

Active tectonic deformation at the transition from the European and Pannonian domain monitored by a local GNSS network.



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Kurzfassung

Tektonische Prozesse, die zur Bildung der Alpen, Karpathen und Dinariden, sowie der Entstehung des Pannonische Beckens führten, sind auch heute noch aktiv. Der Übergang von der Europäischen Plattform und den Ostalpen hin zum Pannonischen Becken ist davon in besonderer Weise betroffen. Deformationsanalysen von GPS-Netzen bestätigen die anhaltende laterale Extrusion von Teilen der Ostalpen hin zum Pannonischen Becken. Erdbeben und rezente Deformationen konzentrieren sich entlang NE-SW streichender, sinistraler Seitenverschiebungen (Mur-Mürz Störung und Störungssysteme im südlichen Wiener Becken). Dieser Bereich ist auch das Untersuchungsgebiet von ALPAACT (Seismological and geodetic monitoring of **AL**pine-**PA**nnonian **ACT**ive **T**ectonics). Das geodätische Monitoring der aktiven Tektonik erfolgt durch ein lokales GNSS Netz, das sich von der Böhmisches Masse im Norden bis hin zum Steirischen Becken im Süden erstreckt und somit den Bereich der aktiven Störungen gut überdeckt. Die insgesamt 23 Stationen gehören entweder dem IGS-Netz, oder regionalen RTK-Positionierungsdiensten (ÖBB, Wien-Energie, BEWAG, EVN) an. Bislang wurden Daten der Jahre 2007 und 2008 mit der Software Bernese 5.0 unter Berücksichtigung präziser Bahninformation reprozessiert. Die Lösung ist über drei IGS-Stationen in ITRF2000 eingebunden. Für eine geodynamische Interpretation wurden die Geschwindigkeiten auf die Station Graz-Lustbühel (GRAZ) bezogen. Die Streuung der einzelnen Geschwindigkeitsvektoren ist groß und ein systematischer Anteil nicht unmittelbar erkennbar. Die mittlere Geschwindigkeit der südlich des Störungssystems Mur-Mürztal und Wiener Becken gelegenen Stationen gegenüber den nördlich davon gelegenen beträgt 1.1 mm/Jahr und ist ungefähr NE orientiert (Azimuth = 55°). Diese Werte entsprechen nahezu exakt einem kinematischen Modell der Ostalpen, das aus der Struktur der Lithosphäre abgeleitet und mittels regionaler geodätischer Deformationsmodelle kalibriert wurde. Die in der Arbeit präsentierten Ergebnisse sind wegen der geringen Relativbewegungen und kurzen Beobachtungsdauer trotz dieser guten Übereinstimmung nur als vorläufig anzusehen. Eine Beobachtungsdauer von mindestens 10 Jahren wird angestrebt.

Schlüsselwörter: ALPAACT, Mur-Mürztal, Wiener Becken, GNSS, Deformationsanalyse

Abstract

Tectonic processes which led to the generation of the Alps, Carpathians, Dinarides, and the Pannonian basin are still on work. In particular they affect the transition zone from the European platform over the Eastern Alps to the Pannonian basin. GPS network solutions confirm the ongoing lateral extrusion of East Alpine crustal blocks directed to the Pannonian basin. Earthquakes and neo-tectonic deformations are concentrated along NE-SW oriented sinistral strike-slip faults (Mur-Mürz faults and Vienna transfer fault system). This area is the target of ALPAACT (Seismological and geodetic monitoring of **AL**pine-**PA**nnonian **ACT**ive **T**ectonics). The geodetic monitoring of active tectonics in this area is realized by a local GNSS network, which extends from the Bohemian Massif in the north to the Styrian basin in the south and spreads out over the active fault zone. The total of 23 stations belongs either to the IGS network or to regional RTK-positioning services (ÖBB, Wien-Energie, BEWAG, EVN). So far GNSS observation data from the years 2007 and 2008 were reprocessed using the Bernese software 5.0 and precise orbits. The solution is tied to the ITRF2000 by three IGS stations. For a geodynamic interpretation the velocities are referenced to the station Graz-Lustbühel (GRAZ). The individual velocity vectors scatter considerably and a systematic trend cannot be recognized directly. The mean velocity of the stations south of the Mur-Mürz valley and the Vienna basin transfer fault system, relative to the stations located in the north, amounts to 1.1 mm/year. Its orientation is about NE (azimuth = 55°). This result fits nearly perfectly the prediction of a kinematic model which was derived from the structure of the lithosphere and calibrated by regional geodetic deformation models. Due to the low relative velocities and the short observation period, these results should be considered as preliminary. Hence efforts will be made to achieve a geodetic monitoring over a time period of ten years.

Keywords: ALPAACT, Mur-Mürz valley, Vienna basin, GNSS, deformation analysis

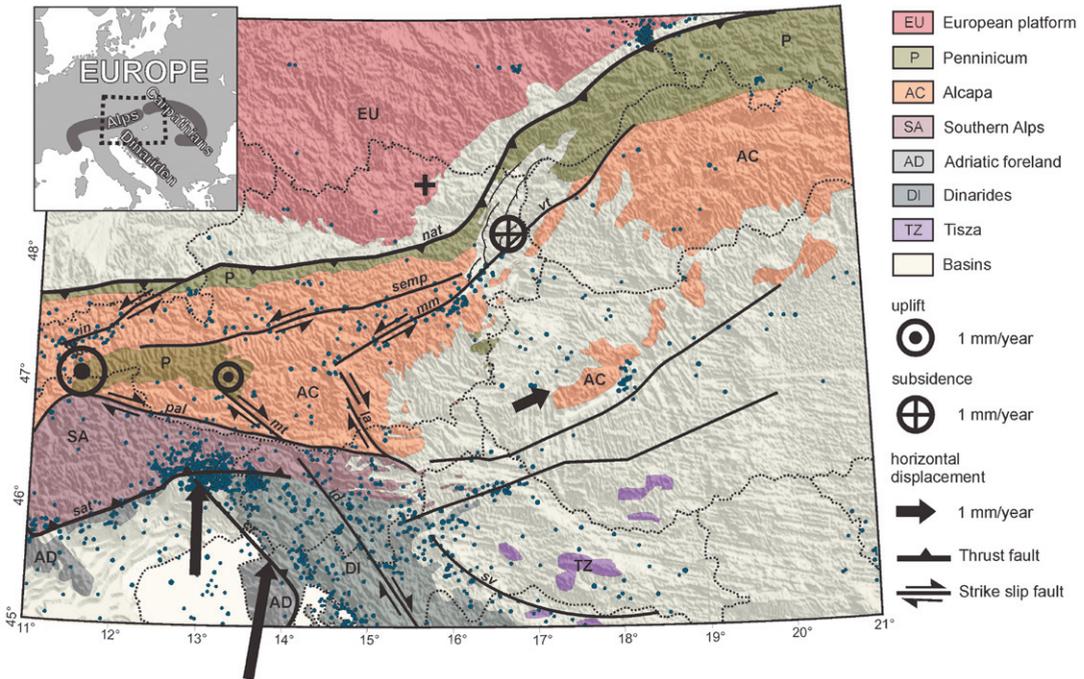


Fig. 1: Tectonic units and structures [7], seismicity (epicentres as blue dots according NEIC catalogue 1973-2008), and crustal deformations, horizontal velocities after [17], vertical velocities referenced to location marked by a bolt cross after [20].

1. Introduction

The transition zone from the European to the Pannonian domain is an area of active tectonic deformation. The most relevant process is the ongoing tectonic extrusion of parts of the Eastern Alps towards the Pannonian basin and the Carpathians [1]. Seismic activity, as an indicator of active tectonics, concentrates on a fault system which follows the Mur-Mürz valley (Styria) and the south-eastern boundary of the Vienna basin. The observation of strain and stress accumulation along these faults is of high importance for the estimation of a seismic hazard; especially for the estimation of the maximum credible earthquake in the capital Vienna and its highly populated and developed surrounding area [2]. The project ALPAACT (Seismological and geodetic monitoring of ALpine-PANnonian ACTive Tectonics¹ aims a detailed investigation of active tectonic processes in this area. The high precise estimation of earthquake locations is achieved by a densification of the existing seismic network [3]. Further, these accurate seismic data enable the correlation of the hypocentre location and the

focal mechanisms with the pattern of faults. Geodetic monitoring is essential to correlate tectonic deformation with the seismic stress relief. On the basis of long term observations the partitioning of a slip to different fault systems and to continuous deformation can be estimated. In this paper we give an overview of the tectonic setting of the study area and of previous work on this theme. In addition, the local GNSS network, the reprocessing and results from an observation period of 20 months are described. A preliminary interpretation is presented.

2. Geodynamic processes and tectonic setting

The Alpine orogen, its bifurcation into the Western Carpathians and Dinarides, as well as the Pannonian basin give evidence of young geological processes. The opening of the Atlantic during Jura (~170 Ma ago) may be considered as the initiation, and some of these processes are still on work, however, with decreasing intensity. The Seafloor spreading of the Penninic Ocean (Alpine Tethys) ended about 130 Ma and subduction of this ocean initiated ~80 Ma ago, with the European plate representing a passive margin. At the same time the Adriatic micro-plate

¹ <http://info.tuwien.ac.at/geophysik/research/alpdynamics/alpaact.htm>

started to move independently from Africa to the north, following the trench suction force of the subducting Penninic lithosphere [4], [5], [6]. The collision between Europe and Adria took place about 35 Ma ago [7]. During Miocene the retreat of the remaining Alpine Thetys into the Carpathian embayment led to the development of the Pannonian Basin and finally the Carpathians [8]. Subduction of the Adriatic continental mantle to the west and the east formed the Apennines and Dinarides [9], [10], [11]. Major blocks of the East Alpine and former Western Carpathians extruded laterally to the east into the Carpathian embayment [1], [12], [13]. These units experienced large extension and created the Pannonian basin before their final collision with the Paleozoic European platform and the formation of the Western Carpathians [14].

Figure 1 shows the mayor tectonic units of the Eastern Alps and their surrounding areas. The Bohemian Massif represents the European platform in the north. In the south, Istria represents the part of the Adriatic plate, which was scarcely affected by the Alpine orogenesis. The Molasse basin in the north and the Venetian and Po plain in the south are typical forland basins, generated by the lithospheric load of the Alps. The Flysch belt in the north of the Alps witnesses the occurrence of turbidity currents, which were deposited at the southern margins of the Penninic Ocean. Molasse und Flysch have been widely overthrust by the Northern Calcareous Alps and the Greywacke units. The later form the Eastern Alps together with the crystalline East Alpine nappes and carbonate units in the south. Ophiolitic units derived from the Penninic Ocean have been exhumed within tectonic windows. In the Tauern window even a gneissic core of European provenience is exposed. The Periadriatic line divides the Eastern and Southern Alps. In contrast to the Eastern Alps the vergence of folding is mainly southward directed in the Southern Alps [9], [15]. At the South Alpine thrust fault (SAT) the Adriatic foreland and the Dinarides thrust under the South Alpine units.

The thrusting of Flysch over Molasse and the Northern Calcareous Alps over Flysch at the northern front of the Eastern Alps, as well as the back thrusting of the South Alpine units over the Adriatic foreland and the Dinarides are directly connected to the collision and continuing convergence between the European and Adriatic plates. During the extrusion of ALCAPA units (Eastern Alps-Western Carpathians – Pannonian units) to the east large dextral strike-slip move-

ments occurred along the Periadriatic line and the Mid-Hungarian fault zone. Sinistral strike-slip faults in the north (Inntal, SEMP, MM) and conjugate dextral strike-slip faults in the south (Mölltal – Idria, Lavant – Sava) are related to this extensional tectonic process. The Vienna basin is bound by the sinistral Vienna basin transfer fault in the south – east and was generated by a pull-apart mechanism. Normal faults within this basin compensate for the extension in the basin.

3. Active tectonics of the study area

Seismic activity is an indicator of current brittle deformation of the Earth's crust related to active tectonic processes. Earthquakes gather at and around active fault systems. Their magnitudes are related to the size of the rupture surface and the seismic slip. Information about the orientation of the rupture surface and the slip vector can be derived from the radiation pattern (fault plain solution). Epicentres of earthquakes with magnitudes three and higher (NEIC 1973-2008), are superimposed on Figure 1. The area of highest seismicity is the Friuli district in the Southern Alps. Hypocenter locations and focal mechanisms correspond to back-thrusting of the Southern Alps and strike slip movements. Another area of relatively high seismicity is the Mur-Mürz fault and the southern Vienna basin. Focal plane solutions indicate mostly a SW-NE oriented left-lateral strike slip with little dip slip components [16]. Distinct stripes of high seismicity follow the Dinaric thrust belt. The Periadriatic line shows weak seismicity with the exception at its transition to the Mid-Hungarian fault zone.

Figure 1 contains also a compilation of geodetically observed horizontal displacements [17], [18], [19] and elevation changes [20]. These data provide a large scale picture of crustal movements and deformation. The EU platform is considered as fix. The arrows correspond to an Euler pole between 46°–47° N and 8°–10° E and indicate movements approximately to the north with rates between 2.5–3.5 mm/year [17], [18]. North of the South Alpine thrust belt and south of Tauern window is a zone of high compressional strain [17]. This zone extends with decreasing strain to the E and SE, covers the Dinarides, and ceases to the Pannonian basin. Data from dense GPS networks crossing the Alps at the latitude of the Friuli district confirm the regional data and the significant N-S compression in the Southern Alps [21]. E to NE oriented velocities of ~ 1 mm/year of the Pannonian basin indicate that the tectonic escape is an ongoing process. A multi-net-

work GPS combined solution [22] confirms this general deformation pattern and reveals additionally N-S directed extension due to a gravitational collapse within the Tauern window. Besides this extension the Tauern window shows still an uplift rate of ~1 mm/year, the Vienna basin subsides up to 1 mm/year [20].

Plate boundaries of oceanic lithospheres are well defined by the topography of the sea floor, the pattern of magnetic anomalies, the distribution of hypocentres, and geodetically observable deformations. In contrast to the situation on oceans, continental plate boundaries find their expression as >100 km wide fault systems. For example, the fault system related to the plate boundary between Europe and Adria in the central area of the Eastern Alps (Tauern window) reach from the NAT to the SAT which are separated by a distance of ~150 km. However, a clear and well defined identification of a continental plate boundary (especially a destructive plate boundary connected to convergence) can be achieved if the structure of the Moho disconti-

nuity is considered. The interpretation of the data from the seismic experiments CELEBRATION 2000 and ALP 2002 [23], [24] and the integration of results from earlier studies in the Western Alps [25], revealed a fragmentation of the Moho and the uppermost mantle into an EU and AD plate and a newly inferred PA fragment. These three plates (EU, AD, PA) form a triple junction SE of the eastern border of the Tauern window (Figure 2). PA' represents a transition zone from the thick crust under the Dinarides (> 40 km) to the thin and extended crust of the Pannonian basin (< 25 km). We do not further consider this subdivision and include PA' into PA.

Brückl et al. [26] developed a kinematic model (Figure 2) of the relative velocities between AD, EU, and PA under the assumption of a stable triple junction AD-EU-PA, pure strike-slip between PA and EU near the triple junction and the large scale geodetically observed N-S convergence of 3.0 mm/year between AD and EU and 1.0 mm/year eastward extrusion of PA relative to AD. According to this model the conver-

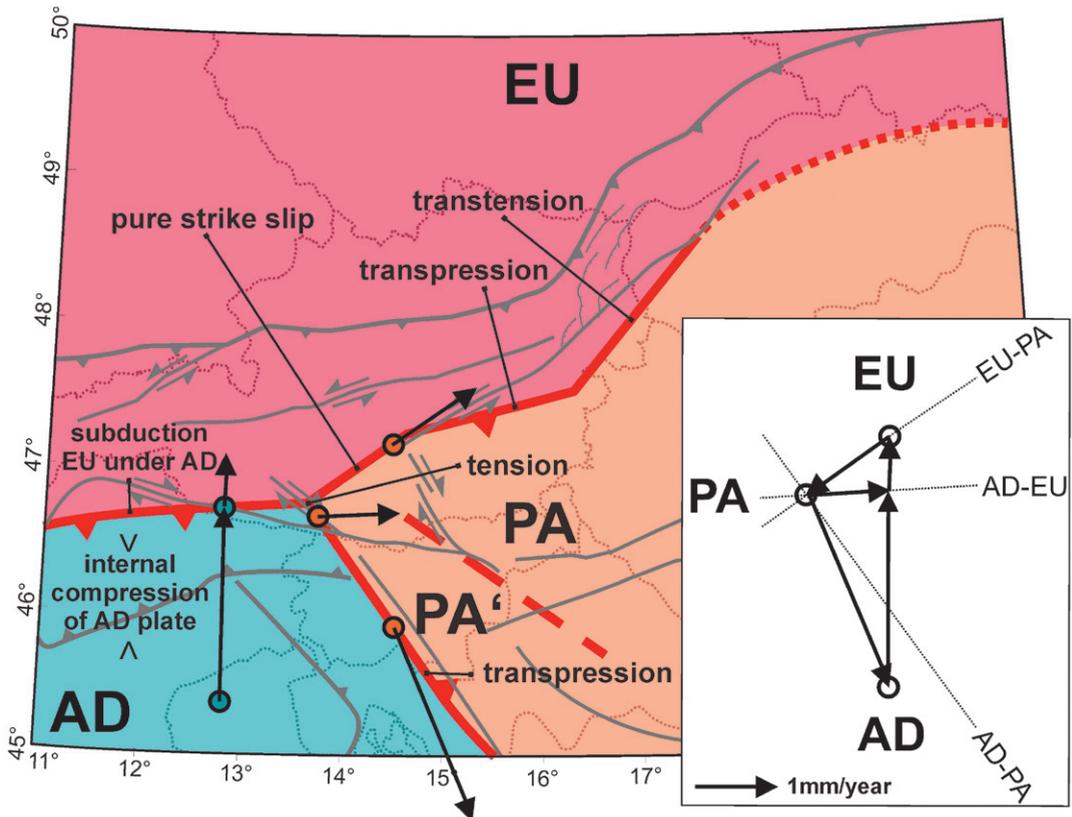


Fig. 2: Kinematic model based on Moho fragmentation red bold lines) into European (EU), Adriatic (AD), and Pannonian plate (PA, PA'); inset shows velocity triangle at the triple junction AD-EU-PA (after Brückl et al., 2010); velocity arrows show the relative velocities of AD to EU, PA to EU, and PA (PA') to AD.

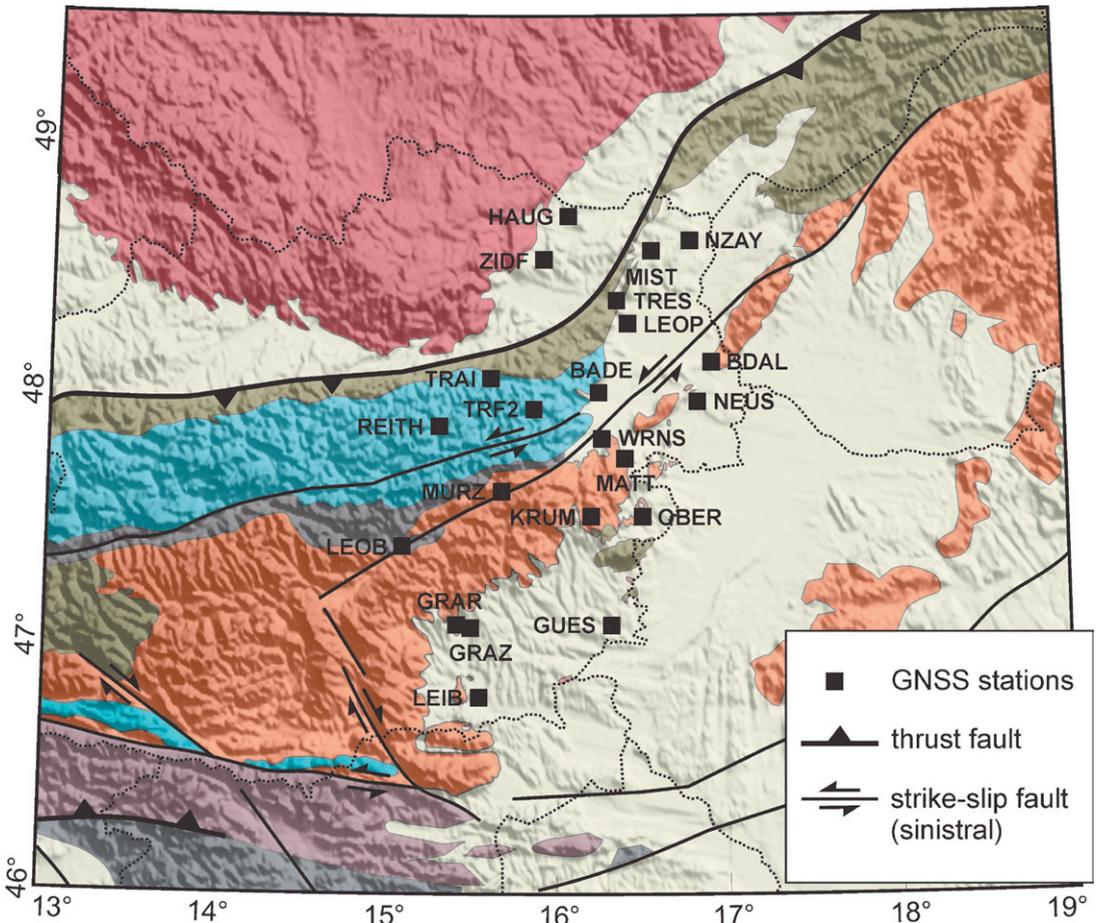


Fig. 3: Location of GNSS stations superimposed on geological map and DTM.

gence between AD und EU can be partitioned into 0.6 mm/year overthrust of AD mantle over EU mantle and 2.4 mm/year compression within the most northern part of AD. At the triple junction PA withdraws from AD to the east by 1.0 mm/year. This extension is being compensated probably by the ongoing extrusion of the Tauern window. South of the compression zone within the Southern Alps the relative velocity between AD and PA changes to dextral transpression with a total amount of 2.5 mm/year. The pure sinistrale strike-slip movement between EU und PA near the triple junction amounts to 1.2mm with an azimuth of 54°. The total amount and the direction of the relative velocity of PA versus EU are preserved further to the NE. However, because of the changing strikes of the MM fault and the Vienna basin transfer fault there is a change to transpression at the MM fault and to transtension along the Vienna basin transfer fault.

4. GNSS stations, data, and reprocessing

In the framework of project ALPAACT observation data of 23 GPS permanent stations obtained in the period Jan 2007 until October 2008 has been reprocessed. These stations belong either to the IGS-network, established for providing high quality GNSS products (e.g. precise satellite orbits and clock corrections) and monitoring geodynamic processes on a global scale (e.g. IGS station network) or to operational regional RTK-positioning services (GNSS sites operated by the Austrian railways (ÖBB) as well as the Austrian power supply companies Wien-Energie, BEWAG and EVN).

As shown in Figure 3 the stations are grouped along the Mur-Mürz and the Vienna basin transfer faults. The most northern stations are located at the Bohemian Massif and the Molasse zone. In the southeast the GNSS network reached into the Styrian basin and to the Pannonian basin. The

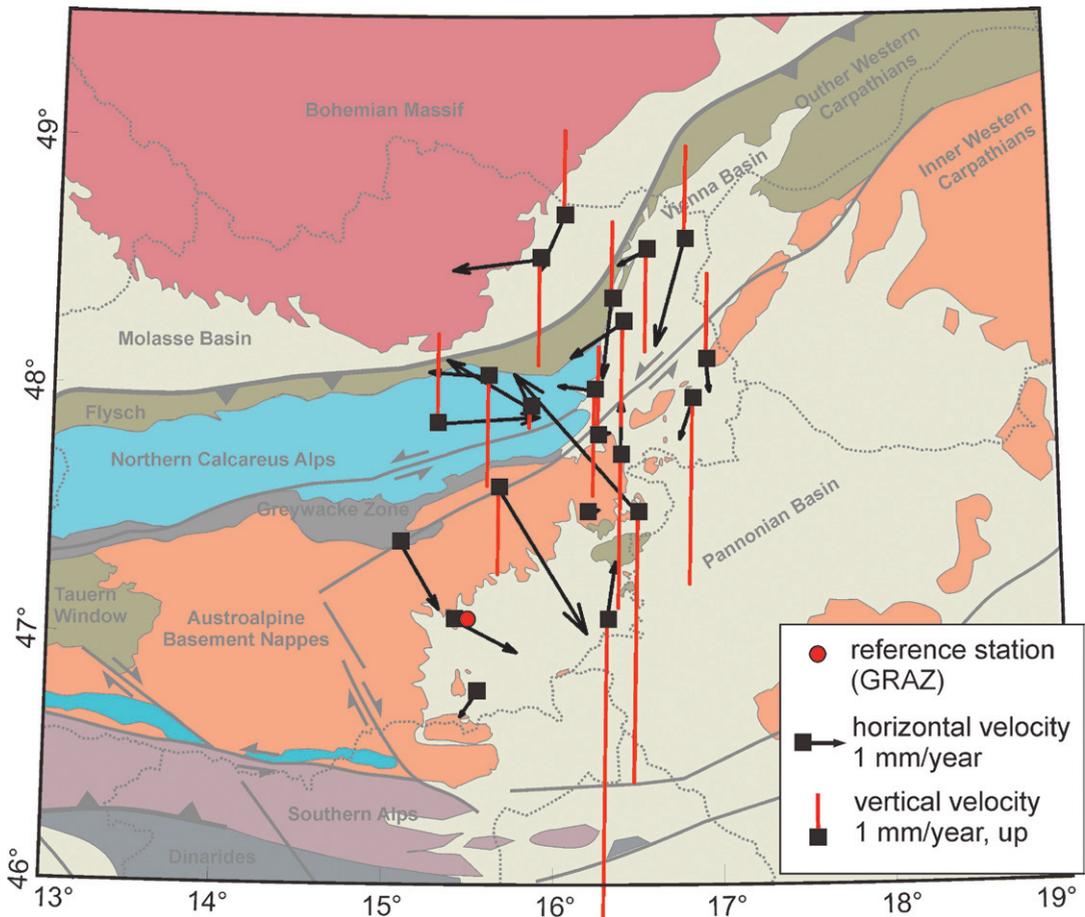


Fig. 4: Horizontal and vertical velocities relative to GRAZ (Graz Lustbühel).

total range of the network covers therefore a wide transition zone from the EU and the PA plate.

Daily station coordinates covering a span of almost 2 years (period from Jan, 1st, 2007 until Oct 30th, 2008) were calculated by means of a classical network approach to obtain station velocities with respect to the ITRF2000 velocity field. The processing was performed with Bernese Software 5.0 [27]. The solution was tied to the ITRF2000 (epoch 1997.0) frame by relatively tight constraints on the coordinates ($\sigma = \pm 0.1$ mm) of the IGS reference stations Graz and Mattersburg (indicated in the graphics and attached tables by their labels GRAZ, MTBG) as well as the Hungarian station at Penc (PENC). This most eastern station Penc is situated on the PA plate but was not depicted in (Figure 3) to maintain clarity of the map.

Precise orbit information (Rapid Products) provided by the IGS (International GNSS Service)

was introduced. Observations down to 5 degree elevation were processed and the tropospheric delay was mapped to zenith by the well known dry and wet Niell Mapping Functions. Tropospheric zenith delay parameters were estimated with 2h time resolution by limiting large temporal variations due to relative constraints of ± 2 mm between subsequent parameters. Utilizing the ionosphere-free linear combination of the dual frequency data ambiguity resolution has been carried out by means of the narrow lane strategy. The formal errors of the resulting daily site coordinates are at the 0.1–0.4 mm level, which suggest at least an accuracy of 2–3 mm in plane and about 3–5 mm in the height component. In a final step the normal equations of the individual daily solutions were stacked while constraining the ITRF2000 velocities of stations GRAZ, PENC and MTBG tightly ($\sigma = \pm 0.1$ mm/year). This procedure resulted in a reference coordinate set

and a residual station velocity field with respect to the ITRF2000 velocity field.

A problematic issue are equipment changes. Antenna changes at the stations PENC (in the period from 25.06.2007 till 12.07.2007) and MTBG (10.11.2008) caused artificial jumps in the reference station coordinates and therefore affected the derived velocities of all stations. For both stations these jumps have been carefully corrected by introducing suitable antenna phase centre correction information. These antenna changes can affect the quality of the estimated height component and the subsequently derived height velocities but usually do not affect the horizontal velocities.

In case of missing observation data from at least one reference station the accuracy of the calculated coordinate solution is degraded. Especially in 2008 the days (DOY 001, 133, 230-231, 271, 280-286) are affected by this data-shortage. These daily solutions were excluded from the estimation of the site velocities. Finally, the calculated velocity vector of station Trafelberg (TRFB), which is part of the APOS network (operated by the Austrian Federal Agency for Survey & Metrology) has been derived from a short observation span of 8 months starting in March 2008 until October 2008.

5. Results, preliminary interpretation, and discussion

Figure 4 illustrates the horizontal and vertical velocity field obtained by the rotation of the derived velocity information to the local plane. The displayed vectors have to be interpreted as station velocities with respect to the ITRF2000 velocity field (station velocities determined in the ITRF2000 where the velocity of station GRAZ was subtracted). Table 1 depicts the corresponding numerical information.

Histograms of the horizontal and vertical velocity components are shown in Figure 5. The horizontal velocities >4 mm/year at stations OBER and MURZ and the vertical velocities <-6 mm/year at stations GUES and OBER are classified as outliers and not further considered. Mean and standard deviation of the total amount of the horizontal velocities relative to GRAZ are 1.4 ± 0.8 mm/year, the directions scatter considerably. The corresponding vertical velocities amount to -0.5 ± 2.4 mm/year.

In standard geodetic reference systems all stations belong to the EU plate. However, according to the results of large scale GPS

campaigns [17], [18] and the new picture of the structure of the Moho discontinuity the stations are distributed over EU, PA, and the plate boundary zone between EU and AD (see Figure 5 and Table 1). We investigate two models to describe the horizontal velocity field in a cartesian coordinate system.

First we assume rigid plate motion and model the observed horizontal velocity data by a rotation around the centroid of the GNSS stations (model A). The location of the centroid is fixed by subtracting an average velocity vector from all data. The angle of rotation around the centroid of the stations is determined by minimizing the squared sum of the horizontal velocity residual. Figure 6a shows the calculated and the residual horizontal velocities (= observed minus calculated velocity). The average residual horizontal velocity is reduced to 1.3 mm/year by the translation and by a subsequent anti-clockwise rotation with $\Omega = 4$ nrad/year.

The second model (model B) considers the fragmentation of the lithosphere into an EU and PA plate. The stations close to the SEMP, Mur-Mürz, and Vienna basin transfer faults (BADE, LEOB, MURZ, WRNS) are not further considered because they are located in the high seismicity area of this active fault system (Figure 1) and an assignment to different plates is not possible. We must be aware that the assumption of a narrow continental plate boundary between EU and PA is inherent in model B. Figure 6b shows the calculated and the residual velocities (= observed minus calculated velocity). The EU plate is fixed by subtracting the average horizontal velocities of the stations located on this plate. The average relative horizontal velocity of PA versus EU is 1.1 mm/year with an azimuth of $\alpha = 55^\circ$. The average of the residual horizontal velocities is 1.2 mm/year. For model B it makes sense to look also at the vertical velocities. According to our data PA subsides relative to EU with a velocity of 0.6 ± 1.2 mm/year. Modelling the vertical velocities by this subsidence of PA relative to EU the standard deviation of the residuals is reduced not significantly by less than 0.1 mm/year.

The models A and B reduced the L1 norm of the observed horizontal velocities only slightly. A decision between the two models or their refinement is not possible on the basis of the existing data which cover a time span of only 22 month. The average residual horizontal velocities (~ 1.2 mm/year) and the standard deviation of the residual vertical velocities after removing the

long	lat	station	location	ve[mm/a]	vn[mm/a]	vu[mm/a]	plate
15.61	48.06	TRAI	Traisen	-1.5	0.1	-2.8	EU
15.31	47.88	REIT	Reith	2.6	0.2	2.3	EU
16.80	48.61	NZAY	Neusiedl/Zayer	-0.7	-2.7	2.4	EU
15.86	47.93	TRFB	Traffelberg	-2.1	1.2	-0.5	EU
16.36	48.37	TRES	Tresdorf	-0.2	-2.0	2.0	EU
15.92	48.63	ZIDF	Ziersdorf	-2.2	-0.3	-2.7	EU
16.07	48.70	HAUG	Haugsdorf	-0.6	-1.4	2.2	EU
16.42	48.27	LEOP	Leopoldau	-1.3	-0.9	-2.6	EU
16.57	48.57	MIST	Mistelbach	-0.7	-0.4	-2.6	EU
15.68	47.61	MURZ	Mürzzuschlag	2.3	-3.7	-2.2	Fault
15.09	47.39	LEOB	Leoben	1.0	-1.7	-0.1	Fault
16.25	48.00	BADE	Baden	-0.9	0.1	-2.7	Fault
16.27	47.82	WRNS	Wiener Neustadt	0.3	0.1	2.3	Fault
16.92	48.12	BDAL	Bad Deutschaltenburg	0.1	-0.8	2.2	PA
16.50	47.51	OBER	Oberpullendorf	-3.2	3.5	-6.9	PA
15.55	46.78	LEIB	Leibnitz	-0.4	-0.6	-0.1	PA
15.49	47.07	GRAZ	Graz (Lustbühel)	0	0	0	PA
16.32	47.07	GUES	Güssing	0.2	1.5	-7.6	PA
15.42	47.07	GRAR	Graz	1.6	-0.8	0.1	PA
19.28	47.78	PENC	Penc, Hungary	0.7	-2.2	1.5	PA
16.84	47.96	NEUS	Neusiedl	-0.3	-1.0	-4.7	PA
16.40	47.74	MTBG	Mattersburg	0.0	1.4	-3.9	PA
16.20	47.50	KRUM	Krumbach	0.3	0.1	0.2	PA

Tab. 1: Approximate reference station coordinates in ITRF2000 and station velocities (north, east, up) tied to the velocity of GRAZ in ITRF2000; last column shows assignment of stations to EU and PA and fault zone according kinematic model B (see text).

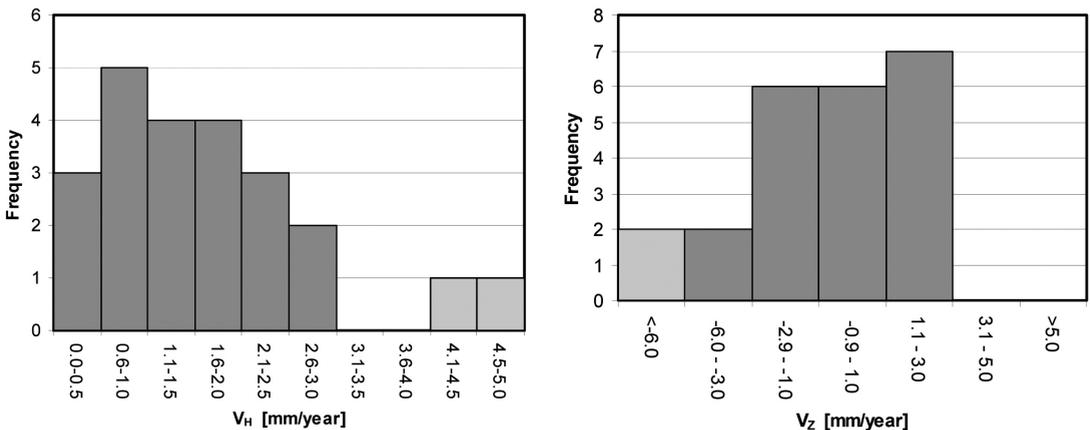


Fig. 5: Frequencies of observed horizontal and vertical velocities relative to GRAZ; Values deemed as outliers are marked in light grey.

mean values for the EU and PA plates (2.5 mm/year) may be regarded as an upper bound of the total observational error, including local technical and geological site effects. Comparing the results with the kinematic model presented in Figure 2 we find a surprisingly high agreement. The active fault systems SEMP, MM, and the Vienna basin transfer fault are sinistral strike-slip faults. Model A indicates a counter-clockwise rotation which corresponds to the rotation of sinistral simple shear. An even better agreement is given between model B and the kinematic model. These two models yield nearly the same magnitude of the relative horizontal velocity between EU and PA (1.1 mm/year, respectively 1.2 mm/year). The azimuth of the vector is 55° for model B and 54° for the kinematic model (Figure 2). Considering the ratios between model parameters and observational errors we must be aware that this nearly perfect agreement is accidental. Only a considerably longer observation period could validate this interpretation.

6. Conclusion

The Mur-Mürz strike-slip fault and the Vienna basin transfer fault area has been selected to observe actual tectonic deformations due to ongoing lateral extrusion processes at the transition from the Eastern Alps to the Pannonian basin and Western Carpathians. Data from 23 GNSS stations in this area, covering a period of 22 months, were processed, taking advantage of precise orbit information and accurate atmospheric corrections. The mean horizontal velocity relative to the ITRF station GRAZ (Graz Lustbühel) and its standard deviation is 1.4 ± 0.8 mm/year. Data from the stations OBER (Oberpullendorf) and MURZ (Mürzzuschlag) yield horizontal velocities > 4 mm/year and are classified as outliers. The corresponding values of the vertical velocities are -0.5 ± 2.4 mm/year. The vertical velocities for OBER and GUES (Güssing) are outliers (> 6 mm/year) and not further considered.

In spite of the highly scattered directions of the relative velocities two reasonable geodynamic conceptions were applied to model the observed horizontal velocities. Model A assumes a rigid plate motion and a counter-clockwise rotation of ~ 4 nrad was derived. Model B follows the kinematic model derived from the Moho structure and a partitioning of the area into an EU, AD, and PA plate (Brückl et al., 2010). A nearly perfect agreement of the approximately NE movement of PA versus EU follows from the available data.

Also the counter-clockwise rotation derived from model A and the sinistral strike-slip movement according to model B have the same polarity of the relative movement. However, the reduction of the data variance by the two models is very low (26 % for the more appropriate model B). Time series longer than 10 years would be necessary to decide between different models, or to refine the geophysical model. Public data from GNSS stations neighbouring our investigation area should also be considered in the future.

Considering the length of GNSS time series in the area of interest we argue for "permanent" observations. Earthquakes $M > 5$ may occur with an average occurrence interval of ~ 50 years along the Mur-Mürz or Vienna basin transfer fault². The seismological observation will continue by ZAMG or further research projects. In order to deepen our understanding of seismicity in this area high resolution and continuous geodetic monitoring is indispensable, for example to estimate seismic slip deficits and seismic hazards [2]. Another point is the spatial resolution of the GNSS network. In order to confine zones by geodetic observations we should at least keep the density of stations. Furthermore, we have to expect outliers in our data, not only because of instrumental problems, "geological noise" (very local movements in the range of mm/year) and velocities of stations near the fault zones (Mur-Mürz, Vienna basin transfer, SEMP) may be also an issue, so far not considered sufficiently.

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² <http://www.zamg.ac.at/erdbeben>

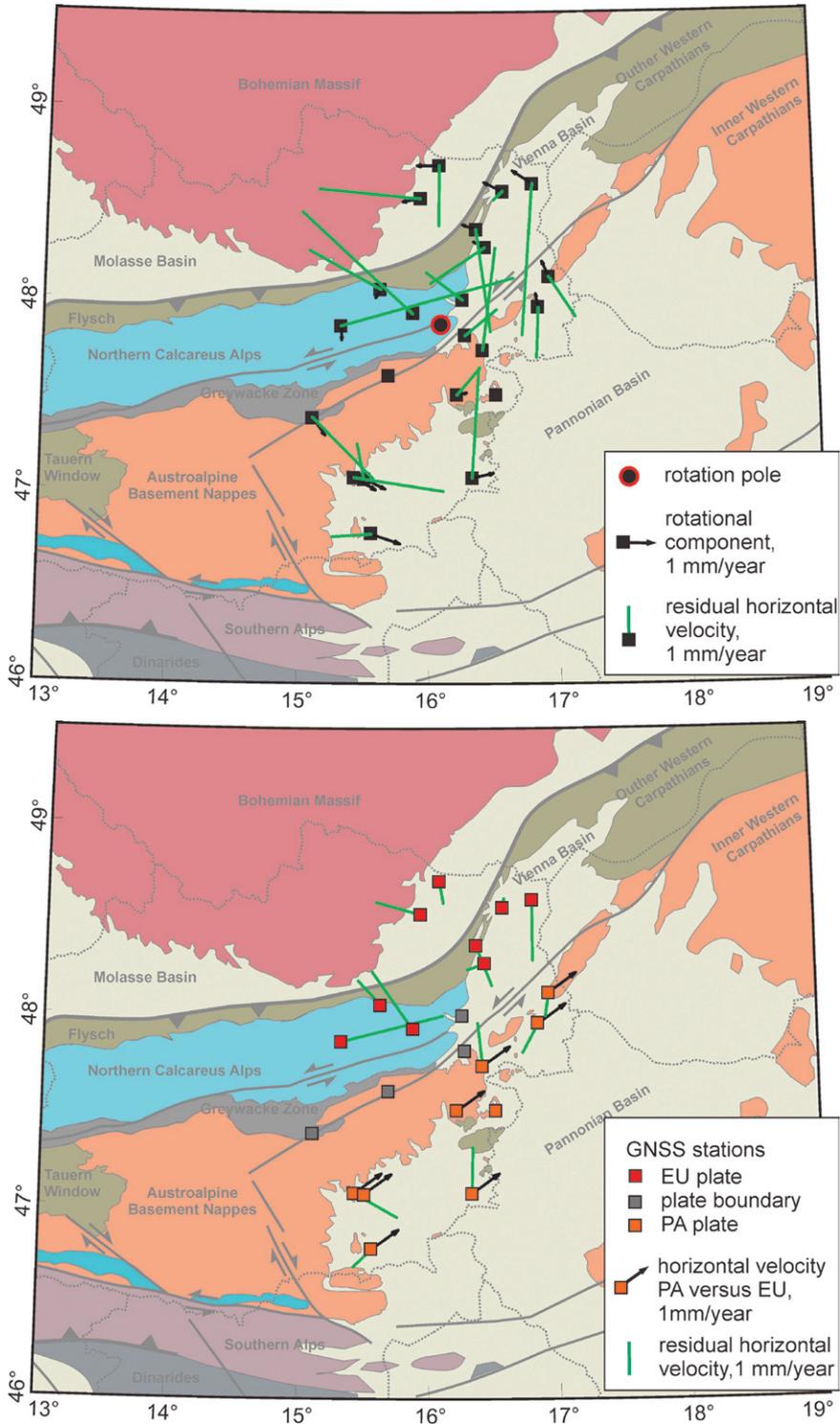


Fig. 6: Interpretation of observed horizontal velocity field; a) modelling by a rotation with the centroid of all stations as rotation pole; b) modelling by translation of stations located on PA relative to stations located on EU; stations located on or near the Mur-Mürz, SEMP, and Vienna basin transfer faults are excluded.

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