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Global crustal movement and tectonic plate boundary deformation constrained by the ITRF2008

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Abstract: On the basis of the newly released International Terrestrial Reference Frame (ITRF2008) by the International Earth Rotation Service (IERS), a new global plate model ITRF2008 plate for the major plates is established. This ITRF2008-derived model is analyzed in comparison with NNR-NUVEL1A model, which is mainly based on geological and geophysical data. The Eurasia and Pacific plates display obvious differences in terms of the velocity fields derived from the two plate motion models. Plate acceleration is also introduced to characterize the differences of the two velocity fields which obtained from ITRF2008-plate and NNR-NUVEL1A models for major individual plates. The results show that the Africa, South America and Eurasia plates are undergoing acceleration, while the North America and Australia plates are in the state of deceleration motion.

Key words: ITRF2008; crustal movement; global plate model; plate acceleration

1 Introduction

Global crust is composed of tectonic plates, which are constantly in motion above mantle. The majority of global plate can be characterized by long term, short term and instant movements. Long term motion, basically defined as the background field, represents the fundamental features of crustal movement in the past several millions of years[1]. On the other hand, deriving a highly accurate and comprehensive background field of global crust plays a fundamental role in research on short term and instant crustal motions on both regional and global scales[2].

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Due to temporal and spatial resolution constraints, traditional geodetic observation techniques can only provide limited constraints on global crustal movement. With the rapid development of the Global Navigation Satellite System (GNSS), Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), it is possible presently to study global plate motion with high precision. The International Earth Rotation Service (IERS) provides a series of International Terrestrial Reference Frames (ITRF), which are dynamically and constantly refined. It can be used in the research on crustal movement and geodynamics, both on the regional and global scales. Some modern crustal movement models have been proposed on the basis of the velocities of previous ITRFs[3-5]. The vectors of rotation of 10 major lithospheric plates were presented by virtue of continuous GPS observations at 192 globally distributed stations and the disagreements between current plate motions and the motions averaged over several million years are debated[6]. Relative plate angular velocities GEODVEL of 11 major plates and the velocity of Earth's center have been estimated using space geodetic observations[7]. Spreading rate, transform fault azimuths and earthquake slip direction are utilized to derive MORVEL, a new closure-enforced set of angular velocities for the geologically current motions of 25 tectonic plates that collectively occupy 97 percent of Earth's surface, with GPS data used to constrain angular velocities for 6 small plates with little or no connection to the mid-ocean ridges[8]. Based on the plate relative model MORVEL, an absolute motion model NNR-MORVEL56 is determined, 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[9]. An absolute tectonic plate motion model ITRF2008-PMM, made up of 14 major plates is estimated, using velocities of 206 sites of high geodetic quality derived from and consistent with ITRF2008[10]. However, a couple of issues need to be addressed: how big is the disagreement between geodes-derived plate motions and the motions averaged over several million years? What does the difference imply in the sense of geophysics and geology?

We have constructed a major plates' movement model in this study utilizing the ITRF2008 data provided by IERS. Compared to the past International Terrestrial Reference Frame, more sites distributed on the globe are included in ITRF2008, and its site velocities are of higher precision. Therefore it can be used to derive a highly refined global tectonic plate model.

2 Site selection

ITRF2008, with total 934 stations, is mainly based on VLBI, SLR, GPS and DORIS geodetic observation, with time span are 29, 26, 12.5 and 16 years respectively for the 4 techniques[11]. Global observation sites and plate boundaries are shown in figure 1. Plate boundaries are referred to the global plate model NNR-NUVELLA[12-14].

This study focuses on the major plates' movement, including Antarctica, Arabia, Australia, Eurasia, India, Nazca, Northern American, Pacific and Southern American and other ten relatively smaller tectonic plates. The below two principles are implemented in selecting observation stations to construct current plate movement model:

1. Far away from the earthquake belt and large deformation zone.

2. Either error of horizontal velocities of the station is less than twice of the average of errors of all sites.

In accordance with the above two principles, 258 sites are selected for the construction of plate model (Fig. 2). The selected sites are composed of 134 GPS, 49 VLBI, 55 SLR and 20 Doris stations, respectively.

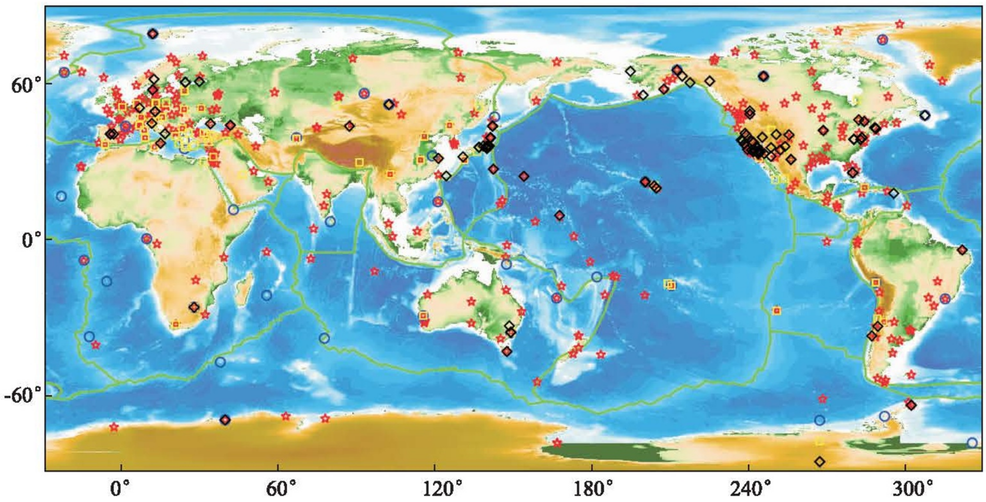

Figure 1 Observation site distribution and the plate boundaries

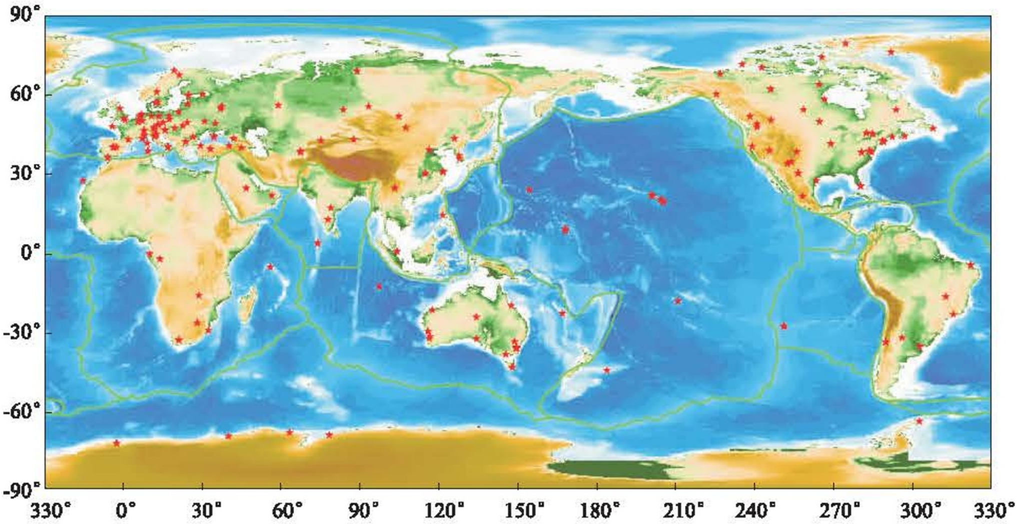

Figure 2 Distribution of the selected 238 stations

3 Method

Assuming that the Earth's surface is covered by a set of rigid plates which move towards each other, we use Euler vectors to describe the motion of these plates. In spherical coordinates, the Euler vector Ω of a tectonic plate can be described as $(\lambda, \theta, \omega)$, which mean longitude, latitude, angular rotation rate, respectively. It can be also expressed in three components Ω_x, Ω_y and Ω_z in Cartesian coordination system. According to the Euler theorem, the motion of a plate can be written as[15]:

$$V_i = \Omega \times r_i \qquad (1)$$

Where r_i and V_i are site position and its velocity, respectively. It can be further formulated in the expression of geodetic coordinates of observational site, shown as equation (2).

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} 0 & r\sin\varphi & -r\text{sins}\lambda\cos\varphi \\ -r\sin\varphi & 0 & r\cos\varphi\cos\lambda \\ r\sin\lambda\cos\varphi & -r\cos\varphi\cos\lambda & 0 \end{bmatrix} \begin{bmatrix} \Omega_x \\ \Omega_y \\ \Omega_z \end{bmatrix} \qquad (2)$$

Considering the lower precision of vertical velocities and horizontal velocities are only utilized. Thus the above equation (2) can be simplified as:

$$\begin{bmatrix} V_e \\ V_n \end{bmatrix} = \begin{bmatrix} -r\cos\lambda\sin\varphi & r\sin\lambda\sin\varphi & r\cos\lambda \\ -r\sin\varphi & -r\cos\lambda & r\cos\varphi\cos\lambda \end{bmatrix} \begin{bmatrix} \Omega_x \\ \Omega_y \\ \Omega_z \end{bmatrix} \qquad (3)$$

The global plate motion model is derived using an iterative linearized weighted least-square procedure, by minimizing the total weighted least square error, as indicated by the following equation (4).

$$\sum_{i=1}^{n} \left[\frac{d_i^{obs} - d_i^{pred}(m)}{\sigma_i} \right] = \min \qquad (4)$$

Where d_i^{obs} is ith horizontal displacement of site located in a specified plate motion, d_i^{pred} the predicted value, and σ_i, the standard error of ith observational displacement. The model parameter vector $\boldsymbol{m}$ can be resolved by using a linearized weighted least square algorithm.

4 Result and discussion

We have calculated the Euler vectors of ten major plates, as shown in table 1, where φ is the longitude, λ the latitude and Ω the angular rotation rate, σ_φ, σ_λ and σ_ω are their respective errors.

Due to larger difference in number of stations selected in accordance with the two principles stated in the above section 2 to calculate Euler vector for various plates, the precision of the Euler vectors for individual plates vary greatly. For example, the precision of Euler vectors of the Eurasia and Northern America plates are relatively higher, since

Table 1 Euler vectors of ten major tectonic plates

Plate	φ (°)	λ (°)	Ω (°/Ma)	σ_φ (°)	σ_λ (°)	σ_ω (°/Ma)
Afrc	51.37	-71.88	0.303	0.045	0.143	0.00039
Anta	59.43	-53.67	0.223	0.176	0.245	0.00119
Arab	0.00	-80.54	0.974	0.049	0.045	0.00058
Aust	32.60	37.68	0.634	0.034	0.056	0.00050
Eura	54.64	-81.69	0.264	0.037	0.086	0.00026
Indi	49.45	-21.79	0.490	0.338	2.705	0.00558
Noam	-4.29	-85.43	0.194	0.231	0.080	0.00053
Naza	62.54	-81.75	0.606	4.551	3.299	0.07290
Paci	-62.33	68.59	0.678	0.205	1.104	0.00486
Soam	-8.79	-67.40	0.146	0.265	0.382	0.00100

Note: φ, λ and Ω, are latitude, longitude and angular rotation vector, respectively, σ_φ, σ_λ and σ_ω are their standard deviations, respectively.

there are more observational sites located in the two plates. While there are only limited number of observation sites on the Arab and Nazca plates, the two plates have lower precision of Euler vectors.

By discretizing each plate into the grid of 10° × 10°, we calculate the horizontal velocities of specified site in the grid, using the Euler vectors of individual tectonic plates, following formula (2). The resultant velocities are shown in figure 3. The focal mechanism of global $M \geqslant 7.0$ earthquakes (http://www.seismology.harvard.edu) are also plotted in figure 3. It can be seen that the Pacific and Eurasia plates are noticeably converging in their boundary of the eastern Asia, especially along the Japanese islands. The movements of Eurasia are almost perpendicular to the Pacific plates in their contact area of the two plates, causing large scale of thrust faults and strong crustal deformation[16]. Applying the same procedure to the NNR-NUVEL1A model, we obtain a horizontal velocity field in the same grids. A close comparison between the two velocity fields shows quite similar motion for the Africa and North America plates. Small difference is identified for the Australia plate. For the Eurasian and Pacific plates, differences between the two velocity fields derived from ITRF2008 and NNR-NUVEL1a are quite obvious. On the basis of the ITRF-derived Euler vectors, we also have computed the major plate boundary velocity, which is schematically demonstrated by relative motion of plate pairs (Fig. 4). Southern Tibet, the boundary between the India and Eurasia plates is

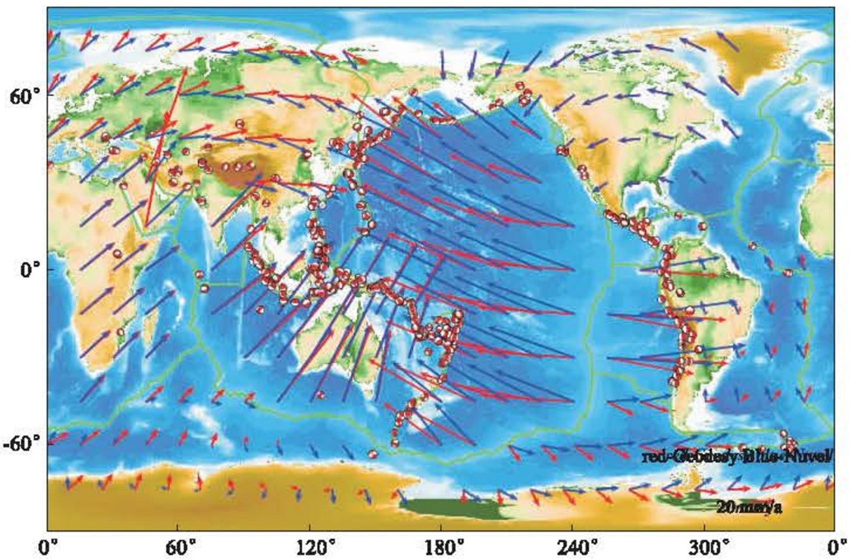

Figure 3 Plate velocity fields and the distribution of global $M \geqslant 7.0$ earthquakes

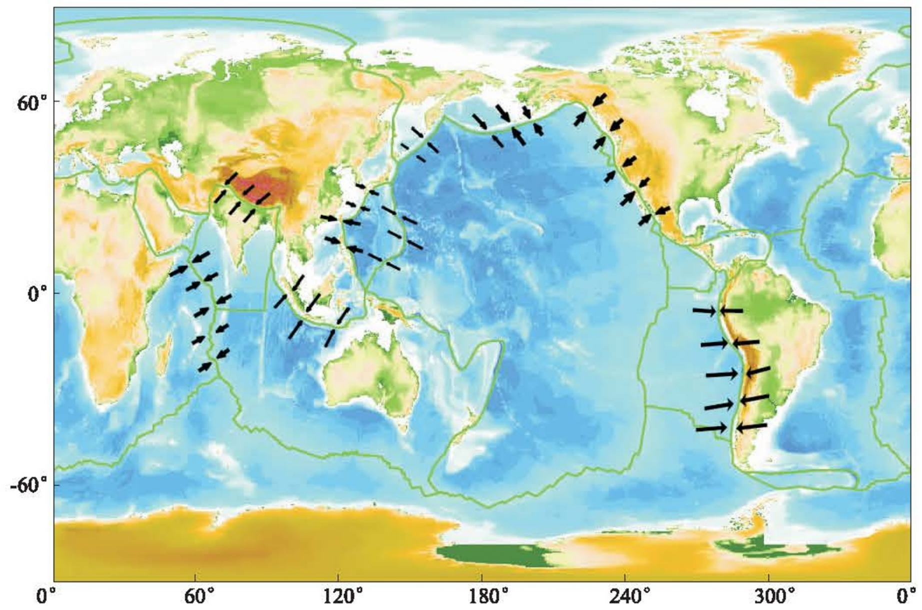

Figure 4 Schematic motions of the major plate boundaries

undergoing strong collision, and Andes range, as the boundary between the Nazca and South America plates behaves noticeable compression. The Pacific plate is conducting subduction along the Aleutian Islands, which is part of boundary of the North America and Pacific plates.

The NNR-NUVEL1A model constructed by geological and physical data could reflects the average velocity in the past 5 Ma. Our ITRF20080-derived plate model indicates present-day motion of global plates. In order to quantify differences between the two models, we introduced the plate acceleration to identify how different the two velocity fields for individual plates with equations (5) and (6), following the procedure of Forte et al[17].

$$a_{rms}^2 = \frac{1}{A_i}\iint \frac{dv}{dt}\frac{dv}{dt}d^2S \tag{5}$$

$$C = \frac{\frac{1}{A_i}\iint \frac{dv}{dt} v d^2S}{a_{rms}\, v_{rms}} \tag{6}$$

Where a_{rms} represents plate acceleration for ith plate, rms the root-mean-square of acceleration; A_i is the surface area of the ith plate, and dv/dt the rate of velocity change. Considering a_{rms} is always positive and does not reveal whether plate velocity change is increasing or decreasing with time. Therefore it is necessary to consider an auxiliary scalar diagnostic C that measures the cross-correlation between plate acceleration and velocity, where v_{rms} is defined by an expression similar to equation (5). Negative values of C imply a deceleration of the mean plate velocity and positive values instead imply a positive acceleration. The computational result is shown as table 2.

Table 2 The acceleration of major tectonic plates(unit: mm. a^{-1}/Ma)

plate	Acceleration	Standard deviation
Afri.	0.218	0.529
Anta.	4.647	3.552
Arab.	8.793	3.254
Aust.	-1.446	0.439
Eura.	3.050	1.563
Indi.	-3.003	1.587
Noam.	-0.845	1.067
Naza.	11.743	7.021
Paci.	-5.569	0.118
Soam.	18.442	6.254

It can be seen from table 2 that the Africa, South America and Eurasia plates are currently experiencing acceleration, while the North America and Australia plates are characterized by deceleration.

5 Conclusions

We have constructed a new global tectonic plate model, using the latest International Terrestrial Reference Frame (ITRF2008) released by International Earth Rotation Service (IERS). The newly established ITRF2008-derived model is generally in agreement with NNR-NUVEL1A, which is constructed on the basis of geological and geophysical data. However the Eurasia and Pacific plates display some differences in terms of the two velocity fields derived from the two plate motion models. Plate boundary motion calculated from Euler vectors of two neighboring plates shows that the Pacific and Eurasia plates are noticeably converging in the eastern Asia, especially along the Japanese islands. The movements of Eurasia are almost perpendicular to the Pacific plates in their contact area. Plate acceleration is also introduced to identify the differences of the two velocity fields obtained from ITRF2008-derived and NNR-NUVEL1A models for individual plates. The results show that the Africa, Australia, South America and Eurasia plates are undergoing acceleration, while the North America and Australia plates are in the state of deceleration.

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