DEFORMATION BETWEEN AFRICAN AND EURASIAN PLATE ESTIMATED FROM THE EUROPEAN AND THE EGYPTIAN GPS GEODETIC NETWORKS RESULTS FROM PRELIMINARY PROCESSING

Antonín ZEMAN [1], Khalil HASSAN [2] Jan HOLEŠOVSKÝ [1]*, Abdel Monem S. MOHAMED [2], Zbyněk NOVOTNÝ [1], Mahmoud M. SALAH [2], Jan KOSTELECKÝ [3] and Radwan M. ALI[2]

[1] *Center for Earth Dynamics Research (CEDR), Department of Advanced Geodesy, Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, 166 29 Prague 6, Czech Republic*
[2] *National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Egypt*
[3] *Research Institute of Geodesy, Topography and Cartography, 250 66 Zdiby 98, Czech Republic*
**Corresponding author's e-mail:* jan_holesovsky@volny.cz

(*Received* November 2009, *accepted* March 2010)

ABSTRACT

The article deals with estimating deformation between the African and the Eurasian Plate in the Eastern Mediterranean on the basis of GPS coordinate time series. Two sources of velocities were used for processing. The first was the freely available site velocities from the European Permanent Network (EPN). The second was the Egyptian GPS permanent network velocities. Their values were determined by the following technique. Firstly, the Egyptian site coordinates were computed from GPS daily observations, using the fiducial EPN stations. The daily site coordinates at a given time interval result in coordinate time series, which were analysed and used on velocity estimation of the Egyptian stations. Then the apparatus of the mechanics of continuum was applied to all resultant velocities. The regions of possible mutual interactions between the Eurasian and the African Plate in the Eastern Mediterranean were detected. The basic idea of this contribution is the common processing of GPS daily measurements from the Egyptian permanent network together with the EPN data. The available Egyptian GPS data cover almost the last three years, which represents a sufficient time interval for velocity estimation. Introducing the Egyptian permanent GPS measurements into processing enables a better estimate of deformations in the Eastern Mediterranean.

KEYWORDS: GPS coordinate time series, Egyptian GPS geodetic network, mechanics of continuum, deformation in the Eastern Mediterranean

1. INTRODUCTION

The aim of this contribution is to detect the regions of possible mutual interaction between the Eurasian and the African Plate based on GPS observations coming from the EUREF (European Reference Frame) Permanent Network (EPN) and GPS observations in the Egyptian GPS permanent network. Following from this, the apparatus of the mechanics of continuum is applied to the resultant coordinate time series to determine the deformation areas.

This article follows the main line of the preceding paper (Zeman et al., 2006), focusing on the Eastern Mediterranean. In the previous paper, the horizontal shifts, the interpolated horizontal shifts in step 2x2 degrees and the resulting strain tensors were computed for 165 EPN stations, covering the whole of Europe. The strain tensors predicate the geodynamic activity on the Eurasian Plate and at its border.

The results from the previous paper were based only on velocities from the EUREF Permanent Network as none of the GPS data from the African Plate were available for the processing at that time. The following conclusions concerning the Eastern Mediterranean, which was detected as the most active European region with a need for more detailed research, were reached in that paper. There are significant horizontal shifts at the sites inland of Turkey, Crete and Israel with a tendency of counterclockwise rotation. The next phenomenon is a significant dilatation in the north-south direction in the region of the southern Aegean Sea. Despite the fact that this effect was based only on the movement of one station TUC2 (Chania, Crete, Greece), characterized by a very different size of relative motion in comparison with surrounding permanent stations, there were no other evident reasons for neglecting its contribution. However, the availability

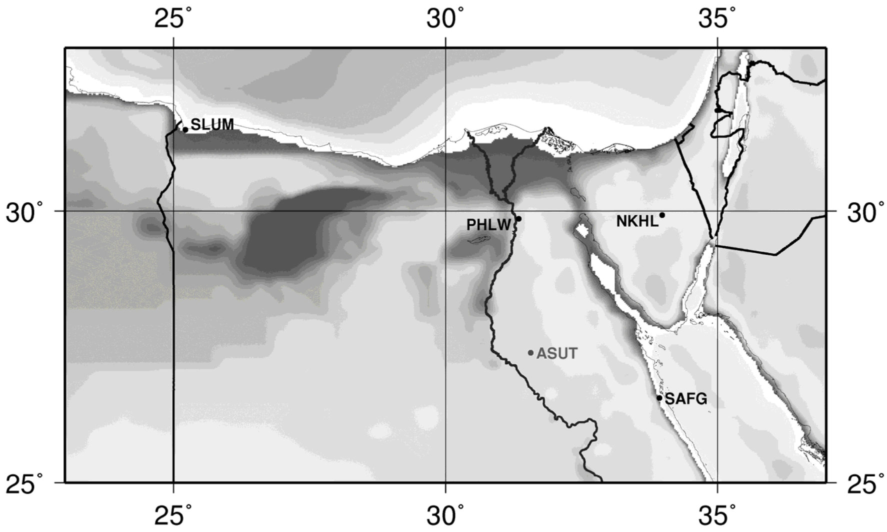

Fig. 1 Location of available stations of the Egyptian GPS permanent network.

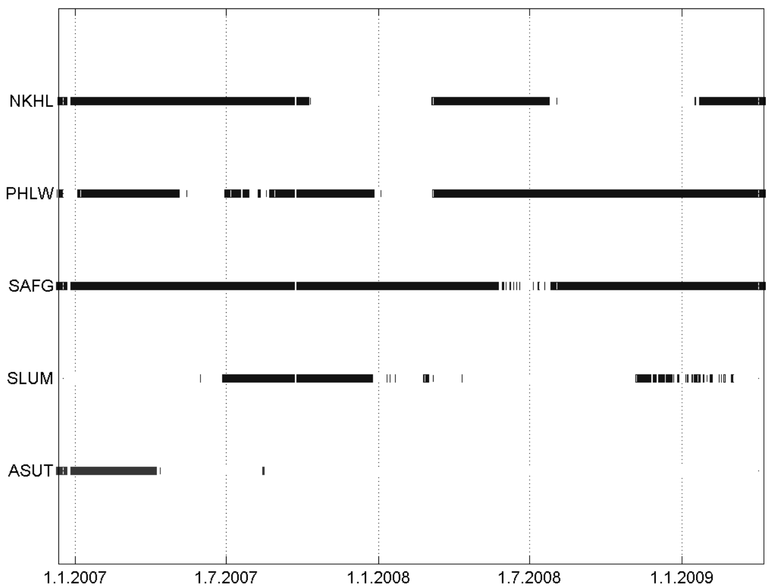

Fig. 2 Time availability of GPS observations at permanent stations

of any other permanent station in this region would strengthen or falsify this statement. Last but not least, the inclusion of the GPS data from the northern regions of Africa into processing was required to determine the geodynamical interaction between the Eurasian and the African Plate more correctly.

This paper concerns the region of the Eastern Mediterranean. The common cooperation between the Center for Earth Dynamics Research (CEDR) at the Faculty of Civil Engineering, Czech Technical University in Prague and the National Research Institute of Astronomy and Geophysics (NRIAG) in Helwan, lasting already two years and comprising reciprocal visits and common research, led to the incorporation of GPS measurements from the region of Egypt into processing. The data from the Egyptian GPS permanent network, which still have never been at disposal for any similar processing, could now be used. This cooperation and the incorporated Egyptian GPS data enable the possibility of a new precise deformation solution for the region of the Eastern Mediterranean.

2. EGYPTIAN GPS PERMANENT NETWORK

The Egyptian GPS permanent network consists of several stations depicted in Figure 1. The abbreviations of the stations correspond to their 4-literal ID and stand for the following sites: Nakhel (NKHL), Helwan (PHLW), Safaga (SAFG), Salum (SLUM), and Asut (ASUT). Distribution of these GPS permanent stations is regular around the northern part of Egypt containing the locations at the Mediterranean

Table 1 Summary of observation days used for preliminary processing.

Epoch year-day of year	Station				Remark
	NKHL	PHLW	SAFG	SLUM	
2006-354 (20.12. 2006)	√	√	√	--	
2007-187 (6. 7. 2007)	√	--	√	√	data start on SLUM
2007-287 (14.10. 2007)	√	√	√	√	
2007-353 (19.12. 2007)	--	√	√	√	
2008-146 (25. 5. 2008)	√	√	√	--	
2008-353 (18.12. 2008)	--	√	√	√	
2009-066 (7. 3. 2009)	√	√	√	√	data end on SLUM
2009-097 (7. 4. 2009)	√	√	√	--	

Sea, the Red Sea, the Nile river and also on the Sinai peninsula. Such geographical locations are suitable for the purpose of this work.

GPS permanent observation data, which were at disposal, cover the time interval from the day 347 in year 2006 (13.12.2006) till the day 097 in year 2009 (7.4.2009). The time availability of GPS observations on each permanent station is depicted in Figure 2. Station ASUT was excluded from the solution because of unsufficient amount of observation data during the whole period. Each station has irregular blackouts, which do not have an influence on the solution. Station SAFG is the one with the longest regular observations.

The solution presented in this paper is preliminary. Due to the short time for processing, which started in May 2009, not all observation days were used. To determine the horizontal shifts of Egyptian sites only the stations with the longest time interval (2.5-year period maximum available) were taken into processing. This is the reason for elimination of the station ASUT. For the preliminary solution only 8 epochs in approximately half yearly steps were chosen, but however, the selection of used days was influenced by the quality of observations and their availability together at all four stations NKHL, PHLW, SAFG and SLUM. Therefore the time step is not exactly equal to a half year. The details about the chosen epochs and the availability of observations at respective stations may be found in Table 1.

3. DATA PROCESSING

The preliminary processing was divided into three separate parts, which consist of the following steps: estimation of horizontal shifts of the Egyptian GPS permanent network stations, estimation of horizontal shifts of the EPN stations, and estimation of strain tensors.

3.1. PROCESSING OF THE EGYPTIAN GPS PERMANENT NETWORK

GPS observations on suitable Egyptian stations (NKHL, PHLW, SAFG, and SLUM) at 8 chosen epochs (see Chapter 2, Table 1) were processed for each epoch individually as independent campaigns. This daily processing was performed in GPS software Bernese v. 5.0 (Dach et al., 2007), using the following computational strategy:

- reference frame ITRF2005,
- velocity model of tectonic plate motion NNR-NUVEL1A,
- usage of IGS final orbits and satellite clocks and IGS final Earth orientation parameters,
- automatic forming of baselines based on OBS-MAX strategy (usage of maximum number of observations) for phase observation processing,
- QIF (quasi-ionosphere-free) strategy of phase ambiguity resolution,
- ionosphere-free frequency L3 eliminating the influence of ionosphere,
- elevation cutoff angle 3°,
- troposphere model Dry Niell, consideration of mapping function for hourly zenith path delay (Wet Niell) and daily horizontal gradient (tilting),
- usage of fiducial stations ANKR, MATE, NICO, NOT1, RAMO, SOFI (minimum constraint solution).

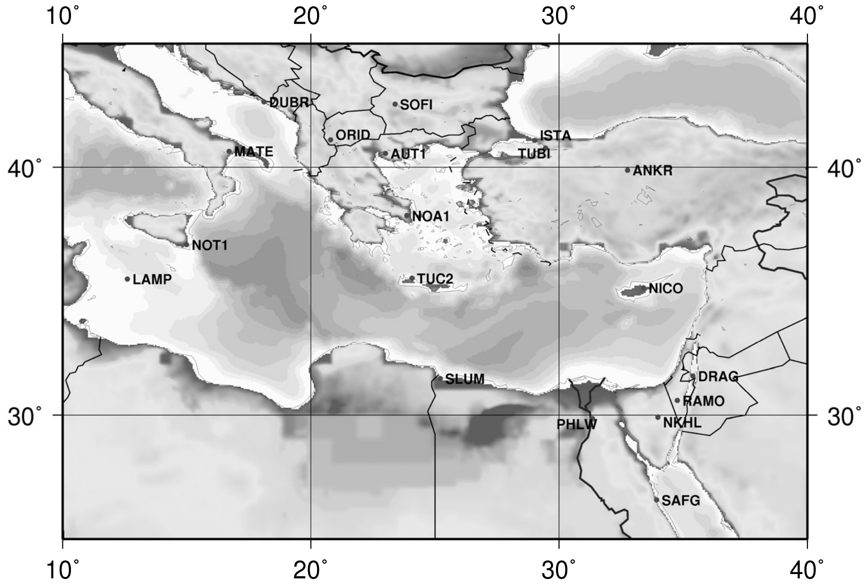

Fig. 3 EPN stations and the Egyptian permanent network stations, on which the horizontal shifts were computed

The above mentioned fiducial stations are located on the edge of the region of interest. The position of the computed Egyptian stations is slightly eccentric to the south with respect to the fiducial stations. On the other hand, it is necessary to mention that the nearest southern IGS stations are situated in the equatorial region.

In the obtained preliminary coordinate time series of the Egyptian sites the linear trend was determined, resulting in cartesian velocities vx, vy, vz of the Egyptian sites in the International Terrestrial Reference Frame (ITRF). To obtain the horizontal velocity components, the cartesian velocities and their standard deviations were transformed into N/E/U-system. In this way the horizontal shifts of the Egyptian permanent stations in ITRF were determined.

Finally, the horizontal shifts of the Egyptian GPS permanent stations were also expressed in the European Terrestrial Reference Frame (ETRF), i.e. relative to the motion of the Eurasian Plate. Their values were computed by subtracting the mean velocity of the Eurasian Plate from the velocities in ITRF for individual stations in N/E/U-system.

3.2. HORIZONTAL SHIFTS OF EPN STATIONS

Horizontal shifts of EPN stations come from a solution independent of determination of horizontal shifts of the Egyptian stations. Their values both in ITRF and ETRF correspond to the velocities in N/E/U-system, which were taken from time series analysis of EPN sites for the region of interest. These coordinate time series (based on Kenyeres, 2004) are the freely available product of the weekly combined EPN solution. The distribution of the EPN stations used for processing (all EPN stations in the Eastern Mediterranean with solved velocities being at disposal till September 2009), is shown – together with the Egyptian permanent sites used – in Figure 3.

3.3. ESTIMATION OF STRAIN TENSORS

The performed deformation analysis is based on the theory of continuum mechanics. The advantage lies in obtaining invariant values of strain tensor independent of the coordinate system. Nevertheless, it is necessary to see that a great geodynamic simplification is committed, because the European and the African Plate actually can not be considered as a continuum environment from the point of view of continuum mechanics.

The input data for strain tensor estimation are the horizontal shifts of GPS permanent stations on the Eurasian and the African Plate. All computations were performed as the spherical approximation on reference sphere. The field of interpolated annual horizontal shifts was created with the step of 2x2 degrees. Interpolated values (including standard deviations) for every node of the field were computed using a weighted average of the horizontal shifts for all stations within the radius 20 degrees from the appropriate node on the reference sphere. This interpolation scheme corresponds to the global approach to the solution, where neither plate boundaries nor the local faults are considered.

The equation for the horizontal components of strain tensor $T_{i,j}$ has the form

$$T_{i,j} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right),$$

Table 2 Horizontal velocities v_N, v_E and their standard deviations in ITRF for the Egyptian GPS permanent stations.

Station	V_N [mm/year]	σ_{VN} [mm/year]	V_E [mm/year]	σ_{VE} [mm/year]
NKHL	18.52	1.02	22.37	0.70
PHLW	18.85	1.19	21.93	0.94
SAFG	18.83	1.29	21.99	0.84
SLUM	20.91	1.10	19.88	1.69

Table 3 Horizontal velocities v_N, v_E and their standard deviations in ETRF for the Egyptian GPS permanent stations.

Station	V_N [mm/year]	σ_{VN} [mm/year]	V_E [mm/year]	σ_{VE} [mm/year]
NKHL	5.07	1.02	-2.40	0.70
PHLW	5.40	1.19	-2.84	0.94
SAFG	5.38	1.29	-2.78	0.84
SLUM	7.47	1.10	-4.89	1.69

Table 4 Comparison of horizontal velocities v_N, v_E and their standard deviations in ETRF for the station PHLW, estimated by different authors.

Source	V_N [mm/year]	σ_{VN} [mm/year]	V_E [mm/year]	σ_{VE} [mm/year]
McClusky et al., 2003	5.03	0.86	-1.65	0.90
Reilinger et al., 2006	5.54	0.51	-2.24	0.54
this paper	5.40	1.19	-2.84	0.94

which was transformed into spherical coordinates. The partial derivatives were computed numerically from the field of discrete values of the interpolated horizontal shifts v_i. The range for the indices is $i \in \{1,2\}$, which applies to the horizontal components.

4. RESULTS AND CONCLUSIONS

The deformation rates in the Eastern Mediterranean are characterized by means of graphical outputs. Deformations are based on annual horizontal shifts of the GPS permanent stations situated in the region of interest. Figure 4 denotes the annual horizontal shifts expressed in ITRF, Figure 5 the annual horizontal shifts in ETRF, i.e. relative to the Eurasian Plate. Numerical values of the horizontal shifts and their standard deviations in ITRF and in ETRF for the Egyptian GPS permanent stations, estimated from the preliminary coordinate time series, are presented in Table 2 and Table 3.

In Table 4, the horizontal velocities in ETRF are compared with the long-term values published in the papers (Reilinger et al., 2006) and (McClusky et al., 2003). The data processed by Reilinger cover an 8-year interval (1994.7 – 2002.7). The GPS measurements used by McClusky come from the years between 1992 and 2000. The comparison of horizontal velocities is possible only for the station HELW/PHLW as the data from the other Egyptian stations (NKHL, SAFG and SLUM) are neither in the above mentioned papers nor in other available references at disposal. Although the solution presented in this paper is preliminary, the estimated horizontal velocities do not differ from the long-term values a lot.

Comparing the results of the previous paper (Zeman et al., 2006), there is not only the new information about the movement tendency in the northern part of Africa, but also in the area of the Aegean Sea. Horizontal velocities of two EPN stations NOA1 (Athens, Greece) and AUT1 (Thessaloniki, Greece) could already be included into the present solution, whereas the coordinate time series analysis leading to estimates of horizontal

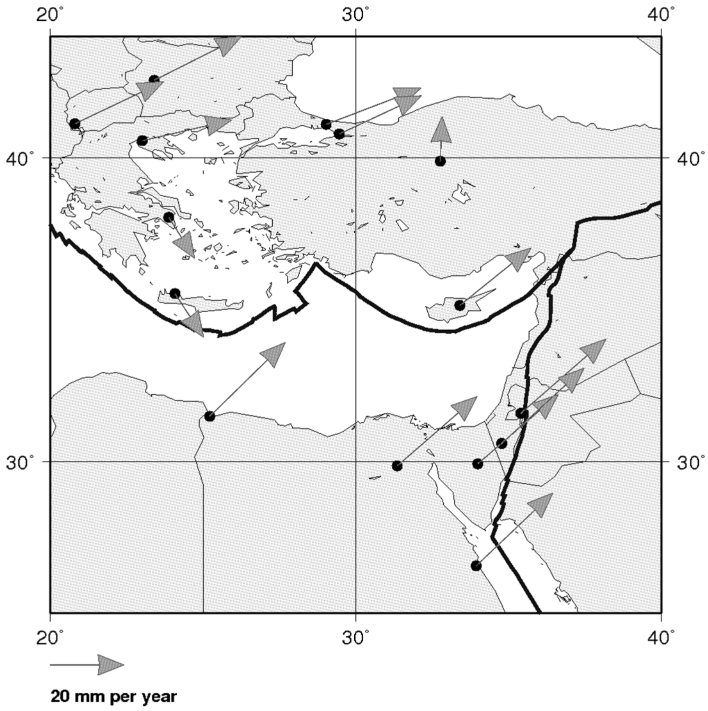

Fig. 4 Annual horizontal shifts in ITRF.

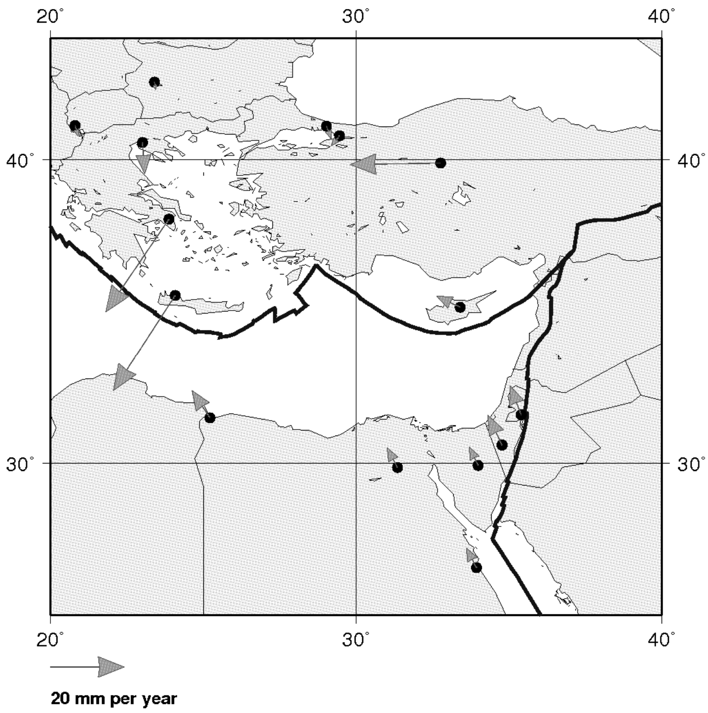

Fig. 5 Annual horizontal shifts in ETRF.

velocities of these EPN stations was still not at disposal in the previous solution. The result of the station NOA1 shows very similar horizontal movement as that of the EPN station TUC2 (Chania, Crete, Greece), which was formerly very different in size in comparison with all, at that time available, surrounding permanent stations. Consequently, the statement about the movement tendency and deformations in the region of the southern Aegean Sea is confirmed.

To describe the deformations, firstly the interpolated annual horizontal shifts (Fig. 6) and finally the interpolated strain tensors (Fig. 7) are presented as the main part of the results. Strain tensors are invariant with respect to the used reference frame.

The ellipses of errors of the interpolated strain tensors are plotted for every node inside the region of interest. Due to the performed solution (horizontal shifts for Egyptian sites estimated from half year measurements) the ellipses of errors in Figure 7 are still huge in the region of Egypt, whereas in the northern part of the Eastern Mediterranean, the ellipses of errors are smaller by some orders because of the relatively very low standard deviations of the input horizontal velocities of the EPN stations. Therefore the results must be still seen as preliminary as the processing of the coordinate time series of the Egyptian sites is not completed. The future final solution, based on estimation of Egyptian site velocities from all available observation days, should lead to reduction of the depicted ellipses of errors. On the other hand, it should not be expected that the estimated basic movement tendency of the Egyptian GPS permanent stations would subsequently change too much.

The main contribution of this article consists in gaining new information about deformations in the region of north Egypt, completing the known deformation rates derived only from movements of the EPN stations. Horizontal shifts of the stations in Egypt and Israel are similar both in direction and size, which refers to the movement of the African Plate in direction to the Eurasian Plate.

Next, the horizontal Shift of the sites with a tendency of counterclockwise rotation in the Eastern Mediterranean and also significant dilatation in the NE-SW direction in the region of southern Aegean Sea, are verified.

The performed solution is based on a global method for determination of deformations, using continuum mechanics. As the global approach is used, the local faults and rifts, i.e. in the region of Turkey and Egypt, are neglected. This paper, as presented in this form, does not propose a detailed description of local deformations and fulfills the assigned research goals.

ACKNOWLEDGEMENT

The authors are gratefully appreciated to Ministry of Education, Youth and Sports of the Czech Republic for support of this work in the frame of the project LC506.

REFERENCES:

Brdička, M., Samek, L., and Sopko, B.: 2005, Continuum Mechanics, Academia, Praha, (in Czech).

Dach, R., Hugentobler, U., Fridez, P., and Meindl, M. (eds.): 2007, Bernese GPS software version 5.0, Astronomical Institute, University of Bern.

Kenyeres, A.: 2004, Contribution of the time series SP to the European velocity field project. EUREF 2004 Symposium, 2-5 June 2004, Bratislava, Slovakia. Products available at http://www.epncb.oma.be/_dataproducts/timeseries/index.html.

Kostelecký, J. and Zeman, A.: 2004, Horizontal and vertical displacements of the stations within the frame of the individual plates based on the ITRS2000 Reference System. Acta Geodyn. Geomater. 1, No. 3 (135), 133–143.

McClusky, S., Reilinger, R., Mahmoud, S., Ben Sari, D., and Tealeb, A.: 2003, GPS Constraints on Africa (Nubia) and Arabia plate motions. Geophysical Journal International. 155, 126–38.

Reilinger, R., et al.: 2006, GPS constraints on continental deformation in the Africa-Arabia-Eurasia continental collision zone and implications for the dynamics of plate interactions. Journal of Geophysical Research. 111, B05411.

Zeman, A., Kostelecký, J., Kostelecký, J. (jr.), and Ryšavý, V.: 2006, Deformations between African and Euroasian plates from the methods of space geodesy. Presented on XIII Assembly of Wegener 2006, 4-7 September 2006, Nice, France.

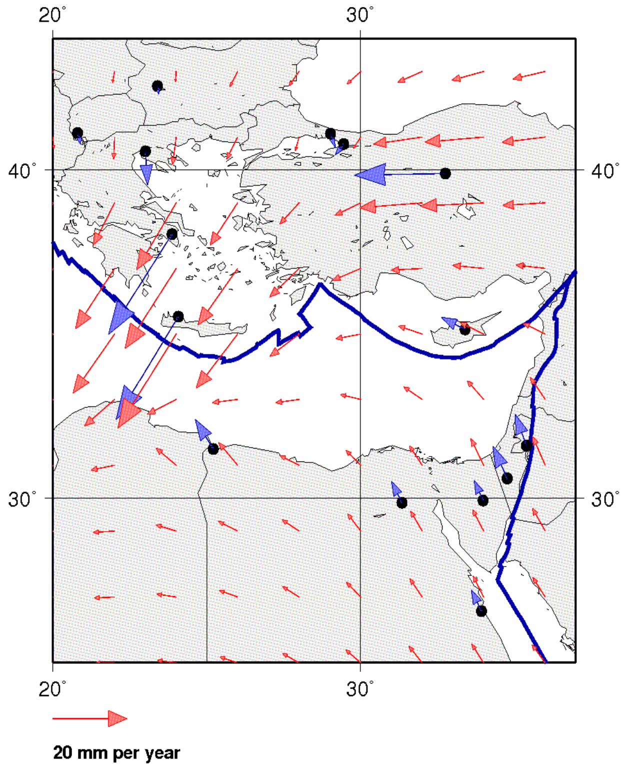

Fig. 6 Interpolated annual horizontal shifts in ETRF.

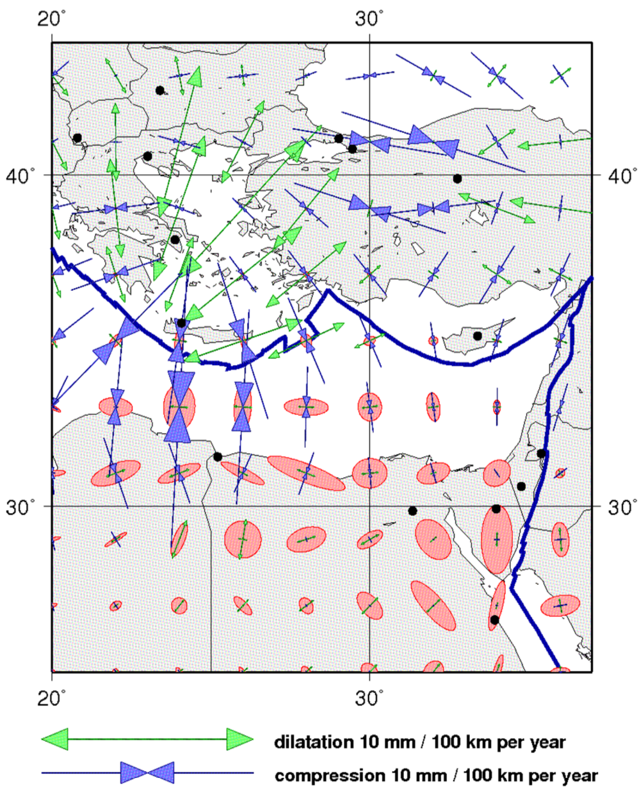

Fig. 7 Interpolated strain tensors.