Geochemistry
Geophysics
Geosystems
G3

Article
Volume 12, Number 11
5 November 2011
Q11001, doi:10.1029/2011GC003751
ISSN: 1525-2027

Published by AGU and the Geochemical Society

Geologically current motion of 56 plates relative to the no-net-rotation reference frame

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[1] NNR-MORVEL56, which is a set of angular velocities of 56 plates relative to the unique reference frame in which there is no net rotation of the lithosphere, is determined. The relative angular velocities of 25 plates constitute the MORVEL set of geologically current relative plate angular velocities; the relative angular velocities of the other 31 plates are adapted from Bird (2003). NNR-MORVEL, a set of angular velocities of the 25 MORVEL plates relative to the no-net rotation reference frame, is also determined. Incorporating the 31 plates from Bird (2003), which constitute 2.8% of Earth's surface, changes the angular velocities of the MORVEL plates in the no-net-rotation frame only insignificantly, but provides a more complete description of globally distributed deformation and strain rate. NNR-MORVEL56 differs significantly from, and improves upon, NNR-NUVEL1A, our prior set of angular velocities of the plates relative to the no-net-rotation reference frame, partly due to differences in angular velocity at two essential links of the MORVEL plate circuit, Antarctica-Pacific and Nubia-Antarctica, and partly due to differences in the angular velocities of the Philippine Sea, Nazca, and Cocos plates relative to the Pacific plate. For example, the NNR-MORVEL56 Pacific angular velocity differs from the NNR-NUVEL1A angular velocity by a vector of length $0.039 \pm 0.011° \text{ a}^{-1}$ (95% confidence limits), resulting in a root-mean-square difference in velocity of 2.8 mm a^{-1}. All 56 plates in NNR-MORVEL56 move significantly relative to the no-net-rotation reference frame with rotation rates ranging from $0.107° \text{ a}^{-1}$ to $51.569° \text{ a}^{-1}$.

Components: 6300 words, 5 figures, 5 tables.

Keywords: plate motion; reference frame.

Index Terms: 1229 Geodesy and Gravity: Reference systems; 1532 Geomagnetism and Paleomagnetism: Reference fields: regional, global; 8158 Tectonophysics: Plate motions: present and recent (3040).

Received 12 July 2011; **Revised** 13 September 2011; **Accepted** 13 September 2011; **Published** 5 November 2011.

Argus, D. F., R. G. Gordon, and C. DeMets (2011), Geologically current motion of 56 plates relative to the no-net-rotation reference frame, *Geochem. Geophys. Geosyst.*, *12*, Q11001, doi:10.1029/2011GC003751.

1. Introduction

[2] MORVEL is a set of geologically current relative plate angular velocities for 25 major plates covering 97% of the surface of the Earth [*DeMets et al.*, 2010]. *DeMets et al.* [2010], however, do not include a specification of global plate boundaries, and the restriction to 25 plates omits many small plates. For some applications of global plate motions, it may be more important to have global coverage than high accuracy of relative plate angular velocities and plate boundaries [*Bird*, 2003]. An example is the determination of the global distribution of deformation and strain rate and the inferred seismic hazards, for which an omitted plate boundary—even if the plate is small—is obviously important [*Kagan et al.*, 2010]. Other examples include estimates of element and volatile recycling and expansion of plate velocities in spherical harmonics [*Bird*, 2003]. The first goal of this paper is to provide not only a global set of plate boundaries, which are merely a minor update to those of *Bird* [2003], but a specification of the relative angular velocities of 31 of his small plates in a manner consistent with MORVEL. It is debatable whether all of these 31 regions should be treated as rigid tectonic plates. For simplicity and expediency, however, we simply follow *Bird*'s [2003] interpretation herein. The 31 additional angular velocities are generally less accurate than those of MORVEL because of the sparseness of high-quality data available to estimate them. To incorporate them into MORVEL, we tie each additional plate through the same plate as that used by *Bird* [2003] to tie it into NUVEL-1A. We refer to this expanded set of relative angular velocities of 56 plates as MORVEL56. The relative angular velocities of the 25 MORVEL plates included in MORVEL56 are identical with those in MORVEL.

[3] A second goal of this paper is to determine two global sets of plate angular velocities relative to the no-net-rotation reference frame, one consistent with MORVEL and one consistent with MORVEL56. Plate angular velocities in the no-net-rotation reference frame are used by many in the geoscience community including geodynamicists, tectonicists, and geodesists as a standard for assessing the net rotation of the lithosphere and, for example, examining the asymmetry of subduction. For 15 years the rotation of the International Terrestrial Reference Frame [*Altamimi et al.*, 2002, 2007] has been defined using NNR-NUVEL1A [*Argus and Gordon*, 1991; *DeMets et al.*, 1990, 1994], a set of geologically current angular velocities of fourteen plates relative to the no-net-rotation reference frame. The new sets of angular velocities differ significantly from the old.

2. Methods

2.1. Plate Boundaries

[4] We mainly use the plate boundaries of *Bird* [2003, Figure 1]. Following *Bird* [2003], we assigned the regions that he inferred to be orogenic belts, which constitute 7.5% of Earth's surface, to the plate to which he assigned them. All but four plates in MORVEL are in the study by *Bird* [2003]. Following *DeMets et al.* [2010], we separate the Sur plate from the South America plate, the Lwandle plate from the Somalia plate, and the Capricorn and Macquarie plates from the Australia plate (Figures 1 and 2). Each of these four separations requires an additional simply defined plate boundary segment. Otherwise, the boundaries that we use are identical with those of *Bird* [2003]. The updated digital plate boundaries are given in Table S1 of the auxiliary material.[1]

2.2. Relative Plate Angular Velocities

[5] We start with the 25 plate relative angular velocities in MORVEL. We next tie each of the 31 plate angular velocities from *Bird* [2003] to MORVEL through the same plate to which *Bird* [2003] tied it to NUVEL-1A. For example, we added *Bird*'s [2003] Shetland plate to MORVEL using *Bird*'s [2003] angular velocity of the Shetland plate relative to the Antarctica plate. We added the Bird's Head, Maoke, Solomon Sea, Woodlark, Conway Reef, Futuna, Kermadec, Niuafo'ou, and Tonga plates of *Bird* [2003] using his angular velocity for each of them relative to the Australia plate, and so forth, going through each of eleven MORVEL plates (Table S2).

2.3. Net Rotation Matrix

[6] We determine the net rotation matrix Q (Table S3) using equation (1) of *Argus and Gordon* [1991]. We determine the angular velocities of the Pacific plate in the no-net-rotation reference frame using equation (2) of *Argus and Gordon* [1991]. We determine the full 168 by 168 covariance matrix

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GC003751.

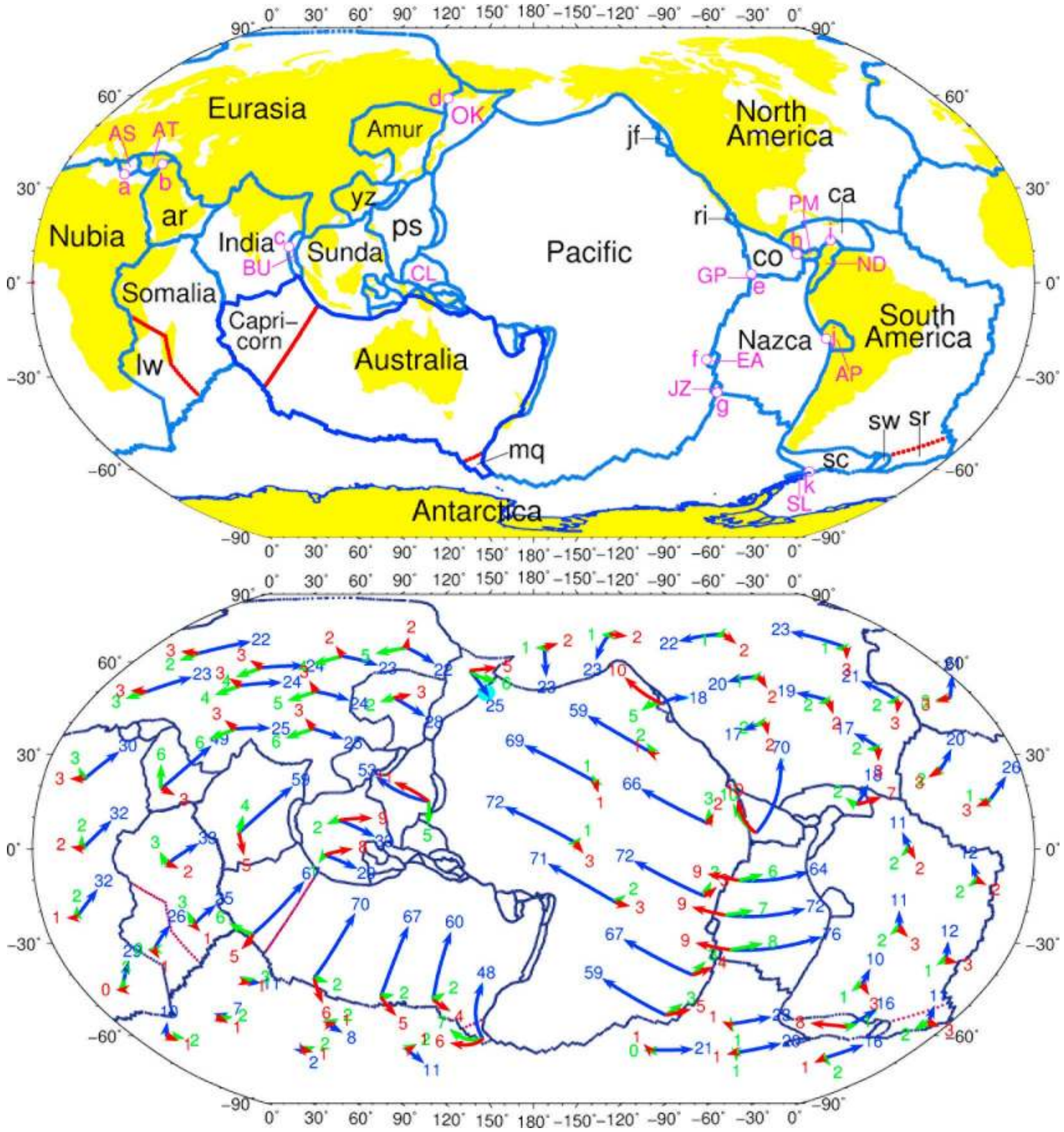

Figure 1. (top) The 56 plates in NNR-MORVEL56, which consist of the 25 plates in MORVEL (black text) [*DeMets et al.*, 2010] and 31 additional small plates from *Bird* [2003] (magenta text). Two-letter abbreviations (see Table 1) are lowercase for MORVEL plates and uppercase for the 31 plates from *Bird* [2003]. Plate boundaries are identical to those from *Bird* [2003] (in blue), except for (in red) the Lwandle-Somalia, Capricorn-Australia, Macquarie-Australia, and Sur-South America plate boundaries. MORVEL56 relative plate velocities at locations (a) through (k) are shown in Figure S1 of the auxiliary material. (bottom) The blue arrows and numerals show the NNR-MORVEL56 horizontal velocities and 95% confidence limits (light blue, imperceptible except for the Okhotsk plate). The red arrows and numerals show velocity differences between NNR-MORVEL56 and NNR-NUVEL1A. The green arrows and numerals show velocity differences between NNR-MORVEL56 and GSRM-NNR-2 [*Kreemer et al.*, 2006]. Speeds are in mm a^{-1}.

describing uncertainties in the 56 plates following the method of *Gripp* [1994].

2.4. Uncertainties in the Plate Angular Velocities of *Bird* [2003]

[7] While *Bird* [2003] specified angular velocities, he did not specify the uncertainties. Here we assign an approximate uncertainty to each plate angular velocity from *Bird* [2003] so that, on Earth's surface, the one-dimensional 1σ uncertainty is equal to the larger of the following two values: (1) 2.5 mm a^{-1} or (2) 5% of the root-mean-square (RMS) velocity of the *Bird* [2003] plate relative to the MORVEL plate to which we tie the *Bird* [2003] plate. For example, we assign an uncertainty of 5.6 mm a^{-1} to the Tonga

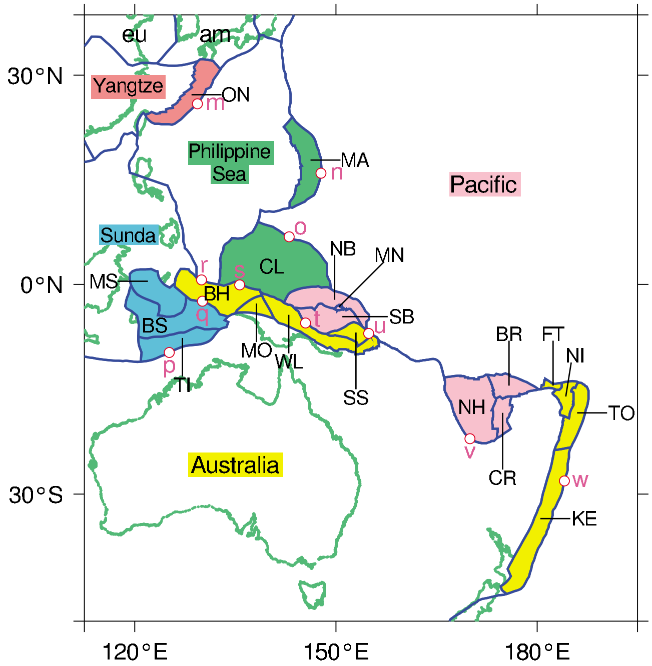

Figure 2. NNR-MORVEL56 plates in the southwest Pacific ocean (enlargement of Figure 1). The colors of the plates from *Bird* [2003] specify the MORVEL plate (text color highlight) that the *Bird* [2003] plate is tied to. MORVEL56 relative plate velocities at locations (m) through (w) are shown in Figure S2 of the auxiliary material.

plate, which has an RMS velocity relative to the Australia plate of 111.8 mm a^{-1}. We assign an uncertainty of 2.5 mm a^{-1} to the Shetland plate, which has an RMS velocity relative to the Antarctica plate of 10 mm a^{-1}. Thus, the uncertainty is initially described in the reference frame of the MORVEL plate to which we tie the *Bird* [2003] plate, but is later transformed to that of the Pacific plate using the full 72 by 72 MORVEL covariance matrix.

3. Results

[8] The NNR-MORVEL56 plate angular velocities are in Table 1. The three by three block-diagonal covariance matrices describing the uncertainties in the angular velocities are in Table 2. The NNR-MORVEL56 angular velocities and uncertainties relative to the Pacific plate are given in Table 3. The NNR-MORVEL56 rotation poles and 95% confidence limits are in Figure 3. All 56 plates in NNR-MORVEL56 move significantly relative to the no-net-rotation reference frame (Table 1).

[9] The auxiliary material includes Table S4, the 56 NNR-MORVEL56 angular velocities and full 168 by 168 covariance matrix, and Table S5, the relative plate angular velocity and 3 by 3 covariance matrix for each of the 1596 plate pairs. Horizontal velocities of locations on Earth's surface indicated by the NNR-MORVEL56 angular velocities can be determined at www.geology.wisc.edu/~chuck/MORVEL.

4. Discussion

4.1. Comparison of NNR-MORVEL56 With NNR-MORVEL

[10] How much does the inclusion of the 31 small plates from *Bird* [2003], which constitute 2.8% of Earth's surface, affect our estimate of plate motion in the no-net-rotation reference frame? To investigate this, after assigning each of the 31 additional plates from *Bird* [2003] to an adjacent MORVEL plate, we determined NNR-MORVEL, a set of angular velocities containing only the 25 plates in MORVEL. (Text S2 and column 3 of Table S3 describe how each of the 56 plates in MORVEL56 are assigned to a MORVEL plate in NNR-MORVEL; we assign the *Bird* [2003] plate to the NUVEL-1A plate to which *Bird* [2003] tied it for all but five plates; Table S6 lists the NNR-MORVEL angular velocities and full covariance matrix.) The angular velocities of the 25 plates in NNR-MORVEL differ little from those of the same plates in NNR-MORVEL56, with the changes in angular velocity being less than 0.001° Ma^{-1} (and in

Table 1. NNR-MORVEL56 Plate Angular Velocities (No-Net-Rotation Frame Fixed)[a]

Plate	Abbreviation	Latitude (°N)	Longitude (°E)	ω (° Ma^{-1})	RMS (mm a^{-1})	Area
MORVEL Plates						
Amur	am	63.17	−122.82	0.297 ± 0.020	28.1	0.1307
Antarctica	an	65.42	−118.11	0.250 ± 0.008	15.2	1.4327
Arabia	ar	48.88	−8.49	0.559 ± 0.016	47.6	0.1208
Australia	au	33.86	37.94	0.632 ± 0.017	63.1	0.9214
Capricorn	cp	44.44	23.09	0.608 ± 0.019	66.2	0.2036
Caribbean	ca	35.20	−92.62	0.286 ± 0.023	14.9	0.0730
Cocos	co	26.93	−124.31	1.198 ± 0.045	74.6	0.0722
Eurasia	eu	48.85	−106.50	0.223 ± 0.009	22.8	1.1963
India	in	50.37	−3.29	0.544 ± 0.010	57.6	0.3064
Juan de Fuca	jf	−38.31	60.04	0.951 ± 0.256	17.4	0.0063
Lwandle	lw	51.89	−69.52	0.286 ± 0.026	26.5	0.1171
Macquarie	mq	49.19	11.05	1.144 ± 0.274	49.5	0.0079
Nazca	nz	46.23	−101.06	0.696 ± 0.029	70.0	0.3967
North America	na	−4.85	−80.64	0.209 ± 0.013	19.8	1.3657
Nubia	nb	47.68	−68.44	0.292 ± 0.007	29.2	1.4406
Pacific	pa	−63.58	114.70	0.651 ± 0.011	65.5	2.5768
Philippine Sea	ps	−46.02	−31.36	0.910 ± 0.050	52.6	0.1341
Rivera	ri	20.25	−107.29	4.536 ± 0.630	11.8	0.0025
Sandwich	sw	−29.94	−36.87	1.362 ± 0.744	72.6	0.0045
Scotia	sc	22.52	−106.15	0.146 ± 0.016	16.2	0.0419
Somalia	sm	49.95	−84.52	0.339 ± 0.011	31.0	0.3548
South America	sa	−22.62	−112.83	0.109 ± 0.011	10.6	1.0034
Sunda	su	50.06	−95.02	0.337 ± 0.020	32.2	0.2197
Sur	sr	−32.50	−111.32	0.107 ± 0.028	11.0	0.0271
Yangtze	yz	63.03	−116.62	0.334 ± 0.013	36.5	0.0542
Bird's [2003] Plates						
Aegean Sea	AS	19.43	122.87	0.124 ± 0.050	13.7	0.0079
Altiplano	AP	−6.58	−83.98	0.488 ± 0.053	16.9	0.0205
Anatolia	AT	40.11	26.66	1.210 ± 0.049	14.0	0.0142
Balmoral Reef	BR	−63.74	142.06	0.490 ± 0.045	44.1	0.0048
Banda Sea	BS	−1.49	121.64	2.475 ± 0.058	33.1	0.0171
Birds Head	BH	−40.00	100.50	0.799 ± 0.089	66.2	0.0129
Burma	BU	−6.13	−78.10	2.229 ± 0.060	40.3	0.0127
Caroline	CL	−72.78	72.05	0.607 ± 0.047	67.3	0.0376
Conway Reef	CR	−20.40	170.53	3.923 ± 0.048	33.9	0.0036
Easter	EA	24.97	67.53	11.334 ± 0.081	44.9	0.0041
Futuna	FT	−16.33	178.07	5.101 ± 0.047	41.9	0.0008
Galapagos	GP	2.53	81.18	5.487 ± 0.063	55.9	0.0004
Juan Fernandez	JZ	34.25	70.74	22.368 ± 0.087	86.8	0.0024
Kermadec	KE	39.99	6.46	2.347 ± 0.048	45.4	0.0124
Manus	MN	−3.67	150.27	51.569 ± 0.061	55.8	0.0002
Maoke	MO	14.25	92.67	0.774 ± 0.049	64.4	0.0028
Mariana	MA	11.05	137.84	1.306 ± 0.070	26.7	0.0104
Molucca Sea	MS	2.15	−56.09	3.566 ± 0.058	20.9	0.0103
New Hebrides	NH	0.57	−6.60	2.469 ± 0.045	84.0	0.0159
Niuafo'ou	NI	−3.29	−174.49	3.314 ± 0.067	86.2	0.0031
North Andes	ND	17.73	−122.68	0.116 ± 0.051	9.6	0.0239
North Bismarck	NB	−45.04	127.64	0.856 ± 0.045	69.0	0.0096
Okhotsk	OK	30.30	−92.28	0.229 ± 0.051	25.0	0.0748
Okinawa	ON	36.12	137.92	2.539 ± 0.050	61.8	0.0080
Panama	PM	31.35	−113.90	0.317 ± 0.055	21.6	0.0067
Shetland	SL	50.71	−143.47	0.268 ± 0.048	22.5	0.0018
Solomon Sea	SS	−2.87	130.62	1.703 ± 0.049	71.9	0.0032
South Bismarck	SB	6.88	−31.89	8.111 ± 0.091	48.3	0.0076
Timor	TI	−4.44	113.50	1.864 ± 0.067	47.8	0.0087
Tonga	TO	25.87	4.48	8.942 ± 0.100	121.8	0.0062
Woodlark	WL	0.10	128.52	1.744 ± 0.049	66.6	0.0112

[a] Each plate rotates counterclockwise relative to the no-net-rotation reference frame. RMS is the root-mean-square velocity of the plate relative to the no-net-rotation reference frame. Area is in steradians for a unit sphere and total to 4π. The RMS velocity of the entire lithosphere is 43.9 mm a^{-1}. 95% confidence limits follow the "±." Some two-letter abbreviations from *Bird* [2003] are identical to those used for other plates by *DeMets et al.* [2010]. To preserve consistency with earlier papers we keep the same two-letter abbreviations while using capital letters for plates from *Bird* [2003] and lowercase letters for plates from *DeMets et al.* [2010].

Table 2. Covariance Matrices of the NNR-MORVEL56 Plate Angular Velocities (No-Net-Rotation Frame Fixed)[a]

		Covariance Matrix					
Plate	Abbreviation	xx	xy	xz	yy	yz	zz
MORVEL Plates							
Amur	am	223	−67	−102	376	309	535
Antarctica	an	49	32	−20	34	−10	36
Arabia	ar	208	182	112	398	104	87
Australia	au	137	68	66	116	2	134
Capricorn	cp	197	105	68	696	−378	370
Caribbean	ca	106	−137	12	485	−41	165
Cocos	co	774	273	−616	1036	−367	613
Eurasia	eu	68	5	7	65	14	87
India	in	65	80	32	451	59	49
Juan de Fuca	jf	10237	13370	−15644	17958	−20659	25637
Lwandle	lw	312	257	−382	281	−324	517
Macquarie	mq	14827	−6847	27711	3509	−13202	52672
Nazca	nz	75	147	−121	564	−199	332
North America	na	59	−30	−18	119	54	108
Nubia	nb	31	0	−27	74	13	54
Pacific	pa	43	31	−5	245	8	72
Philippine Sea	ps	955	−960	−578	1358	644	468
Rivera	ri	23657	77569	−28379	257086	−93915	35257
Sandwich	sw	130549	−65658	−228089	35925	116372	402768
Scotia	sc	244	−296	−756	520	1161	3784
Somalia	sm	32	47	−2	163	−6	37
South America	sa	42	0	−26	62	50	102
Sunda	su	216	−131	21	943	185	190
Sur	sr	1590	−158	−2228	93	322	3340
Yangtze	yz	178	−12	17	283	105	203
PB2002 Plates							
Aegean Sea	AS	1722	99	−4	2210	104	1842
Altiplano	AP	1678	52	−64	2240	162	1827
Anatolia	AT	1721	100	−3	2209	105	1840
Balmoral Reef	BR	1583	31	−4	1783	8	1611
Banda Sea	BS	1777	−246	40	2748	135	1876
Birds Head	BH	6008	−54	88	6224	−56	6110
Burma	BU	1776	−243	40	2750	136	1877
Caroline	CL	2489	−967	−579	2890	645	1994
Conway Reef	CR	1698	−45	88	1911	−56	1807
Easter	EA	4349	307	−117	5751	−428	4544
Futuna	FT	1698	−45	88	1912	−56	1808
Galapagos	GP	1685	305	−117	3084	−430	1879
Juan Fernandez	JZ	5335	306	−117	6736	−428	5530
Kermadec	KE	1696	−45	90	1908	−56	1805
Manus	MN	2964	31	−5	3165	8	2993
Maoke	MO	1697	−45	88	1912	−56	1808
Mariana	MA	2493	−962	−579	2895	645	2005
Molucca Sea	MS	1778	−245	40	2749	135	1878
New Hebrides	NH	1582	30	−3	1779	7	1607
Niuafo’ou	NI	3567	−45	89	3779	−56	3675
North Andes	ND	1677	52	−63	2241	160	1825
North Bismarck	NB	1582	30	−5	1782	8	1609
Okhotsk	OK	1678	17	−46	2282	93	1824
Okinawa	ON	1745	−125	40	2090	53	1905
Panama	PM	1788	−82	−11	2841	61	1936
Shetland	SL	1640	132	0	2094	10	1708
Solomon Sea	SS	1698	−45	88	1912	−56	1807
South Bismarck	SB	6528	26	−4	6724	7	6548
Timor	TI	2612	−245	40	3583	135	2712
Tonga	TO	7857	−44	92	8062	−55	7959
Woodlark	WL	1697	−47	88	1910	−56	1805

[a] Each 3 by 3 covariance matrix is in Cartesian coordinates (*x* axis (0°N °E), *y* axis (0°N 90°E), and *z* axis (90°N)) and in units of 10^{-10} radians^2 Ma^{-2}.

Table 3. NNR-MORVEL56 Plate Angular Velocities and Covariance Matrices (Pacific Plate Fixed)[a]

Plate	Abbreviation	Latitude (°N)	Longitude (°E)	ω (°/Ma)	xx	xy	xz	yy	yz	zz
MORVEL Plates										
Amur	am	65.92	−82.68	0.929	209	−210	−73	400	251	628
Antarctica	an	65.92	−78.53	0.887	82	139	9	428	9	106
Arabia	ar	60.02	−33.23	1.159	254	241	112	1042	84	211
Australia	au	60.08	6.33	1.079	123	−75	95	141	−57	228
Capricorn	cp	62.34	−10.12	1.139	203	3	51	1174	−601	510
Caribbean	ca	55.76	−77.48	0.905	210	−111	−7	1059	58	332
Cocos	co	42.18	−112.78	1.676	872	704	−648	1483	−746	587
Eurasia	eu	61.27	−78.87	0.856	186	81	−19	539	76	258
India	in	61.39	−31.21	1.141	104	115	29	1040	28	173
Juan de Fuca	jf	−0.62	37.84	0.625	10140	13064	−15642	17403	−20787	25574
Lwandle	lw	60.03	−66.90	0.932	331	307	−352	761	−308	592
Macquarie	mq	59.21	−7.98	1.686	14789	−7093	27733	3576	−13360	52758
Nazca	nz	55.86	−87.76	1.311	111	289	−127	1335	−484	306
North America	na	48.89	−71.71	0.750	165	−3	−36	704	151	275
Nubia	nb	58.68	−66.57	0.935	107	49	−63	574	49	222
Philippine Sea	ps	−4.63	−41.87	0.890	910	−991	−577	1117	642	403
Rivera	ri	25.69	−104.80	4.966	23584	77386	−28397	256619	−94195	35207
Sandwich	sw	−3.84	−42.36	1.444	130590	−65861	−228117	36796	116449	402923
Scotia	sc	57.84	−78.02	0.755	342	−262	−801	999	1299	3973
Somalia	sm	59.27	−73.55	0.980	77	137	0	684	−1	155
South America	sa	55.97	−77.03	0.653	124	64	−55	530	164	267
Sunda	su	59.81	−77.96	0.973	203	−271	50	971	130	287
Sur	sr	55.69	−75.77	0.636	1633	−36	−2209	515	400	3442
Yangtze	yz	65.45	−82.38	0.968	164	−155	46	307	45	295
NNR	xx	63.58	−65.30	0.651	43	31	−5	245	8	72
PB2002 Plates										
Aegean Sea	AS	74.36	−70.76	0.648	1726	81	−19	2079	76	1798
Altiplano	AP	34.56	−77.01	0.929	1664	64	−55	2070	164	1807
Anatolia	AT	54.82	9.12	1.667	1726	81	−19	2079	76	1798
Balmoral Reef	BR	45.90	−111.00	0.200	1540	0	0	1540	0	1540
Banda Sea	BS	13.34	122.56	2.248	1743	−271	50	2511	130	1827
Birds Head	BH	11.59	88.39	0.346	5983	−75	95	6000	−57	6088
Burma	BU	7.86	−76.63	2.523	1743	−271	50	2511	130	1827
Caroline	CL	0.99	−27.64	0.199	2449	−991	−577	2656	642	1943
Conway Reef	CR	−12.56	174.43	3.609	1663	−75	95	1680	−57	1768
Easter	EA	28.04	66.32	11.420	4319	289	−127	5542	−484	4513
Futuna	FT	−10.12	−178.82	4.847	1663	−75	95	1680	−57	1768
Galapagos	GP	8.94	79.43	5.307	1651	289	−127	2875	−484	1846
Juan Fernandez	JZ	35.77	70.11	22.532	5304	289	−127	6527	−484	5498
Kermadec	KE	47.61	−1.83	2.832	1663	−75	95	1680	−57	1768
Manus	MN	−3.04	150.46	51.300	2921	0	0	2921	0	2921
Maoke	MO	57.43	79.96	0.918	1663	−75	95	1680	−57	1768
Mariana	MA	39.19	144.24	1.319	2449	−991	−577	2656	642	1943
Molucca Sea	MS	10.54	−56.78	3.915	1743	−271	50	2511	130	1827
New Hebrides	NH	13.00	−12.00	2.700	1540	0	0	1540	0	1540
Niuafo’ou	NI	6.95	−169.62	3.248	3532	−75	95	3549	−57	3637
North Andes	ND	59.68	−80.24	0.716	1664	64	−55	2070	164	1807
North Bismarck	NB	−4.00	139.00	0.330	1540	0	0	1540	0	1540
Okhotsk	OK	55.81	−76.20	0.844	1704	−3	−36	2244	151	1815
Okinawa	ON	49.30	141.58	2.743	1704	−155	46	1847	45	1835
Panama	PM	55.66	−88.73	0.906	1750	−111	−7	2599	58	1872
Shetland	SL	65.24	−92.39	0.870	1622	139	9	1968	9	1645
Solomon Sea	SS	19.26	133.82	1.509	1663	−75	95	1680	−57	1768
South Bismarck	SB	10.61	−32.99	8.440	6488	0	0	6488	0	6488
Timor	TI	15.62	113.28	1.629	2578	−271	50	3346	130	2662
Tonga	TO	28.82	2.57	9.303	7824	−75	95	7841	−57	7928
Woodlark	WL	21.81	131.23	1.578	1663	−75	95	1680	−57	1768

[a] Each plate rotates counterclockwise relative to the Pacific plate. Each 3 by 3 covariance matrix is in Cartesian coordinates (*x* axis (0°N °E), *y* axis (0°N 90°E), and *z* axis (90°N)) and in units of 10^{-10} radians^2 Ma^{-2}.

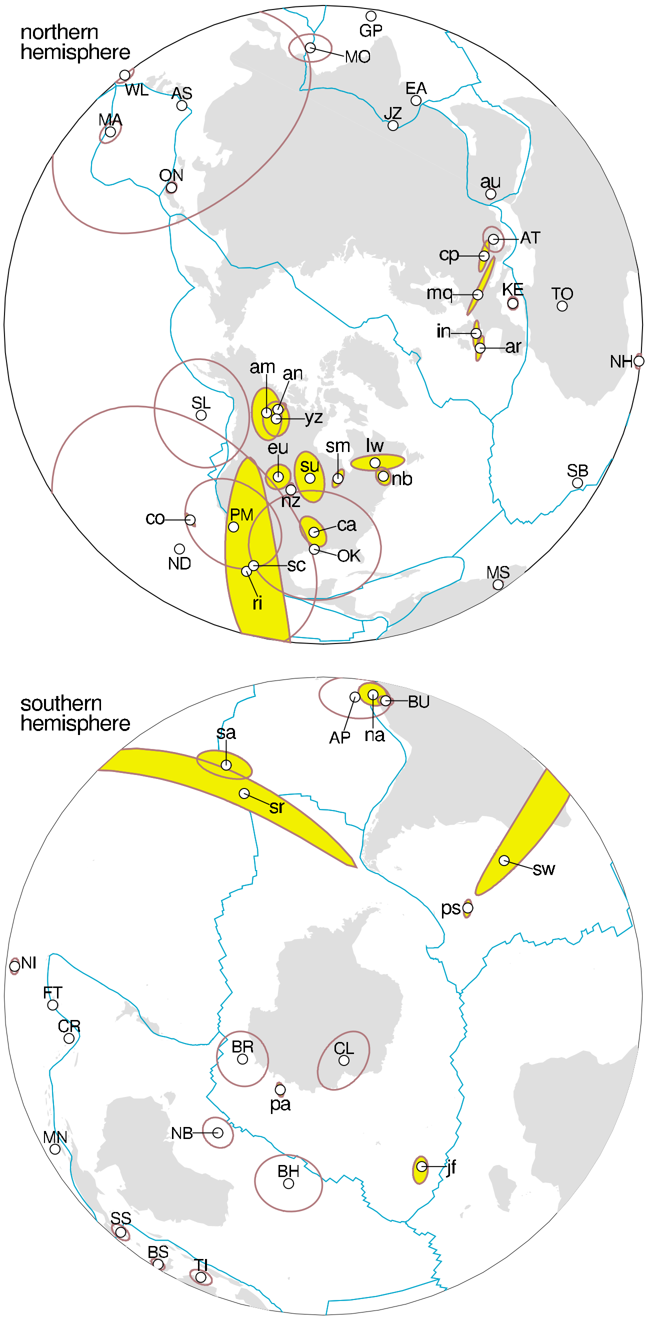

Figure 3. NNR-MORVEL56 rotation ples and 95% confidence limits. For many plates the 95% confidence limits are smaller than the circle marking the location of their rotation pole.

velocity being less than 0.1 mm a^{-1}). The difference between the two sets of angular velocities in the RMS velocity of the surface of the Earth is 5.7 mm a^{-1}, but only 0.1 mm a^{-1} when the average excludes the surface area of the 31 small plates. Thus including the 31 small plates has little effect on the motion of the 25 large plates in the no-net-rotation reference frame.

4.2. Comparison of NNR-MORVEL56 With NNR-NUVEL1A

[11] Given that MORVEL is determined from more and higher-quality spreading rates and azimuths than is NUVEL-1A, we expect MORVEL to be superior to NUVEL-1A. Moreover, MORVEL also differs from NUVEL-1A in that MORVEL excludes circum-Pacific data (earthquake slip vectors and

Table 4. Angular Velocity and Root-Mean-Square Velocity Differences Between NNR-MORVEL56 and NNR-NUVEL1A[a]

Plate	Abbreviation	Latitude (°N)	Longitude (°E)	ω (°/Ma)	RMS (mm a^{-1})	Area	Net Rotation
NUVEL1A Plates							
Philippine Sea	ps	−40.77	105.57	0.128	12.7	0.011	0.043
Juan de Fuca	jf	−56.28	65.23	0.371	9.8	0.001	0.002
Cocos	co	−13.16	90.70	0.365	7.0	0.006	0.009
Nazca	nz	−67.92	102.69	0.052	5.6	0.032	0.056
Caribbean	ca	61.90	−90.41	0.085	7.1	0.006	0.013
India	in	35.53	−147.92	0.052	5.2	0.024	0.040
Arabia	ar	47.22	−128.31	0.046	4.8	0.010	0.015
Somalia	sm	35.23	−126.89	0.061	3.4	0.028	0.027
Pacific	pa	−17.18	−157.39	0.039	2.8	0.205	0.128
Australia	au	−9.75	140.82	0.046	2.8	0.073	0.049
North America	na	−24.32	2.40	0.021	2.1	0.109	0.069
South America	sa	20.63	−16.42	0.023	2.0	0.080	0.047
Eurasia	eu	−39.97	−13.10	0.020	1.9	0.095	0.056
Nubia	nb	−21.04	−14.40	0.024	1.6	0.115	0.046
Antarctica	an	68.97	107.36	0.016	1.1	0.114	0.028
MORVEL Plates							
Sandwich	sw	−37.45	−31.63	1.466	57.4	0.000	0.007
Rivera	ri	18.01	−103.28	3.053	27.1	0.000	0.002
Yangtze	yz	84.38	170.83	0.117	11.3	0.004	0.016
Sunda	su	41.85	−64.43	0.117	9.6	0.017	0.053
Scotia	sc	−77.72	−73.55	0.160	6.9	0.003	0.007
Capricorn	cp	26.36	−111.85	0.148	6.0	0.016	0.027
Amur	am	70.97	123.89	0.090	4.4	0.010	0.014
Macquarie	mq	57.52	−27.83	0.600	3.7	0.001	0.000
Sur	sr	−15.71	5.16	0.028	2.1	0.002	0.001
Lwandle	lw	0.78	48.50	0.016	0.9	0.009	0.003

[a]Net rotation is the fraction of 1. The RMS velocity difference between NNR-MORVEL56 and NNR-NUVEL1A is 7.6 mm a^{-1} for the whole lithosphere, 3.6 mm a^{-1} for the 25 plates in MORVEL (97.2% of Earth's surface), and 3.0 mm a^{-1} for the 14 plates in NUVEL-1A (81% of Earth's surface).

Pacific-North America spreading rates) that are biased measures of relative plate velocity. Thus, in MORVEL the angular velocity of the plates of the Pacific ocean basin (Pacific, Nazca, Cocos) relative to the surrounding continental plates (Eurasia, North America, South America) depend mainly on the plate circuit North America-Nubia-Antarctica-Pacific [*DeMets et al.*, 2010, Figure 2].

[12] Relative plate velocities differ significantly between MORVEL and NUVEL-1A. Of the 36 relative angular velocities between the nine largest plates (Pacific, Nubia, Antarctica, North America, Eurasia, South America, Australia, Nazca, and Somalia), the 95% confidence limits in the MORVEL angular velocity exclude all but one of the corresponding NUVEL-1A angular velocities. Differences in angular velocity among the 36 plate pairs are vectors ranging in length from 0.007° Ma^{-1} to 0.105° Ma^{-1}, with the median difference having a length of 0.053° Ma^{-1}, which corresponds to 5.9 mm a^{-1} or less along Earth's surface [*DeMets et al.*, 2010].

[13] The angular velocities in NNR-MORVEL56 differ significantly from those in NNR-NUVEL1A for all 14 plates that constitute NNR-NUVEL1A. Angular velocity differences are vectors ranging in length from 0.016° Ma^{-1} for the Antarctica plate to 0.0371° Ma^{-1} for the Juan de Fuca plate. RMS velocity differences range from 1 mm a^{-1} for the Antarctica plate to 13 mm a^{-1} for the Philippine Sea plate (Table 4). Among the 14 plates in NUVEL-1A, the largest RMS velocity differences are 13 mm a^{-1} for the Philippine Sea plate, 10 mm a^{-1} for the Juan de Fuca plate, and 7 mm a^{-1} for the Cocos plate. These differences result mainly from differences between MORVEL and NUVEL-1A respectively in the Philippine Sea-Pacific, Juan de Fuca-Pacific, and Cocos-Pacific angular velocities.

[14] The plate for which the net rotation differs most between NNR-MORVEL56 and NNR-NUVEL1A is the Pacific plate (Table 4). The angular velocity of the Pacific plate differs significantly between NNR-NUVEL1A and NNR-MORVEL by 0.039 ± 0.011° Ma^{-1} (95% confidence limits), resulting in a difference of 2.8 mm a^{-1} in RMS velocity. If we substitute into NNR-MORVEL the NUVEL-1A Pacific-Antarctica angular velocity while keeping the angular velocities on either side

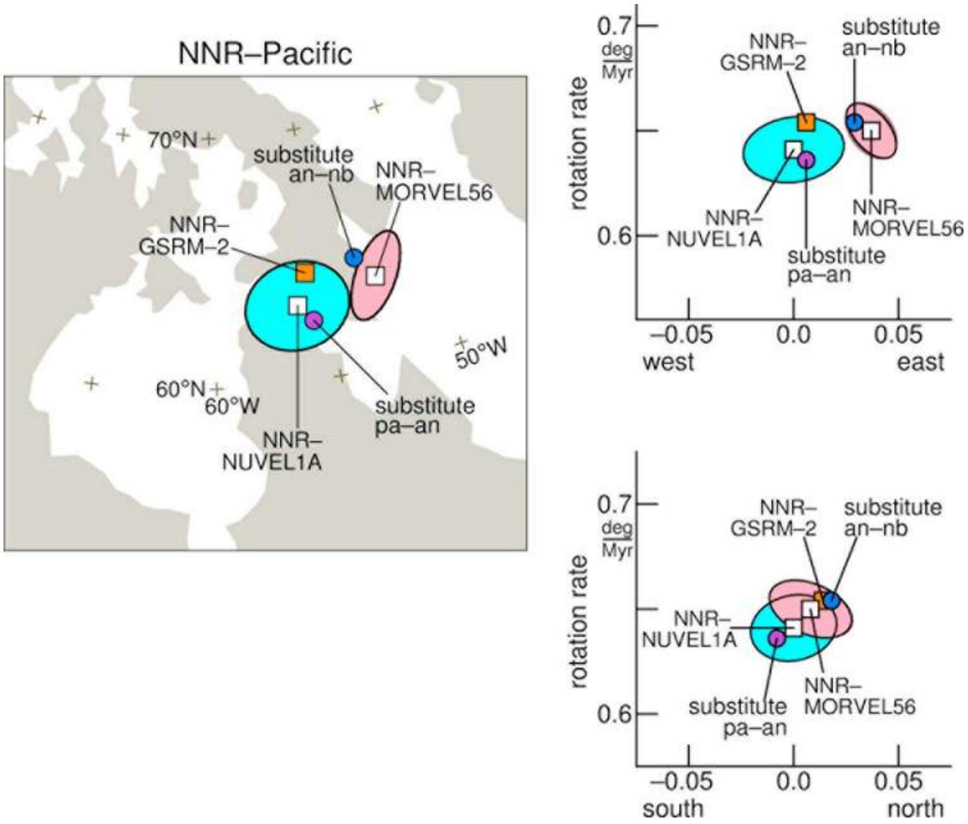

Figure 4. Estimates of the NNR-Pacific plate angular velocity and 95% confidence limits projected onto three perpendicular plates: (left) Rotation poles, (right top) profile from west to east, and (right bottom) profile from south to north. Angular velocities are NNR-MORVEL56, NNR-NUVEL1A, and NNR-GSRM-2 [*Kreemer et al.*, 2006], and the angular velocity determined substituting either the Pacific-Antarctica or Antarctica-Nubia NUVEL-1A angular velocity into NNR-MORVEL56 while keeping the same the MORVEL56 relative plate velocities on either side of the link.

of this link equal to those in MORVEL, we find (Figure 4, violet-filled circle) that the angular velocity of the Pacific plate is nearly equal to that in NNR-NUVEL1A. Thus the change in Pacific plate angular velocity appears to be mainly caused by the change in Pacific-Antarctica angular velocity.

[15] The angular velocity of the North America plate also differs significantly between NNR-NUVEL1A and NNR-MORVEL by 0.021° Ma^{-1} in angular velocity and by 2.1 mm a^{-1} in RMS velocity, which is caused mainly by the difference between NUVEL-1A and MORVEL in the Antarctica-Nubia angular velocity (Figure 5, navy-filled circle).

4.3. Comparison of NNR-MORVEL56 With NNR-GSRM-2

[16] The velocity of Earth's surface differs between NNR-MORVEL56 and NNR-GSRM-2 [*Kreemer et al.*, 2006] by an RMS velocity of 7.2 mm a^{-1}, but the RMS velocity difference for the part of Earth's surface covered by the 27 plates in common is smaller, 3.2 mm a^{-1}. The RMS differences in plate velocity range from 1 mm a^{-1} for the Yangtze plate to 16 mm a^{-1} for the Caroline plate (Table 5). Differences are partly due to differences in the length of time over which plate motions are estimated. Spreading rates in MORVEL56 are determined mainly from magnetic anomalies, which average rates over 780,000 years to 3.2 million years, while rates in GSRM-2 are determined mainly from space geodetic observations over ≈15 years.

[17] Among Earth's nine largest plates, the RMS velocity difference between NNR-MORVEL56 and NNR-GSRM-2 is largest, 7 mm a^{-1}, for the Nazca plate as the east component of the velocity of the Nazca plate relative to the surrounding Pacific, Antarctica, and South America plates has

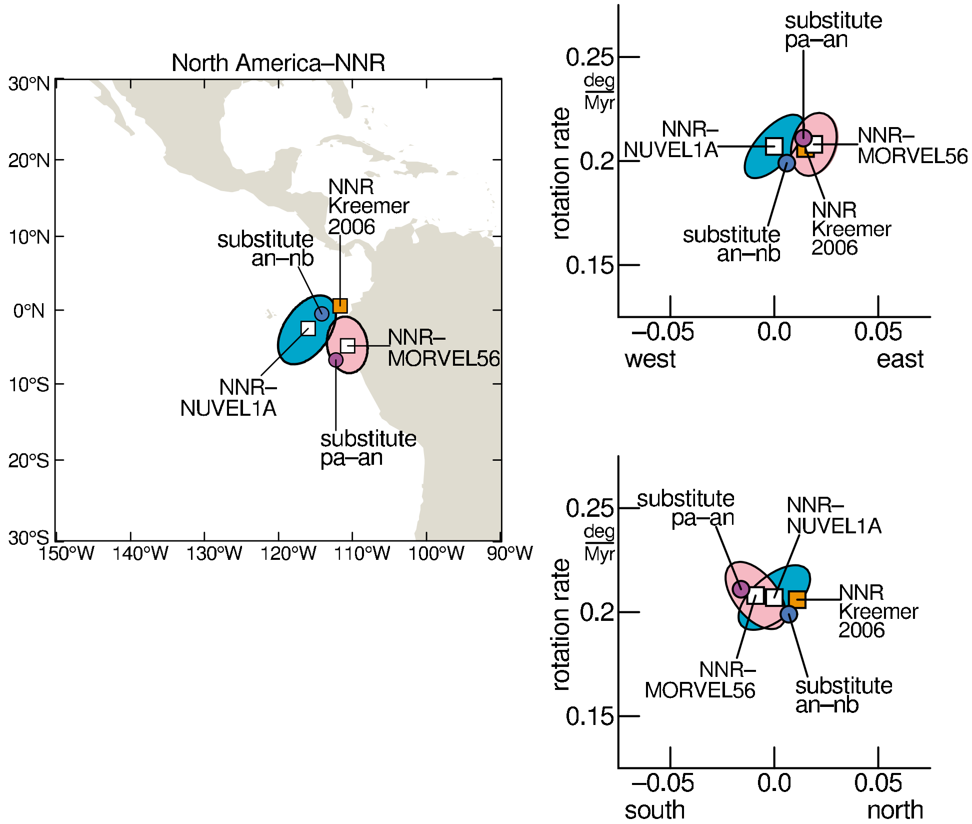

Figure 5. Estimates of the NNR-North America plate angular velocity and 95% confidence limits projected onto three perpendicular plates: (left) Rotation poles, (right top) profile from west to east, and (right bottom) profile from south to north. Angular velocities are NNR-MORVEL56, NNR-NUVEL1A, and NNR-GSRM-2 [*Kreemer et al.*, 2006], and the angular velocity determined substituting either the Pacific-Antarctica or Antarctica-Nubia NUVEL-1A angular velocity into NNR-MORVEL56 while keeping the same the MORVEL56 relative plate velocities on either side of the link.

decreased since 0.8 Ma ago [*Tebbens and Cande*, 1997; *Angermann et al.*, 1999, *Norabuena et al.*, 1999; *Sella et al.*, 2002; *Kendrick et al.*, 2003; *Argus et al.*, 2010], the age of the magnetic reversal used to estimate Nazca-Pacific motion in MORVEL. The 8 mm a^{-1} RMS difference for the Cocos plate may also result from a change in Cocos plate motion since 0.8 Ma. The 4.5 mm a^{-1} RMS difference for the Eurasia plate results from the north component of the velocities of the Nubia, Arabia, and India plates relative to the Eurasia plate having decreased since 3.2 Ma [*Sella et al.*, 2002], the age of the magnetic anomalies used to estimate the motion of these plates in MORVEL.

[18] The largest differences between NNR-MORVEL56 and NNR-GSRM-2 are for small plates and result from differences in the angular velocities used to tie the small plate to a large plate. For example, the 16 mm a^{-1} RMS difference for the Caroline plate results from differences in the Caroline-Pacific angular velocity. The GSRM-2 Philippine Sea-Caroline angular velocity (48.1°N, 73.3°W, 0.152° Ma^{-1}) is incorrect because it predicts 15 mm a^{-1} of convergence across the Ayu trough, not slow divergence as observed [*Bird*, 2003].

[19] Similarly the 12 mm a^{-1} RMS difference for the Okhotsk plate results from differences in the Okhotsk-North America angular velocity. In GSRM-2 the Okhotsk plate is converging with the Amur plate at 11 to 29 mm a^{-1}. In MORVEL56 the Okhotsk plate moves relative to the Amur plate toward the southwest at 3 to 7 mm a^{-1}, suggesting there is slow right-lateral slip and convergence across the boundary, consistent with the earthquake fault plane solutions there. The GPS site Magadan, on the Okhotsk plate, is moving relative to the North America plate toward the southwest at 1.8 mm a^{-1} [*Argus et al.*, 2010], a velocity that differs

Table 5. Angular Velocity and Root-Mean-Square Velocity Differences Between NNR-MORVEL56 and the NNR-GSRM-2[a]

Plate	Abbreviation	Latitude (°N)	Longitude (°E)	ω (°/Ma)	RMS (mm a^{-1})	Area	Net Rotation
MORVEL56 Plates[b]							
Caroline	CL	18.29	143.33	0.534	16.4	0.003	0.017
Okhotsk	OK	62.31	165.41	0.371	11.6	0.006	0.021
Cocos	co	−17.75	87.37	0.346	7.9	0.006	0.013
Nazca	nz	40.03	−114.91	0.075	7.4	0.032	0.082
Arabia	ar	−16.53	−54.49	0.053	5.6	0.010	0.019
Anatolia	AT	−54.29	−159.59	0.160	5.6	0.001	0.002
Juan de Fuca	jf	40.29	−130.01	0.416	4.9	0.001	0.001
Macquarie	mq	56.01	−26.98	0.626	4.6	0.001	0.001
Eurasia	eu	−69.86	156.58	0.062	4.5	0.095	0.123
Philippine Sea	ps	−10.57	−64.11	0.113	4.4	0.011	0.015
Capricorn	cp	6.36	−98.71	0.150	4.0	0.016	0.014
India	in	13.70	28.23	0.046	3.8	0.024	0.032
Rivera	ri	−20.13	−163.82	0.036	3.7	0.000	0.000
Somalia	sm	−27.42	−15.38	0.027	2.7	0.028	0.027
Sunda	su	−10.07	112.03	0.068	2.4	0.017	0.012
Pacific	pa	10.87	−169.38	0.032	2.3	0.205	0.111
Nubia	nb	−3.35	−18.73	0.034	2.2	0.115	0.066
Sur	sr	−55.38	44.29	0.035	2.1	0.002	0.002
Caribbean	ca	−45.33	−100.48	0.021	2.1	0.006	0.004
Amur	am	−1.57	135.85	0.025	2.1	0.010	0.008
Australia	au	12.47	112.34	0.023	1.9	0.073	0.047
Antarctica	an	64.11	42.26	0.025	1.8	0.114	0.056
Lwandle	lw	−31.09	35.78	0.092	1.7	0.009	0.003
Scotia	sc	63.34	145.81	0.072	1.6	0.003	0.002
South America	sa	−53.52	33.54	0.016	1.6	0.080	0.043
North America	na	−79.05	−2.69	0.020	1.5	0.109	0.045
Yangtze	yz	−43.76	−81.70	0.021	0.9	0.004	0.001

[a] Net rotation is the fraction of 1. The RMS velocity difference between NNR-MORVEL56 and NNR-GSRM-2 is 7.2 mm a^{-1} for the whole lithosphere and 3.2 mm a^{-1} for the 27 plates in both MORVEL and GSRM-2 (98.0% of Earth's surface).

[b] Also in the study by *Kreemer et al.* [2006].

insignificantly from both zero and the MORVEL56 prediction.

5. Conclusions

[20] NNR-MORVEL56 improves upon, and differs significantly from, NNR-NUVEL1A. Differences in angular velocities are vectors ranging in length from 0.016° Ma^{-1} (for the Antarctica plate) to 0.371° Ma^{-1} (for the Juan de Fuca plate), with the median difference being 0.046° Ma^{-1} (corresponding to a maximum difference in surface velocity of ≈5 mm a^{-1}). Some of the largest differences in angular velocity occur for the Philippine Sea, Nazca, and Cocos plates, and are mainly due to differences in their angular velocities relative to the Pacific plate.

[21] The difference in angular velocity for the Pacific plate between NNR-NUVEL1A and NNR-MORVEL56 is 0.039° Ma^{-1} and is a consequence mainly of the difference in Pacific-Antarctica angular velocity.

[22] The difference in angular velocity for the North America plate between NNR-NUVEL1A and NNR-MORVEL56 is 0.021° Ma^{-1} and is a consequence mainly of the difference in North America-Nubia angular velocity.

[23] Incorporating the 31 additional plates of *Bird* [2003] into NNR-MORVEL56 changes the angular velocities of the 25 major plates in the no-net-rotation reference frame only negligibly.

[24] NNR-MORVEL56 differs significantly from NNR-GSRM-2 [*Kreemer et al.*, 2006], partly due to differences between plate velocities averaged over hundreds of thousands to millions of years in the former versus plate velocities averaged over years in the latter.

Acknowledgments

[25] We are grateful to Peter Bird (University of California Los Angeles) for the plate boundaries and plate angular velocities in the model of *Bird* [2003]. D. F. Argus completed research at Jet Propulsion Laboratory, California Institute of

Technology, under contract with the National Aeronautics and Space Administration (NASA). RGG was supported by NSF grants OCE-0453219, OCE-0527375, OCE-0928961, and OCE-1061222. We thank Tim Dixon and an anonymous reviewer for their helpful comments and suggestions.

References

Altamimi, Z., P. Sillard, and C. Boucher (2002), ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications, *J. Geophys. Res.*, *107*(B10), 2214, doi:10.1029/2001JB000561.

Altamimi, Z., X. Collilieux, J. Legrand, B. Garayt, and C. Boucher (2007), ITRF2005: A new release of International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters, *J. Geophys. Res.*, *112*, B09401, doi:10.1029/2007JB004949.

Angermann, D., J. Klotz, and C. Reigber (1999), Space-geodetic estimation of the Nazca-South America Euler vector, *Earth Planet. Sci. Lett.*, *171*, 329–334, doi:10.1016/S0012-821X(99)00173-9.

Argus, D. F., and R. G. Gordon (1991), No-net-rotation model of current plate velocities incorporating plate motion model NUVEL-1, *Geophys. Res. Lett.*, *18*, 2039–2042, doi:10.1029/91GL01532.

Argus, D. F., R. G. Gordon, M. B. Heflin, C. Ma, R. J. Eanes, P. Willis, W. R. Peltier, and S. E. Owen (2010), The angular velocities of the plates and the velocity of Earth's center from space geodesy, *Geophys. J. Int.*, *180*, 913–960, doi:10.1111/j.1365-246X.2009.04463.x.

Bird, P. (2003), An updated digital model of plate boundaries, *Geochem. Geophys. Geosyst.*, *4*(3), 1027, doi:10.1029/2001GC000252.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein (1990), Current plate motions, *Geophys. J. Int.*, *101*, 425–478, doi:10.1111/j.1365-246X.1990.tb06579.x.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein (1994), Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.*, *21*, 2191–2194, doi:10.1029/94GL02118.

DeMets, D. C., R. G. Gordon, and D. F. Argus (2010), Geologically current plate motions, *Geophys. J. Int.*, *181*, 1–80, doi:10.1111/j.1365-246X.2010.04491.x.

Gripp, A. E. (1994), Current plate motions, reference frames, and uncertainties, Ph.D. thesis, Northwestern Univ., Evanston, Ill.

Kagan, Y. Y., P. Bird, and D. D. Jackson (2010), Earthquake patterns in diverse tectonic zones of the globe, *Pure Appl. Geophys.*, *167*, 721–741, doi:10.1007/s00024-010-0075-3.

Kendrick, E., M. Bevis, R. Smalley, B. Brooks, R. B. Vargas, E. Lauria, and L. P. S. Fortes (2003), The Nazca-South America Euler vector and its rate of change, *J. South Am. Earth Sci.*, *16*, 125–131, doi:10.1016/S0895-9811(03)00028-2.

Kreemer, C., D. A. Lavallee, G. Blewitt, and W. E. Holt (2006), On the stability of a geodetic no-net-rotation frame and its implication for the International Terrestrial Reference Frame, *Geophys. J. Int.*, *28*, 4407–4410.

Norabuena, E., T. Dixon, S. Stein, and C. G. A. Harrison (1999), Decelerating Nazca-South America and Nazca-Pacific motions, *Geophys. Res. Lett.*, *26*, 3405–3408, doi:10.1029/1999GL005394.

Sella, G. F., T. H. Dixon, and A. L. Mao (2002), REVEL: A model for Recent plate velocities from space geodesy, *J. Geophys. Res.*, *107*(B4), 2081, doi:10.1029/2000JB000033.

Tebbens, S. F., and S. C. Cande (1997), Southeast Pacific tectonic evolution from early Oligocene to Present, *J. Geophys. Res.*, *102*, 12,061–12,084, doi:10.1029/96JB02582.