A Model of Plate Motions

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Abstract. The wide use of space geodesy techniques devoted to geophysical and geodynamical purposes has recently evidenced some limitations due to the intrinsic Terrestrial Reference Frame (TRF) definition. Current TRFs are defined under hypotheses suited to overcome the rank deficiency of the observations with respect to the parameters that have to be estimated, i.e. coordinates and velocities (Dermanis, 2001; Dermanis, 2002).
From a geodetic point of view, one possibility implies the application of the no-net-rotation condition (NNR). One of the main geophysical consequences due to the application of this condition is that it allows only accurate estimations of relative motions, whilst other motions of geodynamical interest, for instance with respect to the inner layers of the Earth body, are not determinable.

The main purpose of this paper is to propose a unified way to describe plate motions, overcoming the problems introduced by the NNR condition, in order to establish a new reference frame useful for geodynamical applications too.

Since we believe relevant the role played by global tectonics inferences, we introduce the concept of the *main tectonic sinusoid* to propose an analytical description of the plate motions flow, which is polarized to the "west" in the hotspot reference frame.

Keywords. Terrestrial Reference Frame, *main tectonic sinusoid*, westward drift, plate kinematics

1 Introduction

The most updated information on present plate motions is based on space geodesy data (Heflin et al., 2004), where motions are essentially estimated from GPS continuous observations in a no-net-rotation frame (NNR), as assumed by the International Terrestrial Reference Frame (Altamimi et al., 2002 a, b).
It is useful to recall that the TRF origin may be sensed by geodetic techniques; this is realized in the geocenter, being well defined by SLR.

The scale is metric, but depends on the speed of light, because the observing sites and the targets in the space are linked by electromagnetic signals. However, TRF orientation cannot be sensed by any geodetic technique, so that it is conventionally defined at a starting epoch and its time evolution is ensured by imposing the NNR condition over the whole Earth.

This condition is currently applied by aligning the TRF (Altamimi et al., 2002) to the NNR-NUVEL-1A model (De Mets et al., 1990; Argus and Gordon, 1991; De Mets et al., 1994), to try to guarantee its co-rotation with the Earth surface.

The practical TRF realization consists of a set of coordinates and velocities of the observing sites at a given epoch.
Figure 1 shows the current ITRF2000 velocities provided by JPL (Heflin et al., 2004), according to which, for what stated above, only accurate relative plate motions are defined.
However, current realization of this condition involves some problems:

- it theoretically requires a whole integral over the Earth, the so called Tisserand condition, but space geodesy observed sites are discrete and quite far from optimally distributed,
- it prevents from actually describing the Earth plate motions, for instance w.r.t the underlying mantle, that may be considered a fundamental geodynamical task

The aim of this paper is to give a first attempt to define an alternative plate motion model, useful for geodynamical tasks, on the basis of the main global tectonic features.

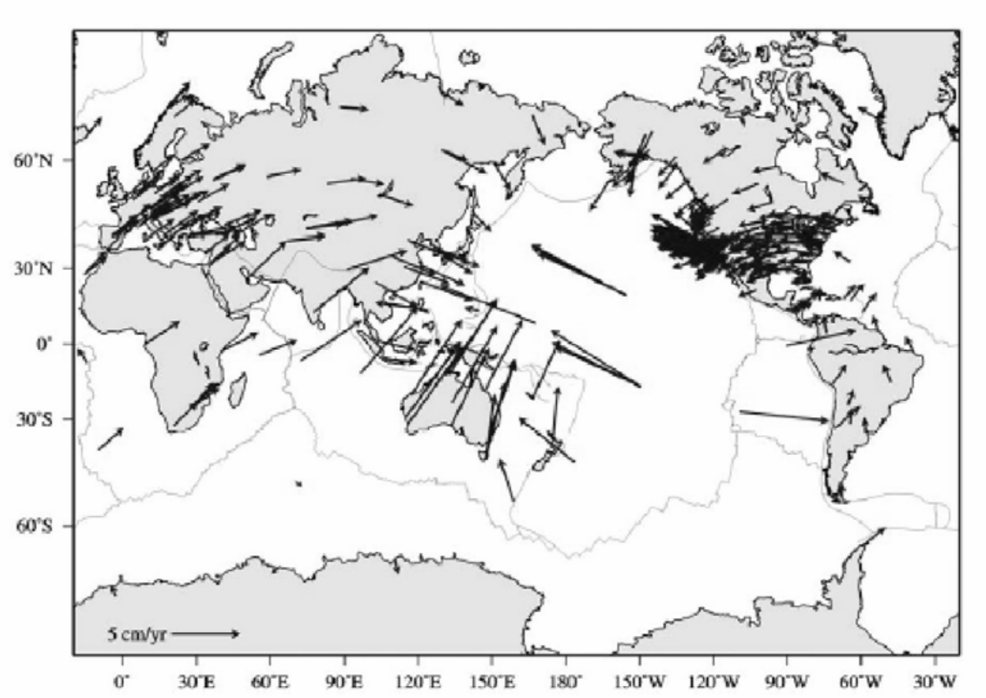

Fig. 1 Current ITRF2000 velocities (Heflin et al., 2004)

2 Tectonic mainstream

In order to establish the geological constraints for the definition of the analytical model, let us consider the first order tectonic structures along the boundaries of six large plates of Earth (Pacific, Nazca, South America, Africa, Arabia-India, and Eurasia), reported in Figure 2: the East Pacific Rise (1), the Mid Atlantic ridge (2), and the Red Sea - Indian ridge (3), for extensional margins, and the western Pacific subduction zones (4), the western northern and southern Americas Cordilleras (5), and the Alpine-Himalayas system (6) for convergent margins.

In the extensional tectonic settings, we assume that transform faults are parallel to the relative plate motions, whereas in convergent settings, the relative plate motions are constrained by the dominant trend of folds and thrusts, where no significant transpressive tectonics occurs. Analyzing the relative motions across these tectonic structures crossing the whole lithosphere, it appears that all the lithospheric plates do not move randomly, but follow a global mainstream, with a sinusoidal shape.

The tectonic mainstream (Doglioni, 1990; Doglioni, 1993) can be described here as an imaginary line named the *main tectonic sinusoid*, with a great undulation from east Africa to the western Pacific.

There are independent evidences of a “westward” drift of the lithosphere with respect to the mantle based on geophysical and geological evidences (Bostrom, 1971; Ricard et al., 1991; O'Connell et al., 1991; Doglioni et al., 1999; 2003).

The westward drift is then polarizing the tectonic mainstream, i.e., plates move, although at different velocities, toward the “west” with respect to the underlying mantle.

The tectonic mainstream may be described as a series of flow lines representing the main plate motion trajectories (Figure 3). The *main tectonic sinusoid* is the line roughly in the middle of the flow where the velocity toward the “west” is maximum within the plates crossed by the sinusoid.

The aim of this work is to give an analytical representation of the proposed *main tectonic sinusoid* useful to describe the plate motions with respect to the mantle.

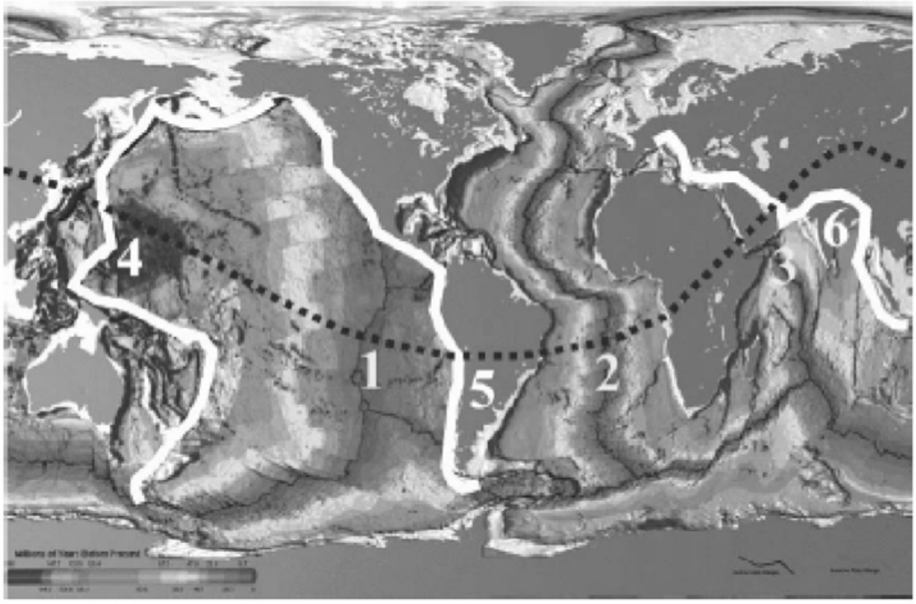

Fig. 2 Construction of a *main tectonic sinusoid*, starting from the Pacific motion direction and linking all the other relative motions in a global circuit using first order tectonic features such as the East Pacific Rise (1), the Atlantic rift (2), the Red Sea, the Indian Ocean rift (3) for the rift zones, and the west Pacific subduction (4), the Andean subduction (5), and the Zagros-Himalayas subduction (6) for convergent margins; base map, Age of the Ocean Floor, World Data Center-A for Marine Geology and Geophysics Report MGG-12, 1996, National Geophysical Data Center, US.

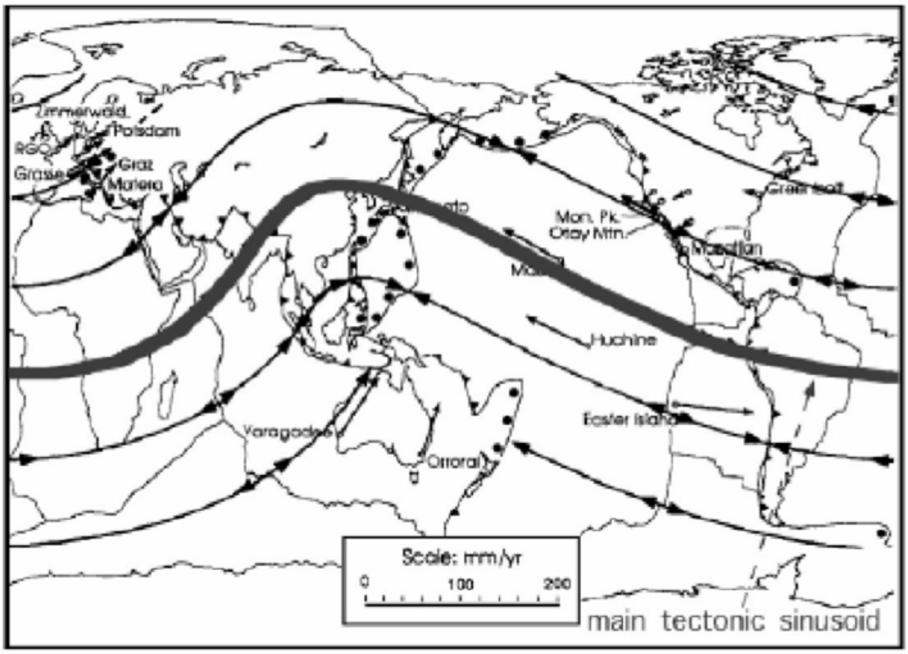

Fig. 3 The flow lines represent the mainstream of plate motions. Since the lithosphere has a net “westward” rotation, the underlying mantle is relatively moving “eastward” .

This can be done starting from a 3rd order Fourier series in geographic coordinates (φ, λ), whose 7 coefficients have to be estimated taking into account the aforementioned geological evidences

$$\varphi(\lambda) = \frac{a_0}{2} + \sum_{i=1}^{3}(a_i \cos(i\lambda) + b_i \sin(i\lambda))$$

The parameters (unknowns) of this equation are: the seven coefficients of the Fourier series (global parameters) and the ratios between the rotation components for each plate (local parameters).

The basic assumptions for the estimation are the following: spherical approximation, plate motions modeled as 3D rotations; moreover for each plate it is required:

- orthogonality between the plane of the eulerian equator and the rotation axes, where the eulerian equator is the mean plane of the main tectonic sinusoid within each plate crossed by the main tectonic sinusoid itself
- velocity horizontal with maximum intensity along the eulerian equator (Figure 4).

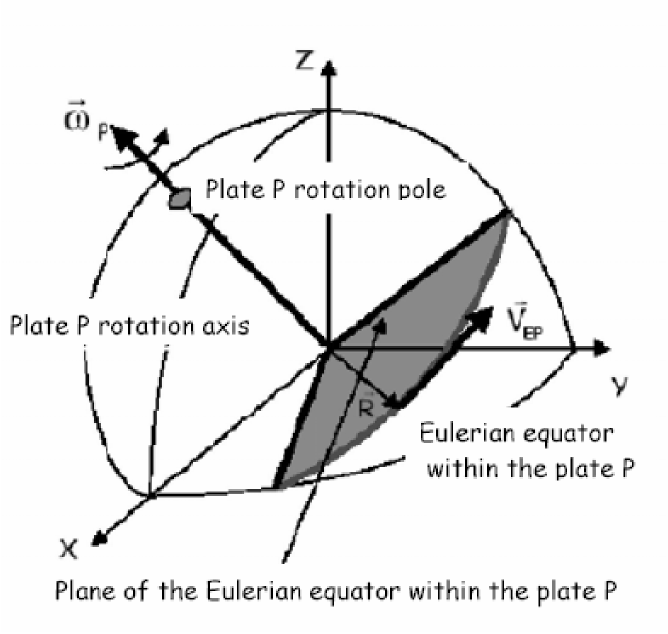

Fig. 4 The kinematic condition under the spherical approximation

This implies that

$$\omega_{XPL} X + \omega_{YPL} Y + \omega_{ZPL} Z = 0$$

The requested orthogonality between the rotation axis and the eulerian equator (kinematic condition) leads to the first equation of the *main tectonic sinusoid* useful for its analytical representation. This is obtained by equating the kinematic condition to the analytical representation:

$$\frac{a_0}{2} + \sum_{i=1}^{3}(a_i \cos(i\lambda) + b_i \sin(i\lambda)) = -\arctan\frac{\omega_{XPL}\cos\lambda + \omega_{YPL}\sin\lambda}{\omega_{ZPL}}$$

The second equation is derived from a geological condition: the direction of the tectonic line must be equal to the mean azimuth α of the direction of motion across the largest tectonic features (Searle, 1986; Gordon, 1995).

This implies to equate the first derivative of the analytical expression of the *tectonic mainstream* to a quantity that depends, on the tangent of the mean azimuth.

$$\sum_{i=1}^{3}[-ia_i \sin(i\lambda) + ib_i \cos(i\lambda)] = \frac{\cos\varphi}{\tan\alpha}$$

For this purpose, we selected the directions (Table1) of some principal tectonic structures (Figure 5), used for the analytical representation of the global tectonic pattern: the Mid Atlantic Ridge (MAR), the Red Sea and East Africa Rift (RSEAR), the Japan Subduction (JS), the Hawaiian sea-mount chain (HH), the East Pacific Rise (EPR) and the Andean Subduction (AS).

Table 1 Azimuth of the selected tectonic features

	λ (rad)	φ (rad)	α (deg)
1 MAR	6.021	-0.262	80 ± 3
2 RSEAR	1.047	0.524	36 ± 3
3 JS	2.583	0.785	301 ± 5
4 HH	3.578	0.349	293 ± 5
5 EPR	4.538	0.000	279 ± 3
6 AS	4.800	0.000	90 ± 5

We introduce these geological conditions into the equation system.

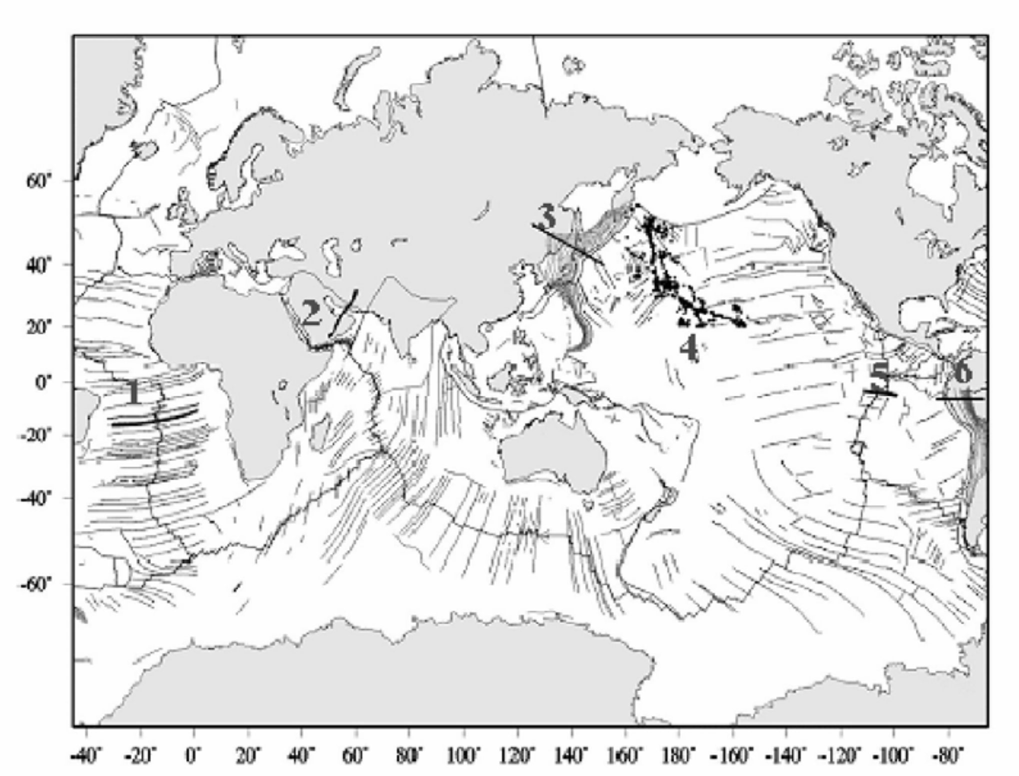

Fig. 5
Map of the main tectonic features selected to introduce azimuthal constraints into the *main tectonic sinusoid* estimation
1=MAR; 2=RSEAR; 3=JS ; 4=HH ; 5=EPR ; 6= AS

The over-determined system is composed by

• a first block of equations, written for points located along the tectonic mainstream, suitably chosen in order to guarantee parameters estimability and reliability for each plate crossed by the main tectonic sinusoid

• a second block of equations, written for the aforementioned tectonic features

The parameters are estimated according to the least squares principle, in an iterative fashion, due to the non-linearity of the equation system, starting from their approximated values.

The final precision of the *main tectonic sinusoid* after the least squares estimation is $\hat{\sigma}_0 = 0.2$ *rad*, which corresponds to about 1000 km of uncertainty along the N-S direction.

3 The Hot Spot Reference Frame (HSRF)

The estimated *main tectonic sinusoid*, defined by the coefficients a_i and b_i, is now suited to establish a new reference frame, according to which it is possible to represent plate motions.

The kinematics of the plates crossed by the *main tectonic sinusoid* can be defined by assigning a starting value of tangential velocity along a sector of the line.

In particular, we focus our attention on the Pacific plate, the fastest plate displaying HS stability with respect to the mantle (Gripp and Gordon, 2002) .

Fixing the Hawaiian HS velocity with respect to the mantle under two different hypotheses and introducing the information on relative plate motions, it is possible to define the rotation components of each plate crossed by the *main tectonic sinusoid* and the velocities of sites located on each of the plates.

This is done by assigning

- a mean velocity $V_{eq,PA}$ to the Pacific plate
- a mean relative velocity between the crossed plates $V_{eq,rel}$

We computed the relative velocities $V_{eq,rel}$ between plates along the *main tectonic sinusoid* from the APKIM2000.0 model, the most recent plate kinematic model incorporating space geodesy observations (Drewes and Meisel, 2003).

In this way, the motions of the plates crossed by the *main tectonic sinusoid* can be defined with respect to the mantle.

In Figure 6, we represent the Pacific velocity under four different reference frame choices. In all the scenarios the relative velocity across the EPR has the same value of 11 cm/yr.

In the first and second case we have the plate motions represented in relative fashion. More in detail, the first is with respect to the Pacific plate, the second attains the well-known NNR solution. In the last two cases, on the contrary, we represent the motion with respect to the HS reference frame.

The idea is based on the fact that the Hawaiian volcanic track indicates that there is a decoupling between the magma source and the lithosphere, which is moving WNW.

We consider two different scenarios for the Pacific HS: the first hypothesizes a deep source located in the mantle, so that the track records the entire shear between lithosphere and mantle and, according to Gripp and Gordon (2002), it reaches the value of 10 cm/yr.

If the source is shallower, for instance located in the middle asthenosphere, the track cannot account for the entire shear between lithosphere and mantle, so there is a missing part of motion.

In this case, considering only the Hawaiian HS, according to Doglioni et al. (2005), the entire motion could reach 20 cm/yr.

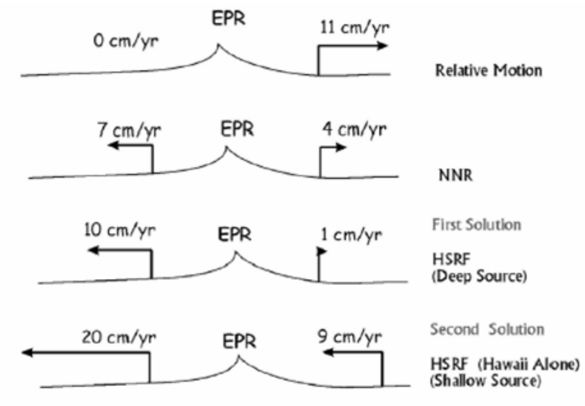

Fig. 6 Pacific plate motion and situation across the EPR. From the top to the bottom: Pacific plate fixed; classical ITRF solution; HSRF deep source; HSRF shallow source

4 Preliminary kinematic model

Under these hypotheses about the Pacific plate velocity, we jointly estimated the rotation poles (Table 2) and the angular velocities (Tables 3 and 4) of the six plates (Pacific-PA, Nazca-NZ, South America- SA, Africa-AF, Arabia-AR, Eurasia-EU) crossed by the *main tectonic sinusoid*, without the corresponding uncertainties, as preliminary proof.

The least square estimation was performed starting from some approximated values of the parameters, i.e. the rotation components from APKIM2000 model (Drewes and Meisel, 2003) and the *main tectonic sinusoid* coefficients from the *twelve ordinates* method, selecting an appropriate number of points in agreement with the geological evidences (Von Karman and Biot, 1951), since the equation system is not linear.

Table 2 Estimated rotation poles

PLATE	φ ° N	λ ° E
PA	-58.3	149.8
NZ	-77.4	168.7
SA	-75.1	172.3
AF	-67.0	110.4
AR	-43.8	118.0
EU	-37.3	124.7

Table 3 Estimated angular velocities if $V_{eq,PA}$ =10 cm/yr

PLATE	ω °Myr^{-1}	ω_x °Myr^{-1}	ω_y ° Myr^{-1}	ω_z ° Myr^{-1}
PA	0.93	-0.42	0.24	-0.79
NZ	-0.14	0.03	-0.01	0.14
SA	0.38	-0.10	0.01	-0.36
AF	0.19	-0.03	0.07	-0.18
AR	0.02	-0.01	0.01	-0.02
EU	0.16	-0.07	0.10	-0.10

Table 4 Estimated angular velocities if $V_{eq,PA}$ =20 cm/yr

PLATE	ω °Myr^{-1}	ω_x °Myr^{-1}	ω_y ° Myr^{-1}	ω_z ° Myr^{-1}
PA	1.80	-0.82	0.47	-1.53
NZ	0.73	-0.16	0.03	-0.71
SA	1.25	-0.32	0.04	-1.21
AF	1.06	-0.14	0.39	-0.98
AR	0.89	-0.30	0.57	-0.62
EU	1.03	-0.47	0.67	-0.63

We applied the estimated kinematic model to some GPS sites located on the plates crossed by the *main tectonic sinusoid*, to present the estimated global pattern.

Figures 7 and 8 show their velocities with respect to the underlying mantle, under the two different HSRF hypotheses.

Both the solutions confirm the presence of a global mainstream, a coherent undulated flow toward the “west”, along which plates move at different velocities. It has to be noted that only under the first hypothesis the Nazca plate remains counterflow.

Concerning the relative motions between plates resulting after the least square estimation of the new plate kinematic parameters, they remain in agreement with their initial approximated values, given by the APKIM2000 model (Drewes and Meisel, 2003), if estimation errors are taken into account.

5 Conclusions and future perspectives

On the basis of geological evidences the concept of *main tectonic sinusoid* is, for the first time, introduced in order to describe the plate motions with respect to the mantle.

Two basic equations, which must be satisfied by the *main tectonic sinusoid* are derived and two preliminar solutions based on different kinematic hypotheses are computed.

The final precision in the *main tectonic sinusoid* definition is $\hat{\sigma}_0 = 0.2\, rad$, which corresponds to about 1000 km of uncertainty in N-S direction.

For the future, the motions of the plates not crossed by the *main tectonic sinusoid* must be computed too, in order to derive a complete description of plate motions.

As a final speculation, the *main tectonic sinusoid* is tilted 25-30° with respect to the Earth's equator, but close to the ecliptic plane of the Earth's revolution plane, and within the band of oscillation of the Moon's revolution (Fig. 9). This evidence might support an astronomical origin of the global ordered tectonic pattern observed on Earth.

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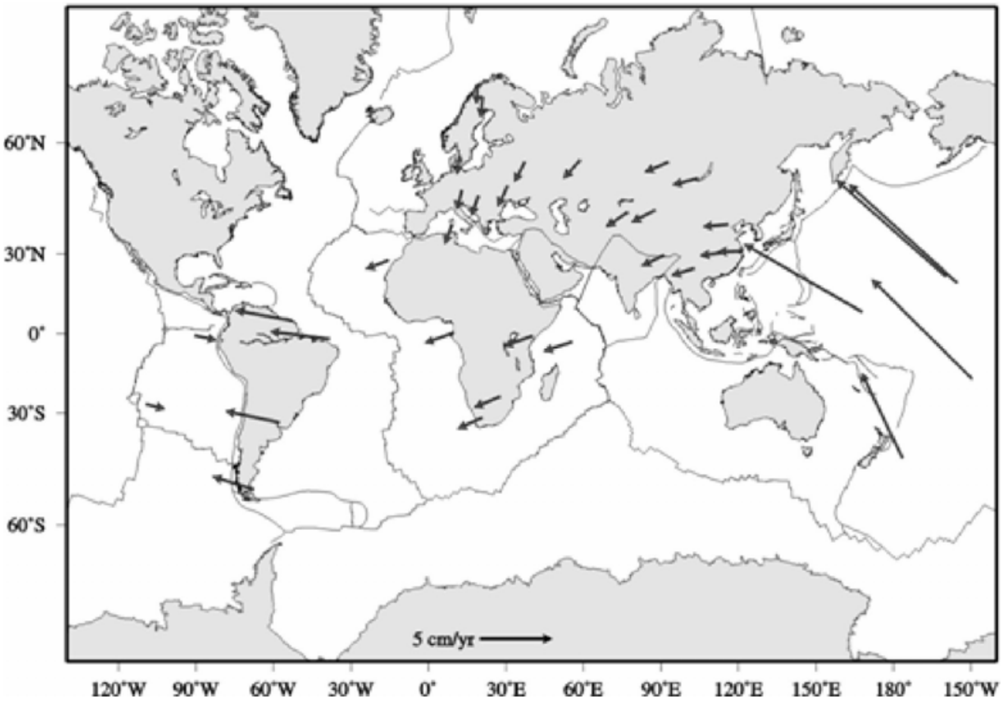

Fig. 7 Plate motion under the first HSRF hypothesis

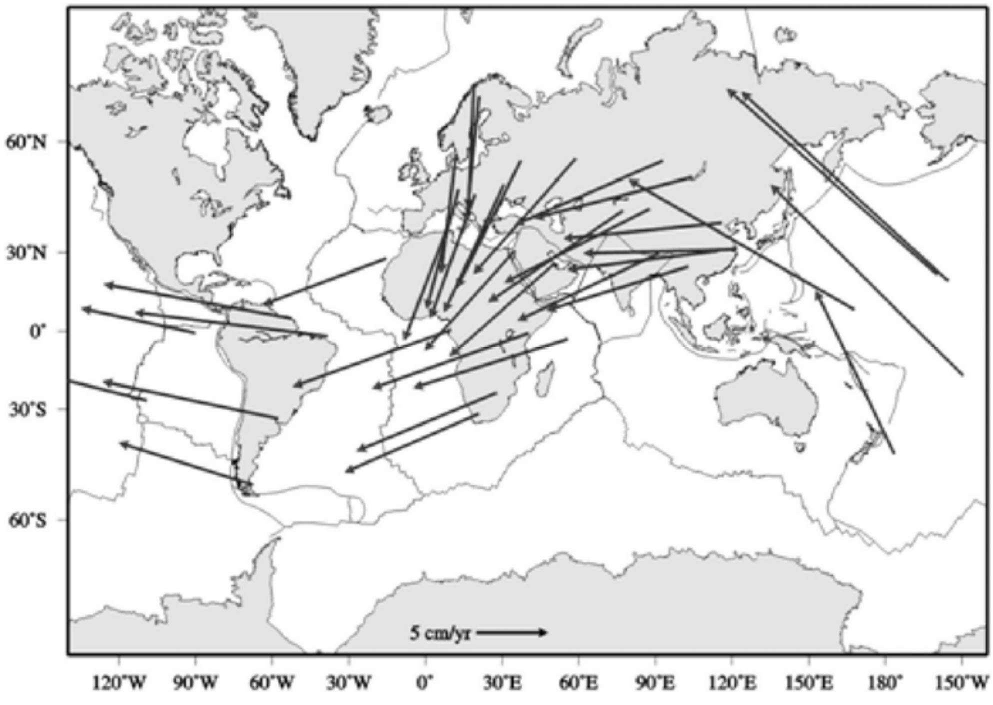

Fig. 8 Plate motion under the second HSRF hypothesis

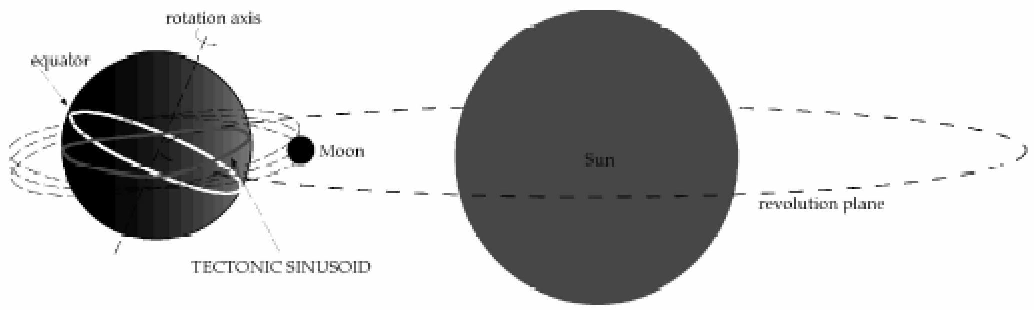

Fig. 9 Cartoon, not to scale, showing how the main tectonic sinusoid falls close to the ecliptic plane, and within the band of oscillation of the Moon's revolution, suggesting a rotational origin of the tectonic flow pattern.

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