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23 **quadrupole moments of plate motions from tectonic reconstructions^{8,9} extended back to the**
24 **early Mesozoic. For present-day plate motions, we find dipole convergence in eastern Asia**
25 **and quadrupole divergence in both central Africa and the central Pacific. These**
26 **orientations are nearly identical to the dipole and quadrupole orientations of underlying**
27 **mantle flow, which indicates that these “net characteristics” of plate motions reveal deeper**
28 **flow patterns. The positions of quadrupole divergence have not moved significantly during**
29 **the past 250 Myr, which suggests long-term stability of mantle upwelling beneath Africa**
30 **and the Pacific. These upwelling locations are positioned above two compositionally- and**
31 **seismologically-distinct¹⁰ regions of the lowermost mantle that may organize global mantle**
32 **flow¹¹ as they remain stationary over geologic time¹².**

33
34 Viscous convection of Earth’s mantle dissipates our planet’s internal heat, and, because it
35 mobilizes Earth’s surface, is ultimately responsible for the Earth’s long history of intense
36 geological activity. Indeed, supercontinent formation and destruction¹³, epeirogeny^{4,5}, mountain-
37 building⁶, intraplate volcanism¹², and plate tectonic motions¹⁻³ have been linked directly to
38 viscous flow in the mantle. Yet, despite these close links, the outlines of present-day global
39 mantle flow have only recently become delineated using tomographic images of the mantle’s
40 heterogeneous density structure to inform viscous flow modeling of the mantle^{6,14}. Even this
41 exercise has been complicated by the uncertain interpretation of mantle tomography, especially
42 concerning the role of two large low shear-wave velocity provinces (LLSVPs) observed in the
43 lowermost mantle beneath Africa and the Pacific¹⁵. While active upwelling from these regions
44 helps explain patterns of seismic anisotropy¹⁴, plate motions³, orogeny^{5,6}, and long-wavelength
45 topography⁴, seismological constraints suggest that these regions are compositionally dense¹⁶⁻¹⁸.

46 Under these conditions, thermochemical convection can help explain the geometry of
47 upwellings¹⁹, but their stability depends on the interaction of the LLSVP regions with mantle
48 flow²⁰. Our knowledge of mantle flow patterns is even poorer for past times, because direct
49 geologic constraints on flow are few and past mantle density heterogeneity can only be inferred
50 from time-reversed flow models²¹ or inverse methods²² based on present-day mantle structure, or
51 subduction models that do not treat mantle upwelling¹.

52
53 Because they are ultimately linked to mantle convection, plate motions should contain
54 information about the underlying mantle flow patterns. Indeed, shear tractions exerted by mantle
55 flow on the lithospheric base may be a primary driver of plate motions¹⁻³ and thus directly link
56 surface tectonics to interior dynamics. We can exploit this link for past times by utilizing tectonic
57 reconstructions of plate motions, which are becoming increasingly better constrained^{8,9}, to infer
58 patterns of past mantle flow. We achieve this by examining the net properties of plate motions,
59 which should reflect the “average” response of Earth’s lithosphere to long-wavelength viscous
60 mantle flow. Previously, net rotation of the lithosphere (Fig 1a) has been linked to present-day
61 mantle flow¹⁴, but its utility for past times⁸ may be limited because observations of net rotation
62 are highly dependent on the choice of mantle reference frame. By contrast, the relative motions
63 between plates are less dependent on reference frame and are of larger amplitude than net
64 rotation rates. To exploit these attributes, we define several new metrics of relative plate motions
65 that are useful for constraining the interaction between plate tectonics and mantle flow, and
66 apply them to published reconstructions of plate motions both for present and past times.

67
68 We defined three new “net characteristics” of plate motions by performing different integrations

69 of the tectonic plate motion vector field over the surface of the earth (see methods). The plate
70 tectonic dipole vector **D** defines a “net convergence pole” toward which plates are moving in an
71 average sense away from an antipodal “net divergence pole” (Fig. 1b). The plate tectonic
72 quadrupole, defined by the quadrupole deformation matrix **Q** (see methods), describes a 2nd
73 order pattern of net plate motions associated with net hemispheric convergence toward two
74 antipodal “positive” poles and divergence away from two antipodal “negative” poles located 90°
75 away from the positive quadrupoles (Fig. 1c). This quadrupole motion occurs as revolution about
76 two intermediate null poles (Fig. 1c). Plate tectonic net stretching, defined by deformation matrix
77 **S** (see methods), describes convergence toward the two null poles of the quadrupole and
78 divergence away from an equator midway between them (Fig. 1d). These net characteristics
79 describe plate motions at the largest scales; they are influenced by both rapid regional-scale (e.g.,
80 northwestern North American convergence) and gradual global-scale deformations (e.g., the
81 circum-Africa ridge system), but are dominated by the longest-wavelength large amplitude
82 deformations.

83

84 We computed these net characteristics for present-day plate motions (Fig. 2a) and for vector
85 fields associated with two major plate-driving forces: slab pull and basal shear tractions (Fig.
86 2b). The relevant pole locations for all three net characteristics (**D**, **Q**, and **S**) are approximately
87 co-located for both plate motions and plate-driving forces. For example, dipole convergence of
88 plate tectonics occurs in eastern Asia, dominated by convergent motion of the Pacific,
89 Australian, Indian, African, and Eurasian plates toward this location (Fig. 2a). The fact that slab
90 pull also converges on average toward this location (Fig. 2b) is perhaps not surprising because
91 subduction results from plate convergence. The convergence of basal tractions toward eastern

92 Asia (Fig. 2b), however, reflects net motion of sub-lithospheric mantle flow toward this region.
93 Within the mantle, downwelling occurs in this location (Fig. 2c), facilitated by a long history of
94 subduction in the western Pacific that is observed tomographically²³. The co-location of these
95 dipoles thus not only indicates the importance of basal tractions for driving plate motions^{1,3}, but
96 also illustrates a direct link between plate motions and global-scale patterns of mantle flow.

97
98 The quadrupole moments for plate motions, slab pull, and basal tractions are also aligned
99 together (Fig. 2). In particular, quadrupole convergence for all three vector fields is centered in
100 the western Pacific and South America (Fig. 2a), near regions of subduction and above major
101 mantle downwellings (Fig. 2c). Similarly, quadrupole divergence is found in the central Pacific
102 and eastern Africa (Fig. 2a,b), above major upwelling regions of the mantle (Fig. 2c) and just
103 east of the location of the LLSVPs in the lowermost mantle (Fig. 2a). Poles orienting (negative)
104 net stretching are also co-located near the geographic poles (Figs. 2a,b), which reflects the
105 equatorial locations of the quadrupoles. As for the dipole, this co-location of quadrupoles reveals
106 the direct link between surface plate motions and mantle flow patterns at depth. If we assume
107 that this link also persisted for alternative plate configurations that existed in the past, then we
108 can use dipole and quadrupole orientations computed for reconstructed past plate motions to
109 infer the large-scale geometry of ancient mantle flow patterns.

110
111 To determine how dipole and quadrupole orientations have changed during Earth's recent
112 history, we computed \mathbf{D} and \mathbf{Q} from a tectonic reconstruction of global plate motions for the past
113 150 Ma⁸ that we have extended back to 250 Ma by combining paleomagnetic constraints on
114 absolute and relative plate motions in the African hemisphere^{24,25} with a reconstruction of the

115 Pacific basin⁹. The latter is largely synthetic (and thus uncertain) because all Triassic seafloor
116 and any Jurassic hotspot tracks for the Pacific have been lost to subduction. Nevertheless, since
117 250 Ma dipole convergence has generally remained near eastern Asia (Fig. 3a), reflecting long-
118 term stability of major downwelling beneath this area. Indeed, the stationary position of the
119 Eurasian continent has been noted²⁶, and is consistent with persistent downwelling of slabs from
120 the adjacent Panthalassa ocean. The central Pacific and eastern Africa positions of quadrupole
121 divergence have also remained stable above the eastern edges of the LLSVPs (Fig. 3b), which is
122 consistent with the long-term stability of upwelling in these areas. By contrast, the locations of
123 quadrupole convergence have circumscribed Panthalassa, finally resting along its northwestern
124 (and southeastern) edges during the late Cretaceous (Fig. 3b), about the time that subduction of
125 increasingly younger lithosphere in the northern Pacific⁹ may have diminished downwelling flow
126 beneath this region. While migration of the convergent quadrupoles reflects changes in the
127 dominant location of subduction-induced downwelling flow, the stationary nature of the
128 divergent quadrupoles reflects stability of the two major mantle upwellings.

129

130 The positioning of mantle upwelling above the African and Pacific LLSVP regions of the
131 lowermost mantle is consistent with flow patterns observed in thermochemical convection
132 models¹⁹. Our observation that these upwellings have remained stably positioned above the
133 current LLSVP regions may indicate that these LLSVPs form stable “anchors” that organize
134 mantle flow and surface tectonics¹¹. Indeed, plume ascent from the edges of the LLSVPs^{12,20} has
135 been used to define an absolute reference frame for plate motions⁸ that allows paleogeography to
136 be reconstructed into the deep past²⁴. Our observation of quadrupole stability indicates that the
137 two LLSVP regions have remained separate and in their current locations since at least the

138 beginning of the Mesozoic, and were not forced into these locations by flow patterns governed
 139 by supercontinental surface tectonics since then²⁷. Thus, if a transition from degree-1 to degree-2
 140 convection occurred after the formation of Pangea⁷ (i.e. after ~320 Ma), it probably occurred
 141 before ~250 Ma. The dipole and quadrupole amplitudes (Fig. S3) have been decreasing slowly
 142 and in concert since the mid-Mesozoic and do not exhibit evidence of a transition between
 143 dominant modes (Fig. S3). Dipole and quadrupole locations are also rarely co-located (Figs. 3,
 144 S6), which implies that the two systems are coupled to avoid degree-1 upwelling in the vicinity
 145 of degree-2 downwelling. Instead, persistent degree-2 upwelling arising from the two LLSVP
 146 structures may induce convergent flow in the lowermost mantle that consolidates these structures
 147 into their current geometries²⁰, thus protecting and isolating them over geological timescales¹⁹.
 148 The surface expression of this flow pattern is recorded in the geologic record of plate tectonics.

149

150 **Methods Summary**

151 **Dipole.** We define the “plate tectonic dipole” \mathbf{D} as the direct integration of the plate motion
 152 velocity field \mathbf{v} over the Earth’s surface A_0 (Fig. S1):

$$153 \quad \mathbf{D} = \frac{3}{2A_0} \int_{A_0} \mathbf{v} dA \quad (1)$$

154 Here the normalization is chosen (see supplemental materials) so that the amplitude of \mathbf{D}
 155 represents the magnitude of net motion on the equator midway between these poles (Fig. S2b).

156 **Quadrupole and Net Stretching.** Higher order net characteristics can be computed by
 157 integrating the outer product of the unit normal vector $\hat{\mathbf{r}}$ and \mathbf{v} (Fig. S1), and separating the
 158 resulting tensor \mathbf{L} into symmetric (\mathbf{M}) and antisymmetric (\mathbf{N}) components:

159
$$\mathbf{M} + \mathbf{N} = \mathbf{L} = \frac{1}{A_0} \int_{A_0} \hat{\mathbf{r}} \otimes \mathbf{v} dA \quad (2)$$

160 Note that the diagonal components of \mathbf{L} always sum to zero because $\text{tr}(\mathbf{L}) = \frac{1}{A_0} \int_{A_0} \hat{\mathbf{r}} \cdot \mathbf{v} dA$ and

161 $\hat{\mathbf{r}} \perp \mathbf{v}$ everywhere (Fig. S1). The three independent components of \mathbf{N} form the net rotation

162 vector according to $R_k = 3N_{ij} \varepsilon_{ijk} / 2$ (see supplemental materials). The three eigenvalues of the

163 symmetric \mathbf{M} matrix ($\mu_1 > \mu_2 > \mu_3$) form the diagonalized matrix \mathbf{M}_D , which is simply \mathbf{M} expressed

164 in a coordinate system defined by the corresponding eigenvectors \mathbf{m}_1 , \mathbf{m}_2 , and \mathbf{m}_3 . We can

165 decompose \mathbf{M}_D into “quadrupole” (\mathbf{Q}) and “net stretching” (\mathbf{S}) matrices as:

166
$$\mathbf{M}_D = \begin{bmatrix} \mu_1 & 0 & 0 \\ 0 & \mu_2 & 0 \\ 0 & 0 & \mu_3 \end{bmatrix} = \frac{\mathbf{Q}}{6} + \frac{4\mathbf{S}}{15} = \frac{1}{6} \begin{bmatrix} Q & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -Q \end{bmatrix} + \frac{4}{15} \begin{bmatrix} -S/2 & 0 & 0 \\ 0 & S & 0 \\ 0 & 0 & -S/2 \end{bmatrix} \quad (3)$$

167 where the positive and negative elements of \mathbf{Q} correspond to eigenvectors \mathbf{m}_1 and \mathbf{m}_3

168 respectively (Fig. 1c), and the unique (middle) element of \mathbf{S} corresponds to eigenvector \mathbf{m}_2 (Fig.

169 1d). The piercing points of the eigenvectors $\pm\mathbf{m}_1$, $\pm\mathbf{m}_2$, and $\pm\mathbf{m}_3$ thus define the positive

170 (convergent) quadrupoles, the net stretching poles (also null quadrupoles), and the negative

171 (divergent) quadrupoles, respectively (Fig. 1c and 1d). We have defined $Q = 6\mu_1 + 3\mu_2$ and

172 $S = 15\mu_2/4$ so that these values correspond to the maximum velocity magnitudes within the

173 “pure” quadrupole and net stretching velocity fields (see supplemental material). Note that the

174 net stretching deformation (Fig. 1d) reverses to become “net flattening” (polar extension and

175 equatorial compression) if $S < 0$ ($\mu_2 < 0$).

176

177

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262

263

264 **Supplementary Information** accompanies the paper and consists of an 11-page document that
265 details the net characteristic normalizations and the extension of the tectonic model back to 250
266 Ma, includes supplementary figures S1-S6, and describes two separate supplemental files that
267 contain the stage poles and plate boundaries of the 150-250 Ma plate motion reconstruction.

268

268

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272

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274 T.H.T. extended the plate reconstruction through the Mesozoic, all authors developed the
275 geologic application and interpretation, C.P.C. prepared the manuscript with input, comments
276 and review from all authors.

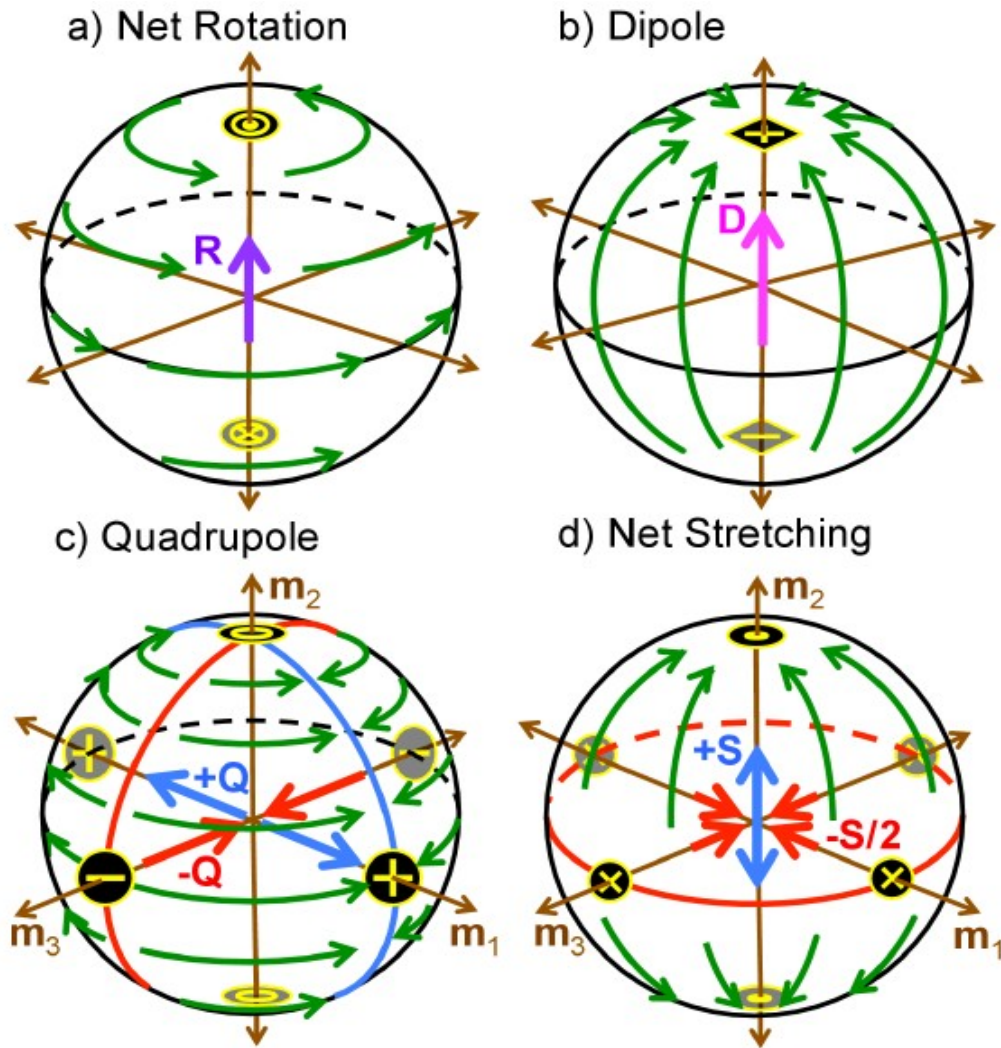
277

278 **Additional Information.** The authors declare no competing financial interests. Correspondence
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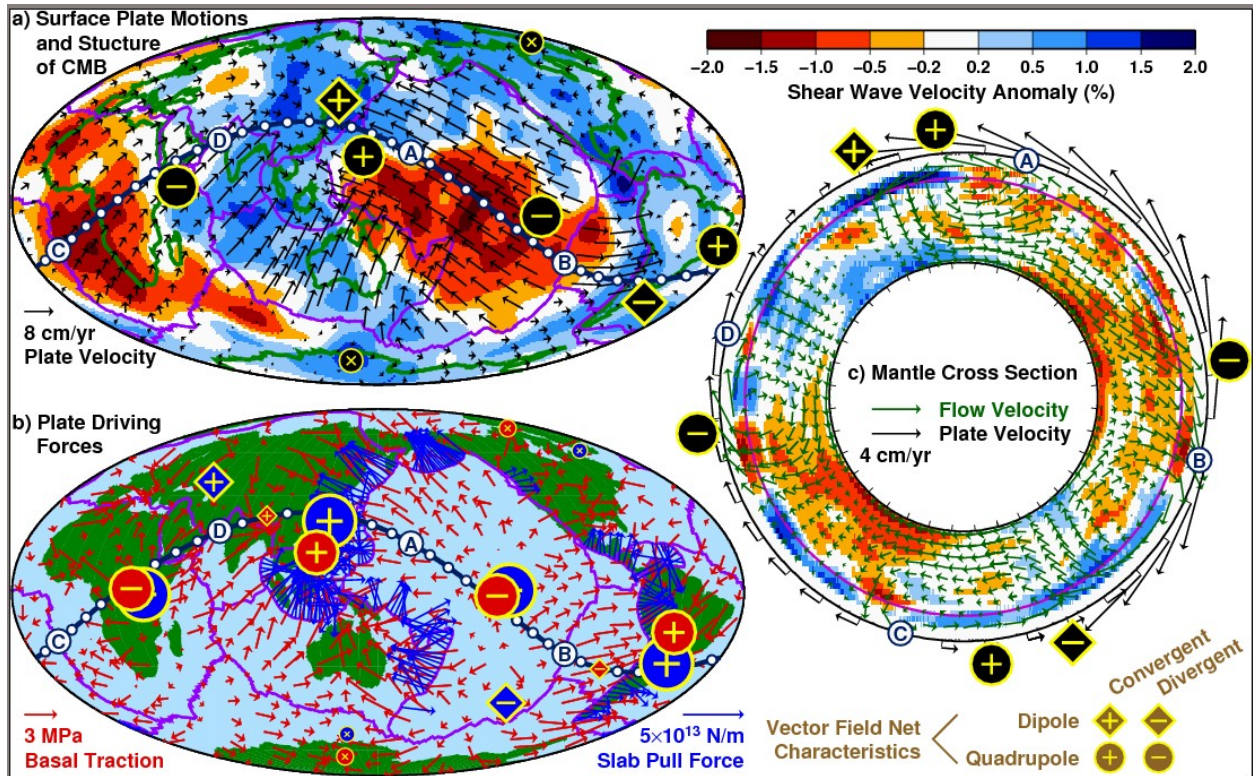
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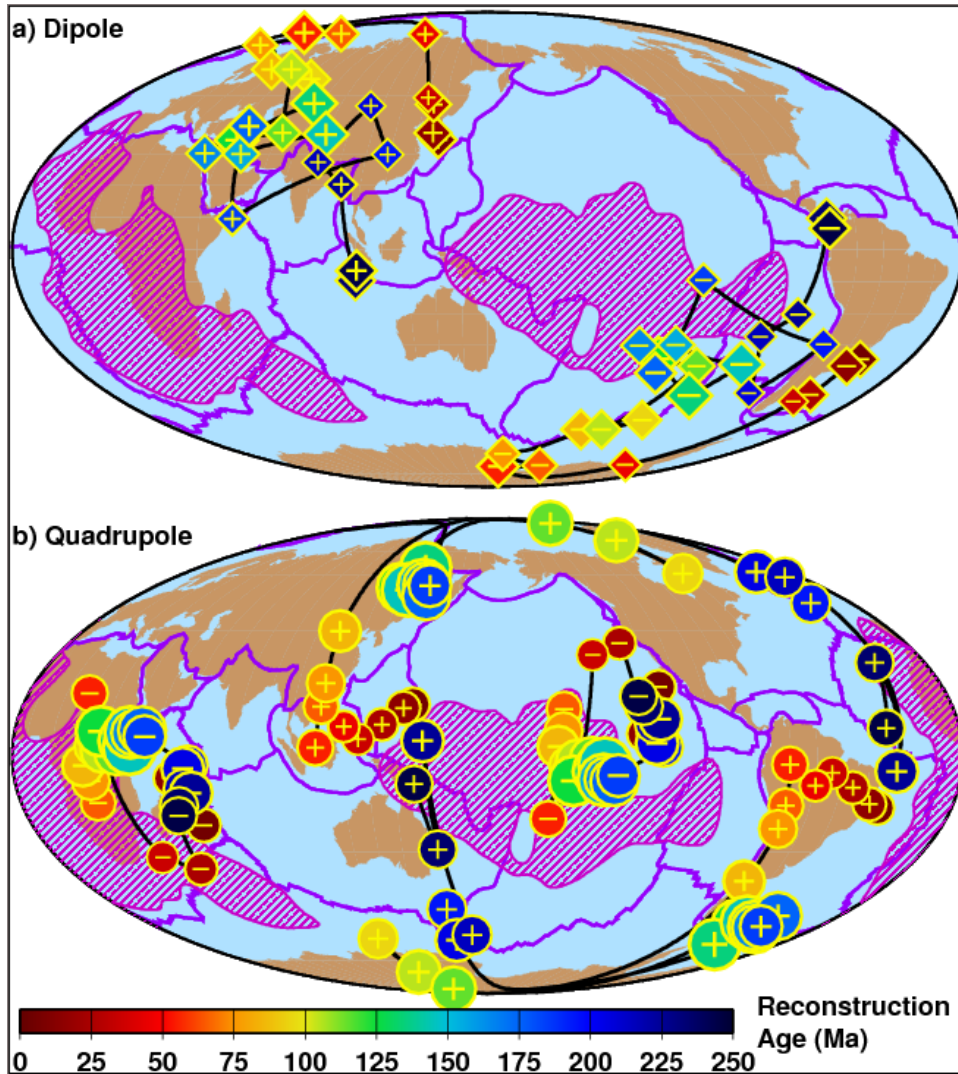
284 **FIGURE LEGENDS**



286 **Figure 1. Definitions of net characteristics.** Plate motions for (a) net rotation, (b) net dipole, (c)
 287 net quadrupole, and (d) net stretching (green arrows, see Fig. S2), their net characteristic vector
 288 definitions (R , D , $\pm Q$, and $+S$, respectively, and the m_1 , m_2 , and m_3 eigenvectors; see methods),
 289 and the symbols used to denote pole locations: encircled dot or cross for positive or negative net
 290 rotation poles (a), plus or minus within a diamond for positive or negative dipoles (b), plus,
 291 circle or minus signs within a circle for positive, null, or negative quadrupoles (c), and dots or
 292 crosses for compressive or extensional net stretching poles (d).



294 **Figure 2. Association of plate tectonic net characteristics with those of underlying mantle**
 295 **flow.** Net characteristic pole locations (symbols as in Fig. 1) for the dipole, quadrupole, and net
 296 stretching components of (a) present-day plate motions²⁸ (black symbols) and (b) estimates for
 297 plate tectonic driving forces associated with slab pull²⁹ (blue symbols) and basal tractions on
 298 plates³⁰ (red symbols). A mantle cross section (c) cutting through great circle ABCD (drawn on
 299 maps) shows tomographic shear velocity anomaly²³ (colors, also drawn in map view in (a) at
 300 2800 km depth), the associated mantle flow field¹⁴ (green arrows), surface plate motion (black
 301 arrows), and net characteristic dipole and quadrupole locations for plate motions (black
 302 symbols).
 303



304 **Figure 3. Temporal evolution of plate tectonic net characteristics.** Plate tectonic (a) dipole
 305 and (b) quadrupole locations as a function of age for a reconstruction of plate motions since the
 306 Triassic (Fig. S6). Symbols as in Fig. 1, with colors indicating reconstruction age and sizes
 307 indicating dipole or quadrupole magnitude (Fig. S3). Note the stability of (a) the plate tectonic
 308 dipole near eastern Asia and (b) the divergent (negative) quadrupole above the western edges of
 309 the two LLSVPs (denoted here as pink hatches showing where shear waves at 2800 km are $>1\%$
 310 slow¹²) beneath Africa and the Pacific. Alternative reconstructions⁹ (Figs. S4, S5) show similar
 311 stability of these features.

Supplementary Materials:

Stability of Active Mantle Upwelling Revealed by Net Characteristics of Plate Tectonics

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1.0 Net Characteristic Normalizations

For any vector field on a sphere $\mathbf{v}(\theta, \varphi)$, where θ is colatitude and φ is longitude (Fig. S1), we can compute several net characteristics of that field by integrating \mathbf{v} over the surface of the sphere. The vector and tensor definitions of four net characteristics (net rotation, net dipole, net quadrupole, and net stretching) are defined in the Methods Summary in the main text, but their magnitudes are determined by the normalization chosen for each net characteristic function. Here we define normalization factors that yield net characteristic amplitudes that correspond to the maximum velocity of a representative velocity field for each net characteristic (Fig. S2).

1.1 Net Rotation

Solid body net rotation about the north pole (Fig. 1a) can be expressed as an eastward-oriented velocity field with amplitude that depends on θ as $v_\theta = 0$ and $v_\varphi = v_R \sin \theta$, where v_R is the maximum velocity amplitude occurring at $\theta = \pi/2$ (on the equator). This vector field is exemplified in Fig. S2a, where $v_R = 5$ cm/yr. In Cartesian coordinates this velocity is expressed as $\mathbf{v} = (-v_R \sin \theta \sin \varphi, v_R \sin \theta \cos \varphi, 0)$. The net rotation vector \mathbf{R} is calculated by crossing the local normal $\hat{\mathbf{r}} = (\sin \theta \cos \varphi, \sin \theta \sin \varphi, \cos \theta)$

with \mathbf{v} and integrating, following the definition of \mathbf{R} given by Ricard *et al.* [1991]:

$$\mathbf{R} = \frac{3}{2A_0} \int_{A_0} \hat{\mathbf{r}} \times \mathbf{v} dA = \frac{3v_R \hat{\mathbf{z}}}{2(4\pi)} \int_0^{2\pi} \int_0^\pi \sin^3 \theta d\theta d\varphi = v_R \hat{\mathbf{z}} \quad (\text{S1})$$

Thus, the magnitude of the net rotation vector, \mathbf{R} , is equal to v_R , which is the net rotation velocity occurring along the net rotation equator (Fig. S2a).

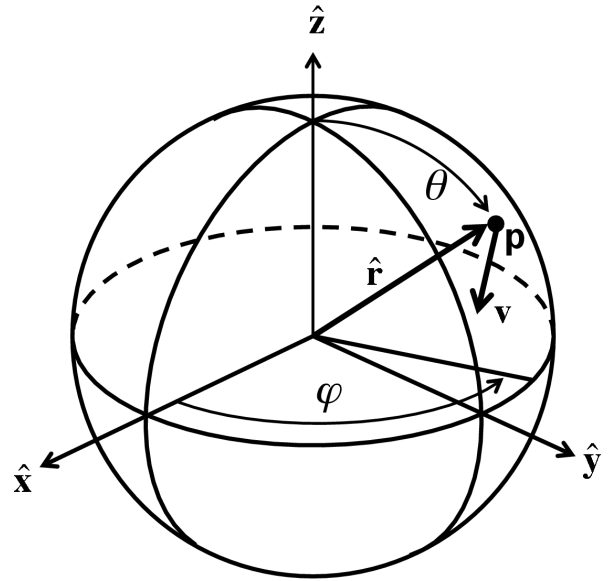


Figure S1. Spherical (θ, φ, r) , and Cartesian (x, y, z) reference frames, and an arbitrary point \mathbf{p} on the Earth's surface ($r = R_E$) moving with velocity $\mathbf{v}(\theta, \varphi)$.

Note that the net rotation vector \mathbf{R} can also be obtained from the antisymmetric matrix \mathbf{N} (defined in eq. 2). We can show this by writing (2) as:

$$\mathbf{L} = \frac{1}{A_0} \int_{A_0} \hat{\mathbf{r}} \otimes \mathbf{v} dA = \frac{1}{A_0} \int_{A_0} \begin{bmatrix} r_x v_x & r_x v_y & r_x v_z \\ r_y v_x & r_y v_y & r_y v_z \\ r_z v_x & r_z v_y & r_z v_z \end{bmatrix} dA \quad (\text{S2})$$

Then the symmetric (\mathbf{M}) and antisymmetric (\mathbf{N}) components of $\mathbf{L}=\mathbf{M}+\mathbf{N}$ are:

$$\mathbf{M} = \frac{1}{2A_0} \int_{A_0} \begin{bmatrix} 2r_x v_x & r_x v_y + r_y v_x & r_x v_z + r_z v_x \\ r_y v_x + r_x v_y & 2r_y v_y & r_y v_z + r_z v_y \\ r_z v_x + r_x v_z & r_z v_y + r_y v_z & 2r_z v_z \end{bmatrix} dA \quad \mathbf{N} = \frac{1}{2A_0} \int_{A_0} \begin{bmatrix} 0 & r_x v_y - r_y v_x & r_x v_z - r_z v_x \\ r_y v_x - r_x v_y & 0 & r_y v_z - r_z v_y \\ r_z v_x - r_x v_z & r_z v_y - r_y v_z & 0 \end{bmatrix} dA \quad (\text{S3})$$

Note that the cross product components of the net rotation vector \mathbf{R} from (S1) can be re-expressed in terms of the components of the anti-symmetric matrix \mathbf{N} :

$$R_k = 3N_{ij} \varepsilon_{ijk} / 2 \quad (\text{S4})$$

where ε_{ijk} is the Levi-Civita permutation symbol. Thus, the components of the antisymmetric matrix \mathbf{N} define the net rotation vector \mathbf{R} .

1.2 Net Dipole

A pure dipole vector field with a (positive) convergence pole at the north pole (Fig. 1b) has the form $v_\theta = -(v_D \sin \theta)$ and $v_\varphi = 0$ (Fig. S2b), or $\mathbf{v} = -v_D \sin \theta (\cos \theta \cos \varphi, \cos \theta \sin \varphi, -\sin \theta)$ in Cartesian coordinates (Fig. S2b). Applying \mathbf{v} to the definition of the net dipole in (1) gives:

$$\mathbf{D} = \frac{3}{2A_0} \int_{A_0} \mathbf{v} dA = \frac{3v_D \hat{\mathbf{z}}}{2(4\pi)} \int_0^{2\pi} \int_0^\pi \sin^3 \theta d\theta d\varphi = v_D \hat{\mathbf{z}} \quad (\text{S5})$$

Thus, the magnitude of the dipole vector \mathbf{D} is equal to v_D , which is the maximum poleward velocity, occurring along the dipole equator (Fig. S2b).

1.3 Net Quadrupole

We define the quadrupole velocity field, with positive (convergent), intermediate (null), and negative (divergent) poles (defined by the \mathbf{m}_1 , \mathbf{m}_2 , and \mathbf{m}_3 eigenvectors, respectively) coincident with \mathbf{y} -, \mathbf{z} -, and \mathbf{x} -axes, respectively (Fig. 1c). In this case $v_\theta = 0$ and $v_\varphi = v_Q \sin \theta \sin 2\varphi$, or

$\mathbf{v} = v_Q (-\sin \theta \sin 2\varphi \sin \varphi, \sin \theta \sin 2\varphi \cos \varphi, 0)$ in a Cartesian system (Fig. S2c). Integration of the outer product (S2) yields:

$$\mathbf{L} = \frac{v_Q}{A_0} \int_0^{2\pi} \int_0^\pi \begin{bmatrix} \sin \theta \cos \varphi \\ \sin \theta \sin \varphi \\ \cos \theta \end{bmatrix} \begin{bmatrix} -\sin \theta \sin \varphi \sin 2\varphi & \sin \theta \cos \varphi \sin 2\varphi & 0 \end{bmatrix} \sin \theta d\theta d\varphi = \frac{v_Q}{6} \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (\text{S6})$$

Solving for \mathbf{Q} by diagonalizing \mathbf{M} and applying (3) as described in the main text, we find:

$$\mathbf{Q} = \begin{bmatrix} v_Q & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -v_Q \end{bmatrix} \quad (\text{S7})$$

where the corresponding eigenvectors \mathbf{m}_1 , \mathbf{m}_2 , and \mathbf{m}_3 are parallel to the \mathbf{y} , \mathbf{z} , and \mathbf{x} axes, respectively (Fig. 1c, S2c), producing divergence poles at $(\theta = \pi/2, \varphi = 0)$ and $(\pi/2, \pi)$, convergent poles at $(\pi/2, \pm\pi/2)$ and intermediate poles at $\theta = 0$ and $\theta = \pi$. The quadrupole amplitude in (S7) is $Q=v_Q$, and thus is equal to that field's largest vector magnitude, which occurs midway between the convergent and divergent poles (Fig. S2c).

1.4 Net Stretching

We define the positive net stretching velocity field as convergent toward both the north and south poles, and divergent away from the equator (Fig. 1d). In this case $v_\theta = -v_s \sin 2\theta$ and $v_\varphi = 0$, which is $\mathbf{v} = -v_s \sin 2\theta (\cos \theta \cos \varphi, \cos \theta \sin \varphi, -\sin \theta)$ in a Cartesian system (Fig. S2d).

Again rewriting the outer product using (S2) and integrating, we find:

$$\mathbf{L} = \frac{v_s}{A_0} \int_0^{2\pi} \int_0^\pi \sin 2\theta \begin{bmatrix} \sin \theta \cos \varphi \\ \sin \theta \sin \varphi \\ \cos \theta \end{bmatrix} \begin{bmatrix} -\cos \theta \cos \varphi & -\cos \theta \sin \varphi & \sin \theta \end{bmatrix} \sin \theta d\theta d\varphi = \frac{4v_s}{15} \begin{bmatrix} -1/2 & 0 & 0 \\ 0 & -1/2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (\text{S8})$$

Solving for \mathbf{S} by diagonalizing \mathbf{M} and applying (3) as described in the main text (assuming that net stretching occurs in the presence of a larger quadrupole field to associate net stretching with the intermediate \mathbf{m}_2 eigenvector, as discussed below), we find:

$$\mathbf{S} = \begin{bmatrix} -v_s/2 & 0 & 0 \\ 0 & v_s & 0 \\ 0 & 0 & -v_s/2 \end{bmatrix} \quad (\text{S9})$$

where the associated eigenvectors \mathbf{m}_1 , \mathbf{m}_2 , and \mathbf{m}_3 are parallel to the \mathbf{y} , \mathbf{z} , and \mathbf{x} axes, respectively (Figs. 1d, S2d). The resulting net stretching expressed by (S9) yields convergence poles at the piercing points of $\pm\mathbf{m}_2$ ($\theta = 0$ and $\theta = \pi$), and divergence away from the equator ($\theta = \pi/2$). The net stretching magnitude is thus $S=v_s$, which is again the maximum velocity within the pure net stretching field (Fig. S2d), occurring at $\theta = \pi/4$ and $\theta = 3\pi/4$. If $S=v_s$ is negative, then the sense of motion is reversed to produce “net flattening” with diverging intermediate poles (at $\theta = 0$ and $\theta = \pi$) and convergence toward the equator.

2.0 Separating the Quadrupole and Net Stretching Components

Note that our method for separating \mathbf{M}_D into quadrupole and net stretching components is not unique. We have chosen to align the positive and negative quadrupole vectors ($+\mathbf{Q}$ and $-\mathbf{Q}$) with \mathbf{m}_1 and \mathbf{m}_3 (Fig. 1c), which correspond to the most positive and most negative eigenvalues of \mathbf{M} (μ_1 and μ_3 , respectively), and the net stretching vector ($+\mathbf{S}$) with \mathbf{m}_2 (Fig. 1d), which is associated with the intermediate eigenvalue (μ_2). However, we could have alternatively associated net stretching with the largest (μ_1) or smallest (μ_3) eigenvalues, which would distribute the deformation between the quadrupole and net stretching differently. For example, associating net stretching ($+\mathbf{S}$) with \mathbf{m}_3 and the quadrupole vectors ($+\mathbf{Q}$ and $-\mathbf{Q}$) with \mathbf{m}_1 and \mathbf{m}_2 changes (3) to:

$$\mathbf{M}_D = \begin{bmatrix} \mu_1 & 0 & 0 \\ 0 & \mu_2 & 0 \\ 0 & 0 & \mu_3 \end{bmatrix} = \frac{\mathbf{Q}}{6} + \frac{4\mathbf{S}}{15} = \frac{1}{6} \begin{bmatrix} Q & 0 & 0 \\ 0 & -Q & 0 \\ 0 & 0 & 0 \end{bmatrix} + \frac{4}{15} \begin{bmatrix} -S/2 & 0 & 0 \\ 0 & -S/2 & 0 \\ 0 & 0 & S \end{bmatrix} \quad (\text{S10})$$

where $Q = 6\mu_1 + 3\mu_3$ and $S = 15\mu_3/4$. Applying this alternative method for separation to a pure quadrupole field for which $\mu_1 = v_Q/6$, $\mu_2 = 0$, and $\mu_3 = -v_Q/6$ (see above), we find new amplitudes for the quadrupole and net stretching components (specifically, we find $Q = v_Q/2$ and $S = -5v_Q/8$), and different orientations of the net quadrupole and net stretching vectors compared to our original method. Both methods accurately express the deformation described by \mathbf{M}_D and associated eigenvectors, but do so in different ways. Our method of aligning the intermediate eigenvector (\mathbf{m}_2) with net stretching associates the largest amplitude eigenvalues (and the associated \mathbf{m}_1 and \mathbf{m}_3 eigenvectors) with quadrupole motion. For global plate motions, quadrupole motion tends to dominate (Fig. S3), which makes our choice of separation method convenient. Regardless of the method, however, the second order net characteristics computed using (2) are uniquely described by the eigenvectors \mathbf{m}_1 , \mathbf{m}_2 , and \mathbf{m}_3 , and their associated eigenvalues. Our method consistently aligns these eigenvectors with the positive quadrupole (+Q), net stretching (+S), and negative quadrupole (-Q) poles, respectively, and thus fully and uniquely describes the second order net characteristics of plate tectonic motions.

3.0 Extension of the *Torsvik et al. [2010]* Reconstruction back to 250 Ma, and Comparison with other Reconstructions

Torsvik et al. [2010] reconstructed plate motions globally back to 150 Ma (Fig. S6a-o), but reconstructed continental areas (i.e. all plates except for those in the Pacific basin) back to 250 Ma. To extend *Torsvik et al.'s [2010]* model back to 250 Ma for all areas, we used the global reconstruction of *Seton et al. [2012]* to reconstruct the motion of plates in the Pacific basin for the 150-200 Ma time period (Fig. S6p-t) and extended these Pacific plate motions for the 200-250 Ma time period (Fig. S6u-y) using the data archive supplementing *Seton et al. [2012]*. Poles of rotation and plate boundaries for the 150-250 Myr time period are included here as supplemental files and can be added to those published by *Torsvik et al. [2010]* to produce a global reconstruction back to 250 Ma.

Due to the lack of hotspot tracks, absolute plate motions in the Pacific basin, and hence the contribution of this basin to the plate tectonic dipole, are rather unconstrained for the entire 150-250 Ma period. *Seton et al. [2010]* assume that the Pacific plate - then a small plate at a triple junction - was fixed. Before ~180 Ma, relative plate motions for the Pacific, and therefore their contribution to the plate tectonic quadrupole, are also rather unconstrained, as no ocean floor is preserved before this time. *Seton et al. [2010]* assume that spreading away from the Pacific basin triple junction had been ongoing before 180 Ma. Before 230 Ma, their model assumes that the Farallon plate was fixed to North America.

The main differences between the models of *Torsvik et al. [2010]* and *Seton et al. [2012]* are that (1) the former use independent Pacific and African hotspot reference frames, whereas the latter use a plate circuit linking both hemispheres after 83 Ma, and that (2) *Torsvik et al. [2010]* use a simplified model of Pacific plate motions prior to 83 Ma. Different from *Seton et al. [2012]*, *Dobrovine et al. [2012]* determine an absolute reference frame that fits hotspot tracks globally after 83 Ma. However, because *Seton et al. [2012]* and *Dobrovine et al. [2012]* were otherwise constructed similarly, their dipole and quadrupole results also look similar (compare Figs. S4 and

S5), apart from a small shift due to their slightly differing absolute reference frames. *van der Meer et al.* [2010] suggest a westward shift of the reference frame peaking at 18° at 150 Ma. Applying a corresponding shift to the dipole and quadrupole locations would move divergent quadrupoles closer to the LLSVP centers.

Similarities and differences between these models help to characterize model uncertainties and to assess which model features are robust. The main uncertainty of our analysis comes from the fact that an increasingly smaller fraction of the ocean floor is preserved for older time periods, which means that the plate configuration for an increasingly larger fraction of the Earth's surface must be "best guessed". This missing fraction is referred to as "world uncertainty" by *Torsvik et al.* [2010], and reaches 60 % at 150 Ma. Given this, it would be difficult, and probably also misleading, to state formal uncertainties of our dipole and quadrupole locations. However, comparison between results for the different models presented here (Figs. 3, S4, S5) indicates that the location and stability of both the dipole axis and the quadrupole divergence are robust. The models also agree that quadrupole convergence poles moved from more polar locations earlier towards more equatorial locations since the late Cretaceous, but differ somewhat in the rate and path of motion prior to the mid-Cretaceous.

4.0 Additional Supplemental Files: Digital Plate Boundaries & Rotation Poles (150-250 Ma)

Two additional files provide the lat-long locations of (1) digitized plate boundaries and (2) plate rotation stage poles for each plate for each 10 Myr interval between 150 and 250 Ma. The format of these files is that same as that of similar files provided for 0-150 Ma by *Torsvik et al.* [2010]. Indeed these files extend *Torsvik et al.*'s [2010] model back to 250 Ma (Fig. S6).

5.0 References Cited in Supplementary Materials

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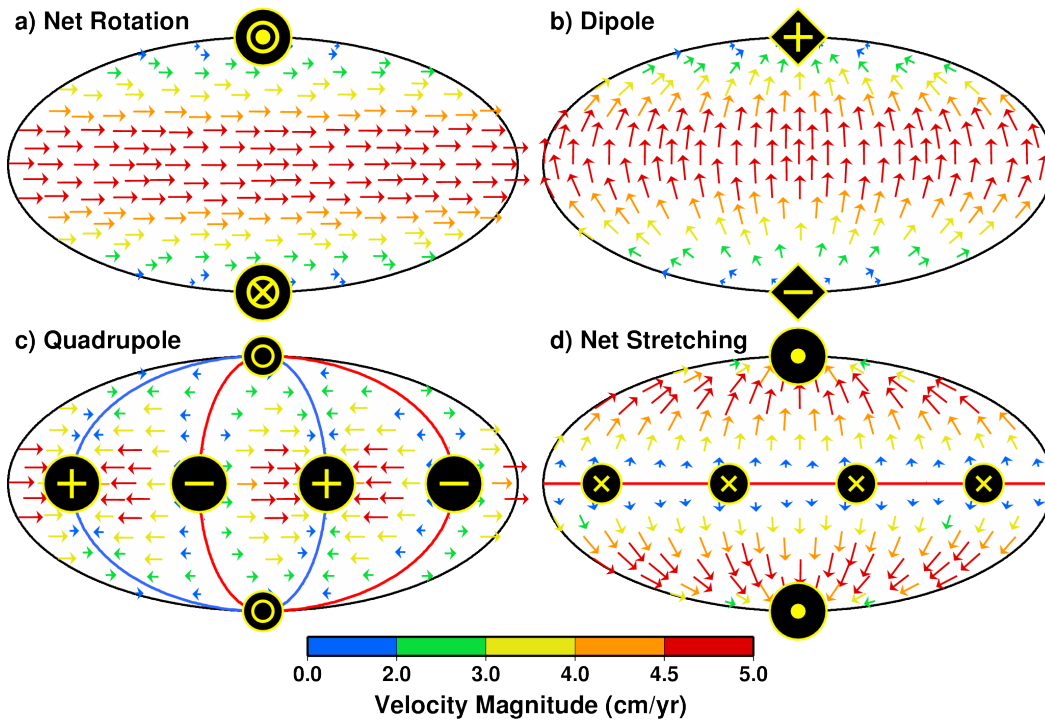


Figure S2. Representative velocity fields for (a) net rotation, (b) net dipole, (c) net quadrupole, and (d) net stretching, with functional forms as described in the text. Velocity direction is shown by arrows, and their length and color correspond to velocity magnitude. The maximum velocity magnitude in each case is 5 cm/yr, which also corresponds to the net characteristic magnitude for each case. The locations of net characteristic poles are denoted by symbols consistent with those defined in Fig. 1.

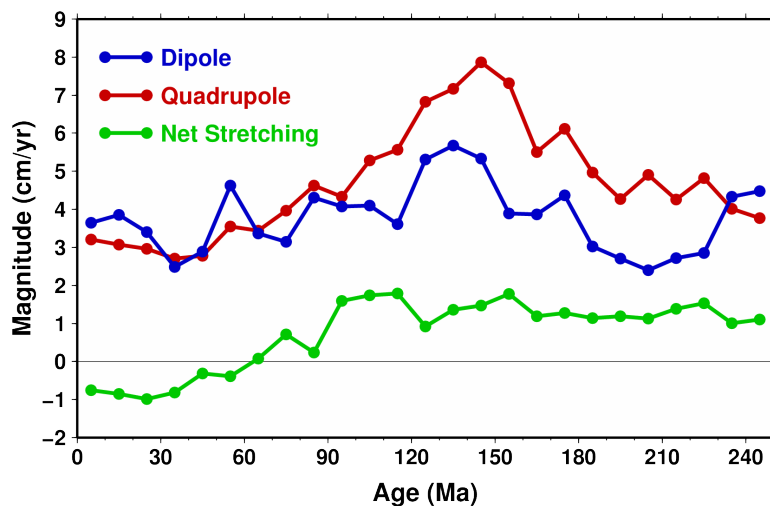


Figure S3. Magnitude of three net characteristic components (net dipole, net quadrupole, and net stretching as blue, red, and green lines) as a function of tectonic reconstruction age (Figs. 3, S6).

Figure S4. Motion of (a) dipole and (b) quadrupole net characteristic poles as a function of reconstruction age (similar to Fig. 3), but computed for the reconstruction of *Seton et al.* [2012], which extends back to 200 Myr.

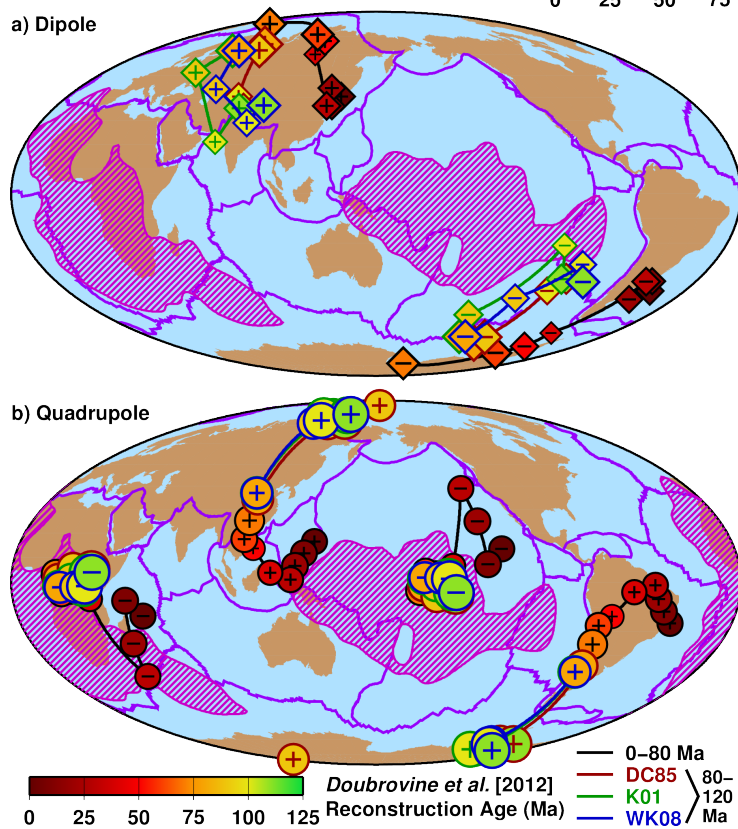
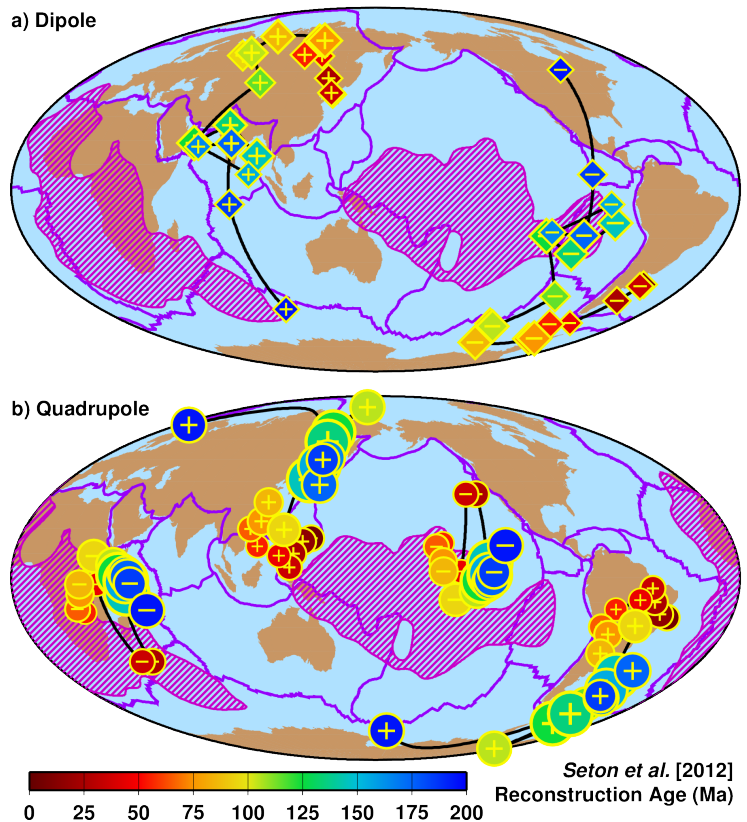


Figure S5. Motion of (a) dipole and (b) quadrupole net characteristic poles as a function of reconstruction age (similar to Fig. S4), but computed for the reconstruction of *Doubrovine et al.* [2012], which extends to 120 Ma. *Doubrovine et al.* [2012] presents three models for the 80-120 Ma timeframe, based on *Duncan & Clague* [1985], *Koppers et al.* [2001], and *Wessel & Kroenke* [2008] (which we denote as DC85, K01, and WK08, respectively). Here these three models can be distinguished by the color of the symbol boundary (red, green, and blue for DC85, K01, and WK08, respectively) for symbols in the 80-120 Ma timeframe. Black symbol outlines are used for the 0-80 Ma timeframe, for which *Doubrovine et al.* [2012] presents only one model.

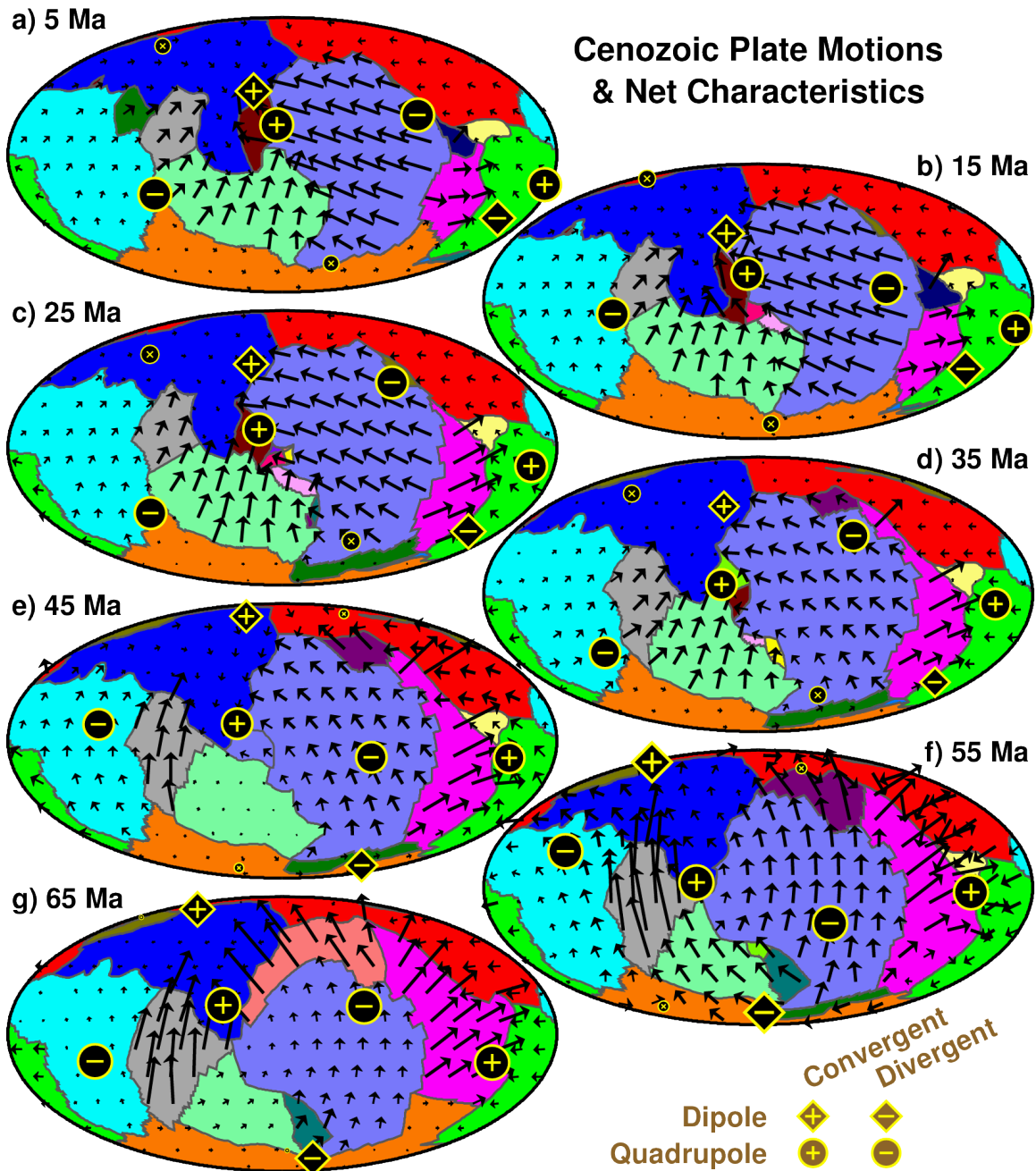


Figure S6. Plate motions (arrows) and computed net characteristic poles (symbols) for the Cenozoic (a-g), Cretaceous (h-o), Jurassic (p-t), and Triassic (u-y) time periods, based on the tectonic reconstruction of *Torsvik et al.* [2010] for the past 150 Ma, and extended back to 250 Ma by reconstructing the Pacific basin following *Seton et al.* [2012]. Reconstructions are in 10 Myr intervals (labeled age denotes middle of interval) over which plate motions are averaged.

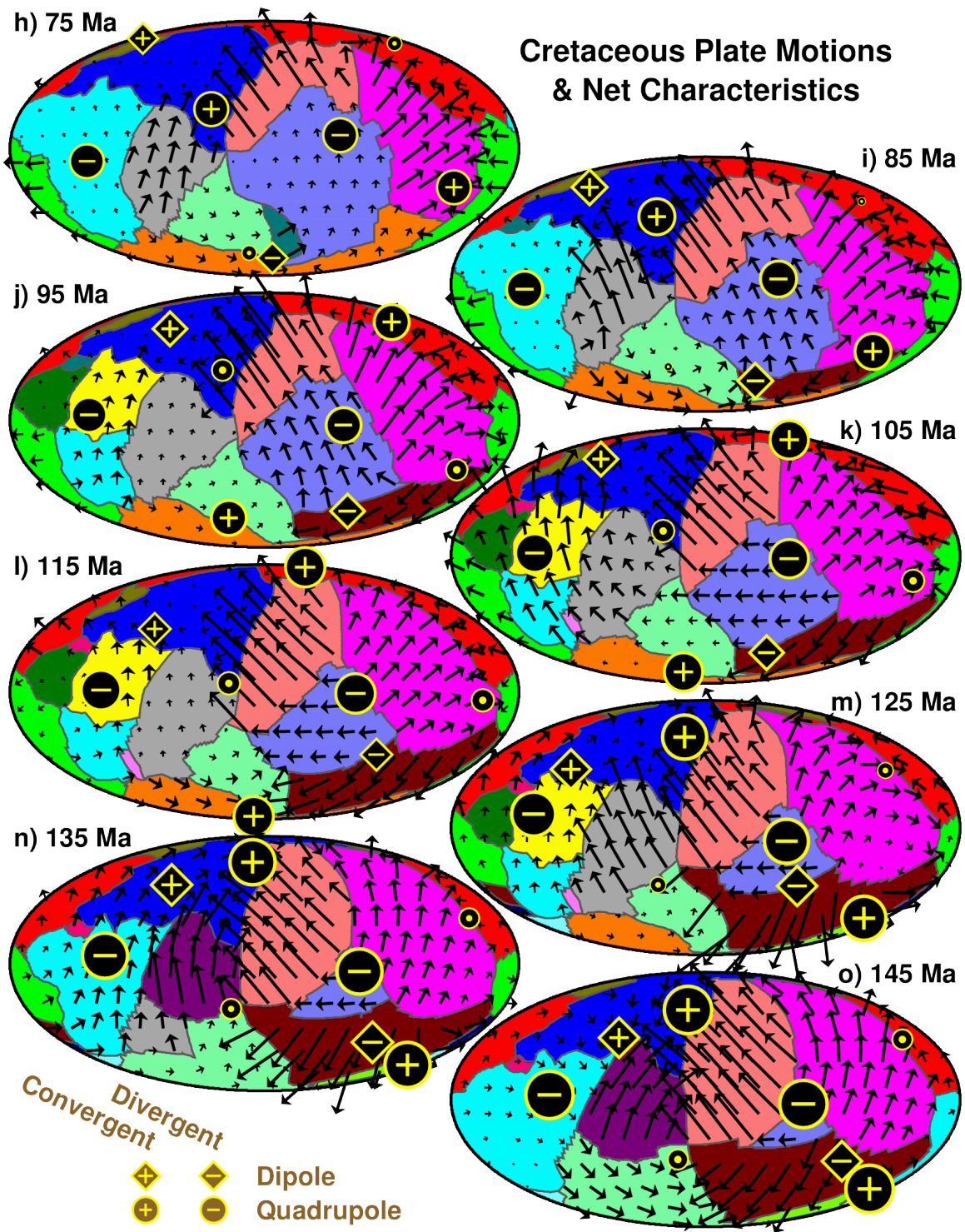


Figure S6. (continued, shown here for the Cretaceous)

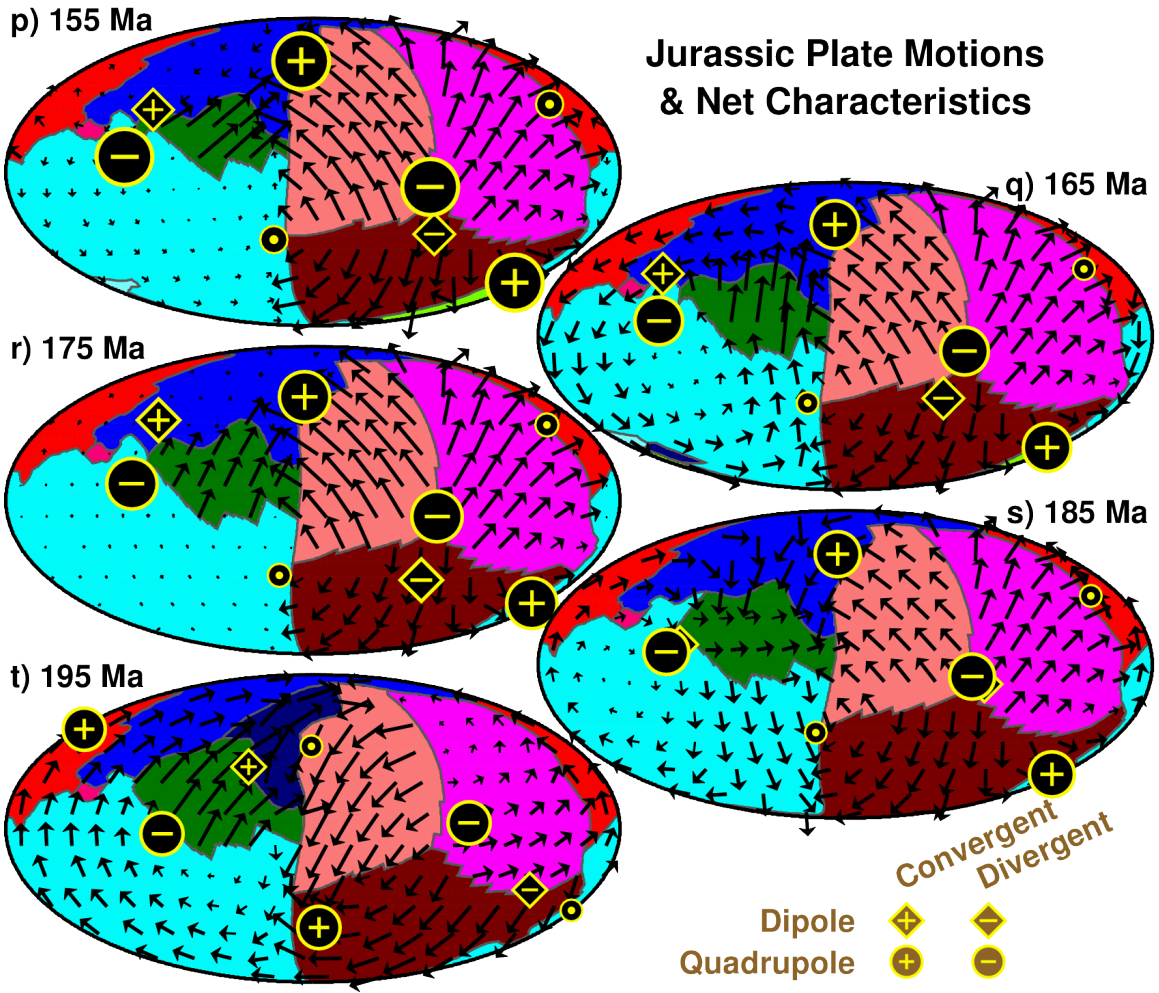


Figure S6. (continued, shown here for the Jurassic)

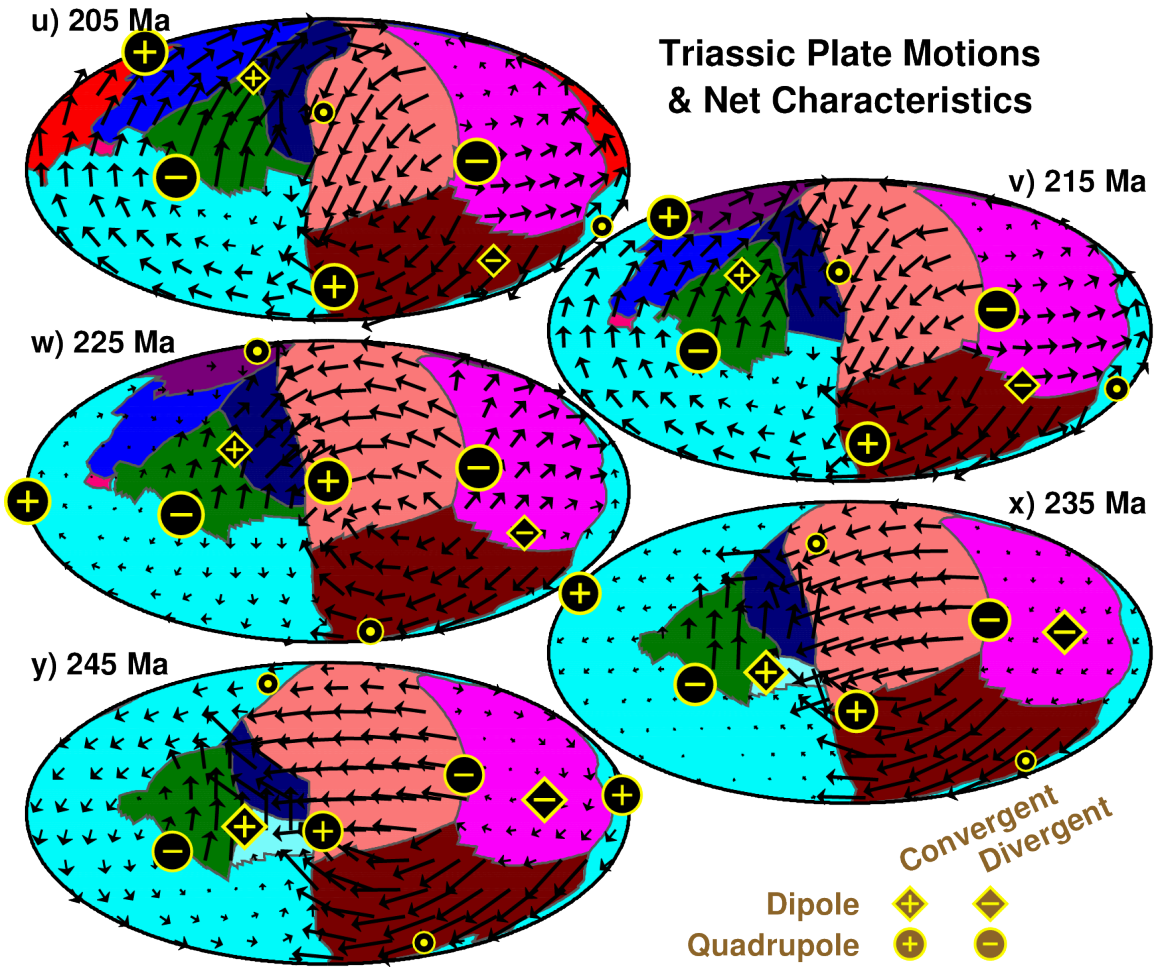


Figure S6. (continued, shown here for the Triassic)