PRESENT DAY GEOKINEMATICS OF CENTRAL EUROPE

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The Central European Geodynamic Research Network CEGRN. The CEGRN consortium has its origin in the framework of the project called CERGOP (Central European Research on Geodynamics Project) that started in 1993-1994 (Fejes and Kenyeres, 1994). The CERGOP consisted originally of 11 countries of Central Europe: Austria, Croatia, the Czech Republic, Germany, Hungary, Italy, Romania, Poland, Slovakia, Slovenia, and Ukraine. In 1998, Albania, Bosnia and Herzegovina, and Bulgaria (associated member since 1996) joined the CERGOP (second phase). All these countries agreed to organize the CEGRN consortium to operate,

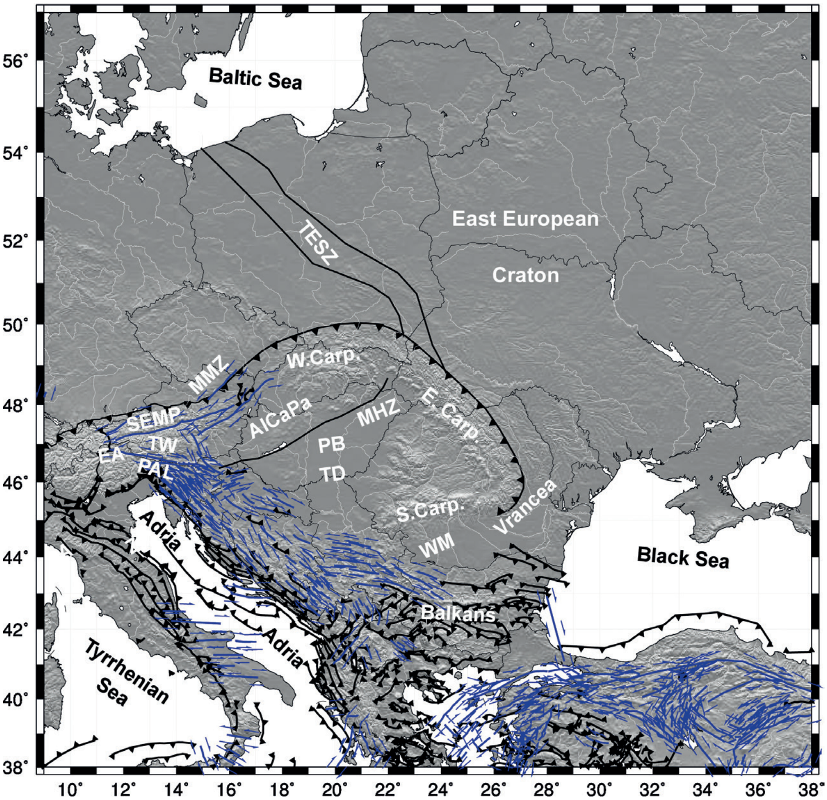

Fig. 1 - Simplified tectonic map of the CEGRN area. The black and blue lines indicate respectively the top trace of the normal and reverse and strike slip faults from the Euro-Mediterranean database of seismogenic sources (SHARE project, Basili et al. 2013). The thick black lines show the principal tectonic structures in the study area. AlCaPa = Alpine–Carpathian–Pannonian terrain; EA = Eastern Alps; E. Carp. = East Carpathians; MHZ = Mid Hungarian Zone; MMZ = Mur-Murz-Zilina line; PB = Pannonian –Basin; PAL = Periadriatic lineament or Pustertal Gailtal fault system. S. Carp. = South Carpathians; TESZ =Trans European Suture Zone; TD= Tisza-Dacia unit; TW = Tauern Window.; W. Carp. = West Carpathians; WM = Wallachian-Moesian region.

maintain and develop the Central European GPS Geodynamic Reference Network (CEGRN network). Nowadays CEGRN collects, processes the GNSS observations from standard RINEX files (IGS, RINEX format) and combines the normal equations, in-house produced as well as delivered by other Analysis Centres (ACs) in standard SINEX (IERS, SINEX format) format. CEGRN analyses the results, produces derived geophysical products from the velocity field, and encourages the collaboration of Research Institutions. The resulting positions and velocity field, among other products, resulting from all these activities are made available through the CEGRN website, presently hosted and maintained by the University of Padova.

The main objective of the CEGRN network is the monitoring of crustal surface deformations by analysis of GPS, now GNSS (GPS and Glonass), measurements of regularly scheduled campaigns. The results of the first phase (1994-1997) are discussed by (Grenerczy *et al.*, 2000). High density 3D velocities and strain rate fields are derived as the basis for geodynamic investigations (Becker *et al.*, 2002). The main study areas cover the Adriatic Microplate, the Balkan and Dinarides, the Carpathian Arc, the Eastern Alps and the Pannonian Basin, all of them active tectonic zones. The long term project is running since 1994 and was sponsored twice by EU projects: CERGOP1 and CERGOP-2 (Environment Central European Geodynamics Project, funded by the European Union from 2003 to 2006) under the 5th Framework Programme (Fejes, 2002; Fejes and Pesec, 2003).

In 2011 a Memorandum of Understanding between EUREF (www.euref.eu) and CEGRN based on the ETRS89 implementation and densification of the velocity field, both of common interest, was signed at the 2011 EUREF Symposium of Chisinau, Moldova (Euref Symposium 2011).

In 2014 the ten weekly campaigns (1996-2013) were re-processed following the EUREF's guidelines for densification and stacked in a combined solution using consistently precision orbits, clocks, antenna models and processing standards (so called IGb08 reprocessing). This solution was validated by the EUREF Technical Working Group (EUREF 2015 Resolutions, 2015; Caporali *et al.*, 2015) as a multiyear network combination consisting of a set of coordinates, velocities (for sites with 4 or more years of tracking) and network variance-covariance matrix.

CEGRN has started receiving, since mid 2017, a large number of high quality SINEX files from Agencies processing new GNSS permanent stations. The CEGRN network has consequently evolved into a very dense GNSS network that presently consists of 1242 different sites (latest CEGRN cumulative solution released on July 2018), covering Central Europe from Lithuania to Makedonia and from Switzerland to Ukraine. The data, from raw data files to final velocities, are made available to the relevant Working Groups of EUREF (http://euref.eu/euref_gb_workinggroups.html) on 'European Dense Velocities', 'EPN Densification' and 'Deformation Models' for validation and comparison with independent analyses.

This paper is based on the last and most complete cumulative solution of the CEGRN network (1996-2017), and aims at investigating velocity profiles across major tectonic structures in Central Europe. This is made possible by the availability of positions and velocities of a regional scale network least squares adjusted in a consistent way according to state of the art processing guidelines (Bruyninx *et al.*, 2018).

Velocity data base and profiles. Eight Analysis Centers (AC) are involved in the delivery of the velocity database for CEGRN: the Military University of Technology (MUT) in Warsaw, Poland, for the backbone European Permanent Network, the CEGRN Analysis Center (CEG) and the University of Padova (UPA), delivering network adjustments for the core CEGRN network and the Italian Permanent Network; the Main Astronomical Observatory in Kiev delivering network adjustments for Ukraine and surrounding areas; the Geodetický a Kartografický Ústav, Slovakia (GKU); Glowny Urzad Geodezji i Kartografii, Poland (ASG); Serbian Geodetic Institute- Republički geodetski zavod (RGZ) and FOMI Satellite Geodetic Observatory, Hungary (SGO). The EPN Guidelines are adopted by every Analysis Center, ensuring consistency and homogeneity of methods and results. The multiyear normal equations stackings of each network computed by the AC's are eventually combined into one position and velocity solution for the entire area covered by CEGRN. For each subnetwork involved in the combination four Helmert parameters (one scale and three translations) are solved for, ensuring consistency in origin and scale relatively to those of the combined solution. At this stage the entire network is aligned in position and velocity to the EPN network (C1980 release), and hence to the IGS14/ITRF2014 global network using Minimum Constraints.

The resulting velocities in an European fixed frame (ETRF2000) form an invaluable sensor of deformation at a regional scale. We summarize in Fig. 2a a number of profiles where the velocities have been interpolated to the profile and projected along the profile. These profiles are useful to visualize regions undergoing compression or extension. One additional profile across the South Eastern Alps (Fig. 2b) shows the velocities projected orthogonally to the profile, to highlight the shear deformation. The profiles have been chosen so as to balance the requirement of geological significance and that of coverage of GNSS velocities, to minimize interpolation errors.

Profile A0-A1: shows the extension associated to the convergence of the Hellenic arc to the boundary with the Nubia plate. The southward increase of the velocity suggests a stretching of the crust driven by the counterclockwise rotation of the Anatolian block, which is considered the consequence of the collision of Arabia with eastern Anatolia, coupled with subduction in

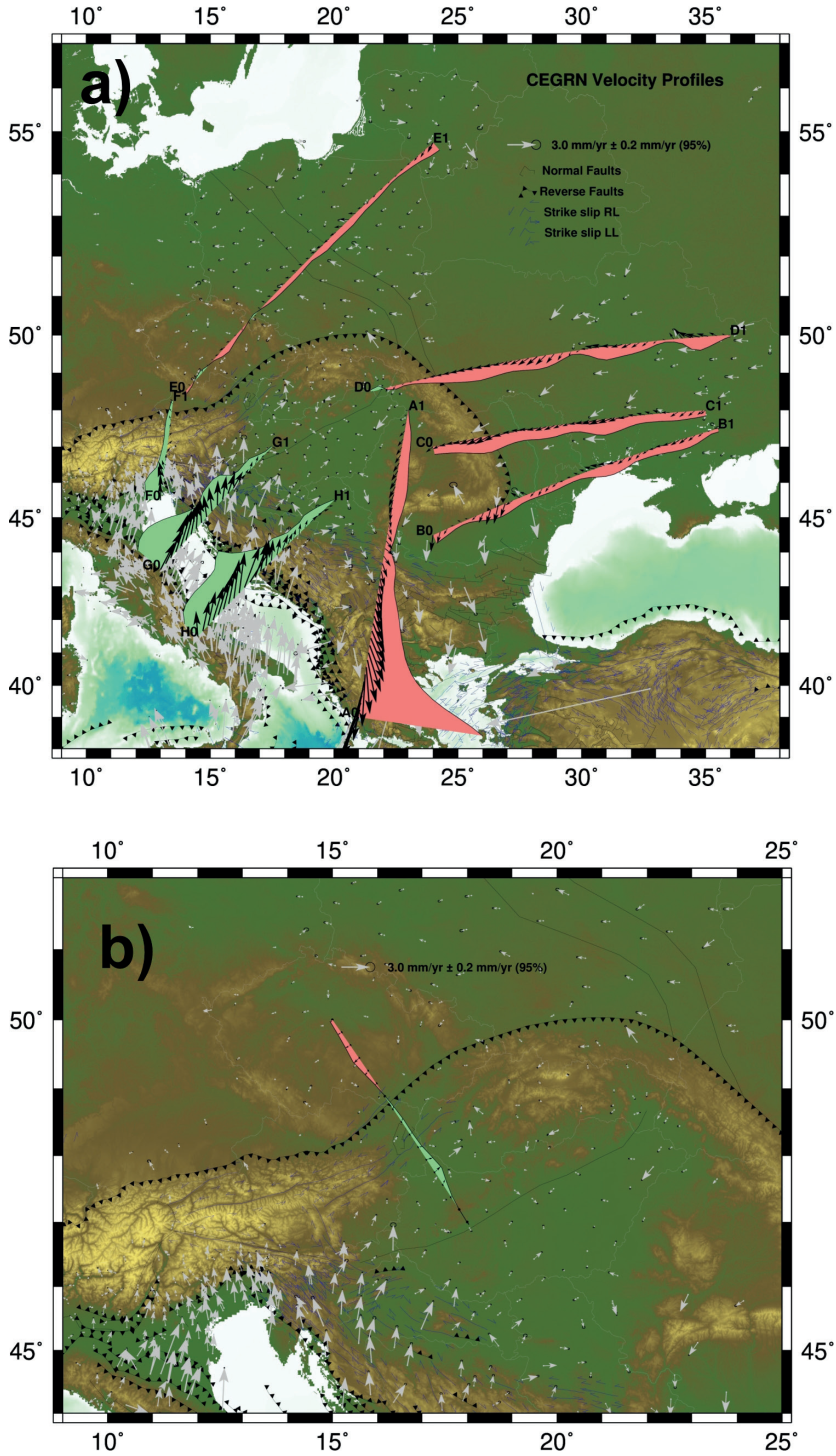

Fig. 2 - a. Extensional (pink) and compressional (green) strain rates implied by CEGRN GNSS velocities interpolated to selected profiles (black arrows) and projected along the profiles; b. Velocity change orthogonally to a profile crossing the PAL dextral shear fault to the south and the SEMP/MMZ sinistral shear fault to the north. The interpolated velocities highlight the extrusion of the Eastern Alps eastwards to the Pannonian basin.The pink area indicates interpolated velocities oriented SW; green area indicates interpolated velocities oriented NE.

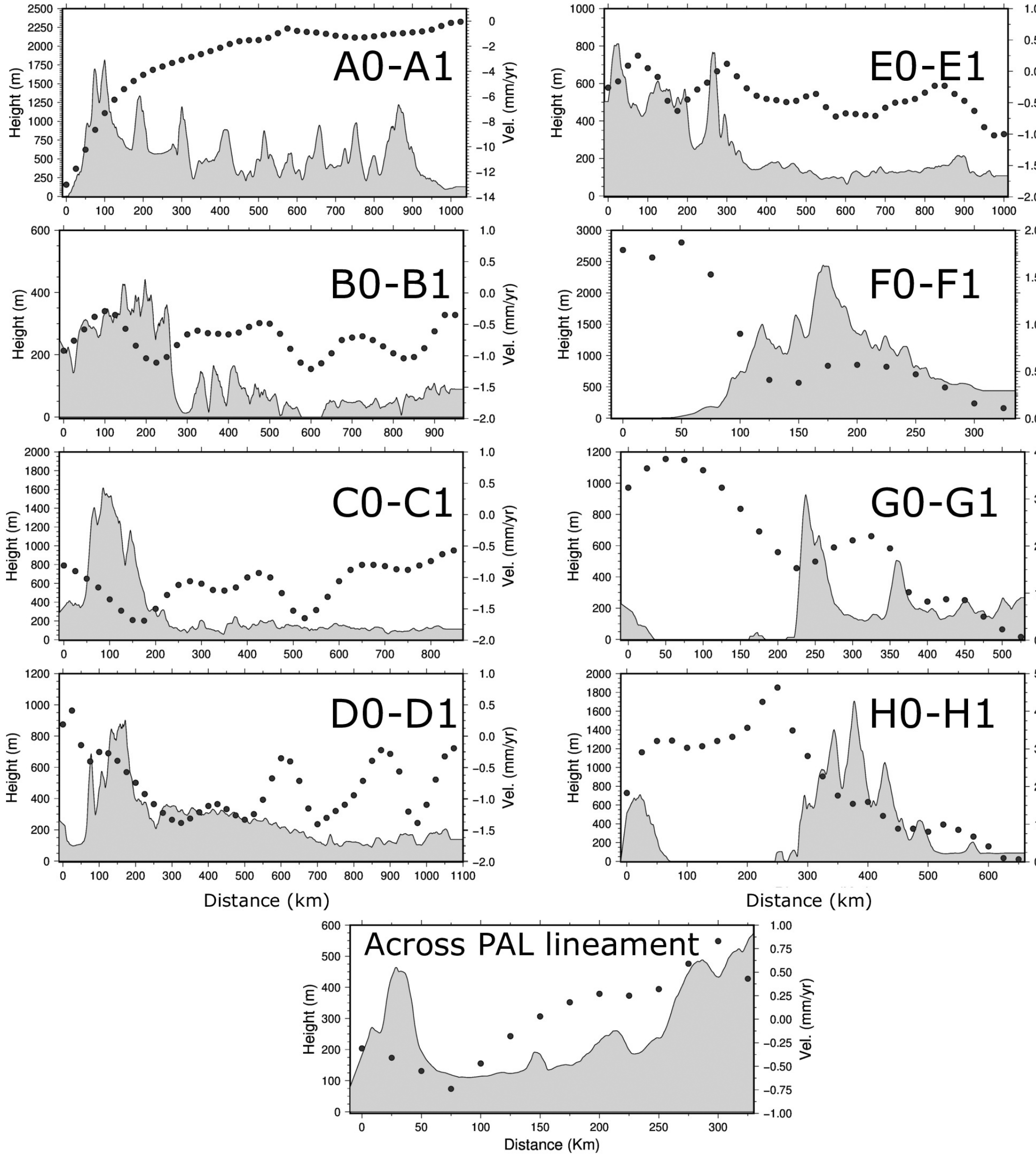

Fig. 3 - The eight profiles A to H with velocity projected along the profile, and the ninth profile (bottom) with velocity projected across the profile, are shown with the corresponding GTOPO30 topographic profile with a 25 km window running average, to highlight the correlation between topography and present day deformation. The bottom profile runs south to north, so that the negative velocities are eastwards and the positive velocities westwards.

the eastern Mediterranean. Several Authors have pointed out (e.g. Le Pichon and Angelier, 1979) that western Anatolia now belongs to the same strain pattern as the Aegean Sea and is dominated by N-S to NE-SW extension. According to Rotstein (1984) this motion cannot be modeled as a rotation about a single Eulerian pole. This idea is supported by the lack of decrease of the westward velocity in the profiles B C and D, as one moves northwards.

Profiles B0 - B1, C0 - C1, D0 - D1: sample the stretching across Ukraine, Moldova and Rumania associated to the dragging of the lithosphere by the counterrotation of the Anatolian plate. For a rotation of the Anatolian block about a single Eulerian pole one would expect a decrease of the velocity as one moves north, roughly the ratio of the sine of the mean latitude of the profiles, so that the velocity of profile B would be expected to be about 90% of that of profiles D. A curved pattern centered on the rotation pole is also expected. None of these signals are visible (see also Fig. 3), implying that the faults splaying from the North Anatolian fault to the north might also generate a non neglegible perturbation of the simple geometry of Euler rotation.

Profile E0 - E1: samples the large scale deformation across the Trans European Suture Zone (TESZ), a major structural divide between Precambrian Europe to the northeast and Phanerozoic terranes to the southwest. The TESZ separates the Precambrian terranes of the Baltic shield and east European craton (EEC) from the younger terranes to the south and west (Thybo et al., 1999). The profile was chosen in analogy with the Polonaise 97 P4 seismic refraction profile (Grad et al., 2003). As Fig. 2a and Fig.3 suggest, there is vitually no change of the interpolated GPS velocities projected along the profile, implying that no deformation takes place, at least at or near the surface.

Profile F0 - F1: shows the negative velocity gradient moving South to North, associated to the indentation of the Adria promontory/microplate. There is a vast literature on the subject and the velocity of indentation has been estimated by various authors, as well as the mechanical and thermal aspects of the indentation (see e.g. Caporali et al., 2013).

Profiles G0 - G1 and H0 - H1: show the velocity drop associated to the closure of the Adria sea and the subduction below the Dinarides. Kastelic and Carafa (2013) have investigated in detail the implications of the velocity drop in models of the Adria subduction,and argued in favor of Adria as a seismically active and deformable lithospheric block.

Fig. 2b and Fig. 3 (bottom) address quantitatively the velocity field associated with the eastwards extrusion of the region comprised between the PAL to the south and the SEMP/MMZ to the north. There is evidence that the process is active at present with a velocity change of ca. 1.8 mm/yr across a 300 km profile, implying a modest shear strain rate of some 6 nstrain/year. The data are necessarily limited by the scarcity of GPS sites and the size of the signal. The velocity pattern is in any case consistent with a kinematics of lateral extrusion approximated by an extrusion-spreading model towards an unconstrained Pannonian basin acting as stress sink, as suggested by Ratschbacher et al. (1991a) and is probably driven by the indentation of the Adria block shown in Profile F.

Conclusion. The analysis of the CEGRN GNSS data accumulated in the period 1996 – 2017 and carried out following the most recent procedures, software and ancillary IGb08/IGS14-based data (orbits, clocks, antenna models) has resulted in a homogeneous set of velocities that spread across Central Europe. The deformation regime is expected to be small, but non negligible. We report a widespread stretching of the crust in South Central Europe, bordering the Black Sea, associated with the dragging by the Anatolian anticlockwise rotation accompanied by lateral splay. We estimate that the N-S extensional strain rate measured by GNSS geodesy is consistent with an Andersonian traction driven solely by topography, over a time interval of ca. 6000 ± 1000 years. Compression is clearly visible wherever the Adria block moves relatively to the Dinarides and the South Eastern Alps. The lateral extrusion of the Eastern Alps is observed as an inversion of the velocity relatively to the SEMP shear zones to the north. Using a simple analytical model for the velocity across the profile we estimate a locking depth of 18 ± 4 km, which would imply that the slip associated with the extrusion is accommodated mostly in the upper crust. Finally, the TESZ seems subject to very small strain, if none.

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