HORIZONTAL AND VERTICAL DISPLACEMENTS OF THE STATIONS WITHIN THE FRAME OF THE INDIVIDUAL PLATES BASED ON THE ITRS2000 REFERENCE SYSTEM

Jan KOSTELECKÝ [1),2)], * and Antonín ZEMAN [1)]

[1)] *CEDR, Department of Advanced Geodesy, Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, 166 29 Prague 6, Czech Republic*
[2)] *CEDR, Research Institute of Geodesy, Topography and Cartography, 250 66 Zdiby 98, Czech Republic,*
**Corresponding author's e-mail:* kost@fsv.cvut.cz

(*Received* February 2004, *accepted* May 2004)

ABSTRACT
Global horizontal and vertical movements were computed for individual tectonic plates from the velocity vectors published for ITRS2000. For the stations within the frame of those plates the differences from the global displacements and their rms errors were then computed. Global vertical motion (expansion/compression) of the Earth if exists is lower 1 cm/year (with 66% probability) or 2.5 cm (with 95% probability). Global horizontal motion of individual plates was detected and model NUVEL-1A was corrected, but accuracy of the model does not allow to detect r esidual motions of individual stations lower 1 cm/year (with 95% probability) in most cases.

KEYWORDS: geodesy, geodynamics, plate movements, terrrestrial reference systems

1. INTRODUCTION

Conventional Terrestrial Reference System (CTRS) is defined by the set of all conventions, algorithms and constants which provide the origin, scale and orientation of that system and their time evolution.

Conventional Terrestrial Reference Frame (CTRF) is defined as a set of physical points with precisely determined coordinates in a specific coordinate system as a realization of an ideal Terrestrial Reference System. Seven parameters are needed to fix a TRF at a given epoch, to which are added their time-derivatives to define the TRF time evolution.

International Terrestrial Reference System (ITRS)

The IUGG Resolution No.2 adopted in Vienna 1991 (Geodesist's Handbook, 1992) recommends the following definitions of the TRS:

1. CTRS to be defined from a geocentric non-rotating system by a spatial rotation leading to a quasi-Cartesian system,
2. the geocentric non-rotating system to be identical to the Geocentric Reference System (GRS) as defined in the IAU resolutions,
3. the coordinate-time of the CTRS as well as the GRS to be the Geocentric Coordinate Time (TCG),
4. the origin of the system to be geocenter of the Earth's masses including oceans and atmosphere,
5. the system has to have no global residual rotation with respect to horizontal motions at the Earth's surface.

Realizations of the ITRS are produced by the IERS ITRS Product Center (ITRS-PC) under the name **International Terrestrial Reference Frame (ITRF).**

The history of the ITRF goes back to 1984, when for the first time a combined TRF was established using station coordinates derived from VLBI (Very Long Baseline Interferometry), LLR (Lunar Laser Ranging), SLR (Satellite Laser Ranging) and Doppler /TRANSIT (the predecessor of GPS) observations. Until the present time 10 versions of the ITRS were published, starting with ITRF88 and ending with ITRS2000, each of which superseded its predecessor. This contribution issued from presentation on the symposium of European Geophysical Society (EGS), Haag 1999, see (Kostelecký, Zeman, 2000), where the reference frame ITRF96 was chosen because this frame is the first where the velocities were determined from real observations. Some stations, however, showed significant dispersion in their results. Therefore the stations which showed rms of the displacements greater than 5 cm/year or if the magnitude of their vector was greater than 10 cm/year, were eliminated from the analysis. Statistically significant vertical change was detected for no tectonic plate; the same was valid for the whole Earth in global extent. Due to accuracy, characterized by the rms error 10.5 mm for global solution, we could state that if some secular vertical changes (secular expansion/contraction of the Earth) exist, their absolute value must be less than 1 cm/year.

In the case of horizontal changes geophysical model responses well to the motions verified by observations. We tried to confront observed values with the theoretical ones and carry out prospective corrections to existing model NNR-NUVEL-1A - see Fig. 1.

2. COORDINATE FRAME ITRF2000

ITRF2000 (Current Reference Realization of the ITRS) is intended to be a standard solution for geo-referencing and all Earth science applications. In addition to primary core stations observed by VLBI, LLR, SLR, GPS (Global Positioning System) and DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite), the ITRS2000 is densified by regional GPS networks in Alaska, Antarctica, Asia, Europe, North and South America and the Pacific – see Figs. 2 and 3.

The criteria retained for site selection are: continuous observation during at least 3 years, sites located far away from plate boundaries and deforming zones, velocity accuracy (as result of ITRS combination) better than 3 mm/y, velocity residuals less than 3 mm/y for at least 3 different solutions. Based on the ITRF2000 preliminary analysis, sites selection was performed using the above criteria yielding 54 sites.

The ITRF2000 results show significant disagreement with the geological model NUVEL – 1A in terms of relative plate motions (Altamimi et al., 2002a,b). Although the ITRF2000 orientation rate alignment to NNR-NUVEL-1A is ensured at the 1 mm/year level, regional site velocity diferrences between the two sites may exceed 3 mm/year. It should be emphasized that these differences do not at all disrupt the internal consistency of the ITRF2000, simply because the alignment defines the ITRF2000 orientation rate and nothing more. Moreover, angular velocities of tectonic plates which would be estimated using ITRF2000 velocities may significantly differ from those predicted by the NNR-NUVEL-1A model.

3. COMPUTATION AND ANALYSIS STRATEGY

Strategy is based on the results from (Kostelecký, Zeman, 2000). In accordance with present geophysical hypotheses it is possible to divide global movements to horizontal and vertical components. Horizontal component can be expressed by help of the vector of global rotation $\omega(\omega_x, \omega_y, \omega_z)$ for individual tectonic plates. The geophysical model NNR-NUVEL-1A, which supposes apriori zero vertical movements can serve as a starting model. For the components of velocities from model we have simple relations

$$v'_x = \omega_y z - \omega_z y, v'_y = \omega_z x - \omega_x z, v'_z = \omega_x y - \omega_y x, \quad (3.1)$$

where v'_x, v'_y, v'_z are velocities in direction of coordinate axes, in our case fulfiling the conditions

$$\begin{vmatrix} v'_x \\ v'_y \\ v'_z \end{vmatrix} = \mathbf{T}'_{x,y,z} \begin{vmatrix} v_S \\ v_E \\ 0 \end{vmatrix} , \quad (3.2)$$

where v_S , v_E are horizontal components in South and East directions respectively. **T'** is transponed matrix to the matrix **T**, matrix **T** is transformation matrix between orthogonal components *x, y, z* and local orthogonal components *S, E, R* (*S* is positive to the South, *E* is positive to the East and *R* is positive in the direction of outer space). It holds

$$\begin{vmatrix} v_S \\ v_E \\ v_R \end{vmatrix} = \mathbf{T}_{x,y,z} \begin{vmatrix} v_x \\ v_y \\ v_z \end{vmatrix}, \mathbf{T}_{x,y,z} = \begin{vmatrix} \sin\varphi\cos\lambda & \sin\varphi\sin\lambda & -\cos\varphi \\ -\sin\lambda & \cos\lambda & 0 \\ \cos\varphi\cos\lambda & \cos\varphi\sin\lambda & \sin\varphi \end{vmatrix} \quad (3.3)$$

where φ, λ are ellipsoidal coordinates of the point with orthogonal coordinates *x, y, z* and *v* are observed components of velocities.

Reference frame ITRF96 gives us observed components v_x, v_y, v_z, velocity in the radial direction v_R, which is important in connection with the hypothesis of the Earth's body expansion, we shall compute using (3.3), for the study of horizontal components we use Eqs.(3.3) and (3.2), respectively.

For further advance it is necessary to take into account following limitations: hypothesis of the Earth's body expansion supposes the phenomenon is "partly continuous" which can be expressed by the function

$$v_R = \frac{1}{l}\sum_{k=1}^{l}\frac{1}{S_k}\int_{dS_k} v_{R,k}\, dS_k \quad (3.4)$$

where *k* is the *k*-th tectonic plate, *l* is number of tectonic plates, S_k is the area of that plate, $v_{R,k}$ is the velocity of vertical movement of the element dS_k. In our case we limit ourselves only to the point representation, therefore the integral in (3.4) will be replaced by summation

$$v_R = \frac{1}{l}\sum_{k=1}^{l}\frac{\sum_{i=1}^{n_k} p_i v_{R,i}}{\sum_{i=1}^{n_k} p_i} \quad (3.5)$$

where n_k is number of the points on the *k*-th plate, and

Table 1 Average vertical shift for the whole globe and individual plates

plate	vertical motion m/year	rms error m/year	No. of stations
global	**-.0002**	**.0088**	**447**
PCFC	-.0001	.0073	53
AFRC	-.0005	.0107	25
ANTA	.0037	.0057	28
ARAB	.0013	.0198	4
AUST	.0007	.0068	18
CARB	.0010	.0120	5
EURA	-.0004	.0092	135
INDI	.0018	.0030	2
NAZC	.0002	.0024	4
NOAM	-.0008	.0077	146
SOAM	.0010	.0114	26

p_i is weight of the i-th velocity, developed from the real observational data.

Similarly, for global horizontal movement of the k-th tectonic plate, described by the velocity vector $\boldsymbol{\omega}_k$ we can write

$$\omega_k = \frac{1}{S_k} \int_{dS_k} (\mathbf{r} \times \mathbf{v})_k \, dS_k \qquad (3.6)$$

where **r** and **v** are radiusvector and horizontal velocity of the element dS_k. In our case we know again only the values at the individual points and we have to replace integration by summation, so that for individual station

$$\omega_k \big|_i = (\mathbf{r}_i \times \mathbf{v}_i)_k \qquad (3.7)$$

is valid, where i means i-th station on the k-th tectonic plate and the resulting $\boldsymbol{\omega}_k$ we obtain by application of the least squares method, considering the accuracy of the i-th velocity, expressed by means of the weight p_i.

The current analysis strategy adopted for the generation of ITRF solutions consists on the following steps:

- removing constraints from the constrained solutions and applying minimum constraints.
- adding minimum constraints to loose solutions.
- leaving as they are, solutions where analysis centers already applied minimum constraints.
- propagating, for each individual solution, station positions at Epochs of Minimal Position Variance (EMPV).
- combining all solutions together with local ties.

In the Table 1 there is given the averaged vertical shift for the whole globe and individual plates, respectively. Here PCFC is Pacific plate, AFRC is Africa plate, ANTA is Antarctic plate, ARAB is Arabian plate, AUST is Australian plate, CARB is Caribic plate, EURA is Euro-Asian plate, INDI is India plate, NAZC is Nazca plate, NOAM is North American plate and SOAM is South American plate. No global tendency (expansion or compression) of the Earth exists on the level of accuracy characterized by rms error 9 mm/year.

In Fig. 4, there are the tendencies which are the residual shifts after *recomputation* of NUVEL-1A by the method discussed above. Evident it is for the region of Turkey and eastern Mediterranean Sea. There is suspicious the border between Euroasian and African plates.

Next Figs. 5, 6, 7, 8 give information on residual horizontal shifts of the whole EURA, AFRC, PCFC and NOAM plates. At EURA plate, residual motions on Turkey and Himalaya are visible.

More details for the border between NOAM and PCFC plates are in Fig. 9. Problems with identification of the stations on individual plate is visible (identification is taken from ITRF2000 solution) and residual motions in the region the St. Andreas Fault are well known.

Interesting information for other plates (SOAM, AUST and ANTA) are in Figs. 10 – 12. Residual west-east compresion on SOAM plate is shown, but these systematic trends on west and east part are only in noise. Interpretation of the information from these results will be done in future analyses.

4. CONCLUSIONS

The ITRF2000 results show significant disagreement with the geological model NUVEL – 1A in terms of relative plate motions (Altamimi et al., 2002a,b). Although the ITRF2000 orientation rate alignment to NNR-NUVEL-1A is ensured at the 1 mm/year level, regional site velocity differences between the two sites may exceed 3 mm/year. Angular velocities of tectonic plates which would be estimated using ITRF2000 velocities may significantly differ from those predicted by the NNR-NUVEL-1A model.

ACKNOWLEDGMENT

Authors are grateful appreciated to Ministry of Education, Youth and Sports of the Czech Republic for support of this work in the frame of projects LN00A005 and MSM210000007.

REFERENCES

Altamimi, Z., Boucher, C. and Sillard, P.: 2002a, New Trends for the Realization of the International Terrestrial Reference System. Adv. Space Res., 30, No. 2, pp. 175-184.

Altamimi, Z., Sillard, P., and Boucher, C.: 2002b, A New Release of the International Terrestrial Reference Frame for Earth Science Applications. J. Geophys. Res./bf 107, B10, 10. 1029/2001 JB000561.

Geodesist's Handbook, Bulletin Géodésique: 1992, 66, 128

Kostelecký, J. and Zeman, A.: 2000, Hypothesis of the Earth's Body Expansion and Global Plate Motions from the Point of View of Contemporary Geodetic Reference Frames. Acta Geod. Geoph. Hung. , Vol. 35(4), pp. 415-424.

Kostelecký, J. and Zeman, A.: 2003, Space displacements of the points within the frame of individual plates based on the ITRS2000. Reports on Geodesy, Proceedings of the EGS-AGU-EUG Symposium G11, Nice, 6 – 11 April 2003, Warsaw University of Technology, No. 1 (64), pp. 56 – 64.

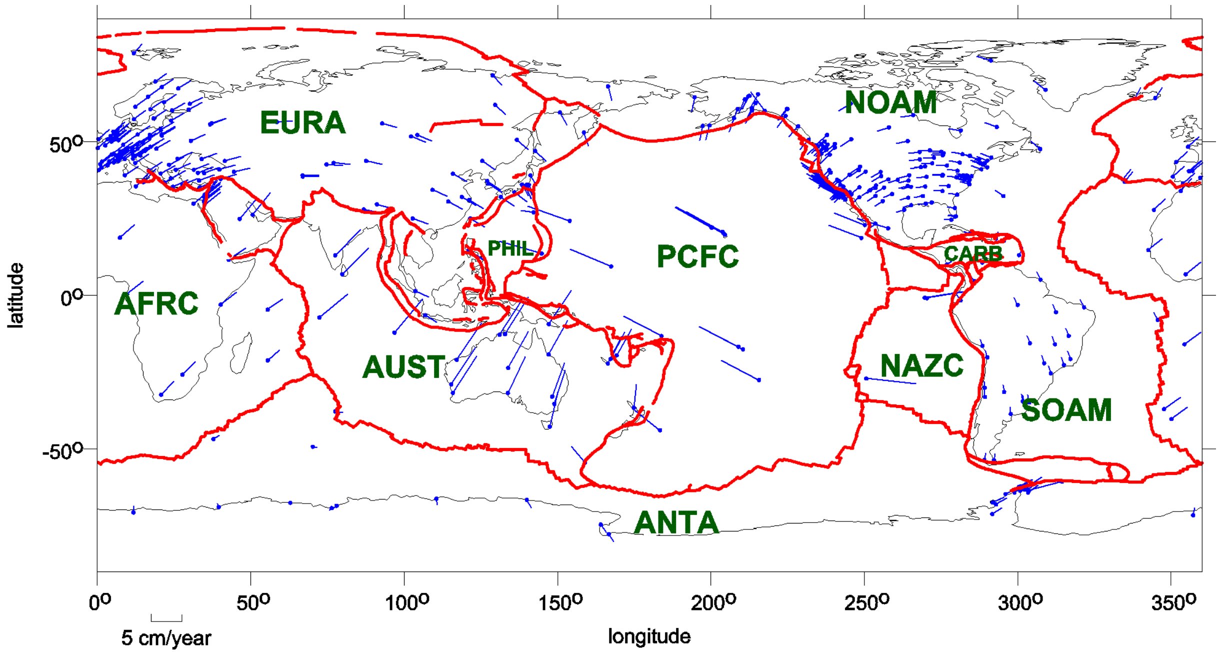

Fig. 1 Plate motions according to NUVEL1-NNR

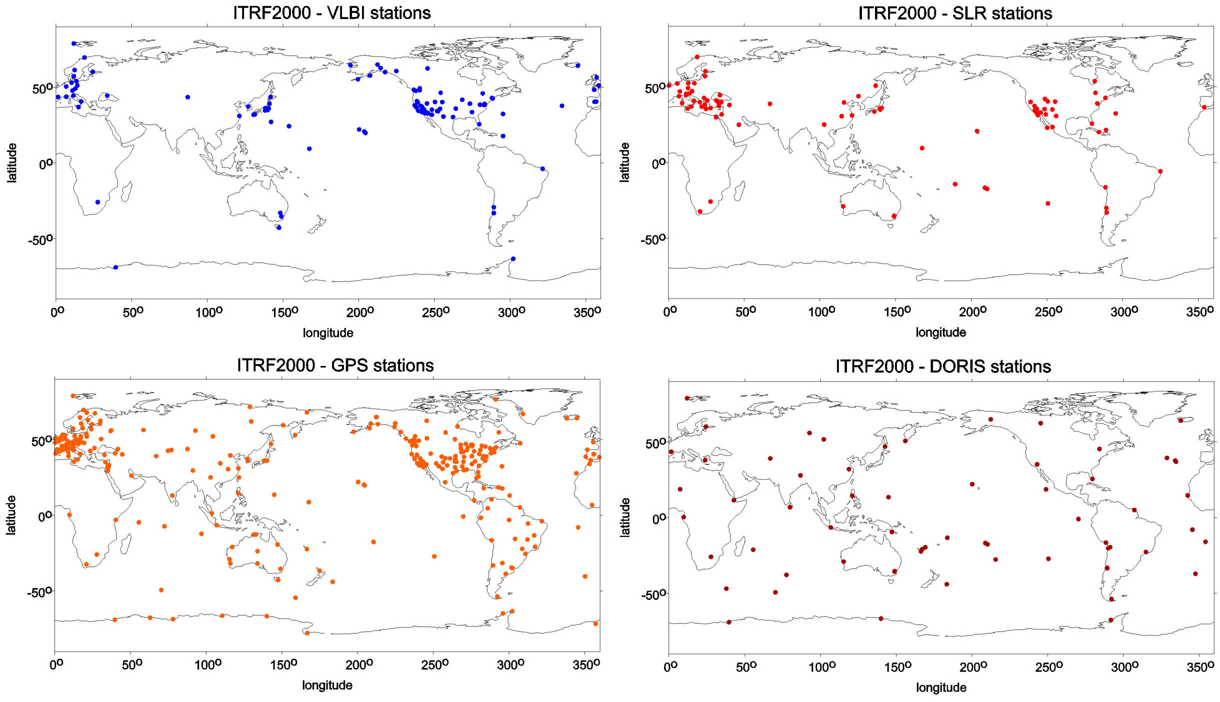

Fig. 2 Reference frame ITRF2000 – VLBI, SLR, GPS and DORIS stations

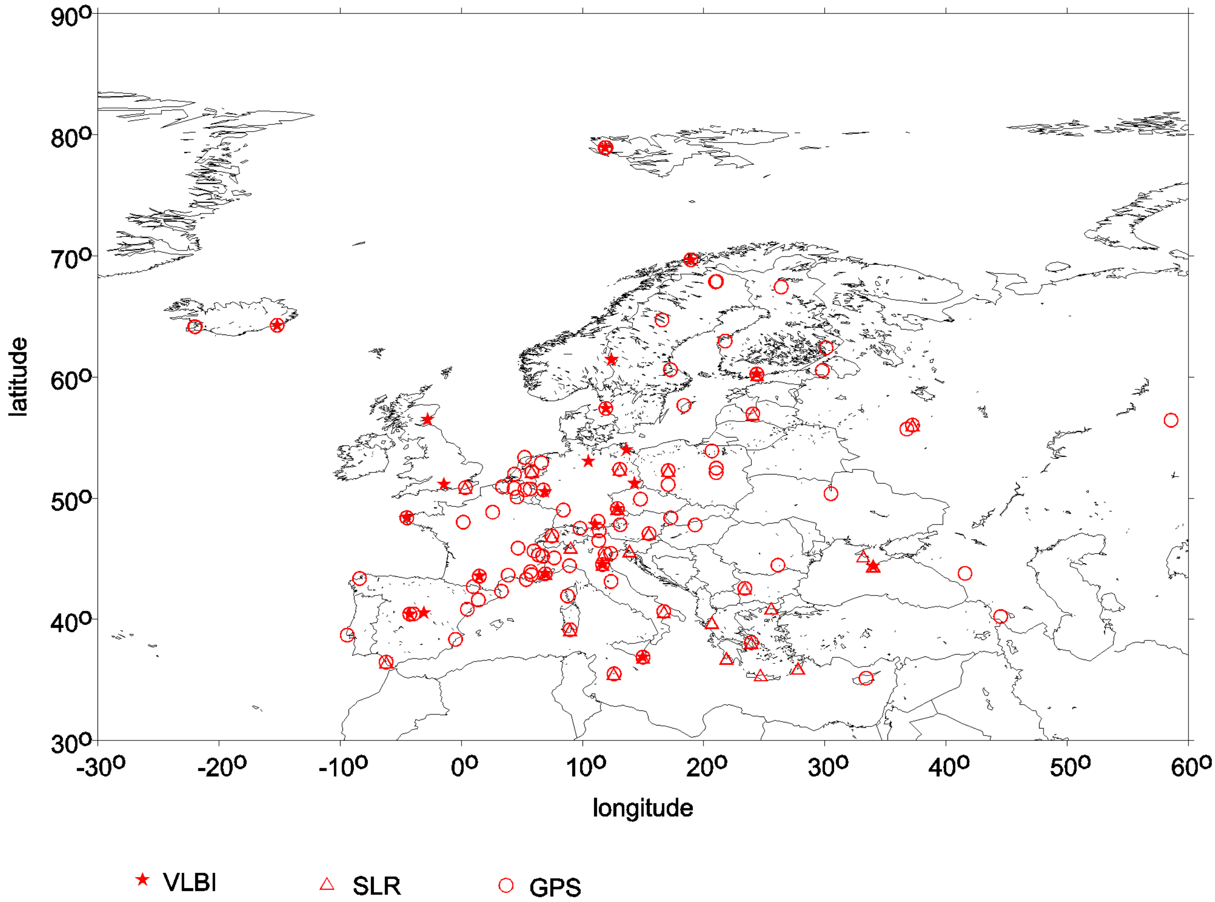

Fig. 3 European part of ITRF2000 – VLBI, SLR and GPS stations

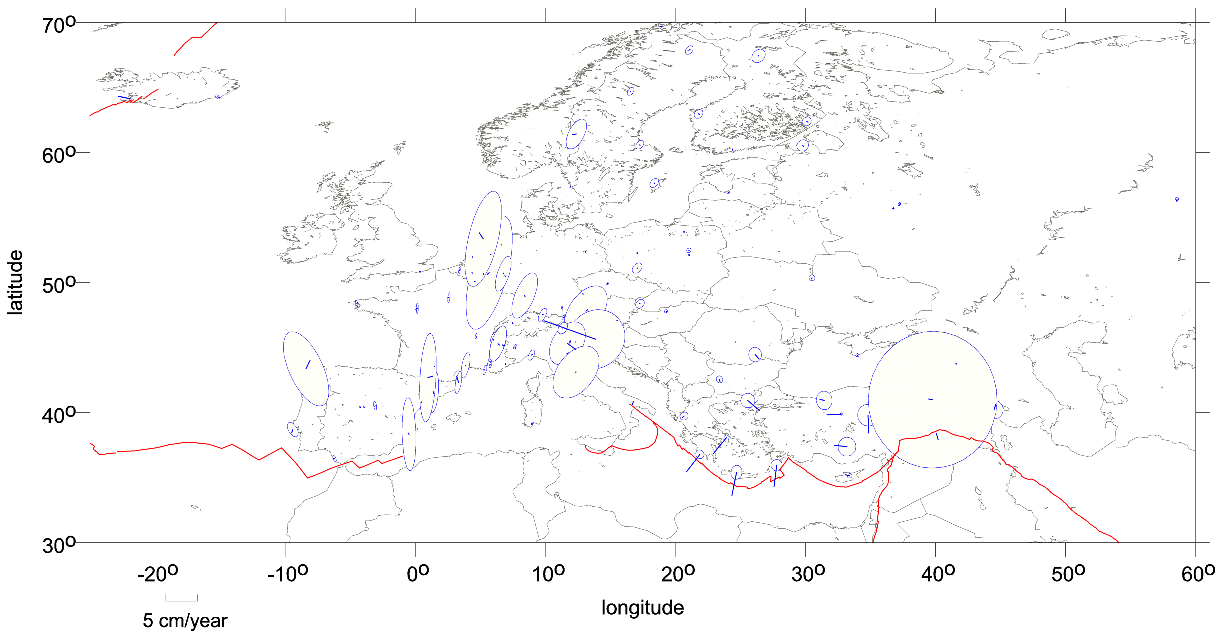

Fig. 4 Residual motions with 2.5 sigma error ellipses, EURA plate – European part only

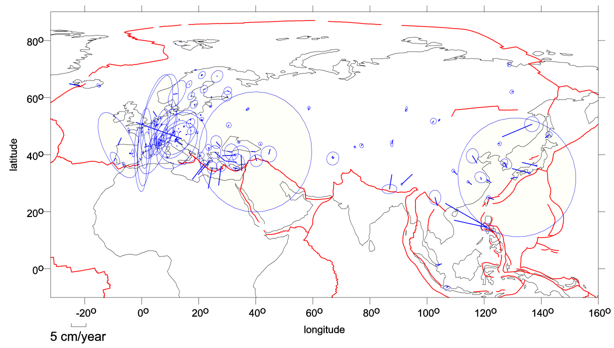

Fig. 5 Residual motions with 2.5 sigma error ellipses, EURA plate

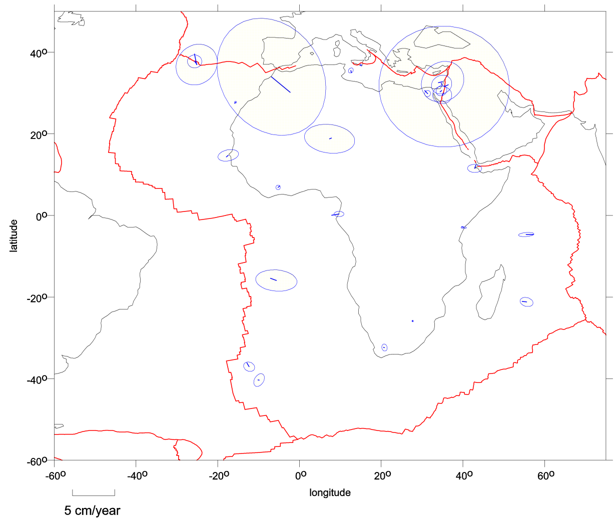

Fig. 6 Residual motions with 2.5 sigma error ellipses, AFRC plate

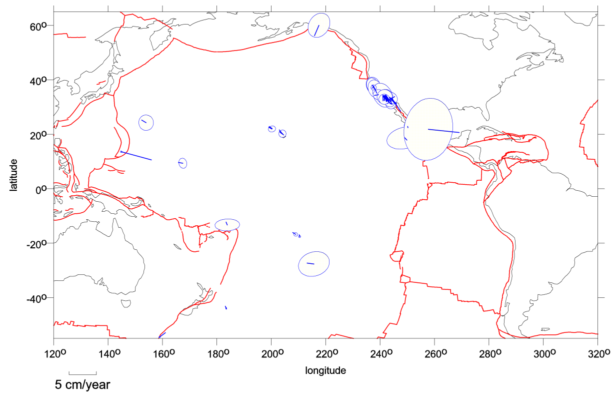

Fig. 7 Residual motions with 2.5 sigma error ellipses, PCFC plate

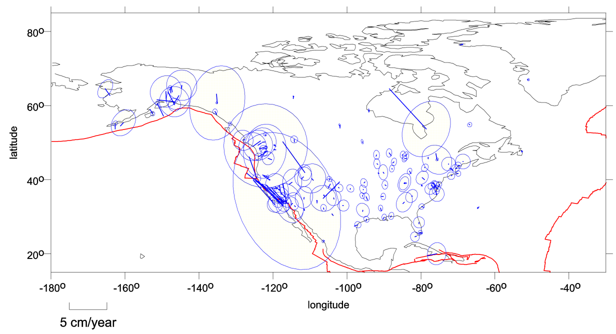

Fig. 8 Residual motions with 2.5 sigma error ellipses, NOAM plate

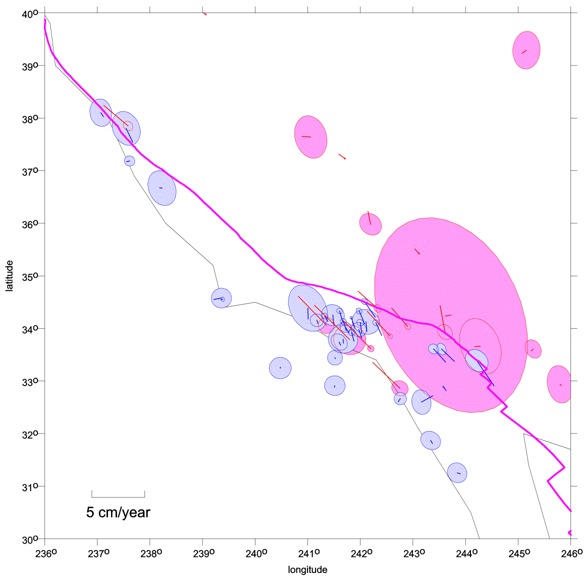

Fig. 9 Residual motions with 2.5 sigma error ellipses, NOAM (red) and PCFC (blue) plates, California part only

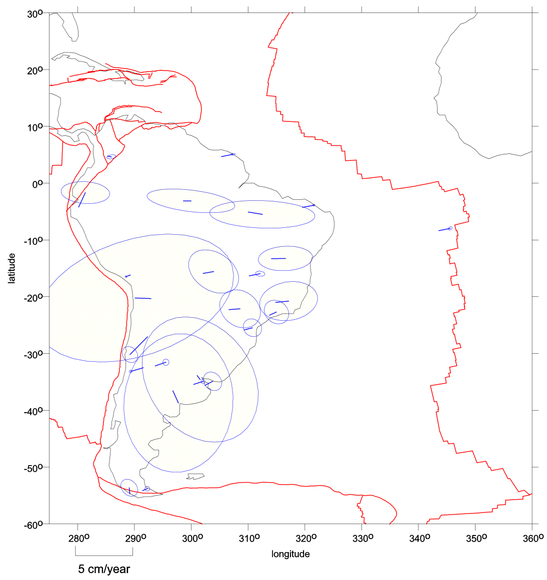

Fig. 10 Residual motions with 2.5 sigma error ellipses, SOAM plate

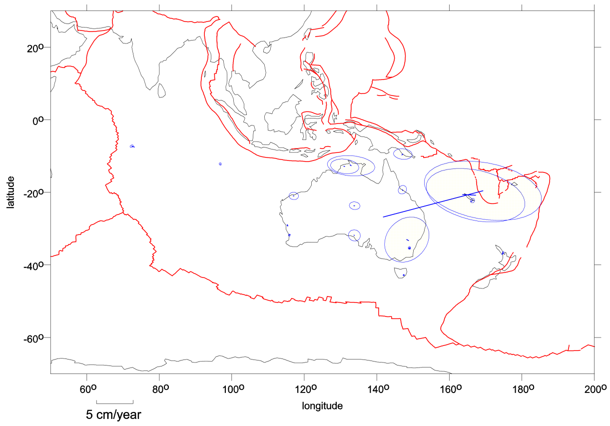

Fig. 11 Residual motions with 2.5 sigma error ellipses, AUST plate

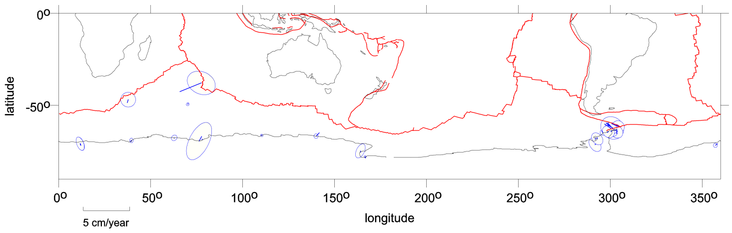

Fig. 12 Residual motions with 2.5 sigma error ellipses, ANTA plate