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Monitoring Tectonic Processes in Eastern Austria based on GNSS-derived site velocities




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Abstract

Still ongoing tectonic processes over the Eastern Alps lead to the extrusion of parts of the Eastern Alps towards the Pannonian basin and the Carpathians. The project ALPAACT investigates intra plate movements in the Austrian region. As part of the studies a geodetically derived horizontal velocity field has been derived.

For a selection of about 20 sites of a permanent GNSS network, which covers the area of interest, coordinate time series have been obtained. The processed GNSS network is located in the eastern part of Austria, between the Bohemian Massif in the north and the Styrian basin in the south and spreads out over the most active zones of the area. The data series span a period of 4 years (2010 to 2013) so far. Daily coordinate solutions were calculated by means of the Bernese Software and station velocities with respect to the global reference frame ITRF2000 have been derived by means of a linear regression approach.

The quality of the time series can evidently be deteriorated by data gaps and physical obstructions surrounding the reference site, significant discontinuities are mainly caused by equipment changes at the observation sites. Apart from the linear station motion also nonlinear variations with predominately an annual period show up in the time series. Nevertheless the accuracy of the provided global velocity estimates can be assumed with accuracy at the level of 0.5 mm/y for individual stations. The geodetic data are consistent with a sinistral strike–slip deformation velocity of sub–mm/y along the Mur–Mürz valley–Semmering–Vienna Basin transfer fault system. The magnitude of the deformation velocity is significantly lower than values derived earlier from large scale GNSS networks and essential for the characterization of the plate tectonic regime and a realistic estimate of seismic hazard in this area.

Keywords: Plate tectonics, Geodetic monitoring, ALPAACT

Kurzfassung

Nach wie vor andauernde tektonische Prozesse in den Ostalpen führen zu einer Extrusion von Teilen der Ostalpen in Richtung des Pannonischen Beckens und der Karpaten. Das Projekt ALPAACT (seismological and geodetic monitoring of ALpine–PAnnonian ACtive Tectonics) untersucht innerplattentektonische Bewegungen in Österreich. Im Rahmen der Studien wurde ein geodätisch abgeleitetes horizontales Geschwindigkeitsfeld generiert.

Das prozessierte GNSS Netz befindet sich im östlichen Teil Österreichs, zwischen der Böhmischen Masse im Norden und dem Steirischen Becken im Süden und erstreckt sich somit über die seismisch aktivsten Bereiche des Untersuchungsgebietes. Für eine Auswahl von ca. 20 permanenten GNSS Beobachtungsstationen wurden bisher Koordinatenzeitreihen über eine Periode von 4 Jahren (2010 bis 2013) mittels der Software Bernese berechnet. Die Koordinatenzeitreihen beziehen sich auf den globalen Referenzrahmen ITRF2000. Anhand einer linearen Regression wurden Stationsgeschwindigkeiten abgeleitet.

Die Qualität der Zeitreihen kann durch Datenlücken sowie Abschattungen an den Referenzstationen beeinträchtigt werden, wobei signifikante Diskontinuitäten vor allem durch Hardwarewechsel an den Beobachtungsstationen verursacht werden. Neben den linearen Stationsbewegungen treten in den Zeitserien auch nichtlineare Variationen mit überwiegend jährlichen Perioden auf. Trotzdem kann von einer äußeren Genauigkeit im Bereich von 0.5 mm/Jahr für die geschätzten Geschwindigkeiten der einzelnen Stationen ausgegangen werden. Die Ergebnisse der geodätischen Beobachtungen sind konsistent mit der Geschwindigkeit im sub–mm/Jahr Bereich und entsprechen einer sinistralen Seitenverschiebung entlang des Störungssystems des Mur–Mürztals, des Semmerings und des Wiener Beckens. Die Magnitude der Deformationsgeschwindigkeit ist signifikant kleiner als die Ergebnisse, welche aus frühen großräumigen GNSS Kampagnen stammen und stellt somit einen wichtigen Beitrag zur Beschreibung der plattentektonischen Situation und einer realistischen Abschätzung des Erdbebenrisikos im Untersuchungsgebiet dar.

Schlüsselwörter: Plattentektonik, Geodätisches Monitoring, ALPAACT

1. Introduction

The collision of the European and Adriatic plates, exhumation forming the Penninic windows and extrusion and tectonic escape of crustal blocks to the Pannonian basin influenced the current appearance of the Eastern Alps most strongly. Neotectonic or reactivated geological structures, seismic activity and large scale deformation patterns observed by GNSS indicate that Neogene tectonic processes are still ongoing. The Vienna Basin and the Mur–Mürz valley have been formed by pull–apart and strike–slip faults crossing the Semmering region and extending along the Mur–Mürz valley. The Mur–Mürztal and Vienna Basin fault zones are seismically the most active regions in Austria.

Within the frame of project ALPAACT (seismological and geodetic monitoring of ALpine–PAnnonian ACtive Tectonics) [6], [7], a GNSS network, located in the eastern part of Austria, between the Bohemian Massif in the north and the Styrian basin in the south, has been processed over a period of 4 years. The most northern sites belong to the Bohemian Massif, which represents the European plate and is seen as a stable part within the network. In the centre of the network, observation stations are directly grouped along the main transfer faults, which are the Mur–Mürz valley and the Vienna basin. Stations in the south–east belong to the Styrian basin, respectively the Pannonian platform.

Coordinate time series were calculated using the Bernese Software and station velocities aligned to the global reference frame ITRF2000 have been obtained to support the geophysical investigations in this area.

2. Tracking Network

The processed GNSS network includes 22 permanent GNSS observation sites, in which the stations Graz, Penc and Mattersburg are part of the global IGS network (International GNSS Service; www.igs.org) and are labelled in Figure 1 according to their official four character identification. Site TRF2 (Trafelberg) belongs to the EPN network (Euref Permanent Network; http://www.epncb.oma.be), the other sites are part of the real time positioning services EPOSA (Echtzeit Positionierung Austria) and the EVN–satellite positioning service respectively. Each station in the network is equipped with a dedicated antenna receiver and/or radome combination.

A station information file records the equipment changes at the observation sites. To account for the antenna phase center variations of the satellite and the ground antennas correction terms have been applied in the GNSS data processing. These PCV model values are derived from absolute antenna calibration techniques.

3. Data and Processing Method

Observation data from the IGS tracking stations (on both GPS carriers L1 and L2 from 24 hour sessions with a time resolution of 30 seconds) as well as other IGS products, such as precise satellite orbits, geocentric coordinates of the IGS tracking stations or Earth orientation parameters are available through the IGS data centers and are free of charge. Observation data from the EPN network are also publicly accessible. All computations have been carried out by means of the Bernese Software. In principle the coordinate time series result from two processing campaigns. One GNSS campaign was mainly set up to contribute to the investigations in the framework of the ALPAACT project and covers the period from 2010.0 to 2013.5. The associated observation network was described above and is shown in Figure 1. The second GNSS campaign, designated as PROAUT started to be operational recently and consists of about 100 sites with a distribution over the whole Austrian territory and parts of the neighbouring countries. It has been established to support various multifunctional requests, such as in the context of atmospheric studies, the estimation of station–specific tropospheric zenith path delays. The coordinate time series for the period July–December 2013 are processed within this nationwide network. Due to the update of the Bernese Software from version 5.0 to version 5.2, the usage of a new ITRF realisation or parameter estimates over unequal time intervals both campaigns cannot be assumed to be completely consistent. The processed coordinate time series for the period from 2010.0 to 2013.5 are tied to the global reference frame ITRF2000. In contrast, the coordinate time series of the last 6 months in 2013 are primarily aligned to the global reference frame ITRF2008, but have been realigned in an additional processing step to the global reference frame ITRF2000 to ensure continuity.

The processing strategies for both campaigns follow likewise the guidelines of a modern GNSS network approach [9], [12], where double differences are applied, the tropospheric refraction is handled by implementing the dry and wet Niell Mapping Functions or the dry and wet Global Mapping Functions [4] respectively. The latter

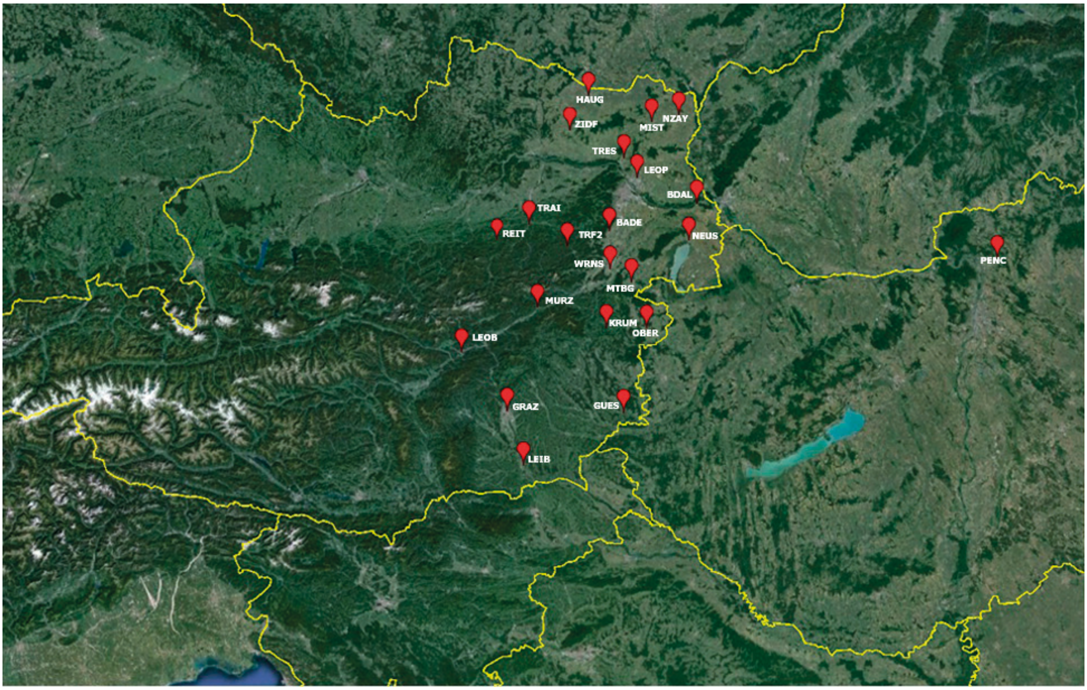

Fig. 1: Tracking GNSS network (ALPAACT)

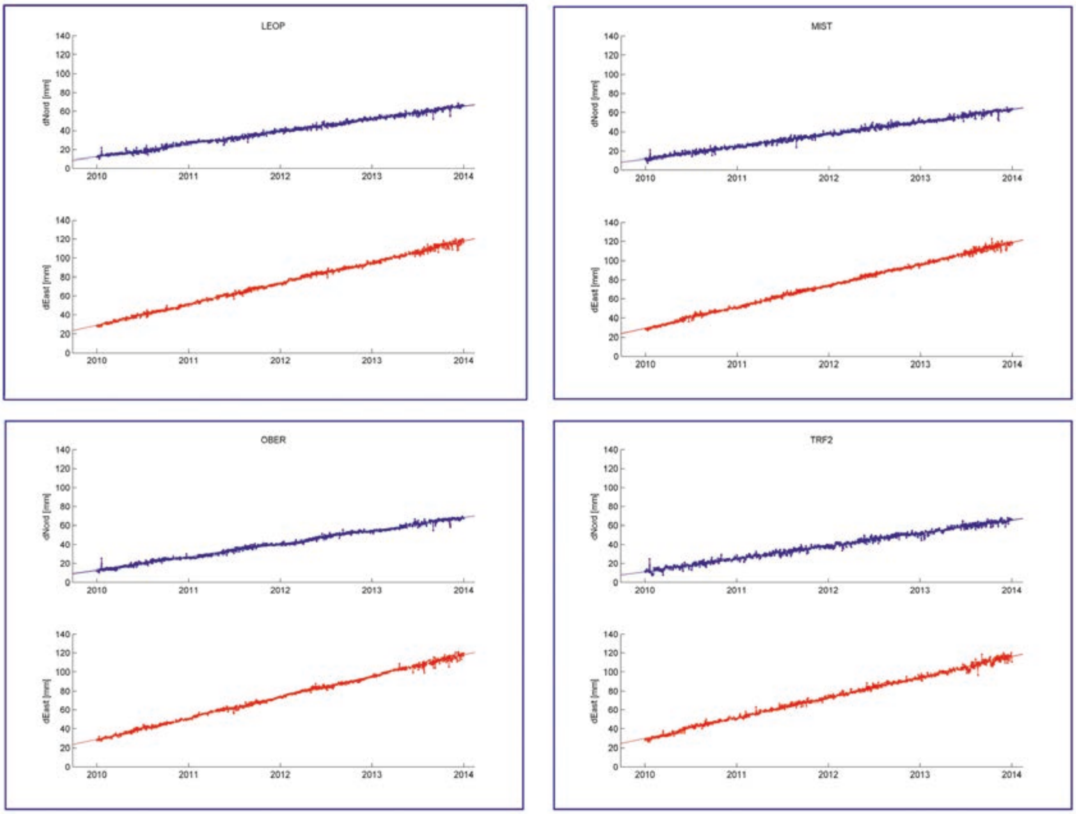

Fig. 2: Coordinate time series (2010 to 2013)

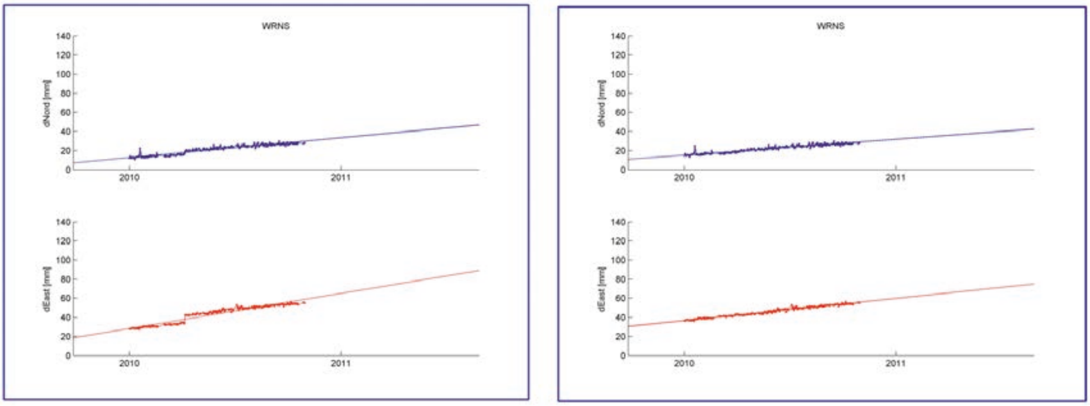

Fig. 3: Coordinate time series WRNS

are used within the nationwide campaign. The impact of the ionosphere is eliminated by computing the ionosphere-free linear combination by means of the narrow-lane strategy and daily coordinate solutions are estimated within a least square adjustment. The underlying datum of the generated network solutions in both campaigns has been defined by implementing IGS site coordinates into the processing. Regarding the ALPAACT campaign the site coordinates of GRAZ (Graz), PENC (Penc) and MTBG (Mattersburg) have been constrained to their ITRF2000 (epoch 1997.0) values. Moderate constraints ±1 mm/coordinate are applied to the coordinates of these 3 frame defining sites to avoid artificial deformations of the network.

4. Coordinate Time Series

The computed coordinate time series start on Jan, 1st, 2010 respectively the date when data for a special reference site are available for the first time. Figure 2 shows a selection of daily coordinate time series (north and east components) of the processed sites with respect at our chosen reference coordinates at epoch 2008.0: LEOP (Leopoldau), MIST (Mistelbach), OBER (Oberpullendorf) and TRF2 (Trafelberg).

Since July 1st, 2013 the temporal resolution of troposphere parameters was raised in the computations to support atmospheric studies. This switch causes due to parameter correlations a slight increase in the noise of the estimated coordinates. Although we have estimated of course 3D site coordinates all further investigations are restricted to the plane coordinates. Apart from the linear station motion, discontinuities, caused by equipment changes at the observation sites and data gaps (if the site has been decommissioned, for instance) show up in the time series. An example is given in Figure 3 (site WRNS-Wiener Neustadt), where no observation data are available since GPS-day 303 in the year 2010 and the hardware change on GPS-day 096 in the year 2010 induces a significant jump in the corresponding time series. Here the coordinate offset has been corrected accordingly before estimating a velocity vector. Figure 3 shows the coordinate time series from WRNS (Wiener Neustadt) before and afterwards the correction.

Another problem is related to natural (mountains) and physical obstructions surrounding the reference site. For example, as shown in Figure 4, poor satellite geometry at site MURZ (Mürzzuschlag) increases the noise of the estimated coordinate time series significantly in comparison to other network sites.

Even in the time series of the horizontal coordinates in north and east direction also nonlinear variations appear with predominately an annual period (seasonal effects). As example the coordinate time series for stations NEUS (Neusiedl) and TRAI (Traisen) are illustrated in Figure 5.

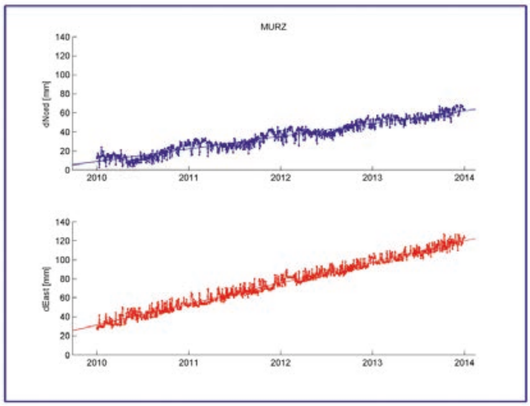

Fig. 4: Coordinate time series MURZ

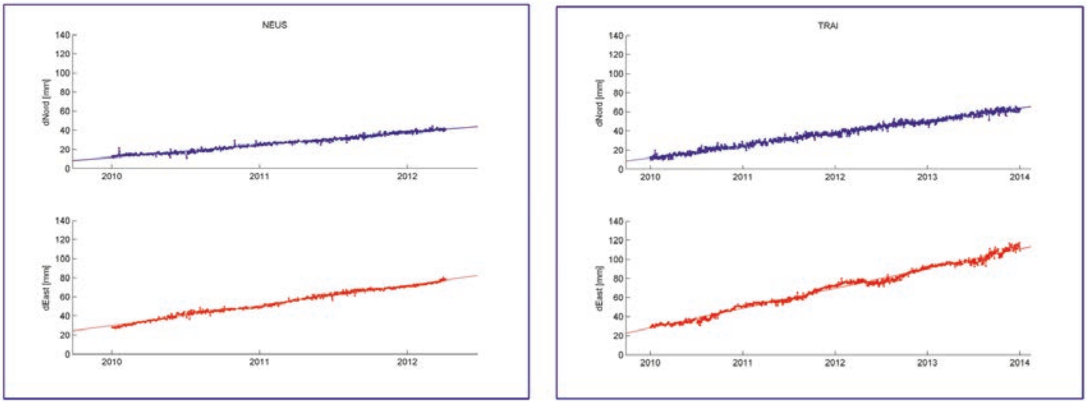

Fig. 5: Coordinate time series NEUS and TRAI

STAT	LAT (approx)	LONG (approx)	ve [mm/yr]	vn [mm/yr]
BADE	48.00	16.25	21.97	13.50
BDAL	48.12	16.92	22.31	13.37
GRAZ	47.07	15.49	21.47	13.92
GUES	47.07	16.32	22.45	13.61
HAUG	48.70	16.07	25.08	13.49**
KRUM	47.50	16.20	22.22	13.53
LEIB	46.78	15.55	21.67	14.85*
LEOB	47.39	15.09	22.67	13.36
LEOP	48.27	16.42	22.15	13.36
MTBG	47.74	16.40	22.05	13.24*
MIST	48.57	16.57	22.36	12.92
MURZ	47.61	15.68	22.07	13.35
NEUS	47.96	16.84	21.15	12.99
NZAY	48.61	16.80	23.02	11.98*
OBER	47.51	16.50	22.22	13.86
PENC	47.78	19.28	22.84	12.84
REIT	47.88	15.31	23.65	14.54*
TRAI	48.06	15.61	20.70	12.91
TRES	48.37	16.36	21.90	12.83
TRF2	47.93	15.86	21.51	13.54
WRNS	47.82	16.27	23.14	16.57**
ZIDF	48.63	15.92	21.74	13.33
* Time series with observation data less than 4 years				
**Time series with observation data less than 2 years				

Tab. 1: ITRF2000 velocities

STAT	ve_eur [mm/y]	vn_eur [mm/y]
BADE	-0.11	-0.99
BDAL	0.23	-1.12
GRAZ	-0.62	-0.57
GUES	0.37	-0.88
HAUG	**	**
KRUM	0.14	-0.96
LEIB	-0.41	0.36
LEOB	0.58	-1.13
LEOP	0.07	-1.13
MTBG	-0.03	-1.25
MIST	0.28	-1.57
MURZ	-0.01	-1.14
NEUS	-0.94	-1.50
NZAY	0.94	-2.51
OBER	0.14	-0.63
PENC	0.76	-1.65
REIT	1.57	0.05
TRAI	-1.39	-1.58
TRES	-0.18	-1.66
TRF2	-0.57	-0.95
WRNS	**	**
ZIDF	-0.34	-1.16
**data gaps		

Tab. 2: Mean Eurasian velocities

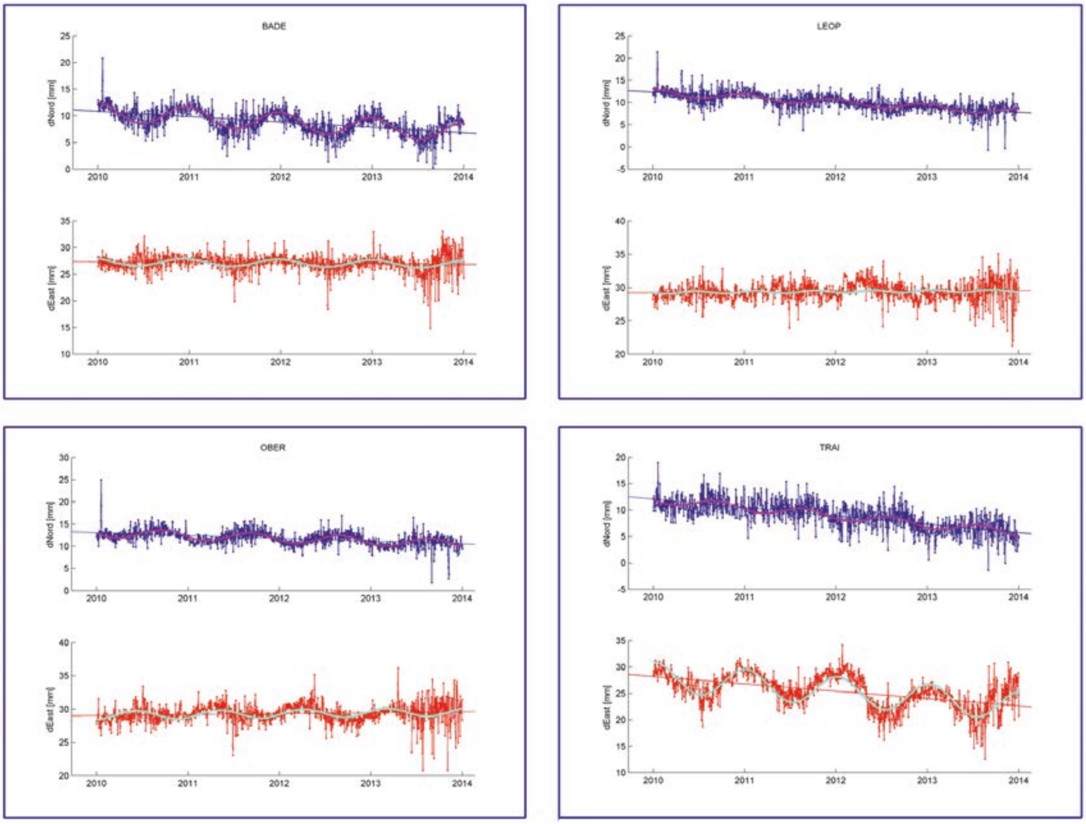

Fig. 6: *Local station movement*

5. Estimation of ITRF Velocites

Annual station velocities with respect to the global reference frame ITRF2000 have been derived by means of a linear regression approach. A full list of the global site velocities for the components east (ve) and north (vn) is detailed in Table 1.

The formal error of the provided velocity components is at the +/– 0.2 mm/year level while a more realistic accurcacy estimate points (depending on the individual site) at the +/– 0.5 mm/y level.

As the velocity estimates during the processing period are partly harmed by missing data, we restrict our further interpretations on the site velocity estimates, where at least observation data for more than 2 years are available.

6. Motion with respect to the Eurasian Plate

To obtain a motion field with respect to the Eurasian plate every ITRF site velocity has to be corrected by the common Eurasian plate motion. There are several meaningful methods to apply this correction. Here we have a straight forward approach by subtracting the mean ITRF2000 velocity of the IGS site GRAZ (ve_Graz = 22.07mm/y; vn_Graz =+14.56mm/y). Practically every site coordinate has been referred to the corresponding motion of site GRAZ. In a further step the remaining velocity has been estimated by means of a linear regression. Table 2 summarizes the estimated mean station velocities in north and east direction (ve_eur) and (vn_eur) with respect to the Eurasian plate.

7. The Local Trend – Non Linear Variations

The remaining trend in the signal reflects the local station movement and can be further analyzed: As already mentioned in chapter 4 at most stations periodical (annual) motions superimpose the mainly linear station motions. To insulate this periodic effects from further interpretation and most of all to prevent a systematically wrong estimation of the underlying linear station motion we tried to estimate phases and amplitudes of this periodic behaviour. The values for the parameters amplitude, phase and period are estimated by applying a minimum search algorithm. Corre-

STAT	eAmp [mm]	ePha [days]	nAmp [mm]	nPha [days]
BADE	0.69	7.33	1.78	19.16
LEOP	0.39	20.74	0.72	12.40
OBER	0.62	14.07	1.03	13.77
TRAI	2.74	18.86	0.76	13.33

Tab. 3: Amplitude and phase computed from data for the time span (2010 to 2013)

sponding for a selection of sites the periodicity in east and north direction is illustrated in Figure 6.

As all the resulting periods were close to one year (346 days – 375 days) we fixed the period to exactly one year. The remaining values for the amplitudes (eAmp, nAmp) and phase (ePha, nPha) in the components east and north are shown in Table 3. North and east components are handled separately.

Additionally corrections (due to the correct accounting for periodical effects) for the site velocities have been obtained from the processed period from 2010.0 to 2014.0. Most of this corrections are well below the 0.05 mm/y level, but some are not negligible (such as for instance for site NEUS with correction values of 0.14 mm/y in east and –0.08 mm/y in north direction respectively). These corrections are due to phase angles far different from 0 degree of the periodic effects which map into the linear motion coefficients.

8. Resumé

Coordinate time series for the years 2010, 2011, 2012 and 2013, which are tied to the global reference frame ITRF2000 (epoch 1997.0) have been processed. The velocity estimates of the stations HAUG and WRNS are of less quality due to equipment changes and large data gaps during the considered observation period and have not been considered in the further analysis. Finally the station velocities with respect to the Eurasian plate have been computed from the available data sets. The finally achieved velocity estimates (ve_vel, vn_vel) with respect to a mean motion of the Eurasien plate are summarized in Table 4 below.

Figure 7 shows the velocity vectors plotted on a geological map. The average velocity value of all stations in the target area has beeen subtracted in order to enhance the local tectonic kinematics. At a first view these velocity vectors appear rather randomly distributed with a few outliers (LEIB, NZAY, REIT, TRAI). We consider the velocity components parallel to the Mur–Mürz and Vienna Basin transfer fault system and exclude stations on or near the fault system (BADE, BDAL, LEOB, MTBG, MURZ). A sinistral

STAT	ve_vel [mm/y]	vn_vel [mm/y]
BADE	–0.12	–1.01
BDAL	0.16	–1.10
GRAZ	–0.61	–0.58
GUES	0.27	–0.85
HAUG	**	**
KRUM	0.12	–0.97
LEIB	–0.43	0.41
LEOB	0.56	–1.11
LEOP	0.06	–1.14
MTBG	0.02	–1.30
MIST	0.24	–1.57
MURZ	–0.01	–1.08
NEUS	–0.80	–1.58
NZAY	0.90	–2.52
OBER	0.16	–0.72
PENC	0.73	–1.63
REIT	1.57	0.08
TRAI	–1.34	–1.63
TRES	–0.21	–1.70
TRF2	–0.60	–0.99
WRNS	**	**
ZIDF	–0.34	–1.18
**data gaps		

Tab. 4: Final estimated velocities in the components north and east

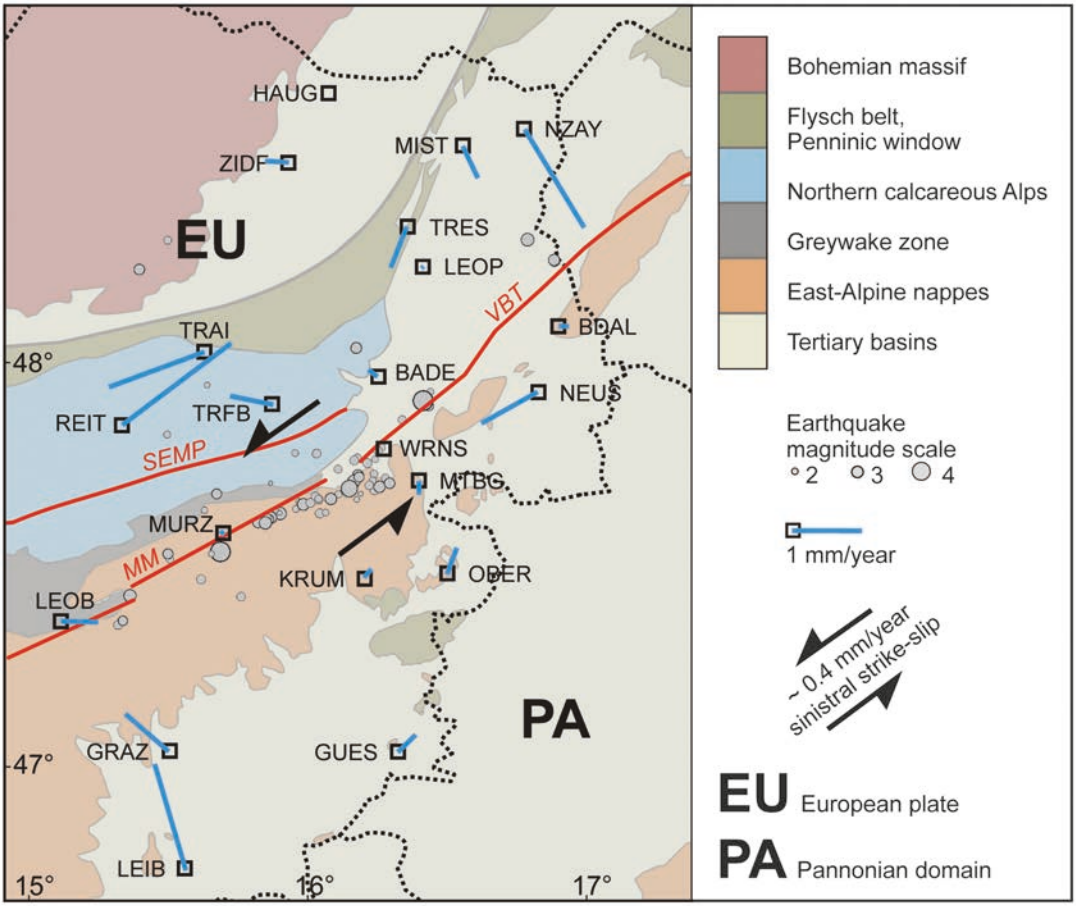

Fig. 7: Generalized geological map of the study area (generalized after [13]) and velocity vectors; SEMP …Salzachtal – Ennstal – Mariazell – Puchberg fault, MM …Murtal – Mürztal fault, VBT …Vienna basin transfer fault system; earthquake epicentres from 2009–05–07 to 2013–09–20 [7].

strike–slip movement of 0.35 mm/y of the Pannonian domain (GRAZ, GUES, KRUM, LEIB, OBER) relative to the European plate (LEOP, MIST, NZAY, REIT, TRAI, TRES, TRFB, ZIDF) along the fault system (average strike 54°, NE–SW) follows from this data. In case we exclude the outliers from the calculation we get 0.43 mm/y. Both values for the magnitude of the strike–slip movement are much lower than the value of about 1.5 mm/y assumed in earlier studies [3], [11]. The average seismic slip rate was estimated to 0.22 – 0.31 mm/y for the Vienna Basin transfer fault by the analysis of earthquake catalogues [11]. Therefore our new geodetically observed slip rate reduces significantly the estimated seismic slip deficit and should be considered in future studies concerning seismic hazard in the Vienna Basin.

The magnitude of sinistral slip along the Mur–Mürz and Vienna Basin transfer faults system imposes a constraint on the plate tectonic system in the Eastern Alps. This system is built by the European plate (EU), the Adriatic micro–plate (AD) and the Pannonian domain (PA), which may be considered as a third tectonic plate [5]. The lithospheric mantles of these tectonic blocks form a triple junction at 13.6°E, 46.7°N. Figure 8a shows a simplified model of this plate tectonic scheme valid for the actual geodynamic situation [8].

It is assumed that the triple junction is actually moving along the AD–PA plate boundary to the southeast, changing the plate boundary from dextral strike–slip to subduction behind it. The velocity triangle at this triple junction (Figure 8b) is determined by the northward orientation of the

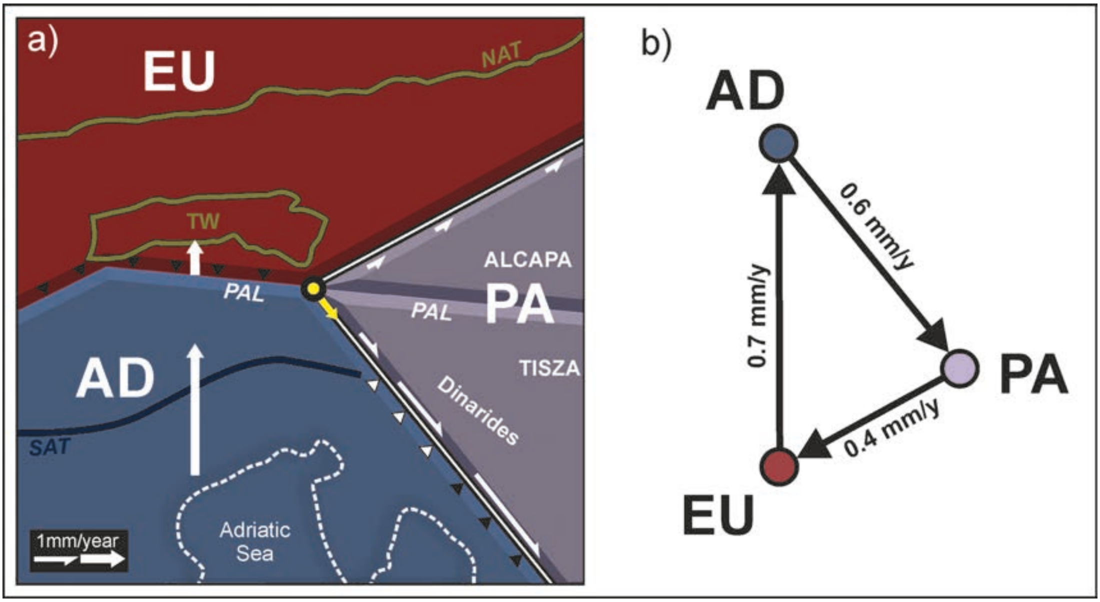

Fig. 8: Plate tectonic model of the lithospheric mantle of the Eastern and Southern Alps; ***a)*** *generalized model of the plate tectonic regime (modified after [8]); AD (Adriatic micro–plate), EU (European plate), PA (Pannonian domain), NAT (Northern Alpine thrust fault), PAL (Periadriatic lineament), SAT (Southern Alpine thrust fault), TW (Tauern Window);* ***b)*** *velocity triangle of the stable triple junction AD – EU – PA marked by a black circle with yellow fill in a).*

velocity of AD versus EU, the stability condition for this type of triple junction and the sinistral strike–slip velocity at the EU–PA boundary as derived from our new GNSS data (Figure 8b). It is assumed that a compressional zone observed by GPS in the Southern Alps [10] comprises also the lithospheric AD mantle [5]. The northward oriented velocity of AD versus EU is reduced from about 2.5 mm/y to a subduction velocity of 0.7 mm/y at the AD–EU boundary by this intra–plate compression.

Future investigations should clarify if the outliers could be caused by geotechnical circumstances (e.g., unstable foundation of the buildings where the antennas are installed) or be local geological processes (e.g., mass movements). Further, the time series shall be enhanced by regularly processing the observation data close to the current day. Currently GNSS observation data from 2010.0 to 2015.0 (even for the whole Austrian territory) can be made available by the contributing organisations. To enhance the time bases of the coordinate series towards half of a decade promises consistent velocity estimates for individual stations at the +/–0.3 mm/y level. Furthermore a more detailed investigation of non–linear station motions is proposed.

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