Tectonic implications of the GPS velocity field in the northern Adriatic region

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[1] Continuous and episodic GPS observations between 1991 and 2004 show that Adria moves independently of both stable Eurasia and Nubia. Adria moves NNE at 3–4.5 mm/yr increasing from N to S relative to Eurasia and may be fragmenting along the Gargano-Dubrovnik seismic zone. The observed 2–3 mm/yr of N-S Adria-Eurasia convergence is taken up by contraction across a narrow (~70 km) zone in the Eastern Alps and concomitant extrusion of the Alpine-North Pannonian unit. The Adria-Central Dinarides boundary is a broader collisional zone with intense 1–1.5 mm/yr shortening near shore and 2 mm/yr spread across the Dinarides. The remaining 1–2 mm/yr motion E of the Alps and NE of the Dinarides is absorbed by the inverted contracting Pannonian basin leaving no significant deformation above 0.5 mm/yr in the Western and Northern Carpathians, and European Platform.
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1. Introduction

[2] The geometry and motion within the Eurasia-Nubia convergent boundary zone in the northern Adriatic remain poorly known. Models based on geological and recent geodetic data provide different relative velocity values for the two major plates ranging between 3–9 mm/yr. The NUVEL-1A geologic model predicts 8–9 mm/yr [*DeMets et al.*, 1994] at 36°N 15–20°E. The GPS based REVEL-IT97-2000 predicts 6 mm/yr [*Sella et al.*, 2002] whereas other space geodetic models summarized by *Nocquet and Calais* [2004] show slower rates.

[3] Various models have been proposed for the geometry of the central Eurasia-Nubia boundary zone. Adria, the NE-SW oriented essentially aseismic area mostly under the Adriatic Sea may have evolved as a promontory of Africa [*Channell*, 1996]. It may now be part of Nubia, a single independent microplate [*Anderson and Jackson*, 1987; *Ward*, 1994], or two blocks either attached to the major plates [*Oldow et al.*, 2002] or independent of them [*Battaglia et al.*, 2004]. It is also unclear how Adria interacts with Eurasia along its eastern and northern boundaries in the Dinarides and Eastern Alps. Understanding these interactions is important not only because of the active deformation and seismic hazard along the boundaries but also because they impose far-field stresses on the broad Alpine-Dinaric-Carpathian system. Although the general evolution of the Carpathian-Pannonian complex is well constrained [*Csontos et al.*, 1992], there have been recent changes in the tectonic regime including the inversion of the Pannonian basin such that extensional structures are now under compression [*Bada et al.*, 1999]. Quantifying present crustal motions is thus important for neotectonics and seismic hazard assessment.

2. Data

[4] We investigate these issues using data from the Central European GPS Geodynamic Reference Network (CEGRN) and the European Permanent GPS Network (EPN). The CEGRN, established in 1993 [*Fejes et al.*, 1993] is operated by the CEGRN Consortium, funded by the European Union [*Pesec*, 2002], and covers 14 countries in the region. CEGRN sites have fixed antenna mounts, and half of them are directly on outcropping bedrock. Seven campaigns were organized between 1994 and 2003 at the same time of the year, and all sites were occupied simultaneously for five 24 hr periods. After expansion and densification of the network in 1997, the number of the sites doubled. Data were processed using Bernese 4.2 [*Beutler et al.*, 2001]. IGS pole information, satellite maneuvers, and precise orbits were used, and the SIGMA dependent strategy was applied for ambiguity resolution. Daily coordinate and covariance files were calculated on L3 linear combination, using double differences, Saastamoinen troposphere model, elevation dependent weighting, and hourly troposphere parameter estimation using all observations above 10°. We obtained daily repeatabilities of 1.5–2.5 mm in the horizontal and 4.5–6 mm in the vertical components and used them to scale the covariance matrices. We also computed a cumulative solution of all EPN continuous GPS sites since GPS week 860. After the detection of offsets in the time series due to equipment

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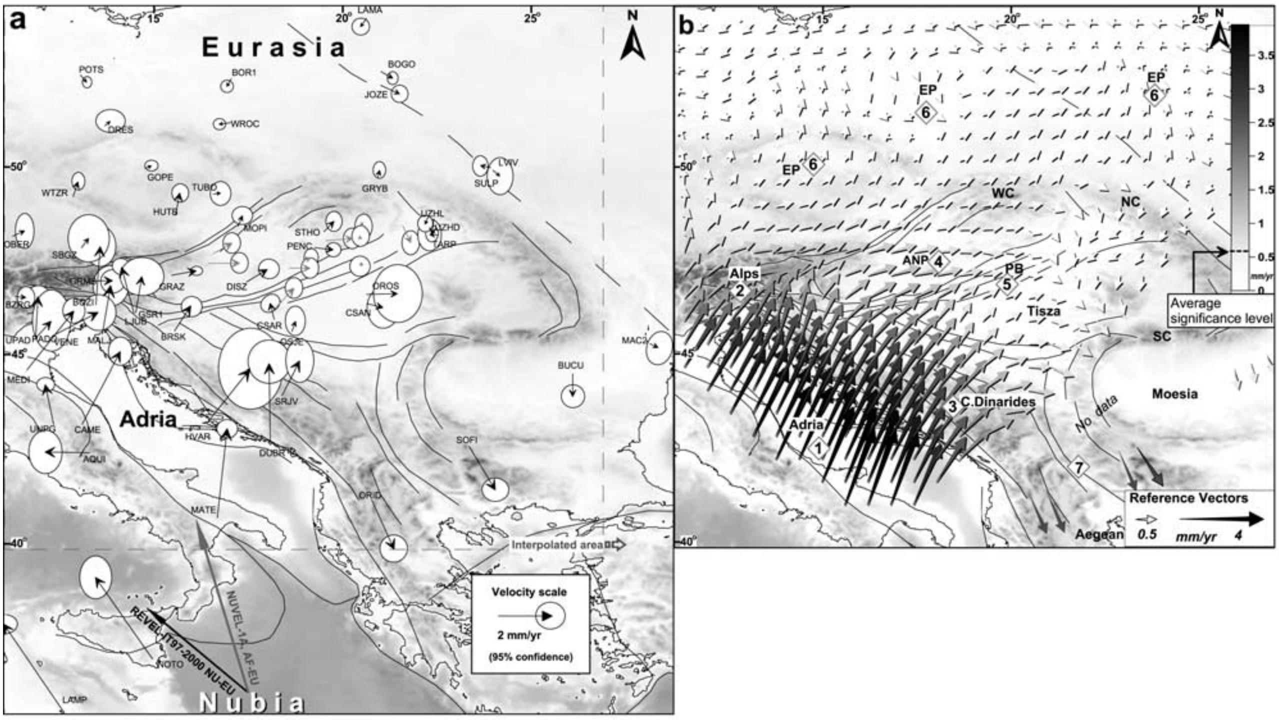

Figure 1. (a) GPS velocities with respect to Eurasia. A velocity solution from the Pannonian basin in the same frame is also indicated in grey after *Grenerczy* [2002]. (b) Interpolated GPS velocity field and tectonic interpretation for different regions. EP: Domains of the European Platform, WC, NC, SC: Western, Northern, and Southern Carpathians, ANP: Alpine-North Pannonian unit, PB: Pannonian basin. Numbers denote suggested major tectonic processes: 1: 3–4.5 mm/yr NNE motion of the Adria microplate; 2: Adria-Alpine collision with 2.3 mm/yr shortening; 3: Adria-Dinarides collision with 3.5 mm/yr shortening; 4: 1–1.5 mm/yr extrusion of the Alpine-North Pannonian unit; 5: 4 ppb/yr contraction and inversion of the Pannonian basin; 6: <0.6 mm/yr stability of the Carpathians and the European Platform; 7: 2–2.5 mm/yr extrusion and extensional collapse between Adria-Moesia.

change, antenna and monumentation problems, and periodicities, the scaled velocity uncertainties were estimated accounting for both white and flicker noise based on the maximum likelihood estimation approach of *Williams et al.* [2004]. The single self-consistent velocity solution was performed with the combination of weekly normal equations of the EPN, and those of the CEGRN using the ADDNEQ module of the Bernese 4.2. We used 11 IGS sites to tie the solution to the ITRF2000 with similarity transformation. The motion of rigid Eurasia was removed by a least squares inversion of the ITRF velocities at sites located on the stable European Platform (Table A1[1]). The random orientation and the ~0.3 mm/yr mean residual velocity indicate the accuracy and high rigidity of this frame.

3. Results

[5] Figure 1a shows the calculated GPS site velocities (Table 1) in the central part of the Eurasia-Nubia plate boundary zone. Based on this velocity map an interpolated velocity field was also calculated (Figure 1b) using the point Kriging method with linear variogram. No faults were introduced during the interpolation that would allow abrupt changes since their present activity and extent are not adequately resolved. The resulting velocity field highlights our tectonic interpretation indicated with numbers on Figure 1b.

4. Discussion

[6] GPS sites on Nubia converge on Eurasia at 5 ± 0.5 mm/yr oriented ~326° (Figure 1a), 3–4 mm/yr slower and more westward than predicted by NUVEL-1A. Applying F-ratio tests [*Stein and Gordon*, 1984] to subsets with increasing numbers of sites from N to S that may be on the Adria microplate shows that an independent Adria can be resolved. The North Adria subsets provide similar poles and angular velocities. However, the residuals at the southernmost sites and the change in Euler vector resulting from including these sites (Figure 2) together with the seismicity (Figure 3) suggest a deformation zone within the microplate. This likely corresponds to the Gargano-Dubrovnik seismic zone (GDSZ) where transpressional deformation from the differential motion of the fragmented microplate occurs.

[7] On South Adria, sites move to the N instead of NNE predicted from North Adria Euler vector. The whole Adria pole also shifts to west and the fit gets worse. However, assessing the existence of a rigid block south of the GDSZ

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL022947.

Table 1. Velocities Relative to Eurasia (Figure 1) in North (N) and East (E) Together With 95% Error Limits[a]

Name	N	Err	E	Err	Name	N	Err	E	Err	Name	N	Err	E	Err	Name	N	Err	E	Err
AQUI	0.0	1.1	−2.2	0.8	GRAZ	0.2	0.2	1.2	0.3	MEDI	2.9	0.7	2.2	0.6	SULP	−0.3	0.9	0.4	0.6
BOGO	−0.3	0.3	0.6	0.2	GRMS	0.0	0.6	1.0	0.6	MOPI	0.5	0.4	0.2	0.5	TARP	0.0	0.8	−0.4	0.6
BOR1	−0.4	0.3	−0.2	0.3	GRYB	0.4	0.4	0.1	0.3	NOTO	3.9	1.1	−2.7	0.8	TORI	0.3	0.5	0.5	0.6
BOZI	2.8	1.0	0.2	0.8	GSR1	1.7	0.9	0.3	1.1	OBER	0.3	0.9	0.6	0.4	TUBO	0.1	0.6	0.4	0.5
BRSK	1.2	0.5	0.8	0.5	HUTB	1.1	0.4	0.2	0.4	ORID	−2.4	0.7	1.1	0.7	UNPG	1.9	0.3	−0.4	0.5
BUCU	−1.1	0.6	0.0	0.6	HVAR	2.5	2.0	2.0	1.6	OROS	0.0	1.4	1.5	1.2	UPAD	2.0	0.5	0.1	0.7
BZRG	0.0	0.5	0.5	0.4	JOZE	−0.4	0.4	0.9	0.4	OSJE	0.5	0.7	0.2	0.4	UZHD	−0.8	0.4	−0.1	0.3
CAME	3.4	0.7	1.8	0.6	LAMA	−0.4	0.4	−0.3	0.4	PADO	0.7	1.5	0.6	0.9	UZHL	−0.4	0.4	−0.2	0.4
CSAN	−0.2	1.0	0.8	0.8	LAMP	4.2	0.4	−2.8	0.7	PENC	−0.1	0.3	0.9	0.4	VENE	1.2	0.9	2.2	0.9
CSAR	0.8	0.4	−0.2	0.5	LJUB	2.2	0.4	−0.6	0.5	POTS	−0.4	0.3	0.3	0.2	WROC	−0.1	0.3	−0.6	0.3
DISZ	0.6	0.5	1.0	0.5	LVIV	0.1	0.5	−0.5	0.3	SBGZ	0.5	1.2	0.3	1.0	WTZR	0.8	0.4	0.2	0.3
DRES	0.2	0.6	0.3	0.8	MAC2	−0.2	0.9	0.4	0.7	SOFI	−2.1	0.6	1.2	0.7					
DUBR	3.8	1.1	−0.1	1.1	MALJ	2.3	1.0	0.4	0.9	SRJV	1.7	1.1	0.9	0.7					
GOPE	0.1	0.2	0.3	0.3	MATE	4.3	0.4	0.4	0.5	STHO	0.5	0.5	0.5	0.4					

[a]All data are in mm/yr. Eurasia-IT00 pole is listed on Figure 2. For details see Table A1.

is not possible as only two sites (MATE, DUBR) are available. In addition DUBR has a short time series and may be in the eastern boundary zone of Adria.

[8] As a result of the ccw Adria-Eurasia rotation (Figure 2) the Alps experience different deformation styles. In contrast to extension and transtension obtained for the Western Alps [*Calais et al.*, 2002], we observe 2–3 mm/yr N-S convergence between the Eastern Alps and Adria (Figure 3a). This motion abruptly drops below 0.5 mm/yr implying a net 30 ppb/yr contractional strain rate. However, the Eastern Alps are not a linear belt experiencing pure N-S shortening. Instead, the GPS velocities show that the Alpine-North Pannonian unit (ANP) is being squeezed out between Adria and the European Platform (Figure 1b), so strike-slip motion also plays a major role in absorbing the shortening. The seismicity profile shows increased, moderately deep activity (<60 km) in the Eastern Alps south of the Periadriatic lineament (PL). Both the GPS velocities and the seismicity profile indicate that the contraction is concentrated within a narrow ∼70 km deformation zone south of the PL, whereas to its north, northward motion ceases (Figure 3a). Consequently, faults south of the PL have both dextral transpression and pure thrust faulting, whereas the motion is primarily sinistral strike-slip at the northern boundary of the ANP that is consistent with the focal mechanisms [*Gerner et al.*, 1999].

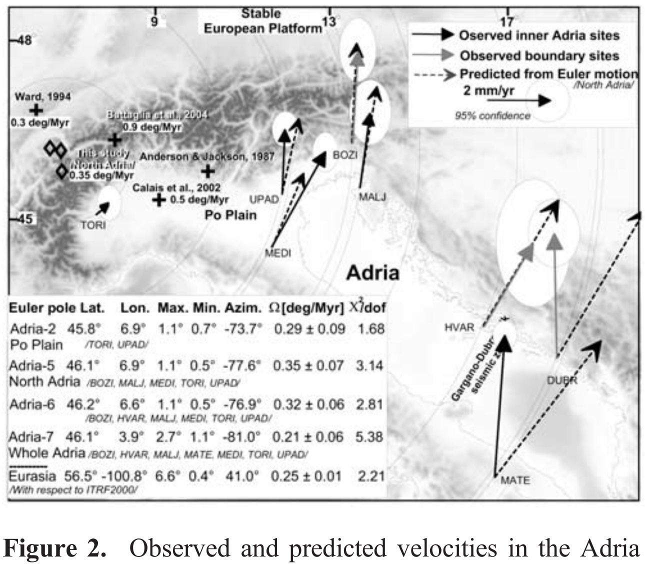

Figure 2. Observed and predicted velocities in the Adria region. Insert shows the Euler vectors with respect to Eurasia.

[9] A velocity profile across the Central Dinarides (Figure 3b) shows Adria moving 4–4.5 mm/yr NNE. The seismicity in the Adriatic Sea is localized along the GDSZ with areas on either side being relatively aseismic (compare upper seismic profile in Figure 3b with the lower and that of 3a). The seismicity and GPS velocities suggest that 1–1.5 cm/yr intense shortening occurs near the shore along the SE rigid part of Adria and probably decrease to the NW where Adria seems to have internal deformation along the GDSZ. Inland across the Central Dinarides the limited data seem to indicate uniform ∼2 mm/yr shortening across the whole mountain range, but intermediate or deep seismicity has not been clearly observed under the Dinarides. The fault mechanisms are mainly pure thrust but because of the slightly oblique convergence dextral transpression also occurs.

[10] In contrast to the Eastern Alps, the Central Dinarides do not absorb the total convergence, leaving 1 ± 0.5 mm/yr motion further inland. This contrast is probably due to the different tectonic styles. Because the thin, weak lithosphere of the Pannonian basin is located E of the N-S compression in the Eastern Alps, eastward extrusion and strike-slip deformation contribute to taking up the deformation. However, because the basin is behind the Central Dinarides rather than to their side and there is no rigid "backstop" like the European Platform behind the Alps, no lateral extrusion occurs. Finally, to the south between Adria and rigid Moesia we observe 2–2.5 mm/yr SE extrusion (Figure 1b), probably related to the Aegean extension.

[11] We observe 1.5 ± 0.5 mm/yr shortening across the Pannonian basin (Figure 1), reflecting present-day inversion of extensional structures from its Neogene formation. The GPS data show that the basin absorbs both the motion of the squeezed-out ANP and the remaining motion across the Dinarides at the Tisza unit. Thus the basin experiences E-W shortening in the north and NE-SW in the south. However, the kinematics of the implied transpressional NE-SW shear zone crossing the basin cannot yet be well quantified.

[12] The Miocene orogens of Western and Northern Carpathians form the boundary between the Pannonian

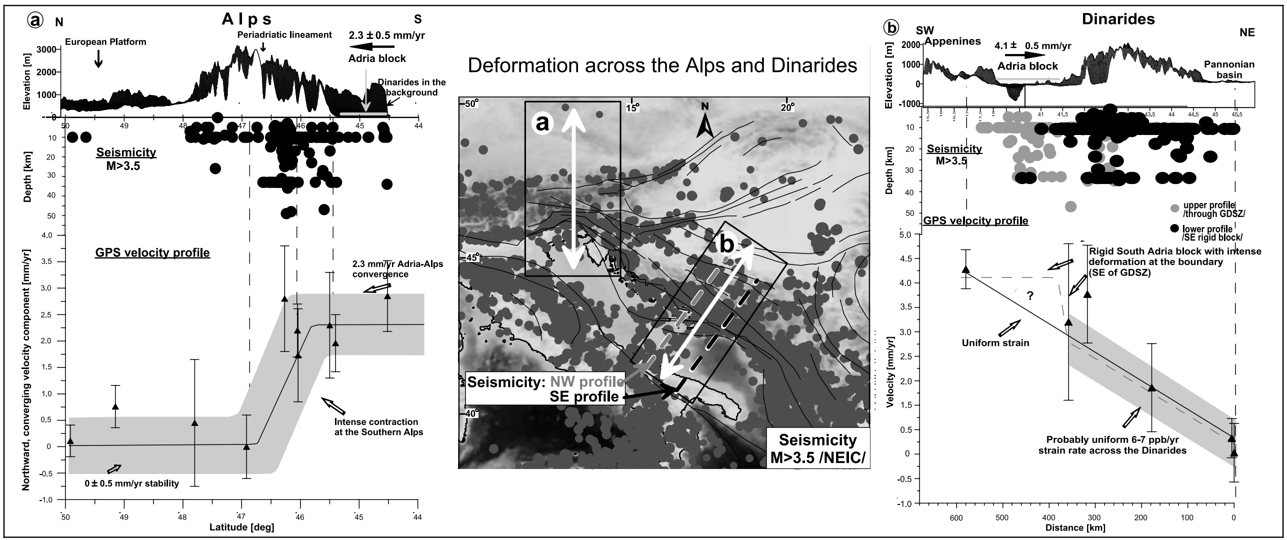

Figure 3. Topography, seismicity, and GPS velocity profiles across the Eastern Alps (a) and the Central Dinarides (b). Cross sections are perpendicular to the mountain belts, contraction, seismic belt, and parallel with the trajectories of the Adria convergence.

basin and the stable interior of Eurasia. We find no present deformation at the mm/yr level here, indicating that the Alps, Dinarides, and Pannonian basin take up the shortening caused by Nubia/Adria convergence. Hence the Western and Northern Carpathians are no longer active thrust fronts and can be considered parts of the stable and rigid European Platform.

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