

Observation of present-day tectonic motions in the Southeastern Carpathians: Results of the ISES/CRC-461 GPS measurements

A.G.A. van der Hoeven^{a,*}, V. Mocanu^b, W. Spakman^c, M. Nutto^d, A. Nuckelt^d,
L. Matenco^e, L. Munteanu^f, C. Marcu^g, B.A.C. Ambrosius^a

^a Department of Earth Observation and Space Systems (DEOS), Delft University of Technology, The Netherlands

^b Faculty of Geology and Geophysics, University of Bucharest, Romania

^c Faculty of Geosciences, University of Utrecht, The Netherlands

^d Department of Geodesy, Technical University of Karlsruhe, Germany

^e Faculty of Earth and Life Sciences, Free University, Amsterdam, The Netherlands

^f National Institute for Earth Physics (NIEP), Romania

^g Faculty of Geodesy, Technical University of Bucharest, Romania

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Abstract

Results are presented from GPS measurements performed in the Southeastern Carpathians between 1997 and 2004. Data from 25 stations observed during 13 campaigns were analyzed by the Department of Earth Observation and Space Systems (DEOS) of Delft University of Technology. The repeatabilities of the solutions are on the order of 1–4 mm for the horizontal, and 4–8 mm for the vertical component. The resulting velocity estimates have an uncertainty of <1 mm/yr and <3 mm/yr, respectively. The region southeast of the Carpathian bend zone shows a horizontal movement towards SSE of ~2.5 mm/yr, while the Transylvanian Basin shows very small motions with respect to Eurasia. The vertical velocity field indicates the existence of uplift and subsidence domains in the SE Carpathians, in good agreement with Pliocene–Quaternary orogen and basin studies. Another 29 GPS stations installed in the last 3 yr will generate a denser velocity field in the coming years for this region.

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1. Introduction

In late 2001, the Surface Behavior and Dynamical Units of the Southeast Carpathians Tectonics (SUBDUCT) program was initiated by ISES (Netherlands

Research Center for Integrated Solid Earth Science), together with the Faculty of Geology and Geophysics at the University of Bucharest, and National Institute for Earth Physics (NIEP) [1]. The aim of this program is to monitor, analyze, and interpret the surface motions occurring in response to active crust–lithosphere dynamics of the southeast Carpathians in Romania, using GPS. For this region (Vrancea), observations of GPS surface kinematics are additional, independent data sources: in combination with the geological and geophysical studies, they help to unravel the recent late

* Corresponding author.

¹ Currently working at: Emmauscollege, High-school for Havo, Ath and Gymnasium, Alexandriëstraat 40, 3067 MR Rotterdam, The Netherlands.

stage post-collisional processes in the SE Carpathians. Particularly, SUBDUCT focuses on the surface expression of these dynamic processes, which at depth generates the intermediate-depth Vrancea seismicity, releasing the highest strain in continental Europe [2].

The genesis of the Vrancea earthquakes (Fig. 1) is debated, but is most commonly related with processes such as detachment, delamination or thermal re-equilibration (e.g., [3–6]) in a nearly vertical lithospheric slab, long after orogenic shortening and continental collision ended in the Late Miocene (~10 Ma, e.g. [7]). These orogenic movements represent the last stage of a mobile zone evolution, i.e., the Outer Dacidian

Trough (or Ceahlau-Severin ocean [8]), an eastern branch of the NeoTethys [10], which opened in Late Jurassic–Early Cretaceous between the Rhodopian fragment units (sensu [11]) and the stable platform units of East Europe and Moesia. Furthermore, this mobile zone was probably closed through subduction and collision during the late Cretaceous–Miocene tectonic events [8].

To analyze the surface expression of the mechanisms inducing the Vrancea earthquakes, ISES has initiated a cooperation for GPS monitoring with the CRC-461 (Collaborative Research Center 461 ‘Strong Earthquakes: A Challenge for Geosciences and Civil Engineering’) program of the University of Karlsruhe

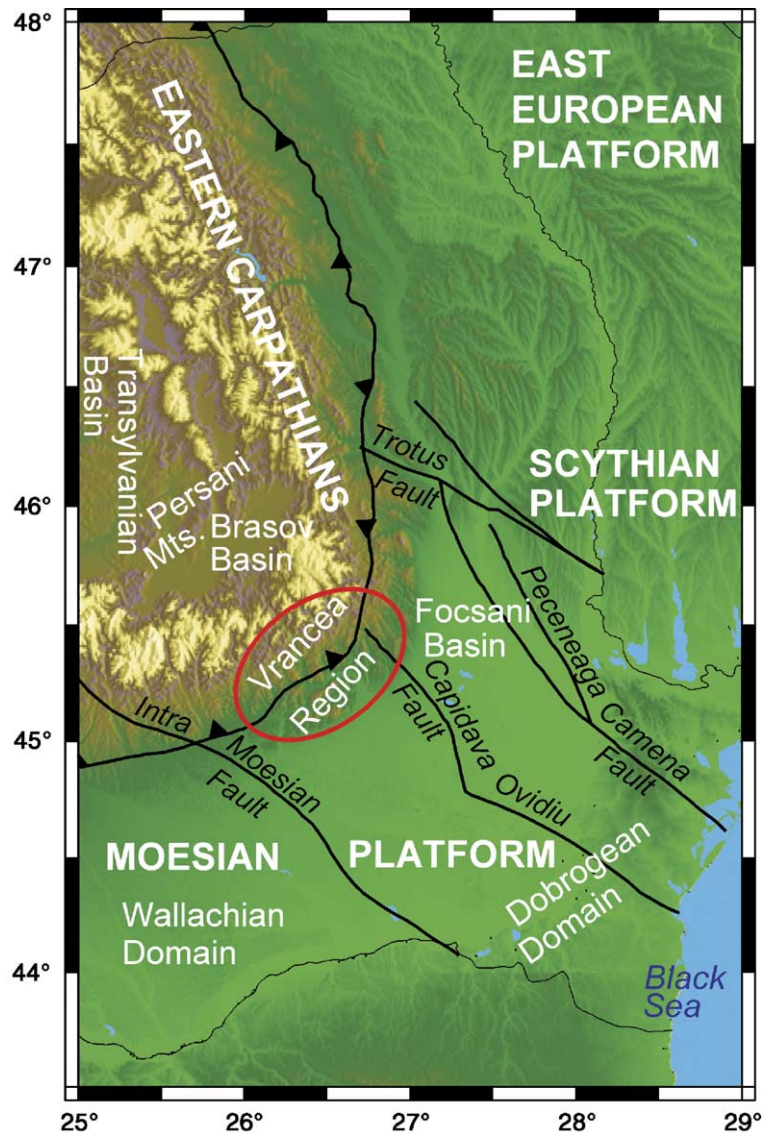


Fig. 1. Different main tectonic units and crustal faults on a topography background for the Southeastern Carpathians orogen and neighboring areas. The red circle indicates the Vrancea Seismogenic Zone.

in 2002. This institute has been performing investigations in the region since 1997. The ISES/CRC-461 network also incorporates previous GPS measurements in the area performed by the Central European GPS Geodynamic Reference Network (CEGRN) consortium since 1995 [9].

2. The ISES/CRC-461 GPS network

The ISES/CRC-461 network (Fig. 2) covers an area of about 350×350 km around the bend-zone of the Eastern Romanian Carpathians. The stations provide good coverage of the different tectonic units in the

region (Fig. 1), with particular focus on the significant Pliocene–Quaternary vertical movements detected by integrated studies in the SE Carpathian foreland, in the area of the Focsani Depression and adjacent thin-skinned thrust belt (e.g., [12]).

The core of the network consists of 6 permanent GPS stations, installed between 2001 and 2004. These stations are all equipped with Leica CRS-1000 GPS receivers and AT-504 chocking antennas. Around this network the campaign GPS points are located. The campaign network has slowly evolved from 8 points in 1995 to 54 points in 2004. The campaign style observations have been performed from 1997 to 2004 (Table 1).

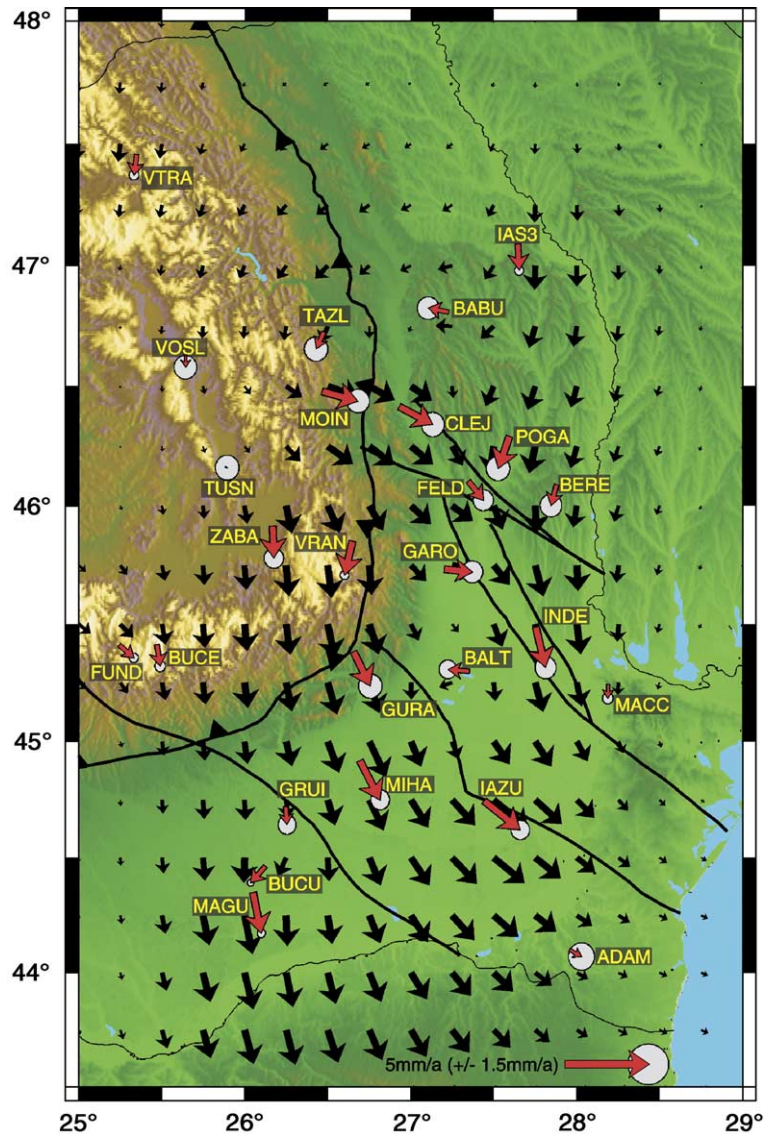


Fig. 2. Interpolated velocity field with respect to a fixed Eurasian plate. The red arrows indicate the measured GPS vectors. The error ellipses show the 95% confidence level. The motion at the Eurasian plate boundaries is defined to be zero.

Table 1
Overview of GPS campaigns performed in Romania between 1995 and 2004

Year	Date	Institute	No. of sites	Obs. duration
1995	29-5/2-6	CEGRN	8	120 h (cont.)
1996	10-6/15-6	CEGRN	8	120 h (cont.)
1997	4-6/10-6	CEGRN	8	120 h (cont.)
1997	27-9/2-10	CRC461	24	2 × 8 h
1998	20-8/27-8	CRC461	27	3 × 8 h
1999	14-6/19-6	CEGRN	5	120 h (cont.)
1999	3-7/14-7	NATO	12	3 × 12 h
2000	19-8/27-8	CRC461	34	3 × 8 h
2001	10-5/18-5	NATO	12	3 × 12 h
2001	18-6/23-6	CEGRN	2	120 h (cont.)
2002	2-6/26-6	ISES	33	72 h (cont.)
2003	12-8/22-8	ISES/CRC461	54	72 h (cont.)
2004	8-8/18-8	ISES/CRC461	54	72 h (cont.)

To facilitate the mapping of the network into the International Terrestrial Reference Frame (ITRF-2000) [13], data from 16 stations of the International GPS Service for Geodynamics (IGS) tracking network in the region are included (i.e., ANKR, GLSV, GRAZ, JOZE, KOSG, LAMP, MATE, METS, MOPI, NICO, ONSA, SOFI, VILL, WTZR, ZECK and ZIMM).

Six major campaigns were carried out during the project by ISES and CRC-461, and another major campaign is planned for 2006. During the first three campaigns (1997, 1998 and 2000), Leica 300 and 500 systems and antennas were used and during the last three campaigns (2002, 2003 and 2004) only Leica 500 systems with corresponding antennas. During the CEGRN and NATO campaigns, Trimble and Ashtech systems were used.

3. GPS data processing

Data processing was performed by GIPSY-OASIS II v2.5 [14] with precise-point strategy (ppp). With ppp, pre-calculated orbits and clocks from a global network are used, while solving for a single station position. Accurate GPS satellite orbits and clocks are obtained from Jet Propulsion Laboratory (JPL) and antenna phase center tables from NGS-NOAA (National Geodetic Survey of The National Oceanic and Atmospheric Administration, USA). Every station position is individually solved for, while downsampling the data to 5-min intervals using a 15° cut-off angle. During data processing, the ionospheric-free combination is used and tropospheric parameters are estimated every 5 min by Niell models [15]. Furthermore, ocean loading corrections computed by [16] are applied during processing. After a separate processing at all stations, the covariance

matrices and solutions are combined, and ambiguities are solved for in an iterative network process. Repeatabilities of the daily solutions with respect to the combined campaign solutions range from 1 to 4 mm for the horizontal, and 4 to 8 mm for the vertical components.

3.1. Campaign data consistency

The daily solutions calculated with the ppp strategy are combined into campaign-averaged solutions with tools included in the GIPSY-OASIS package in order to inspect the campaign consistency. An optimized 7-parameter Helmert transformation is used to calculate an unreferenced combined solution using a least-squares adjustment. During this process, station solutions detected as an outlier (<5%) are removed from the averaged solution. Daily repeatabilities of the combined campaign solutions are given in Table 2, and range from 1 to 4 mm for the horizontal, and 4 to 8 mm for the vertical components.

Using the IGS stations, the daily solutions are mapped onto the ITRF-2000 reference frame using a 7-parameter Helmert transformation while fixing the IGS station coordinates to their ITRF-2000 positions. During this transformation, outliers in the mapping stations are detected and removed from the procedure. The average mapping RMS for each campaign is shown in Table 2.

3.2. Velocity field estimation

The velocity field for the Southeast Carpathians area is obtained by estimating a linear fit through the daily solutions. During the estimation, outliers are removed

Table 2
Overview of daily repeatabilities and mapping RMS of the IGS permanent stations with respect to the ITRF-2000 reference frame after transformation

Year	Institute	RMS residuals (mm)			Mapping RMS (mm)		
		North	East	Up	North	East	Up
1995	CEGRN	2.6	1.9	5.3	1.6	2.4	4.1
1996	CEGRN	2.3	3.6	5.3	1.7	2.3	6.0
1997	CEGRN	1.8	2.7	6.6	1.5	2.7	6.1
1997	CRC461	2.3	2.7	6.2	1.8	2.8	5.3
1998	CRC461	2.6	3.7	7.3	1.8	2.9	5.7
1999	CEGRN	1.7	3.1	6.2	1.9	2.6	7.2
1999	NATO	2.0	3.4	8.0	2.0	2.6	7.3
2000	CRC461	2.5	3.0	7.8	2.3	2.5	6.0
2001	NATO	1.6	2.0	4.9	1.9	2.8	5.9
2001	CEGRN	1.8	2.5	5.2	1.5	3.3	6.5
2002	ISES	1.6	2.3	5.4	2.1	2.7	6.7
2003	ISES/CRC461	1.2	1.4	4.1	2.3	2.7	6.9
2004	ISES/CRC461	1.4	1.4	5.3	2.5	3.2	6.7

from the process (in general <2% of the data). Furthermore, vertical antenna offset parameters are estimated for each individual system used in the field. This has been done to reduce the influence of vertical antenna offsets introduced by the use of different antenna setups during various campaigns that were unfortunately not always properly noted on the logsheets. This has been implemented by introducing an extra offset parameter in the estimation of the velocities for every individual antenna used during a campaign. It is assumed that the offset stays constant during the campaign. From this estimation, it showed that only a small number of antennas already suspected of having trouble with the setups gave a consistent offset (rms around 1–2 mm and an

offset of sometimes several centimeters) during some campaigns. These offsets have been implemented in the final solution. Because of the small tectonic motions in the region (<5 mm/yr), only the solutions that have a formal (calculated by the processing) 95% confidence level of <1.3 mm/yr are being considered into the final solution. In practice, these are the permanent stations with a time-span longer than 1.5 yr, campaign stations that have been measured for at least 4–5 consecutive years, or with a time-span longer than 5 yr. Finally, the reference framework was changed from the ITRF-2000 no-net-rotation frame to a fixed one with respect to assumed-stable Eurasia. For the transformation, the Eurasian pole from the DEOS2k model [17] (54.61°N,

Table 3
Estimated velocity field for Romania

Station	4 char code	Latitude	Longitude	ITRF-2000		Euroasia			95% _{ns}	95% _{ew}	95% _{vert}	Time span (yr/occupation)
				V_{ns}	V_{ew}	V_{ns}	V_{ew}	V_{vert}				
Adamclisi	ADAM	44.10	27.96	11.67	24.44	-0.42	0.73	-1.33	1.02	0.96	2.91	5/5
Babusa	BABU	46.81	27.23	12.47	21.89	0.25	-1.25	1.35	0.83	0.81	2.57	7/6
Balta Alba	BALT	45.30	27.35	12.31	22.13	0.11	-1.29	-7.39	0.70	0.65	2.32	7/8
Beresti	BERE	46.09	27.88	10.84	23.03	-1.27	-0.33	-2.54	0.84	0.82	3.22	7/6
Cleja	CLEJ	46.42	26.93	11.19	25.18	-1.08	2.02	-0.50	0.90	0.86	2.69	7/6
Feldioara	FELD	46.10	27.35	11.03	24.20	-1.16	0.91	-1.10	0.77	0.74	2.56	7/7
Fundata	FUND	45.41	25.24	11.78	23.97	-0.77	0.88	2.82	0.35	0.34	1.06	9/8
Garoafa	GARO	45.73	27.20	12.05	25.04	-0.17	1.71	-2.84	0.82	0.78	2.73	7/7
Gruuiu	GRUI	45.72	26.25	11.30	23.43	-1.08	0.07	-3.34	0.71	0.67	2.29	7/8
Guru Vaii	GURA	45.38	26.65	10.24	24.31	-2.08	1.00	1.40	0.90	0.86	2.97	7/6
Iasi	IAS3	47.09	27.64	10.56	23.23	-1.60	0.08	-2.89	0.35	0.34	0.97	9/8
Iazu	IAZU	44.73	27.44	10.43	25.69	-1.75	2.16	-3.52	0.72	0.68	2.21	7/8
Independenta	INDE	45.49	27.76	9.67	24.02	-2.45	0.57	1.83	0.82	0.78	2.52	7/8
Macin	MACC	45.24	28.19	11.22	23.53	-0.83	-0.03	1.86	0.41	0.38	2.07	9/8
Magurele	MAGU	44.35	26.05	9.95	23.87	-2.47	0.49	-2.36	0.32	0.31	0.92	9/10
Mihailesti	MIHA	44.92	26.69	9.93	24.60	-2.37	1.21	-4.60	0.74	0.70	2.27	7/8
Moinești	MOIN	46.48	26.47	11.74	25.24	-0.61	2.16	-0.64	0.87	0.84	2.88	7/6
Pogana	POGA	46.29	27.59	10.22	22.60	-1.94	-0.68	-0.21	0.89	0.87	3.37	7/6
Potoci ^a	POTO	46.96	26.12	9.67	20.13	-2.74	-2.80	8.30	0.89	0.87	2.90	7/6
Tazlau	TAZL	46.73	26.48	11.32	22.58	-1.03	-0.46	2.82	0.90	0.88	2.97	7/6
Tusnad	TUSN	46.16	25.88	12.39	23.16	-0.06	0.12	3.15	0.92	0.87	2.94	7/6
Voslobeni	VOSL	46.63	25.64	11.75	22.94	-0.74	0.02	-0.29	0.85	0.83	2.72	7/6
Vrancioia	VRAN	45.85	26.65	10.26	22.75	-2.05	-0.48	1.51	0.34	0.33	0.97	9/10
Vatra Dornei	VTRA	47.46	25.34	11.28	22.56	-1.24	-0.17	-2.61	0.37	0.36	1.13	9/10
Zabala	ZABA	45.91	26.16	10.46	32.20	-1.93	0.06	-2.23	0.76	0.71	2.94	7/8
<i>Permanent stations</i>												
Balvanyos ^a	BALY	46.11	25.95	14.42	19.20	1.99	-3.87	-0.27	0.37	0.35	0.94	Feb. 2002+
Bicaz ^b	BICA	46.82	25.85	13.19	21.61	0.75	-1.31	8.39	1.23	1.11	3.38	Aug. 2003+
Bucegi	BUCE	45.41	25.47	11.22	23.32	-1.30	0.20	0.50	0.43	0.39	1.20	Apr. 2002+
Bucuresti	BUCU	44.46	26.13	11.38	22.47	-1.02	-0.90	-1.06	0.27	0.25	0.75	May 1999+
Histria ^b	HIST	44.54	28.77	12.11	22.83	0.16	-0.93	10.77	1.18	1.20	3.84	Aug. 2003+
Lacauti ^b	LACP	45.82	26.37	-	-	-	-	-	-	-	-	Aug. 2004+
Vrancioia ^b	VRAP	45.85	26.64	11.04	17.73	-1.28	-5.50	-7.68	2.43	2.17	6.25	Apr. 2004+

^a Velocities not used in the final solution because of high residuals probably caused by monument instability.

^b Horizontal and vertical velocities not used in the final solution because of short operational time span (<1.5 yr).

103.78°W, 0.249°/My) was used. Table 3 summarizes the estimated horizontal and vertical velocities in ITRF-2000 and this Eurasian reference frame. Figs. 2 and 3 show the horizontal and vertical velocity field obtained for the region with respect to fixed Eurasia.

4. Results and discussion

GPS studies performed from 1995 to 2004 give indications for the local tectonic motions in the Carpathians Bending Zone. From Table 3, a 95% confidence level of <1 mm/yr for the horizontal component and of <3 mm/yr for the vertical component is derived.

The horizontal velocity field indicates kinematic zoning of the Romanian Carpathians foreland (Fig. 2). Two main movement directions can be observed in the Moesian Platform, separated by the crustal scale Intramoesian Fault. The Dobrogean domain, between the Peceneaga–Camena Fault and Intramoesian Fault, has a movement trend towards SSE at ~2.5 mm/yr, while the Wallachian domain, west of the Intramoesian Fault has a south oriented motion of about 1–2 mm/yr. This is consistent with dextral transtension across the Intramoesian Fault at a rate of around 1 mm/yr, which is found from Pliocene–Quaternary kinematics detected by geological and

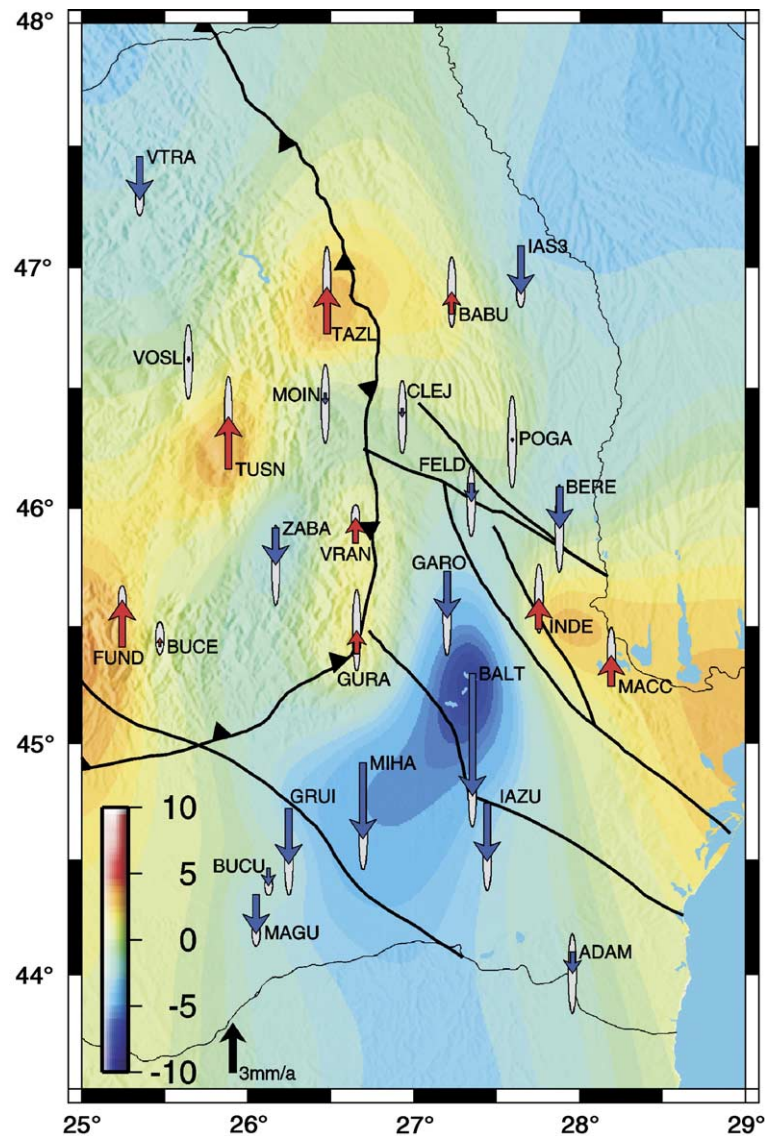


Fig. 3. Interpolated vertical velocity field for the Vrancea region. Red/blue arrows indicate the measured vertical GPS vectors (scale in mm/yr). The error ellipses show the 95% confidence level.

seismic studies (e.g., [12]). A significant change in velocity is recorded at the limit between the Dobrogean domain and the East European platform near the Trotus Fault, indicating a sinistral strike-slip zone. This is compatible with geological and neotectonic studies which suggest increased late Miocene–Quaternary sinistral transtensional deformation along a NW–SE oriented corridor limited southwards by the Trotus Fault (e.g., [12,18]). This zone accommodates and separates the horizontal stable and uplifting East European/Scythian domain from subsidence and SSEward movement of Moesia in the area of the Focsani basin. For the Transylvanian domain, most of the velocities indicate small residual motions with respect to stable Eurasia.

Although the vertical solutions (Fig. 3) are of a lower quality than the horizontal solutions they still give a good indication of the behavior of the region in recent times, but they have to be interpreted carefully. The vertical velocity field shows the existence of alternating domains of uplift and subsidence in the SE Carpathians, particularly along a NW–SE oriented corridor, in good agreement with Pliocene–Quaternary orogen and basin studies (e.g., [18]). The subsiding areas are spatially juxtaposed over the Focsani and Brasov basins, with significant accumulation of Pliocene–Quaternary sediments (5 km and 0.5 km, respectively). The highest GPS subsidence is symmetrically observed in the Focsani basin, where velocities of 2–3 mm/yr are in agreement with the 2.5-km thickness of Quaternary deposits (1.5 mm/yr average). This geologically recorded subsidence is common for the entire eastern part of the Moesian platform, but with much reduced (up to 400 m Quaternary) values, compatible with the reduction of the GPS subsidence outside the Focsani basin. In contrast, the uplifting areas correspond to domains where significant Pliocene–Quaternary uplift took place. These domains are spatially juxtaposed over the frontal thin-skinned units of the SE Carpathians, the Persani Mountains and the part of the North Dobrogea orogen buried under the foredeep. The highest geological uplift is recorded in the first domain (up to 4 km during the Pliocene–Quaternary, [19]), while the latter display more moderate magnitudes (up to 500 m).

The mechanism responsible for the active tectonic deformations in the SE Carpathians corner is currently being studied and several hypotheses are being proposed. The short and constant ~50 km horizontal wavelength of the uplift-subsidence in the NW–SE corridor from the Transylvania basin to North Dobrogea suggests an active crustal folding mechanism observed in the geological record [20]. The increased vertical velocities

in the Focsani basin-frontal SE Carpathians nappes area possibly indicate active lithospheric loads inherited from the assumed Cretaceous–Miocene subduction, most probably via slab detachment still taking place at the Carpathians scale [3], generating the large Vrancea seismicity. The decrease in the horizontal movement of the Dobrogean block towards the SE can be the effect of the attenuation of folding-related shortening from high values near the orogen towards low values in the distal foreland [18].

Overall, the computed GPS velocity field is in good agreement with the Southeast Carpathians Pliocene–Quaternary geological evolution. The currently running GPS network consists of approximately twice the number of stations used for computations in the present paper. The time series for the additional stations was too short for interpretation, but campaigns planned in the near future will significantly detail the interpretation resulting in an accurate velocity field constraining the unusual post-collisional evolution of the Carpathians orogen.

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