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MOTIONS AND DEFORMATIONS OF TECTONIC PLATES INFERRED FROM THE ITRF 2005

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ABSTRACT
According to the theory of plate tectonics, the Earth crust is composed of 14 to 16 major independent segments - tectonic plates. These plates are in motion relative to one another. Not all the plate boundaries are exactly defined. The paper focuses on the behaviour of tectonic plates in the collision zones.
Space geodesy techniques allow us to determine precise positions and velocities of the sites on the Earth surface. The global horizontal motions of the tectonic plates were derived from the coordinates and velocities of the stations defining the International Terrestrial Reference Frame - ITRF 2005 which is based on these techniques. The method described in (Kostelecký and Zeman, 2000) was employed. In the Mediterranean area, which is a contact area between the Eurasian, the Arabian and the African plate, also relative movements of the points located along the plate boundaries were computed. Further, a continuum mechanics approach was applied to detect surface deformations on the European continent and around collision zones between the tectonic plates all over the globe.

KEYWORDS: plate tectonics, plate motion, horizontal surface deformation, ITRF 2005

1. INTRODUCTION

The plate kinematic models based on the theory developed since sixties have described the motion of the earth lithospheric plates on the basis of geophysical observations – sea floor spreading rates, transform fault azimuths, earthquake slip vectors. According to the theory the Earth's crust and the uppermost mantle consists of 14 to 16 major lithospheric plates floating on the fluid asthenosphere. Frequently used models are the absolute motion and the relative motion models. The data underlying these models reflect geologic phenomena as an average over millions of years. The models describe plate motions by a rotation vector of the plate based on a pole of rotation. The kinematic plate parameters to be estimated are the individual rotation vectors, which can be represented by the geographical position of the pole of rotation and by the rotational velocity. For example, one of the most frequently used models NUVEL-1 and/or its re-scaled version NUVEL-1A describes motions between 14 major rigid plates relatively to the fixed Pacific plate. The absolute motion models (eg. NNR-NUVEL-1A) are based on the no net rotation (NNR) condition with respect to the Earth's lithosphere and can be mathematically expressed as the Tisserand Condition (the total angular momentum of global plates is zero). The model gives absolute angular velocities of the plates.

Recent plate kinematic modelling benefits from the following space geodetic techniques:

- Satellite Laser Ranging (SLR)
- Very Long Baseline Interferometry (VLBI)
- Global Navigation Satellite System (GNSS)
- Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS).

From continuous or repeated observations in a sufficiently long time interval the site motions can be derived either in terms of coordinate shifts or as baseline changes, which may be transformed into spherical distance changes. The space geodetic observations carried out over a time interval of several years can provide information on the present day plate motions that may not be identical with the motions described by the geophysical models.

The International Terrestrial Reference System (ITRS), provided by the International Earth Rotation and Reference Systems Service (IERS), constitutes a set of prescriptions and conventions together with the modelling required in order to define origin, scale, orientation and time evolution of a Conventional Terrestrial Reference System (CTRS). The system is realized by the International Terrestrial Reference Frame (ITRF) based upon estimated coordinates and velocities of a set of stations observed by above mentioned space geodetic techniques (http 1).

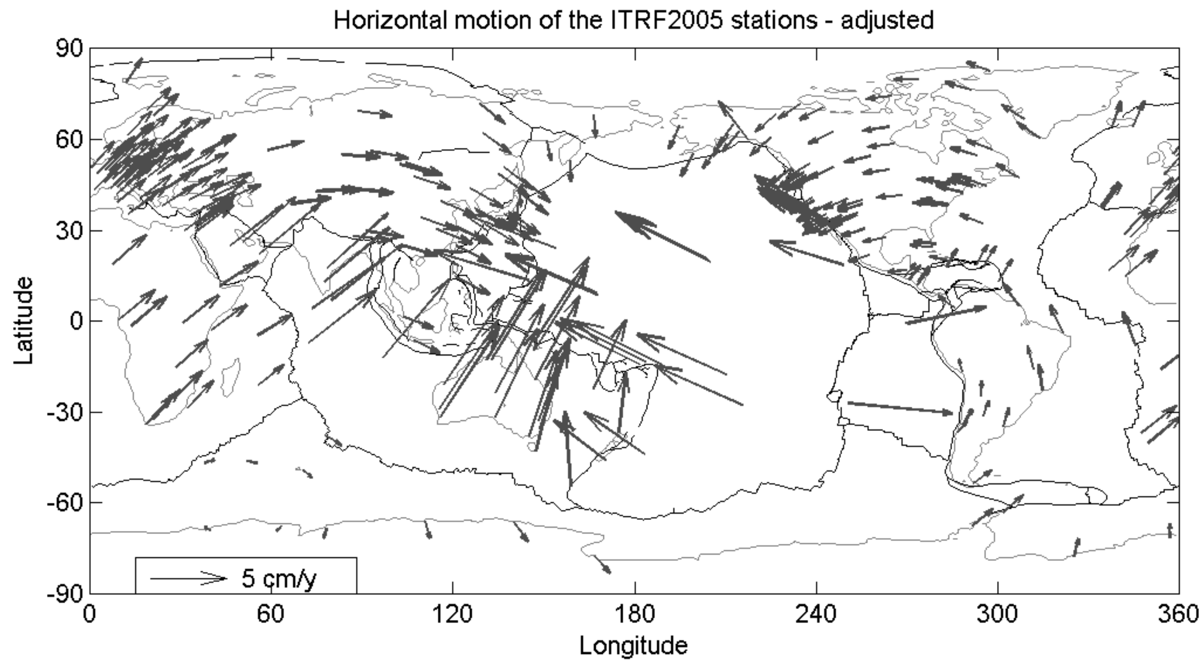

Fig. 1 Adjusted horizontal motion of the ITRF 2005 stations.

To determine the motion of tectonic plates, the ITRF 2005 coordinates and velocities of the definition stations were used by applying the method from (Kostelecký and Zeman, 2000 and 2005). Further, continuum mechanics tools were applied to detect surface deformations of the Mediterranean area.

2. ITRF 2005

The International Terrestrial Reference Frame (ITRF), which is represented by a set of coordinates of sites located on the earth surface, is a realization of the International Terrestrial Reference System (ITRS). Thanks to evolving tracking network and increasing volume of observation data the ITRF is constantly being updated, which results in a series of regularly released ITRS realizations. Since 1988 until now eleven realizations have been published, the last one is the ITRF 2005. Unlike preceding reference frames, the ITRF 2005 input was not a set of station coordinates. In this case the normal equations (or covariance matrixes) for station coordinates and, for the first time, the Earth orientation parameters were used. All the data was adjusted en block.

Period and type of the input data for the ITRF 2005:

- VLBI: 1980.0 – 2006.0 – daily solution
- SLR: 1992.9 – 2005.9 – weekly solution
- GNSS: 1996.0 – 2006.0 – weekly solution
- DORIS: 1993.0 – 2005.8 – weekly solution.

The adjustment results in the so called Long Term Solution (LTS). In addition to the station coordinates in the given epoch and their time changes, LTS contains daily solution of the Earth orientation parameters and time series of the transformation parameters between LTS and weekly solutions (Kostelecký et al., 2008).

3. TECTONIC PLATE MOTION

The motion of tectonic plates can be decomposed into horizontal and vertical components. In geophysical models with the NNR condition, the vertical motion is constrained to zero. The horizontal component for an individual tectonic plate can be described by the rotation vector ω:

$$\boldsymbol{\omega} = \boldsymbol{r} \times \boldsymbol{v}' \,, \qquad (1)$$

where r is the radius vector and v' is the horizontal velocity of the tectonic plate.

The resulting rotation vectors of individual tectonic plates were obtained as least squares estimates from the velocities of the ITRF2005 definition stations (see Fig. 1). Only velocity components less than 20 cm per year were accepted (larger values must be considered as unreal). The NNR-NUVEL1 rotation vectors were used as initial values. The zero vertical motion constraint was applied in accordance with (Kostelecký and Zeman, 2000 and 2005).

The plates Juan de Fuca, Scotia, Cocos and Philippine were not included in the processing because of insufficient number of stations located on them.

Further, a 5° rectangular grid was created for each tectonic plate and for each grid point (except the four above mentioned plates which were not considered) the horizontal velocity was determined using the equation (1). The results are presented in

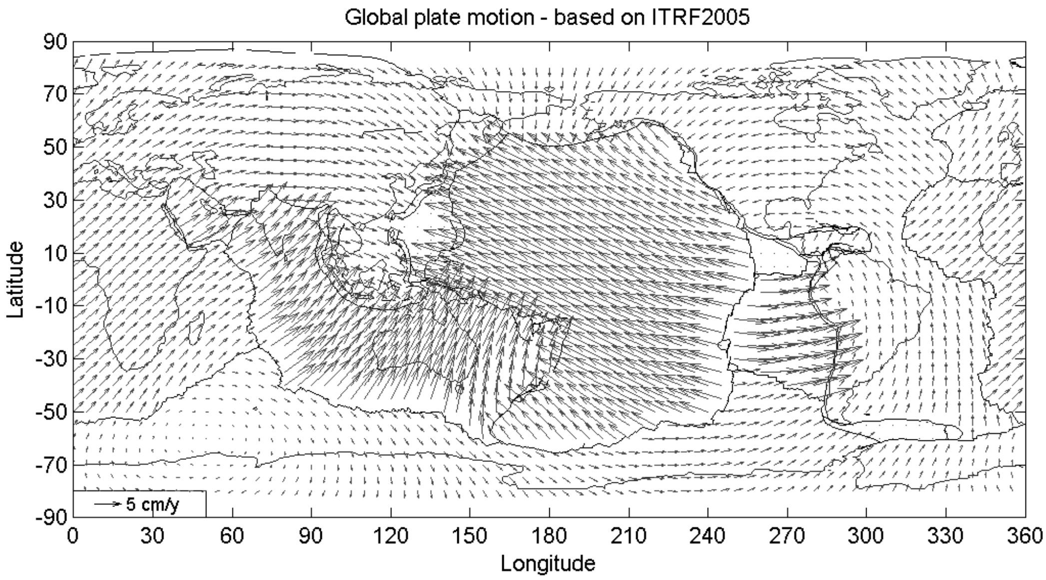

Fig. 2 Global plate motion.

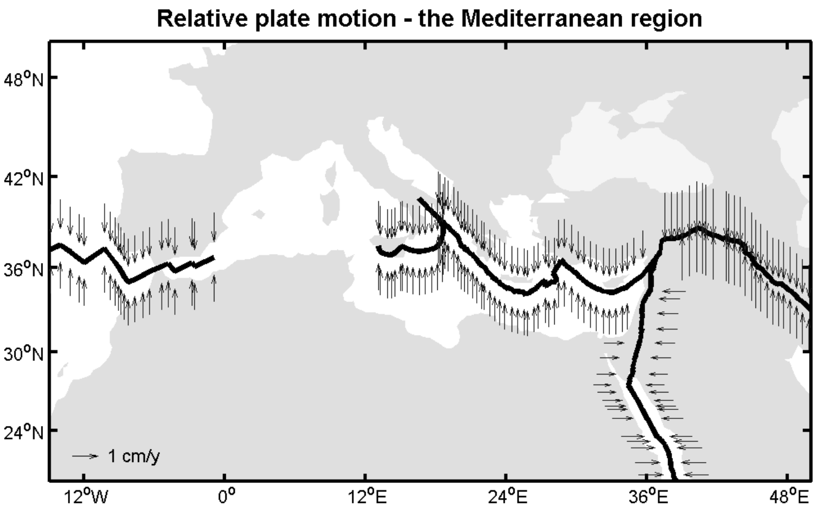

Fig. 3 Relative plate motion.

Figure 2. In case that the border between the plates is not exactly known, an appropriate parallel was chosen to split them off. Thus, the Indian and the Australian plate were separated by the equator and in the Atlantic Ocean the parallel 15 was chosen as a boundary between the North and the South American plate.

Finally, for the Mediterranean area, which is a collision zone between the Eurasian, African and Arabian tectonic plates, relative movements of these three plates were computed – see Figure 3.

4. SURFACE DEFORMATIONS

There is often an evidence of deformations of the earth surface in contact areas between tectonic plates. If we assume the investigated area to be a continuum, we can apply the continuum mechanics tools (see e.g. Altiner, 1999) to detect its deformations independently of the coordinate system. That means that the results are not influenced by possible errors related to the reference frame used (ITRF 2005 in this case).

4.1. CONTINUUM MECHANICS

The continuum mechanics is a branch of mechanics that deals with an examination of mechanical processes which are connected with changes of displacements between points (particles) of continuum (continuous solids or fluids). It is possible to describe a deformation of a continuum in its arbitrary point $P(x_j)$ with a field of displacement vectors $\boldsymbol{u}(x_j)$. The components of a displacement vector in a given point can define a small strain tensor e. Its components e_{jk} describe a relative prolongation in the direction of coordinate axes and a change of the angle between two originally orthogonal material lines in a given point.

The small strain tensor:

$$e_{jk} = \left(\frac{\partial u_j}{\partial x_k} + \frac{\partial u_k}{\partial x_j} \right) \quad (j, k = 1,2), \tag{2}$$

is a symmetric Cartesian second rank tensor. The axes of its strain ellipsoid are called principal deformation axes (directions).

4.2. SURFACE DEFORMATIONS IN EUROPE AND IN THE MEDITERRANEAN

For the zone under study (Europe and the Mediterranean) a 2° rectangular grid was created. The displacements in the grid points were determined by the interpolation of annual horizontal velocities of the ITRF2005 stations located within the range of 15° in longitude and latitude from the computation grid point (Fig. 4).

The small strain tensor was determined in each grid point using the theory of small deformations. The application of this theory supposes small gradients of displacements ***u(x)***. Subsequently, principal directions, dilatations and compressions were computed. Finally, the deformation field was plotted – see Figure 5.

The number of ITRF definition stations is relatively low, especially on the African and the Arabian plates and in the Mediterranean, where the border line between the Eurasian and the African plate runs. This has an impact on the computation of the deformation field. Therefore, the displacement field was computed according to (1) using the adjusted rotation vectors of individual tectonic plates (see chapter 3). The resulting deformation field is represented in Figure 6. The same approach was used for processing all tectonic plates – see Figure 7.

5. CONCLUSIONS

The tectonic plate motion determined from adjusted global rotation vectors of the plates is consistent with the geophysical model NNR-NUVEL-1A. Relative movements in the Mediterranean are showing that the Eurasian, Arabian and African plates are moving in about the same direction (see Figures 2 and 4), but at different rates (Fig. 3). A consequence is the collision of the plates in this area.

A simplified continuum mechanics can serve to find collision and deformation zones. However, it is necessary to consider some limitations connected with this method; mainly the assumption of continuum, which does not reflect the existence of tectonic faults and motions along them.

The displacement field obtained from the interpolation of velocities of ITRF 2005 stations (Fig. 4) is considerably influenced by the distribution of stations (especially near plate boundaries – Fig. 5). Another distortion comes from the omission of tectonic faults. Nevertheless, the deformation field derived by this approach confirms the existence of the European most active regions in Greece and Turkey, which show a strong seismicity. Other parts of Europe seem to be calm.

If we use global rotation vectors for computation of the displacement field, then, as a consequence of the applied method, there is no possibility to see any deformations in the central parts of the plates. Still this approach nicely illustrates theoretical behavior of the plates in the border zones. In the Mediterranean, there is a clear compression in Turkey – the North Anatolian Fault zone is well-known for frequent earthquakes. A distinct dilatation can be found in the Red Sea on the border between the Arabian and the African plate (Fig. 6).

In the global deformation field (Fig. 7) there is a distinctive compression in the Pacific Ring of Fire. The Ring of Fire is a horseshoe shape area with prevalence of earthquakes and volcanic eruptions running along the western and northern boundaries of the Pacific plate. It ends in the southern tip of the South America (Kious and Tilling, 1996). Because of lack of data on the Juan de Fuca and the Cocos plate, some parts of the Ring of Fire are not displayed in Figure 7.

Another significant compression area can be found on the border between the Indian and the Eurasian plate, a well-known convergent boundary.

The dilatation is characteristic for oceanic ridge systems, e.g. the Mid-Atlantic Ridge or the East Pacific Rise. A combination of dilatation and compression is the outstanding feature of the San Andreas transform fault in California.

ACKNOWLEDGMENT

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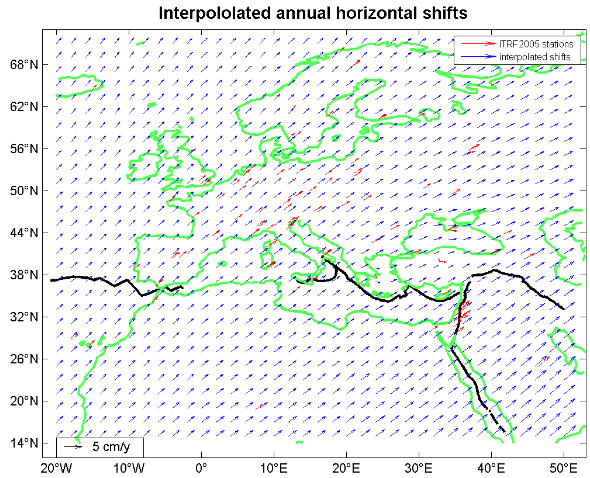

Fig. 4 Interpolated displacements field.

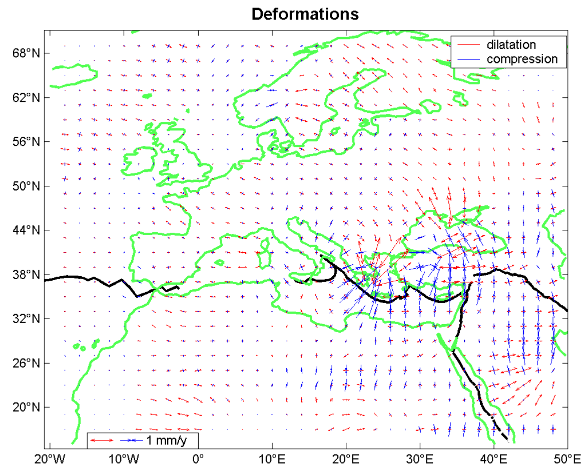

Fig. 5 Deformations from the interpolated annual horizontal shifts.

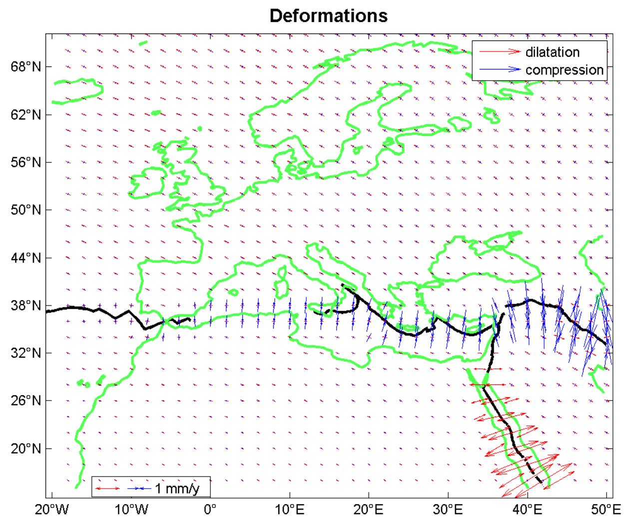

Fig. 6 Deformations from global rotation vectors of individual tectonic plates in Europe and Mediterranean.

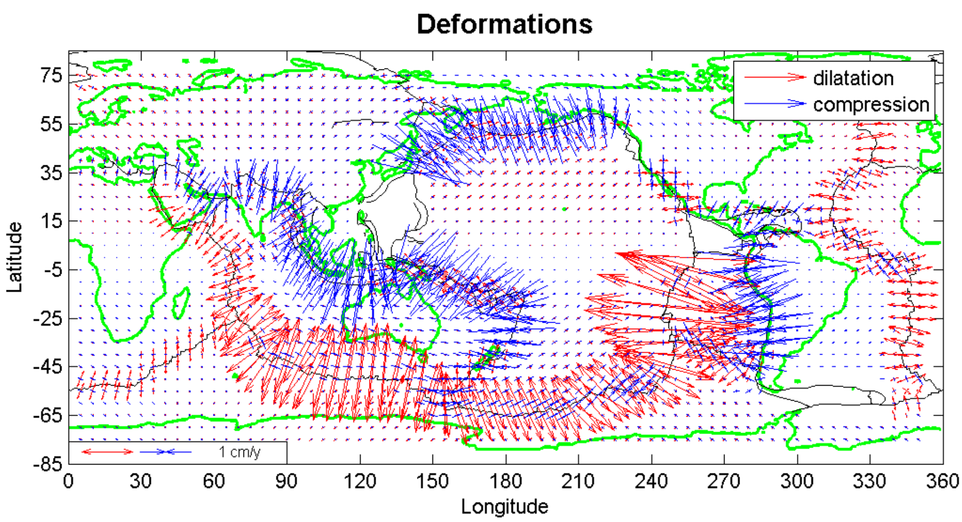

Fig. 7 Deformations from global rotation vectors of individual tectonic plates – world.