4E14 to 5.7E14
Length of boundary*, km	10,138	18,020	19,375	62,200	41,322	8,658	42,169
Mean* velocity, mm/a	22.7	27.6	17.1	48.5	43.4	18.5	63.9
Assumed fault dip q, deg.	25°	90°	45°	45°	90°	25°	23°
Assumed modulus m, GPa	38	31	31	49	49	70	70
$m\int \mathrm{cosec}(q)\left(v_p + v_o \sec q\right) d\ell$, N/s	9.2E8	5.7E8	7.4E8	1.01E1 0	2.4E9	1.16E9	2.00E10
Coupled thickness $c\ z$, m	2,400	7,000	570	33	1,500	7,200	7,000 to 28,500
Assumed seism. lith. z, m	12,000	10,000	6,000	8,000	10,000	15,000	90,000
0 < coupling < 1	~0.2	~0.7	~0.1	~0.004	~0.15	~0.5	0.08 to 0.32

*excluding earthquakes and plate boundary steps inside the 11 "zones of distributed deformation".

From the comparison of the total moment rates for each plate boundary class to the moment rates expected from plate boundary model PB2001, we estimate the coupled seismogenic lithosphere thickness ($c\ z$) for each plate boundary class. (This involves assumptions about fault dip and elastic shear modulus, which are also shown in the table.) This product is the quantity most essential for forecasting seismic hazard of each plate boundary. Because it is also of academic interest to estimate coupling separately, the last row of the table presents estimates based on additional assumptions about the vertical extent of the largest earthquake ruptures for each class.

Reports Published

Kagan, Y., D. D. Jackson, Y.-F. Rong, and P. Bird (1999) Plate tectonics and earthquake potential on the Pacific rim (abstract), EOS Trans. AGU, Fall Meeting Supplement, p. F680.

Bird, P., Y. Y. Kagan, H. Houston, and D. D. Jackson (2000) Earthquake potential estimated from tectonic motion (abstract), Eos Trans. AGU, Fall Meeting Supplement, p. F1226-F1227.

Bird, P., Y. Y. Kagan, and D. D. Jackson (in press), Plate tectonics and earthquake potential of spreading ridges and oceanic transform faults, in: S. Stein and J. T. Freymueller (editors), *Plate Boundary Zones*, AGU Geophysical Monograph, in press.

Bird, P. (submitted) Plate boundary model PB2001, submitted to Geochemistry, Geophysics, Geosystems, October 2001.

Data Availability

Global plate boundary model PB2001 is available by request in a preliminary version; changes may yet occur as the result of ongoing peer review. The model is contained in a set of 4 ASCII files and one Microsoft Word™ document:

PB2001_boundaries.dig: Digitised lines separating pairs of plates.

PB2001_plates.dig: Digitised outlines for each of the 42 plates (This is the same information as in PB2001_boundaries, but in a different format.)

PB2001_zones.dig: Digitised outlines of the 11 zones of distributed deformation, within which the rigid-plate model is not expected to be accurate.

PB2001_steps.dat: Flat-file table of information for each digitisation step along plate boundaries, including relative velocity vector, elevation, seafloor age, and classification into one of 7 plate boundary classes.

PB2001_poles.doc: Table of plate name abbreviations, areas, and Euler vectors.

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Non-Technical Project Summary

We are preparing a global probabilistic forecast of earthquakes by determining the long-term rates of fault slip, and strain between faults, and assuming that future seismicity will be proportional to these rates. We have updated the global plate model by including 28 small plates that are documented in the literature. We have analyzed 20th-century seismicity to determine the maximum magnitudes and seismic coupling factors for each of 7 kinds of plate boundary. There are large variations in coupling, from 70% for continental transform faults, through values of 8-32% for subduction zones, down to less than 1% for mid-ocean spreading ridges.