# Does quadrupole stability imply LLSVP fixity?

**ARISING FROM** C. P. Conrad, B. Steinberger & T. H. Torsvik *Nature* **498,** 479–482 (2013)

The African and Pacific large low-shear-velocity provinces (LLSVPs) at present dominate the structure of the Earth's lowermost mantle, but there is considerable debate as to whether these structures have remained fixed throughout geologic time or whether they have shifted in response to the changing configurations of mantle downwellings associated with zones of surface tectonic plate convergence. In a recent Letter, Conrad *et al.*[1] performed a multipole expansion of the Earth's plate motions from 250 million years (Myr) ago to the present and used the relatively stationary positions of quadrupole divergence to argue that the two LLSVPs have remained stationary at least for the past 250 Myr and further speculated that the two LLSVPs formed "stable anchors" in the more distant geologic past. Here we show that the quadrupole divergence of plate motions is not a representative diagnostic for overall plate divergence patterns, owing to cancellation effects in the multipole expansion. Hence, the conclusion by Conrad *et al.*[1] that the presence of stationary quadrupole divergence implies fixity of the LLSVPs is not well founded. There is a Reply to this Brief Communication Arising by Conrad, C. P., Steinberger, B. & Torsvik, T. H. *Nature* **503,** doi:10.1038/nature12793 (2013).

Conrad *et al.*[1] define "net characteristics" of plate tectonics on the Earth based on the dipole and quadrupole contributions to the plate motions. These net characteristics are very similar to the spherical harmonic representation of the poloidal component of the plate motions, which represents convergent and divergent motion on the sphere[2,3]. It can be shown that the pure dipole in ref. 1 is identical within a multiplicative constant to the (1, 0) spherical harmonic of the divergence field when the dipole axis is aligned with the axis of rotational symmetry in the spherical coordinate system, and that the pure quadrupole is similar to the (2, 2) spherical harmonic contribution. In Figure 1 of this Comment, we show the degree-1 and degree-2 contributions to the plate motions at 200 Myr ago (left column) from ref. 4, similar to those in ref. 1 and at 300 Myr ago (right column) from ref. 5. The locations of degree-1 and degree-2 spherical harmonic extrema (circles and diamonds in Fig. 1) are very similar to the dipole and quadrupole orientations in figure 3 of ref. 1.

Divergent plate motion in the African hemisphere (that is, within Pangaea) may have started around 290 Myr ago with the Neo-Tethys seafloor spreading[6], but the divergence in the African hemisphere was much weaker than in the Pacific hemisphere at 200 Myr ago (bottom row of Fig. 1). However, degree-2 divergence has equal amplitude in the two hemispheres (second row of Fig. 1). When we examine spherical harmonic degrees up to and including 40 (bottom row of Fig. 1), we can see that the apparent degree-2 divergence in the African hemisphere is largely cancelled by other modes (including degree-1). This suggests that in general the degree-2 divergence alone is not a good proxy for the long-wavelength structure of plate motions.

In fact, the degree-2 divergence field for a proxy plate motion model at 300 Myr ago (right column in Fig. 1) is similar in both amplitude and orientation to that at 200 Myr ago, despite the complete absence of divergence in the African hemisphere[5,6]. At 300 Myr ago, we assume[5] that seafloor spreading in the Panthalassic hemisphere was accommodated by circum-Pangaea subduction. The amplitude of degree-2 motion at 300 Myr ago (4.45 cm per year) is greater than at 200 Myr ago (3.47 cm per year). However, at 300 Myr ago, the degree-1 convergence maximum is closely aligned with the degree-2 divergence maximum located within Pangaea, resulting in cancellation. Because we are concerned chiefly with the long-wavelength characteristics of the plate motions, only the presence of spreading (not the precise details of plate motions) in the Panthalassic hemisphere is important.

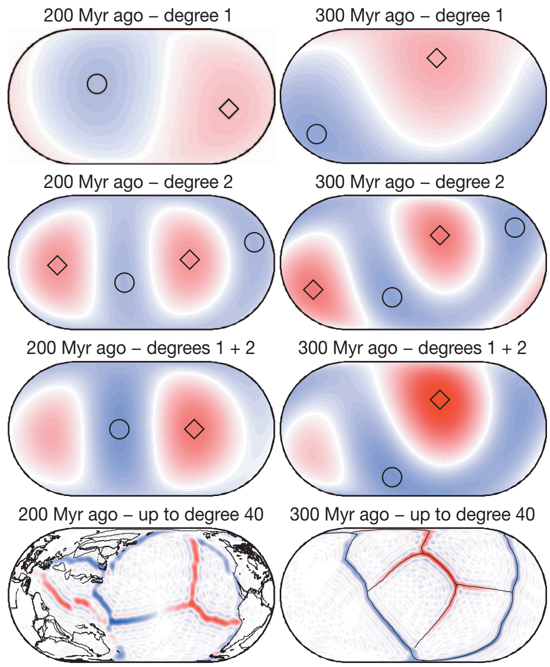


**Figure 1 | Spherical harmonic contributions to the poloidal velocity field.** Top row, for spherical harmonic degree 1; second row, for degree 2 only; third row, for degrees 1 and 2; and bottom row, for all degrees up to 40. Circles indicate convergence maxima; diamonds indicate divergence maxima.

Although we agree with ref. 1 that plate motions provide constraints on changes in mantle buoyancy structure, the plate divergence in the African hemisphere has changed from strongly positive since the break-up of Pangaea to weakly positive at around 200–250 Myr ago, becoming neutral at around 300 Myr ago, and was most probably negative before the formation of Pangaea at 330 Myr ago (that is, reflecting convergence associated with the assembly of Pangaea). This clearly suggests that mantle buoyancy forces in the African hemisphere have changed significantly during the last supercontinent cycle. In laboratory and numerical studies, cold downwelling material that reaches the core–mantle boundary tends to push aside compositionally dense material, a process that is thought to be analogous to the interaction of LLSVPs with subducted oceanic crust[5,7–9]. Hence, changes in mantle buoyancy structure are expected to change the LLSVP arrangement, and numerical simulations driven by velocity boundary conditions successfully reproduce the present-day arrangement of the LLSVPs[5,7,10] while allowing the LLSVPs to shift in response to changes in downwelling structure. Robust observations are needed to test the time evolution of the LLSVP structures, and the quadrupole divergence component alone is not a sufficiently robust indicator of the past mantle flow field to assess the long-term fixity of the LLSVPs.

## METHODS

We calculated the surface divergence and radial vorticity of the velocity field defined by plate reconstructions for 200 Myr ago[4] and defined by a proxy plate reconstruction prior for 300 Myr ago[5] using CitcomS[11] and performed spherical harmonic expansion of the resulting scalar fields representing poloidal and toroidal motion, respectively[2,3]. The amplitudes of individual spherical harmonic degrees reported in the text are calculated using the normalizations introduced in ref. 3. (This

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# Conrad *et al.* reply

**REPLYING TO** M. L. Rudolph & S. Zhong *Nature* **503,** http://dx.doi.org/10.1038/nature12792 (2013)

We thank Rudolph and Zhong for their Comment[1], which allows us to highlight important aspects of our original Letter[2]. In particular, they have provided an example of plate motions at 300 million years (Myr) ago (see right column of figure 1 of ref. 1) in which the plate tectonic quadrupole is not representative of plate tectonic divergence patterns (that is, there is no divergence in the middle of their supercontinent, despite a divergent quadrupole there). However, our study[2] does not claim that there should be a correspondence between quadrupole locations and the specific locations of plate tectonic divergence—instead we argue that plate tectonic dipole and quadrupole locations are representative of underlying mantle flow only.

This 300-Myr example actually demonstrates the utility of our method. To see this, consider mantle flow beneath a supercontinent covering one-third of the globe: mantle upwelling is expected beneath the opposing ocean's spreading ridges, but mantle downwelling occurs neither opposite to this upwelling (as for dipole flow) nor in bands 90° away (as for quadrupole flow), but instead associates with subduction occurring between these two locations on the supercontinent's periphery. Return flow from this downwelling should drive upwellings beneath both the supercontinent and the oceanic plates. Indeed, upwelling is expected beneath a supercontinent that will soon disperse[3,4].

Thus, we expect strong upwelling beneath the oceanic plates and weaker upwelling beneath the supercontinent; such a flow field is described by a combination of dipole and quadrupole flow fields that partially cancel beneath the supercontinent. This pattern is exactly predicted by the net characteristics (or spherical harmonics) of surface plate motions: the 300-Myr analysis of ref. 1 shows weak divergence within the supercontinent, indicating underlying upwelling. Thus, the lifetime of the two antipodal upwellings in the mantle may extend beyond the 250 Myr that we demonstrated in our original Letter[2]. More importantly, this analysis[1] demonstrates the importance of using only the longest-wavelength components of plate motions to visualize the underlying mantle flow patterns. By including shorter-wavelength spherical harmonic degrees, Rudolph and Zhong have incorporated the influence of regional and local tectonics into their interpretation[1]; doing this obscures the underlying mantle flow patterns that are only apparent at the longest wavelengths[2].

We agree with the Comment[1] that quadrupole stability alone does not prove long-term stability of the LLSVP regions, and that additional constraints from "robust observations" are necessary. Indeed, the locations of large igneous provinces and kimberlites have been shown to source from the margins of two antipodal LLSVPs[5], and would arise above a cold downwelling on the African side if the degree-1 interpretation of ref. 1 is correct. Furthermore, the 300-Myr plate motion example[1] is based on a study[6] that does not control for palaeolongitude or true polar wander, so it is unclear how surface features are related to LLSVP locations. Their portrayal of Pangaea as a stable coherent polygon additionally ignores much of the tectonic complexity of that supercontinent's evolution[7]. These problems illustrate the importance of using a carefully reconstructed model of past plate motions when attempting to use "net characteristics" to constrain LLSVP stability.

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