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GPS study (1996–2002) of active deformation along the Periadriatic fault system in northeastern Slovenia: tectonic model

MARKO VRABEC[1], POLONA PAVLOVČIČ PREŠEREN[2] and BOJAN STOPAR[2]

[1]University of Ljubljana, Faculty of Natural Sciences and Engineering, Department of Geology, Aškerčeva 12, SI-1000 Ljubljana, Slovenia; mvrabec@ntfgeo.uni-lj.si
[2]University of Ljubljana, Faculty of Civil and Geodetic Engineering, Department of Geodesy, Jamova 2, SI-1000 Ljubljana, Slovenia; polona.pavlovcic@fgg.uni-lj.si; bojan.stopar@fgg.uni-lj.si

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Abstract: We present GPS-derived 6 year (1996–2002) displacements of 9 sites in northeastern Slovenia, spanning across the faults of the Periadriatic fault (PAF) system. Site velocities relative to the stable Eurasian plate, while close to or within the uncertainty limits, indicate predominately N- to NNE-directed movements in the range from 0.5 to 2 mm/yr, which is consistent with the previously published continuous and episodic GPS observations from the region. Our results support the recent idea about the ongoing eastward extrusion of the Eastern Alpine domain and confirm that the PAF system could represent the dextral southern boundary of the extruding unit. However, the deformation in the Slovenian part of the PAF system is not limited to a single strike-slip zone, but is accommodated within the larger area. Measurable dextral displacements in the range of ~1 mm/yr exist on the Sava and Labot (Lavanttal) faults of the PAF system. No dextral displacements were observed along the eastern continuation of the Sava fault, which suggests southward displacement transfer and possibly absorption of deformation in the transpressive Sava Folds foldbelt situated south of the fault. Ongoing thrusting of the Northern Karavanke unit north of the PAF implies active transpression along the main PAF zone, whereas the region between the PAF and the Sava fault is apparently deformed transtensionally.

Key words: Slovenia, Periadriatic fault, GPS geodesy, neotectonics, transpression, transtension, extrusion.

Introduction

The Periadriatic fault (PAF) is a major post-collisional structural feature of the Alpine Orogen. Along its entire length, the PAF system exhibits complex geometrical and kinematic relationships (e.g. Schmid et al. 1989), some of which remain controversial (e.g. Viola et al. 2001). The easternmost outcropping segment of the PAF is located approximately on the Austrian-Slovenian border (Figs. 1, 2). Displaced paleogeographical markers and kinematic reconstructions indicate that it accomodated at least 100 km of dextral motion (Kázmér & Kovács 1985; Frisch et al. 1998; Fodor et al. 1998), which mostly happened in the Miocene during eastward extrusion of the Eastern Alps out of the Adria-Europe collision zone (Ratschbacher et al. 1991). The dextral PAF acted as a southern border of the extruding wedge, whereas the sinistral northern boundary was located along the Northern Calcareous Alps (Ratschbacher et al. 1991; Frisch et al. 1998). The main phase of dextral movements on the easternmost PAF segment ended at the beginning of the Pliocene (Fodor et al. 1998), when extrusion was stopped due to the termination of subduction in the Carpathians, providing until then a free boundary for eastward escape (Horváth & Cloething 1996). This event was reflected by the onset of inversion of extensional structures of the Pannonian Basin (Fodor et al. 1999) and by transpressional deformation in most of central and northern Slovenia (Fodor et al. 1998; Márton et al. 2002). In the territory of eastern Slovenia and northeastern Croatia, this inversion episode is documented to have lasted at least until the end of the Pliocene (Tomljenović & Csontos 2001), and could have continued into Quaternary times (e.g. Placer 1999).

It has recently been realized that extrusional tectonics in the Eastern Alpine-Pannonian domain might be active today. For example, Quaternary to Recent reactivations of strike-slip zones were documented in the Pannonian Basin (e.g. Lőrincz et al. 2002). Some of those deeply-seated intra-basinal fault zones are believed to have acted as a continuation of the PAF during the Miocene extrusion processes (Fodor et al. 1998). But more importantly, a GPS-based analysis of intraplate deformation in Central Europe (Grenerczy et al. 2000; Grenerczy 2002) suggests that the territory of the Eastern Alps is being actively displaced eastward at the rate of ~1.3 mm/yr, as the N- to NW-moving Adriatic microplate collides with Europe (Fig. 1). Due to the sparse network of GPS sites available to those studies, the exact position and character of the southern boundary of the extruding Alpine-North Pannonian block remained unclear. Is it the PAF, as assumed by Grenerczy (2002), or is the deformation distributed in a wider belt? For example, the distribution of seismic activity in Slovenia, in terms of both magnitude and frequency of events (Poljak et al. 2000), suggests that the tectonically most active area is located in the Dinarides, closer to the rigid Adria. Could then a significant part of the Adria-

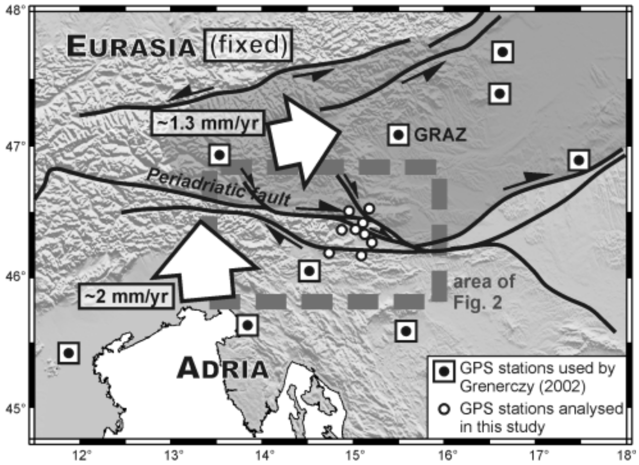

Fig. 1. Active deformation in the eastern part of the Adria-Europe collision zone, inferred from wide-aperture GPS data (Grenerczy 2002). Velocities shown are relative to the stable Eurasia reference frame. The Eastern Alpine–North Pannonian unit (shaded) is moving eastward with respect to both the Adriatic microplate and Europe, and the Periadriatic fault system is the presumed southern boundary of the extruding unit. White squares with dots are the GPS stations used in the analysis of Grenerczy (2002); several additional stations outside the area covered by this map were also used. Permanent IGS network station GRAZ, shown also in Fig. 4, is marked for reference. White dots — GPS network analysed in this study.

Europe convergence be absorbed in the PAF zone, or close to it, as implied by wide-aperture GPS data? To address these questions, we present the analysis of GPS-derived 6 year (1996–2002) displacements of 9 stations in northeastern Slovenia, spanning across the Sava, Šoštanj, Periadriatic and Labot faults of the Periadriatic fault system.

Structure and evolution of the PAF system in Slovenia

The **Periadriatic fault** is a major, WNW-ESE- to E-W trending structural and topographical boundary, running along the Slovenian-Austrian border (Figs. 2, 3). The fault zone is up to several km wide and is organized into elongated fault-parallel shear lenses and strike-slip duplexes, which contain highly-deformed Paleozoic, Mesozoic and Tertiary rocks (Fig. 3). The fabric of the synkinematic tonalite intrusion of Oligocene age emplaced along the fault zone suggests initial coaxial N-S shortening (von Gosen 1989), but all subsequent brittle deformation is dextral to reverse-dextral (von Gosen 1989; Polinski & Eisbacher 1992; Fodor et al. 1998). Displaced paleogeographical markers of Paleozoic–Mesozoic (Kázmér & Kovács 1985) and Tertiary (Fodor et al. 1998) age imply 300–500 km of dextral separation along the PAF. However, a realistic esti-

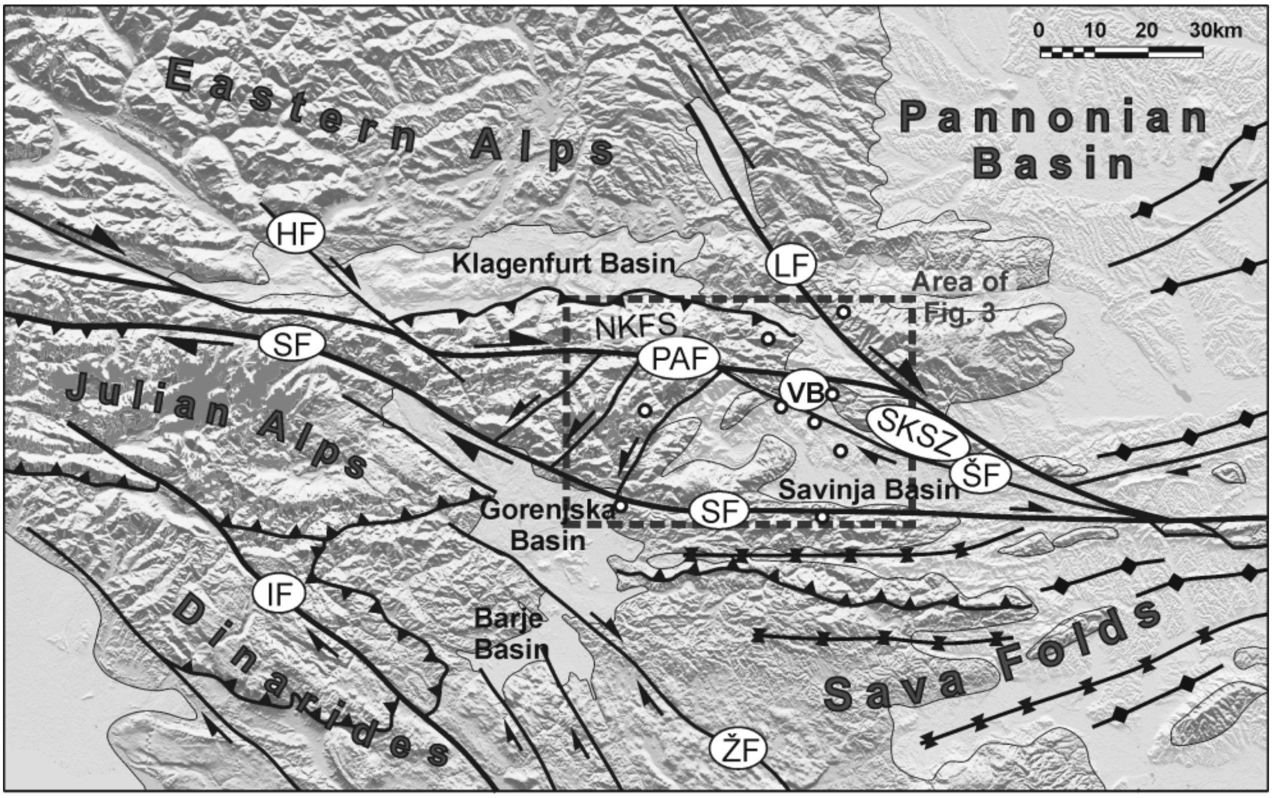

Fig. 2. Simplified tectonic map of the easternmost outcropping part of the Periadriatic fault system, Slovenia and Austria (see Fig. 1 for location). Tertiary-Quaternary basins are shown in lighter colour. White dots — positions of GPS stations analysed in this study. **IF** — Idrija fault, **HF** — Hochstuhl fault, **LF** — Labot (Lavanttal) fault, **NKFS** — Northern Karavanke flower structure, **PAF** — Periadriatic fault, **SF** — Sava fault, **SKSZ** — Southern Karavanke shear zone, **ŠF** — Šoštanj fault, **VB** — Velenje Basin, **ŽF** — Žužemberk fault.

mate of the actual dextral slip on the PAF is around 100 km (e.g. the kinematic reconstruction of Frisch et al. 1998). The rest of the present-day separation was produced by extreme extensional stretching of the extruding northern block. The easternmost outcrop of the Periadriatic fault zone is overlain by 17 Ma old Miocene sediments (Fig. 3), indicating that major strike-slip movements on the main fault terminated by then. Displacement was then transferred southward to the adjacent **Southern Karavanke shear zone** (Fig. 3). Disrupted and tilted Neogene sediments inside the zone imply that the deformation lasted until after mid-Miocene, but ceased by Pliocene as the Pliocene sediments covering the faults in the zone are unaffected (Fodor et al. 1998). The post-mid-Miocene slip alone might be significant, since the stratigraphic successions of Eocene to mid-Miocene sediments differ markedly across the shear zone (Jelen et al. 1992).

A major change in regional tectonics occurred at around the Miocene-Pliocene transition, when termination of subduction in the Carpathians blocked further eastward extrusion of the Eastern Alpine domain (Horváth & Cloething 1996). Perhaps triggered by this event, the Adria microplate might have started rotating in a counterclockwise sense at about the same time (Márton et al. 2002, 2003). The changed boundary conditions have profoundly affected the architecture and organization of the Slovenian PAF system, which is not a straight strike-slip corridor in its present configuration, but comprises of two major parallel to subparallel faults with several tens of kilometers of known displacement, the PAF and the Sava fault, and of younger oblique faults with smaller displacements, which either branch off the main PAF zone or dextrally displace it (Fig. 2).

Both the main PAF fault branch and the Southern Karavanke shear zone are dextrally offset for 10–14 km by the NW–SE trending **Labot (Lavanttal) fault** (Figs. 2, 3). The majority of dextral displacement is believed to have occurred in Pliocene–Quaternary (Kázmér et al. 1996); dextral activity clearly postdates the mid-Miocene–Pliocene time bracket of the latest activity of the Southern Karavanke shear zone which the Labot fault cross-cuts (Fodor et al. 1998). **Šoštanj fault,** which forks off the PAF zone and joins with the Labot fault (Figs. 2, 3) might have acted as a bypass fault, transferring dextral deformation from the western PAF branch eastward. Pliocene activity of the Šoštanj fault is evidenced by formation of the transtensional Velenje Basin situated at the fault (Fig. 3). The basin contains an up to 1000 m thick succession of Pliocene-Quaternary sediments, which thickens considerably towards the Šoštanj fault (Brezigar 1986). Well-documented post-depositional dextral deformation of the basin fill in the fault zone (Vrabec 1999), as well as a prominent geomorphological expression

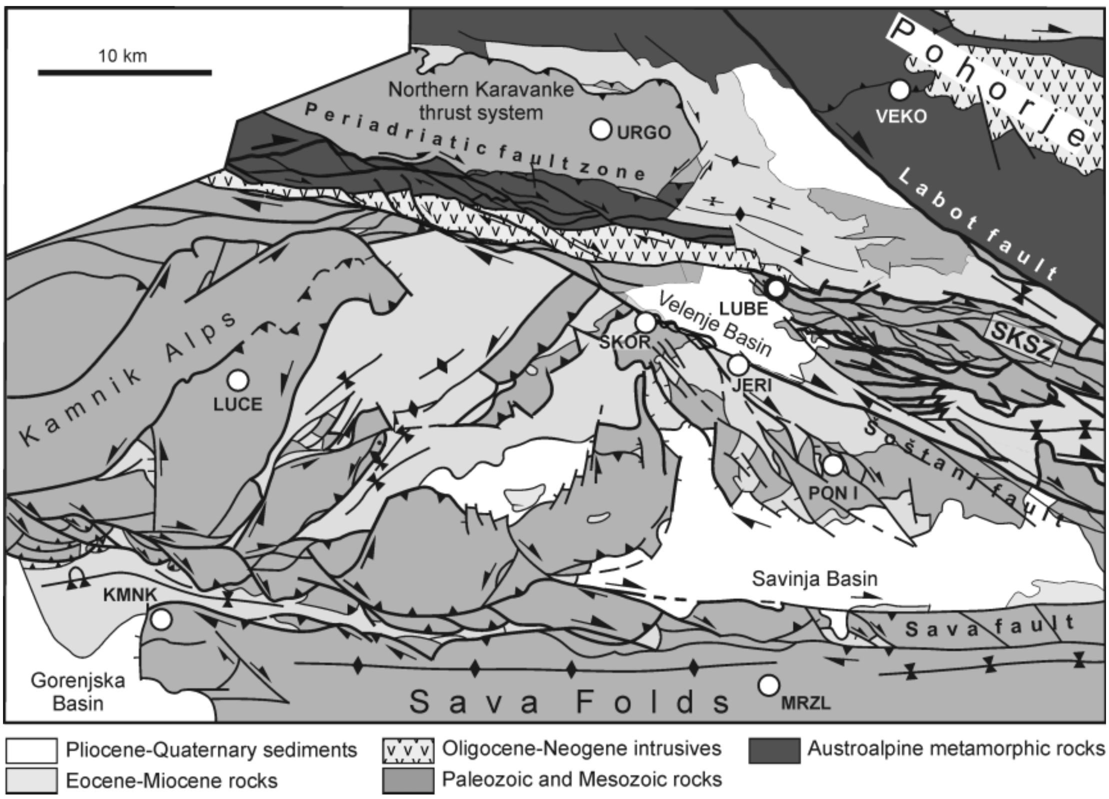

Fig. 3. Detailed structural map of the Periadriatic fault and associated structures in northeastern Slovenia (see Fig. 2 for location), compiled and extended from structural interpretation maps of Fodor et al. (1998) which were based on Buser (1978), Mioč & Žnidarčič (1977, 1983), and Premru (1983). Fault kinematics (where shown) are geological time-scale kinematics inferred from map relationships and fault-slip data. Big white dots show locations of GPS stations. **SKSZ** — Southern Karavanke shear zone.

of the fault trace and possible offsetting of the fluvial network (Fodor et al. 1998), prove continuation of fault activity into Quaternary and possibly Recent times.

Most of the post-Miocene deformation in the PAF system was probably taken by the **Sava fault,** a regional-scale structure subparallel to the Periadriatic fault, which extends from the eastern Italy across northern Slovenia and eventually merges with the Šoštanj fault and Labot fault in the east (Figs. 2, 3). Dextral kinematics of the fault are obvious from the architecture of the fault zone, fault-slip data (Fodor et al. 1998; Vrabec 2001), and from separation of a distinct Oligocene volcanogenic formation, which indicates 30–60 km of dextral displacement (Hinterlechner-Ravnik & Pleničar 1967; Placer 1996a,b). Deformed Neogene sediments inside the fault zone only roughly constrain timing of activity to post-mid-Miocene times (12 Ma), but the association of the fault with Pliocene-Quaternary basins, as well as indications for deformation of Quaternary sediments along the fault zone (Vrabec 2001), impressive topographic expression of the fault, and occasional seismicity, indicate Pliocene-Quaternary and probably recent activity.

Additionally, part of the deformation was absorbed in the lenticular area between the Sava and Periadriatic faults (Fig. 2). Structural analysis, fault-slip data and paleomagnetic declination measurements in Tertiary rocks demonstrate complex internal deformation within this "shear lens", involving clockwise domino-block rotations (Fodor et al. 1998). Transpressional deformation and high topography prevail in the western part of the lens, whereas the eastern part was probably deformed transtensionaly, as suggested by the occurrence of small fault-bounded Pliocene-Quaternary basins (Fig. 3) and by fault-slip data (Fodor et al. 1998). North of the Periadriatic fault, the Northern Karavanke Mts form a dextral transpressive flower structure, which is thrusted over the Pliocene-Quaternary sediments of the foreland Klagenfurt Basin for several kilometers (Fig. 2; Polinski & Eisbacher 1991; Nemes et al. 1997). This implies that some strike-slip deformation along the main PAF branch persisted well into the Quaternary. Thrust structures of the Northern Karavanke unit extend into the study area (Fig. 3).

Part of the displacement from the Sava fault might also have been transferred southward during the Quaternary (Fodor et al. 1998; Vrabec 2001; Vrabec & Fodor 2006). The rectangular **Gorenjska Basin** of Quaternary age could have formed due to extension in a releasing step between the Sava fault and the Žužemberk fault system (Figs. 2, 4). East of the Gorenjska Basin, the E-W trending foldbelt named the **Sava Folds** (Figs. 2, 4) formed in Pliocene–Quaternary times (Placer 1999; Tomljenović & Csontos 2001). The structure of the Sava Folds region suggests it could have formed by transpressive shortening, perhaps absorbing a part of the Sava fault dextral movement by deformation partitioning (Vrabec 2001). Geomorphic indicators, like high relief, elevated Pliocene-Quaternary gravel terraces, and an antecedent fluvial network (Placer 1999) imply young, possibly active uplift of the Sava Folds region.

The Slovenian part of the PAF system displays only modest seismicity, at least compared to the areas south of its southern boundary, the Sava fault (e.g. Poljak et al. 2000). Many of the instrumentally recorded earthquakes are distributed along or close to the faults of the PAF system. Events are generally too weak to allow reliable determination of focal mechanisms, but the few published solutions favour nearly horizontal dextral strike-slip motions on the Sava and Labot faults (Reinecker & Lenhardt 1999; Poljak et al. 2000).

GPS data acquisition and processing

Network setup

A network of 9 GPS stations was established in 1995–96 with the primary goal of providing a high-precision external coordinate frame for monitoring mining-induced subsidence in the Velenje coal mine area, but also with potential usefulness for geodynamic applications in mind, as the network traverses all the major faults of the PAF system: Sava fault, Šoštanj fault, Periadriatic fault and Labot fault (Fig. 3). The stations are marked either by metal pins driven into bedrock (sites KMNK, PONI, LUCE, URGO and MRZL), or are established on ~1 m tall concrete pillars seated in bedrock (sites JERI, SKOR, LUBE and VEKO). Stations JERI, SKOR and LUBE are located close to the Velenje Basin, where underground mining of the Pliocene coal seam is causing surface subsidence and horizontal deformation of up to several cm/yr. Decade-long observations of the Velenje Basin local GPS network (not presented here) indicate that those 3 stations, seated in competent pre-Pliocene bedrock, are not influenced.

Measurement campaigns

The stations were occupied in 3 campaigns, performed on 10–12 July 1996, 1–3 September 1999, and 3–5 September 2002. In each campaign, all stations were occupied simultaneously. Measurements were done in two 24-hour sessions with a sampling interval of 15 s (1996) or 30 s (1999 and 2002). Data were collected by dual-frequency receivers Trimble 4000SSE and 4000Ssi with Trimble Compact L1/L2 (with ground plane) and Trimble 4000SST external geodetic GPS antennas. To ensure maximum consistency of observations, the same receivers and antennas were used at each network station in all three campaigns. To minimize periodic influences, the campaigns were performed at the same time of the year.

Data processing

GPS observations were processed using the Bernese GPS Software, version 4.2 (Hugentobler et al. 2001) in ITRF2000 reference frame. International GPS Service (IGS) precise orbits were used and five IGS reference stations, Wettzell, Zimmerwald, Graz, Medicina and Penc, which have known precise coordinates and velocities in ITRF2000, were used to fix the network and the reference frame.

GPS observations for the IGS reference stations were obtained from Scripps Orbit and Permanent Array Center at the University of California, San Diego, USA (ftp://garner.ucsd.edu/pub/). Information about the receivers and antenna types used at the IGS stations was obtained from the IGS Central Bureu (http://igscb.jpl.nasa.gov/network/list.html). Coordinates of the IGS stations and their velocities in ITRF2000 reference frame were taken from the ITRF web site (ftp://lareg.ensg.ign.fr/pub/itrf/itrf2000/). Precise ephemeris of the GPS satellites and Earth rotation parameters were obtained from the GPS-Informations-und-Beobachtungssystem (GIBS) at the Bundesamt für Geodaesie und Kartographie, Germany (http://gibs.leipzig.ifag.de/). Those parameters, available only in ITRF94 for 1996 and in ITRF97 for 1999, were transformed to a common ITRF2000 reference frame with the computer program TRNFSP3N of J. Kouba, obtained at National Geodetic Survey, USA (http://www.ngs.noaa.gov/gps-toolbox/trnfsp3.htm). Phase center corrections were accounted for by using IGS phase center calibrations. Station coordinates were then recalculated to the epochs of the individual campaigns (1996.53, 1999.67 and 2002.67).

GPS phase observations were processed in a differential mode, that is on the basis of the carrier-phase differences. For each day of observation 13 independent baseline vectors were computed. After the construction of single differences, double differences of the ionosphere-free linear carrier-phase combination L3 were processed. For short baselines, the L1&L2 ambiguities were solved using a SIGMA-dependent strategy, and a QIF (Quasi-Ionosphere-Free) algorithm was used for long baselines. We applied elevation dependent weights of observations (model cos$z$). Processing was performed with the Saastamoinen troposphere model, with one site troposphere parameter for two hours of observations.

The initial results of the GPS data processing were daily solutions for baseline vectors, and daily positions of all network points. For consistency check, point coordinates computed for each day of observation were transformed with the Helmert transformation. Normal equations for daily solutions of all 3 campaigns were then combined to make the final solution, with IGS stations fixed in the ITRF2000 reference frame. The results are coordinates of network points in ITRF2000 for each campaign epoch.

Site velocities and velocity error estimations

Velocity components of network stations were estimated from computed positions at each campaign epoch, following the strategy of Bernese GPS Software (Hugentobler et al. 2001, p. 287). For apriori velocities of our network sites we used the velocities computed according to the NUVEL-1A NNR model (McCarthy 1996), where velocities of the IGS reference stations in ITRF2000 were held fixed. For campaign measurements, we estimated the long-term station velocities by assuming constant displacement rates between the campaigns. Velocity components according to ITRF2000 with their respective formal errors are listed in Table 1.

The formal errors of site velocities determined from repeated GPS campaigns are generally estimated on the assumption that measurement noise is uncorrelated in time (»white« noise). However, if time correlated noise (»coloured« noise) is present, the true velocity noise is underestimated with the scale factor of 2 to 11 (Mao et al. 1997; Dixon et al. 2000). Since our three campaigns were performed in nearly the same period of the year (1996.53, 1999.67 and 2002.67), we assumed that no seasonal signal in computed velocities exists, but we nevertheless inflated our estimated formal errors of velocity vectors with a pessimistic scale factor of 10.

Computed horizontal velocities of network points were then transformed from ITRF2000 to the stable Eur-

Table 1: Velocities computed for the 1996–2002 period, with RMS (root mean square error, 1σ). Initial processing results in ITRF2000 with formal RMS are given in the left half of the table. Velocities relative to stable Eurasia with scaled-up RMS (accounting for reference frame transformation and possible presence of coloured noise) are presented in the right half.

	Estimated velocities in ITRF2000 with formal RMS values				Estimated velocities relative to stable Eurasia with inflated RMS values			
Station	North [mm/yr]	RMS [mm/yr]	East [mm/yr]	RMS [mm/yr]	North [mm/yr]	RMS [mm/yr]	East [mm/yr]	RMS [mm/yr]
JERI	15.80	0.06	21.93	0.05	1.85	0.86	0.44	0.81
SKOR	13.97	0.06	21.67	0.05	0.01	0.86	0.19	0.81
LUBE	13.96	0.06	21.39	0.05	0.01	0.86	–0.10	0.81
PONI	15.27	0.06	21.89	0.05	1.33	0.86	0.37	0.81
URGO	15.16	0.06	21.59	0.05	1.19	0.86	0.15	0.81
VEKO	13.41	0.06	21.96	0.05	–0.53	0.86	0.48	0.81
KMNK	14.49	0.06	20.64	0.05	0.49	0.86	–0.80	0.81
LUCE	15.13	0.06	22.16	0.05	1.14	0.86	0.73	0.81
MRZL	14.35	0.06	21.85	0.05	0.40	0.86	0.31	0.81
GRAZ	14.45	0.01	22.13	0.01	0.54	0.63	0.73	0.64
MEDICINA	16.14	0.01	23.35	0.01	1.83	0.63	2.03	0.64
PENC	12.69	0.01	22.57	0.01	–0.76	0.63	0.67	0.64
WETTZEL	14.37	0.01	20.29	0.01	0.19	0.63	–0.12	0.64
ZIMMERWALD	15.07	0.01	20.14	0.01	0.40	0.63	0.16	0.64

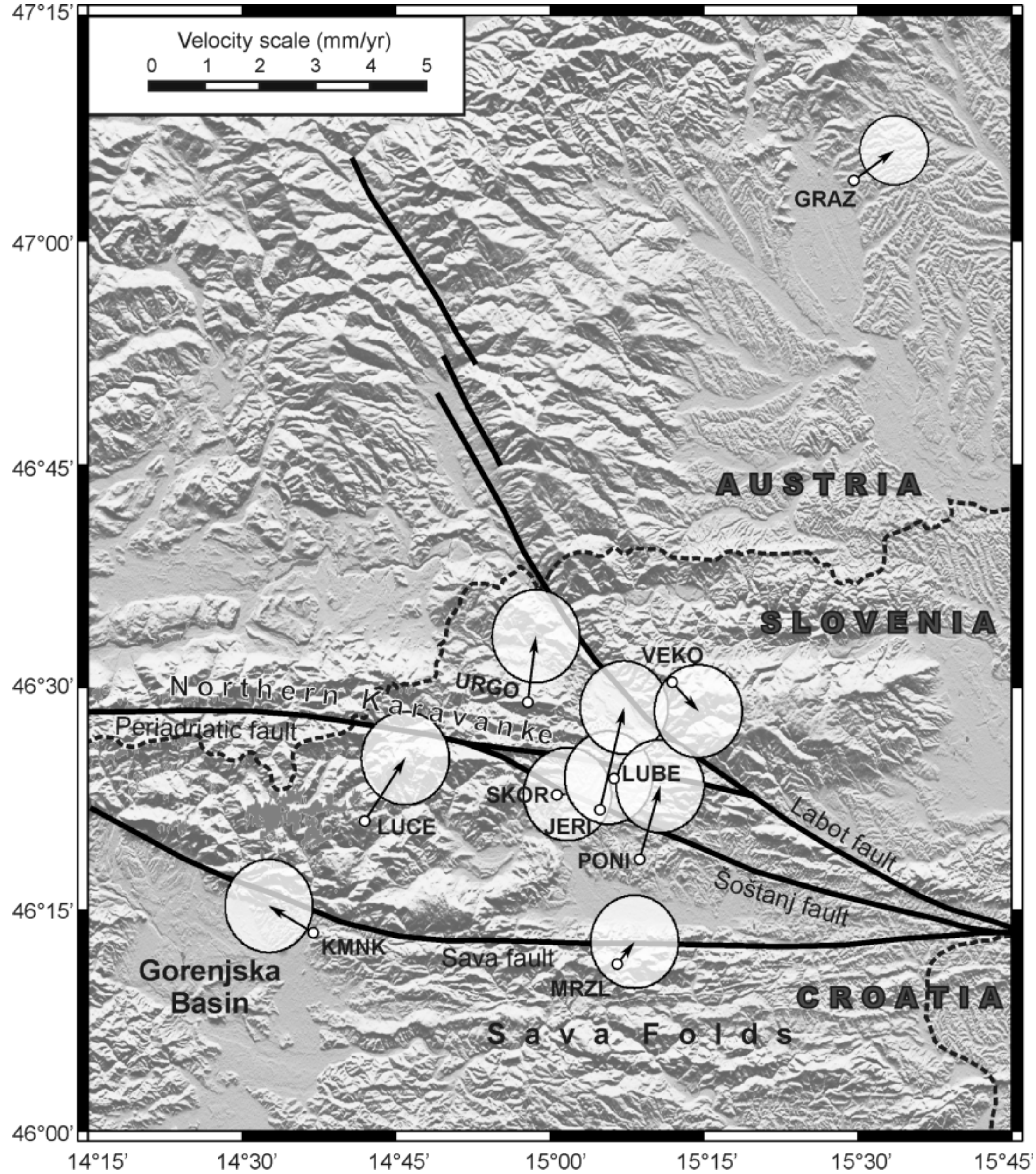

Fig. 4. Estimated 1996–2002 station velocites relative to stable Eurasia. Error circles represent scaled-up RMS error at 1σ level. Only major faults of the Periadriatic fault system are shown; refer back to Figs. 2 and 3 for more detailed structural maps.

asia reference frame according to the EURA/ITRF2000 absolute rotation vector defined by Altamimi et al. (2002). The RMS (Root Mean Square error) of EURA/ITRF2000 rotation vector, which for our network points amounts to ~0.6 mm/yr, was formally propagated to the estimated velocities. Final RMS of estimated velocities in the stable Eurasia reference frame, taking into the account both the inflated (10 times the computed) RMS of velocities in ITRF2000 and the propagated RMS of EURA/ITRF2000 rotation vector, resulted in velocities RMS of 0.8–0.9 mm/yr. Estimated velocity vectors relative to stable Eurasia with their respective RMS, computed for the 1996–2002 period, are presented in Table 1.

Tectonic interpretation

Our results indicate movements in the range from 0.5 to 2.0 mm/yr in predominately N- to NNE-ward direction relative to the stable Eurasian plate (Fig. 4). The determined velocities are consistent with previous GPS observations from Central Europe, which show up to a couple mm/yr of movement relative to Eurasia (Grenerczy et al. 2000; Grenerczy 2002). However, at this stage the low deformation rates, coupled with a relatively short 6-year timespan of observations (which nevertheless matches or exceeds the observation periods in the above mentioned previous studies), allow only for a rough assessment of relative tectonic movements within the study area.

The station VEKO from our network and the IGS permanent station GRAZ, both belonging to the Eastern Alpine tectonic unit, show an obvious, statistically significant difference in velocity compared to the other stations of our network (Fig. 4). The high-strain boundary between the two domains matches the position of the Labot fault. The relative velocities of stations across the fault suggest ~1 mm/yr of dextral movement, which is consistent with the slip sense postulated from focal mechanisms of earthquakes (Reinecker & Lenhardt 1999). While similar in magnitude, the diverging velocity vectors of sites VEKO and GRAZ do not suggest that the Eastern Alpine unit behaves like a coherent, eastward-moving block. This is not surprising since the kinematic model of Miocene extrusion, based on palinspastic restoration (Frisch et al. 1998), demands considerable internal deformation of the extruding unit, which was achieved predominatly by translation and rotation of internal fault-bounded blocks. Miocene counterclockwise rotations of such blocks were also demonstrated by paleomagnetic data (Márton et al. 2000). Diverging site velocities, as well as the occurrence of earthquakes along the NNW–SSE trending faults north of the PAF and only minor seismicity in the areas between them (Reinecker & Lenhardt 1999), could suggest that a similar domino-block tectonic mechanism is active today. A denser network of GPS stations within the Eastern Alpine unit will be needed to investigate this possibility.

Another high-strain zone, likely corresponding to the Sava fault, can be inferred in the southern part of the study area (Fig. 4). The relative velocities of stations KMNK and LUCE indicate ~1.2 mm/yr of dextral displacement along the fault. However, the area south of the Sava fault apparently does not behave as a rigid block, since the stations KMNK and MRZL diverge significantly. The station KMNK is located at the margin of the Quaternary Gorenjska Basin, where N-S trending normal faults were observed, thus the movement of site KMNK away from MRZL could indicate active extension in the Gorenjska Basin. The site MRZL, located in the Sava Folds, does not show statistically significant movement with respect to Eurasia, and no fault-parallel movement relative to stations PONI and JERI north of the Sava fault. One possible explanation could be slip absorbtion by active shortening and uplift of the Sava Folds area, producing predominantly vertical movement of the MRZL site. Due to the inherently large uncertainty of determining vertical movements with GPS (e.g. Hugentobler et al. 2001), we could not check this hypothesis at the present stage of our study, since the measured vertical movement rates are still way below statistical significance.

The station URGO, located in the Northern Karavanke Mts north of the PAF (Fig. 4), moves northward more than 1 mm/yr with respect to stable Eurasia. This could reflect ongoing thrusting of the Northern Karavanke range onto its foreland. The Quaternary age of transpressive thrusting is clearly documented west of the study area in the Klagenfurt Basin (e.g. Polinski & Eisbacher 1992). For the Northern Karavanke Peca thrust, located close to the URGO station, a geologically young age of thrusting was also inferred from significantly tilted deposits of unconsolidated laminated clay, which fill karstic channels within the Mesozoic beds of the thrusted unit (Placer 1996b).

The PAF segment between the stations URGO, LUCE, JERI, LUBE and PONI does not seem to accomodate any dextral slip (Fig. 4). However, only one of those stations (URGO) is located north of the PAF, and if indeed situated on an active thrust of possibly transpressive character, it could be following a complex displacement trajectory, which could easily obscure mm-scale dextral movements relative to the stations south of the PAF. At least one additional station positioned in a stable foreland of the Northern Karavanke thrust system would be needed to address these concerns.

The stations LUCE, JERI and PONI, located within the Sava-PAF shear lens, exhibit very uniform NNW-ward movement of ~1.4 mm/yr with respect to stable Eurasia. Movement of those sites relative to the stations KMNK and MRZL south of the Sava fault indicates active transtension inside the eastern part of the shear lens. The transtensional deformation is in agreement with structural and geomorphic indicators (Fig. 3; Fodor et al. 1998), presented in the introductory chapter. An additional station from this area, SKOR, is not moving with respect to stable Eurasia and is possibly an outlier due to unknown non-tectonic influences.

Active deformation in the Šoštanj fault area is at present not well understood. The sites LUBE, JERI and PONI imply significant fault-perpendicular shortening of ~1.5 mm/yr, and only a very small (insignificant at the present precision level) component of dextral shear (Fig. 4). A detailed surface and subsurface structural study of the Šoštanj fault zone, covering the area between stations SKOR and JERI (Vrabec et al. 1999), did not reveal any indications for fault-perpendicular shortening. The station LUBE north of the fault does not move with respect to stable Eurasia, but similarly to station MRZL it might undergo vertical uplift, not presently detectable with GPS because of the lack of vertical precision. Significant local relief and high altitude (relative to surroundings) of the entire Southern Karavanke shear zone region might indicate uplift of this area. Perhaps, as speculated for the PAF and Northern Karavanke thrust, the deformation in the Šoštanj fault–Southern Karavanke shear zone area is transpressive and the dextral component is too small to be detectable geodetically within the 6-year timespan. But alternatively, like the similarly stationary site SKOR, the LUBE station could be an outlier too, especially since neither of those sites is monumented directly into the bedrock, but are instead positioned on concrete pillars.

Conclusions

While the results of our GPS data analysis after the first 6 years of observation are still close to or within the uncertainty limits, they demonstrate that measurable dis-

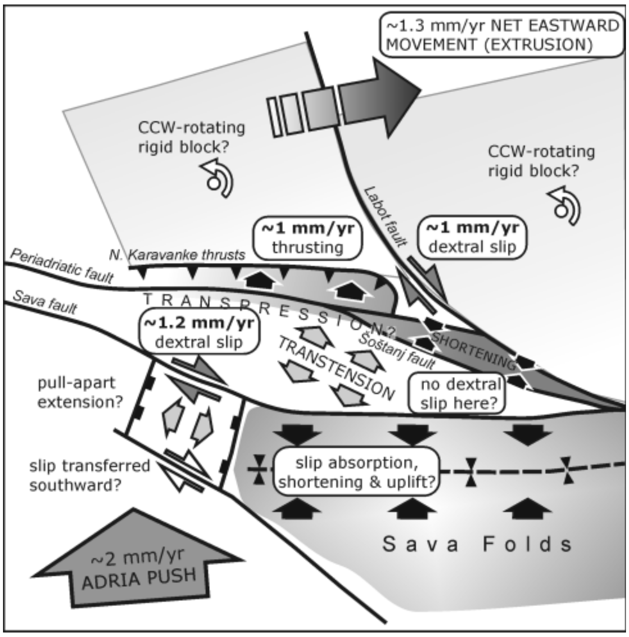

Fig. 5. Fault slip rates and possible modes of ongoing deformation, inferred from our GPS data. See text for discussion. Tectonic model based on Vrabec & Fodor (in press). Depicted Adria movement and net extrusion rate according to Grenerczy (2002).

placements exist in the Slovenian PAF system. The derived velocity field and inferred modes of ongoing deformation are for the most part consistent with geological knowledge of the area and with the published earthquake focal mechanisms. We summarize the inferred displacement rates, modes of deformation, and possible mechanisms of displacement transfer in Fig. 5.

Our results confirm that the active dextral deformation accross the PAF system could account for the difference in kinematics between the Adria microplate and the extruding Eastern Alpine–North Pannonian unit, determined from the wide-aperture GPS data (Grenerczy 2002). However, deformation in the PAF system of northeastern Slovenia is complex and obviously not tied to a single strike-slip corridor. We could resolve ~1.2 mm/yr of dextral movement on the Sava fault which parallels the PAF, but no displacement on the fault was detected in the eastern part of the study area, which implies transfer of deformation to other structures. In our preliminary analysis the movements of stations south of the Sava fault are seemingly consistent with the established model for Pliocene-Quaternary displacement transfer southward via the pull-apart Gorenjska Basin, and/or absorbtion of dextral slip by transpressive shortening and uplift of the Sava Folds south of the restraining bend of the Sava fault (Fodor et al. 1998; Vrabec 2001; Vrabec & Fodor 2006). No dextral displacement was detected along the PAF zone, but there is indication for active ~1 mm/yr northward propagation of the Northern Karavanke thrust system situated just north of the PAF. This could indicate transpressive deformation with an at present undetectable dextral component along the PAF and its branching fault, the Šoštanj fault, where also significant fault-perpendicular shortening is implied. The region between the Sava fault and the PAF apparently undergoes transtension, which is also indicated by structural and geomorphic features of that area. A detectable dextral slip of ~1 mm/yr was found along the Labot fault. We speculate that this slip could reflect the domino-block deformation mechanism inside the extruding Eastern Alpine unit.

To better constrain site velocities in terms of reduced uncertainty, we plan to continue re-occupying the network in 2-year intervals. Additionally, the recent public concern about increased seismicity in the Velenje Basin stimulated expansion of the network with 9 more stations that were stabilized and measured for the first time in Summer 2003. The new stations were primarily selected to monitor the Šoštanj fault, but also reach over the PAF and the Labot fault. The expanded network will hopefully provide better insight into the kinematics of the area that is currently least understood. On the other hand, a deeper understanding of the kinematics of regional deformation and testing the validity of our findings would require a wider network of reasonably spaced GPS sites, covering the length of the PAF system and entering the surrounding areas. We initiated such a project in 2003 in the framework of the PIVO (Periadriatic fault–Istria Velocity Observations) experiment, which included 36 stations distributed in the territory of Slovenia and northern Croatia. While the data analysis is still in progress, the first preliminary results (Weber et al. 2006) agree with conclusions about the kinematics of the PAF system presented in this paper.

Finally, it is hoped that other workers will provide data which would further test and elaborate the ongoing extrusion model. One area of particular interest is the sinistral northern boundary of the extruding wedge. The other major challenge would be studying internal deformation of the extruding unit and investigating how extrusion is compensated in front of the extruding wedge.

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